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Dendroclimatological Analysis and Fire History of Longleaf Pine (*Pinus Palustris* Mill.) in the Atlantic and Gulf Coastal Plain

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To the Graduate Council:

I am submitting herewith a dissertation written by Joseph P. Henderson entitled "Dendroclimatological Analysis and Fire History of Longleaf Pine (*Pinus Palustris* Mill.) in the Atlantic and Gulf Coastal Plain." 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:

Carol Harden, Ken Orvis, David Buckley

Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

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

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Graduate Studies

DENDROCLIMATOLOGICAL ANALYSIS AND FIRE HISTORY OF LONGLEAF PINE (*Pinus palustris* Mill.) IN THE ATLANTIC AND GULF COASTAL PLAIN

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

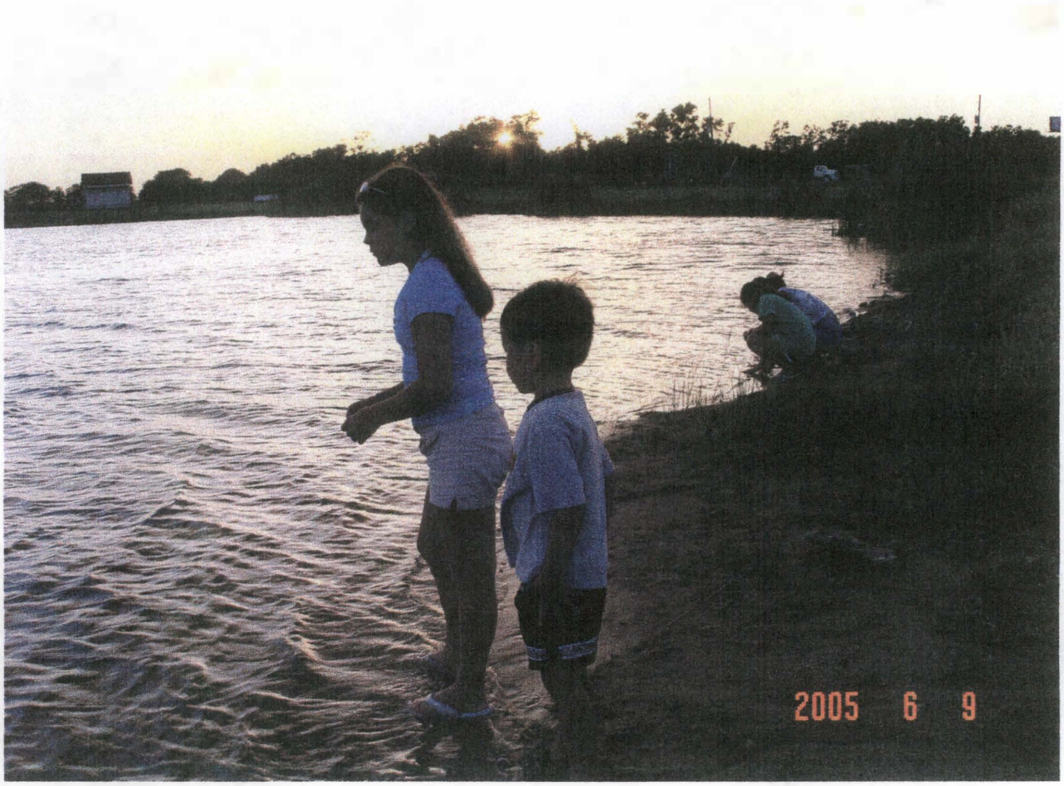
Joseph P. Henderson
August 2006

Dedication

This dissertation is dedicated to my wife, Kye Hwa,

and children, Rose, Suzie and Shane,

for all their support, inspiration, and love.



Dedication

This dissertation is dedicated to my wife, Kye Hwa,

my children, [illegible] and [illegible],

for all their support, sympathy, and love.

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I want to express my sincere appreciation to my major professor, Dr. Henri Grissino-Mayer, for his teaching, mentorship, and enthusiastic encouragement in the pursuit of my degree. Dr. Grissino-Mayer inspired me daily to go above and beyond the "call of duty." I also thank the members of my dissertation committee, Drs. Carol Harden, Ken Orvis, and David Buckley, for their guidance and superb instruction.

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Abstract

The purpose of this research was to use longleaf pine trees at three major sites in the Southeastern Coastal Plain to: (1) determine how longleaf pine trees respond to climate, (2) reconstruct past climate conditions using long tree-ring chronologies, (3) determine the effects of atmospheric teleconnections on longleaf pine growth, and (4) reconstruct fire history from fire-scar data. The native range of longleaf pine and its associated communities extends from southeastern Virginia south and westward to the Trinity River in eastern Texas. I collected samples from living and remnant longleaf pine wood in coastal South Carolina, Eglin Air Force Base in the Florida panhandle, and the Big Thicket National Preserve of Texas.

In the climate response analysis, the Palmer Drought Severity Index (PDSI) and Palmer Hydrological Drought Index (PHDI) had the highest correlation with longleaf pine growth. The strongest relationships between longleaf pine growth and the Palmer indices occur between the months of July and November. Precipitation in the spring and summer was also positively related to growth at all sites. The relationship between temperature and growth was the weakest among all climate variables, but warm summer temperatures had a consistent, negative relationship with longleaf pine growth. The climate signal in the latewood was generally more robust than those in total ring width and earlywood width.

I developed chronologies for total ring width at all sites and for earlywood and latewood widths in Texas and South Carolina. The master chronologies for each site spanned the years from 1629–2003 in Texas, 1503–2003 in Florida, and 1455–2003 in

South Carolina. I reconstructed September PHDI at all sites using a transfer function with tree-ring indices as the independent variable. For all reconstructions, the most widespread and intense year of drought since 1700 was 1925. The driest five-year period common to all reconstructions was 1951–1955. At decadal scales, extremely wet periods were often followed immediately by extremely dry periods. My reconstructions showed evidence for several historic disturbances, including the Charleston earthquake of 1886 and the arctic outbreak of 1835. Spectral analysis showed no significant spectral signatures in any of the reconstructions.

Atmospheric teleconnnections such as El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), the North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO) significantly affected longleaf pine growth at all sites, but the strength of the teleconnections varied through time. ENSO in the summer and fall correlated significantly with tree growth in Texas and South Carolina. The PDO in the year prior to growth was generally directly related to longleaf pine growth, while PDO in the current year usually showed an inverse association. The NAO from August of the previous year and May of the current year were generally negatively related to longleaf pine growth. The AMO was generally positively associated with longleaf pine growth in all months of the year.

The reconstruction of fire history revealed that fire was frequent at all sites prior to the advent of fire suppression in the 20th century. The nature of the fire regime varied according to site conditions, such as the size of fire compartments and soil types. Fire frequency and seasonality of fires were also variable over time, reflecting the combined influence of climatic conditions and anthropogenic ignitions. Fire-scarred samples were

not particularly abundant at any of the sites, and most scars were embedded deep inside the tree rather than on obvious, fire-scarred surfaces. Trauma rings that are abundant at the root-stem interface may be useful indicators of injury from fire, but more samples will be required to verify this hypothesis.

Table of Contents

Chapter Page

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Purpose

The purpose of this dissertation is to reconstruct climate and fire history in the Atlantic and Gulf Coastal Plain over the past several centuries using data obtained from longleaf pine (*Pinus palustris* Mill.) trees. In addition, this study examined the climate response of longleaf pine to a number of variables that included atmospheric teleconnections. Because longleaf pine is both long-lived and widely distributed across the Coastal Plain, this tree is ideal for the spatial and temporal context of the research. The study is the first conducted in the Southeast to combine both dendroclimatology, the science of reconstructing past climates using tree rings, and dendropyrochronology, the science of reconstructing past fire regimes using tree rings.

1.2 Theoretical Context

1.2.1 Proxy Indicators of Paleoenvironment

1.2.1.1 Climate Proxies

Predicting future trends in climate conditions requires an understanding of climatic trends in the past and an examination of the cycles of climate change on various temporal and spatial scales. Having the historical context to evaluate present conditions is crucial as we confront increasing concerns about possible human-caused changes in the environment during the 20th century (Swetnam *et al*. 1999). In the continental United

States, the instrumental record provides a generally reliable gauge of climate variability, but the data are limited to little more than a hundred years (and less in most locations). While the instrumental record may be adequate for examining weather phenomena and making short-term predictions, 100 years of data are woefully inadequate for understanding the slow-moving engine that is climate. In the broader context of climate history, the instrumental record is sometimes far from what is "normal," and examining the bigger picture of climatic trends enables a more accurate assessment of the magnitude and significance of environmental changes taking place today (Norris 2000). Studying natural variability over longer timeframes also helps to reveal complex connections and oscillatory modes in ocean-atmospheric systems that may operate on extended timescales (for example, ≥ 25 years).

Because of this information gap in instrumental data, other indicators of climate are needed to reconstruct climate conditions in the distant past. These clues are commonly known as "proxy" indicators because they are substitute or indirect measures of the climate variables in question. Numerous climate proxies are commonly employed in paleoclimatic studies and include measures of lake levels (Rosenmeier *et al.* 2002) and analysis of relict landforms such as eolian deposits (Menking and Anderson 2003) and glacial moraines (Yarocque and Smith 2003). In addition, cores from lakes (Delcourt and Delcourt 1985), marine bottoms (Hodell *et al.* 1991; Poore *et al.* 2005), ice sheets/caps (Thompson *et al.* 1984; Ramirez *et al.* 2003), and long-lived trees serve as excellent climate proxies (Mann 2002). Stable isotope data from corals provide annual resolution of historical sea surface temperatures (Quinn *et al.* 1993; Dunbar *et al.* 1994). Packrat midden records have also proven to be useful archival records of climate (Betancourt *et al.* 1990).

Each of these climate proxies has its own merits and deficiencies, but only a few possess the accuracy and resolution of tree-ring data. Trees can be highly sensitive to changes in moisture and temperature conditions from year to year, and the trees respond to climatic variation by changing their rates of annual growth (Kozlowski 1971; Schweingruber 1988; Fritts 2001). Proxy data that display annual resolution, such as tree-ring data, are rare. Moreover, the accuracy of the climate response can be statistically verified in tree-ring studies by comprehensive mathematical techniques. In fact, tree-ring reconstructions are the most rigorously verified proxies of past climate (Stahle and Cleaveland 1992). Thus, the annual rings of trees show year-to-year climate variability, and using very long tree-ring chronologies, climatic trends can be examined on a range of temporal scales, from annual to millennial.

1.2.1.2 Fire History Proxies

Wildland fires are significant disturbance agents in forest, woodland, and grassland ecosystems. As such, an understanding of fire regimes is integral for understanding most North American ecosystems, as fire may be the most influential agent of change in temperate forests (Mutch and Cook 1996). The severity, frequency, and spatial extent of fires can affect biological diversity, vegetative structure, and population dynamics (Harper 1911; Wright and Bailey 1982; Van Lear and Waldrop 1989; Gliztenstein *et al.* 1995; Harrod and White 1999; Heyerdahl *et al.* 2001). Fires remove accumulated fuels and allow seeds to germinate and herbaceous plants to thrive where they would be inhibited in the absence of fire (Means 1996; Frost 2000; Glitzenstein *et al.* 2003). Moreover, the periodic reduction of fuel loads lowers the possibility of stand-replacing fires that may be potentially hazardous to surrounding human development when the fire intensity is high (Lewis 2003). Increasingly intense and severe wildfires in many areas of the U.S. have been attributed to unnaturally large fuel loads caused by fire exclusion during the 20th century (Swetnam and Betancourt 1998; Swetnam *et al.* 1999). For these reasons, the sound management of fire in forest ecosystems is critical.

To successfully manage an ecosystem, the processes that maintained the ecosystem over long periods must be restored (Kaufmann *et al.* 1994). In other words, historical knowledge of an ecosystem is essential to informed management of that ecosystem (Swetnam *et al.* 1999). As such, land managers are often interested in the presettlement fire regime because fire history reveals important information for evaluating changes in plant communities (Dieterich and Swetnam 1984). Presettlement refers to vegetation conditions and the natural fire regime as they existed at the time of first European contact (Frost 2000). Fire managers can use this information to restore forests to their pre-contact state using prescribed fire plans that emulate the long-term historical and natural disturbance regime (Lorimer 2001). A recent proliferation of land management agency reports that outline planning stages dependent on obtaining historical ecology information confirms the applied nature of fire history studies, especially in cases such as park lands where natural-process maintenance is legally mandated (Swetnam *et al.* 1999). Studies in the past few decades have guided policies in national parks away from suppression and towards natural fire management (Stottlemyer 1981).

Unfortunately, since the arrival of European settlers, natural fire regimes have been altered in many areas by human activities (Swetnam 1990; Agee 1991; Taylor and Skinner 2003; Grissino-Mayer *et al.* 2004). Over the past century, fire suppression policies have drastically reduced the frequency of fire in much of the U.S. (Pyne 1982; Swetnam 1993; Morgan *et al.* 1994; Masters *et al.* 1995; Veblen *et al.* 2000; Grissino-Mayer and Swetnam 2000). Moreover, the reference conditions for fire that prevailed in presettlement conditions are unknown (Norris 2000). Records of fire activity before the early 1900s are rare in many locations, so fire history must be reconstructed through other means.

Techniques for reconstructing fire history are threefold and include examining charcoal deposits in lakes or soils (Cohen 1975; Swain 1980; Watts 1980; Harmon 1980; Horn *et al.* 1994; Watts 1996; Welch 1999), inferring fire frequency or seasonality from presettlement vegetative assemblages and land survey records (Lorimer 1980; Frost 1995; Frost 2000), and analyzing fire scars and tree rings. For the first two techniques, the temporal resolution is coarse (except in the case of the charcoal record in varved sediments), so the data are insufficient for the interpretation of fire regimes, except on evolutionary time scales (Clark and Robinson 1993; Christensen 1993b). Furthermore, charcoal deposits from lakes are inherently biased toward inundated lowlands in which fossils are preserved (Clark and Robinson 1993). In addition, the nature of the presettlement vegetation may be unknown, or the information of past species composition is limited to the earliest plant surveys of an area (Delcourt and Delcourt 1974; Delcourt and Delcourt 1977a; Frost 2000). Only studies using fire-scar data provide "point" fire frequencies with annual to seasonal resolution and thus are the most accurate record of actual fire events from the past. Trees are excellent recorders of environmental changes and are well-suited to investigating the role of fire disturbances in the past (Grissino-Mayer and Fritts 1995). Fires can kill part of the vascular cambium, and the exact date of the disturbance can be determined by examining the annual ring where the scar formation began (Arno and Sneck 1977; Smith and Sutherland 2001). However, the information from the fire scar record in tree rings is limited because not all fires are recorded by every tree, and in the eastern U.S., the age of fire-scarred remnants normally does not exceed 500 years BP.

1.2.2 Paleoenvironmental Research in the Southeastern Coastal Plain

1.2.2.1 Paleoclimatological Studies

In the Southeastern Coastal Plain, much of the research in past climate has been conducted using paleolimnological techniques (Whitehead 1964; Watts 1971; Larson *et al.* 1972; Delcourt and Delcourt 1977b; Delcourt 1980; Watts 1980a; Whitehead 1981; Watts *et al.* 1996). In paleolimnology, organic samples in lake sediments are dated using radiocarbon techniques, and the climate of the past is inferred using the fossil pollen and existing vegetation. While information gleaned from lake sediments extends the record of Coastal Plain vegetative assemblages (and hence, climate) tens of thousands of years, the temporal resolution is extremely coarse because no lakes in this region contain annually laminated (varved) sediments. Only a handful of dendroclimatological reconstructions have been attempted in the Coastal Plain, and virtually all these reconstructions have been from a single tree species, baldcypress (*Taxodium distichum* (L.) Rich.) (Stahle *et al.* 1988; Stahle and Cleaveland 1992; Stahle and Cleaveland 1994; Stahle *et al.* 1998). Therefore, a significant gap exists in our knowledge of past climate for this region.

1.2.2.2 Paleoecological Studies

Fire history is a key component of historical ecology studies. Fire has played a major role in the evolution of forest ecosystems throughout the Southeast, especially in the Coastal Plain (Christensen 1981). Much has been speculated about the historic fire regimes in the longleaf pine forests that were once prevalent across the region (Heyward 1939; Pyne 1984; Robbins and Myers 1992). Fires were believed to be frequent and widespread in longleaf pine ecosystems, but no study has solidly verified this hypothesis.

The control of the natural fire regime through fire suppression has affected the species composition and structure of forest stands throughout the Coastal Plain (Boyer 1987; Frost 1993; Gilliam and Platt 1993; McKay 2000). Deciduous shrubs and hardwood tree species moved into some areas of the original longleaf pine forests when fire was excluded (Croker 1968; Delcourt and Delcourt 1977a; Gilliam and Platt 1993; Glitzenstein *et al.* 2003). The need to restore longleaf pine forests to their pre-contact condition has generated a tremendous amount of interest in restoring the natural fire regimes, as fire is vital to both longleaf pine reproduction and regeneration (Chapman 1932; Wahlenberg 1946; Boyer 1990). Moreover, endangered species such as the red-cockaded woodpecker (*Picoides borealis* Vieillot) inhabit and depend heavily on the longleaf pine forests, so the preservation and restoration of these ecosystems is an important environmental concern as well (Masters *et al.* 1995).

Although the need for information on past fire regimes in the Southeastern Coastal Plain is great, little research has been conducted on fire history in this region. Very few studies are available of fossil charcoal in lake sediments in the Coastal Plain (Watts 1980b; Watts and Hansen 1988; Clark and Robinson 1993; Watts *et al.* 1996). Moreover, the methodology of fine charcoal stratigraphy has not been applied to any Coastal Plain site (Watts 1980b). Evidence from charcoal studies points to the importance of fire in the history of the Southeastern Coastal Plain. Small fragments of charcoal at low density were found in sediment horizons of Lake Louise, Georgia, that could support the theory of frequent fires (Watts 1971). Okefenokee peats in Georgia show abundant evidence of past fires with many charcoal-rich horizons (Cohen 1975; Watts 1980b).

In addition to charcoal studies in the region, Frost (2000) used an innovative approach that synthesized a number of techniques including historical vegetation records and remnant natural vegetation, to develop a historic fire frequency map of the southeastern U.S. (Frost 2000). The map represents a window of time ranging from around the mid-1500s to the late 1800s (Frost 2000). This synthesis used all existing fire-scar chronologies because of their value as actual data points on the landscape, but very few fire-scar chronologies were available for the Southeast when Frost developed his map (Frost 2000). Moreover, none of these fire-scar chronologies was from the Southeastern Coastal Plain region. Because few fire history studies using tree rings have ever been published for this region, much of our current knowledge on historical fire frequency and seasonality is based on observations obtained during the 20th century or from oral or written records from prior centuries, and a clear void exists in this information.

1.2.3 Major Objectives

In this dissertation, I attempt to fill some of these knowledge gaps concerning the paleoenvironment of the Southeast. This study emphasizes for the first time the importance of longleaf pine in paleoenvironmental reconstructions in the Southeast. The research encompasses a range of spatial (regional to site-specific) and temporal (annual to multi-centennial) scales that provides a geographic perspective using dendrochronological techniques.

The science of dendrochronology has numerous applications for the study of the environment and climate (Fritts and Swetnam 1989; Fritts 2001), and I incorporate two of the more prominent subfields, dendroclimatology and dendropyrochronology, in this dissertation. Most research in these subfields has been conducted in the western United States (Swetnam and Betancourt 1990; D'Arrigo and Jacoby 1991; Grissino-Mayer and Swetnam 2000) on sites where the climate is arid, making conditions for tree growth more limiting. Even though research in the southeastern United States has been increasing in the past two decades, scant data from tree rings are available for several prominent species, and no study has combined the analysis of both climate and fire over the breadth of the region.

The goal of my dissertation is to help breach this information gap in the Southeast by utilizing longleaf pine, a long-lived southern pine that once ranged from southern Virginia to eastern Texas along the Coastal Plain region. Few chronologies exist for this species, despite its broad geographic range. Moreover, this species is almost entirely dependent on fire for its perpetuation on the landscape, but no dendroecological reconstruction of fire history using longleaf pine has ever been attempted.

This research involves three overarching objectives. First, I will develop several century-scale tree-ring records for longleaf pines in the Southeastern Coastal Plain. Second, I will use these proxy records to explore the effects of ocean-atmosphere teleconnections (such as the El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), the North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO)) on radial tree growth. These findings will be important for understanding not only past climate conditions in the Southeast, but also for understanding how interhemispheric climate linkages may affect this region. In addition, the dendroclimatological data will provide a better understanding of how longleaf pine trees respond to variations in climate across their range. Third, I will develop reconstructions of past fire for selected sites that document changes in fire regimes from presettlement periods to the present. These findings will be significant in the effort to understand the role of fire in shaping the structure and composition of longleaf pine ecosystems. Moreover, this new information will further our knowledge of how to effectively manage fire in longleaf pine areas.

1.3 Dendroclimatological Research

1.3.1 Introduction

The study of past climate conditions is important for assessing future climate change. Tree-ring data are a useful proxy for climate conditions prior to the period of meteorological instrumentation (Fritts 2001). In the absence of other high-resolution proxies, such as archival records and varves, tree-ring evidence is extremely valuable for discerning past annual variations in climate (Stahle and Cleaveland 1992).

Paleoclimatological research using tree rings in the continental U.S. has been mainly conducted in the western regions, where several species of long-lived trees exist and remnant wood is slow to deteriorate. Extensive tree-ring networks have been developed in the Southwest, where millennia-long chronologies are used to reconstruct historical drought and other climatic events (D'Arrigo and Jacoby 1991; Grissino-Mayer 1996).

1.3.2 Dendroclimatic Research in the Southeast

In the American Southeast, dendroclimatological reconstructions of past climate have been limited because of the relatively young age of the trees and poor preservation of remnant wood in humid environments. Nonetheless, several studies have examined the growth response of certain tree species to climatic variables. One of the seminal works in the Southeast was conducted by Hawley (1941) in the Mississippi drainage (including the Tennessee Valley) and described the value of numerous eastern tree species to dendrochronology. Another early study derived a central Georgia chronology on the Macon Plateau in the 1930s (Willey 1937). The chronology was developed using longleaf and shortleaf pine trees and extended back to 1800 (Willey 1937). Twenty "marker rings" that were anomalously large or small were identified in the chronology (Willey 1937).

In the past two decades, research on the climate response of trees using dendrochronological techniques has increased considerably in the Southeast. Studies have shown that precipitation is generally more important for tree growth than temperature conditions in the East (McClenahen and Vimmerstedt 1993; Pan *et al.* 1997). Orwig and Abrams (1997) demonstrated that the response to drought was dissimilar for several eastern tree species in the Piedmont and Coastal Plain of northern Virginia. Tryon *et al.* (1957) found a significant positive relationship between May-June precipitation and ring width in yellow poplar (*Liriodendron tulipifera* L.), but no relationship with temperature.

In northern Georgia, shortleaf pine (*Pinus echinata* Mill.) growth showed a significant positive relationship with precipitation in the growing season (Grissino-Mayer and Butler 1993). Furthermore, changes in pine growth rates since 1963 were attributed to nonclimatic factors, so their climate/growth models for the latter part of the 20th century may not adequately model growth (Grissino-Mayer and Butler 1993). In eastern Texas, precipitation in the current year and rainfall in the previous summer significantly affected the radial growth of loblolly pine (*Pinus taeda* L.) (Chang and Anguilar 1980). Parker *et al.* (2001) found that the climate response of two varieties of sand pine (*Pinus clausa* Chapm. ex Engelm.) differed between coastal and inland locations in northern Florida. An innovative study that involved 16 tree species from the West Gulf Coastal Plain determined that genetics plays an important role in how certain phylogenetic groups of trees respond to climate, and this response is largely independent of the immediate environment of the site (Cook *et al.* 2001).

A few climate reconstructions have been produced in the Southeast region. Cook *et al.* (1986) reconstructed June PDSI for the southern Appalachians since 1700 to compare the severity of the 1986 drought to past dry spells. Cook *et al.* (1986) concluded that the 1986 drought was unprecented in severity for a single year event. Post oak (*Quercus stellata* Wang.) chronologies from Texas and southern Oklahoma were used to reconstruct Texas drought history from 1698 to 1980 (Stahle and Cleaveland 1988). Stahle and Cleaveland (1988) concluded that the multiyear drought of the 1950s was the most severe continuous drought episode since 1698. Neither of these reconstructions was applicable to the Southeastern Coastal Plain.

The only regional climate reconstructions in the Southeastern Coastal Plain have been developed using baldcypress in Georgia, South Carolina, and North Carolina. Baldcypress is an exceptionally long-lived tree in the Southeast that thrives in frequently flooded sites. Baldcypress chronologies have been used as a proxy for summer drought and spring rainfall, extending the climate record back more than 1,500 years for specific locations (Stahle *et al.* 1988; Stahle and Cleaveland 1992; Stahle and Cleaveland 1994; Stahle *et al.* 1998). Cook *et al.* (1999) used many of these baldcypress chronologies to reconstruct drought for the continental U.S. since 1700. Despite the long chronologies provided by baldcypress, tree-ring research using this species has declined because of the difficulty in dating, the relatively weak climate signal, and the amount of work required for sample collection. Furthermore, "the apparent ability of baldcypress to adapt to long-term water-level changes is antagonistic to the registration of possible century-scale rainfall trends and may diminish as well the registration of multi-decadal rainfall changes in baldcypress chronologies" (Stahle and Cleaveland 1994).

Another long-lived species in the Southeast that has tremendous potential for dendroclimatological reconstructions is longleaf pine, but no reconstructions have been attempted using this species. Longleaf pine was a prominent species throughout the Southeastern Coastal Plain prior to European settlement (Hickman 1962; Delcourt 1980; Frost 1991). This shade-intolerant southern yellow pine grows in a variety of soil types, from quite xeric Entisols to mesic, even wet Ultisols (Wahlenberg 1946; Christensen 1993a). The longleaf stands found on xeric sites with sandy, nutrient-poor soil are particularly sensitive to fluctuations in moisture conditions (Foster and Brooks 2001). Not only does this species show excellent climate sensitivity, longleaf pine is ideally suited for climate reconstructions because of its longevity and superior preservation.

Although this species was extensively logged until the early 20th century, old-growth stands still remain across the Southeast (Mean 1996). Moreover, remnant wood in stumps, snags, and logs is still intact in these forests. Because longleaf pine wood is very resinous, these old wood remnants are unique in their ability to withstand moisture and decay. Because longleaf pines may live for up to 500 years or more, long chronologies can be developed using living and remnant wood. To date, however, all of the dendroclimatological research in longleaf pine has only been concerned with the climate response of tree rings and not climate reconstruction.

1.3.3 Dendroclimatic Studies in Longleaf Pine

Results of dendrochronological research on longleaf pine have been fairly consistent but sometimes contradictory (Meldahl *et al.* 1999). The first studies conducted in the 1930s involved sites in northern Florida and southern Georgia. Lodewick (1930) found no correlation between radial growth and temperature, but observed a strong correlation between radial growth and growing season rainfall of the current year. Coile (1936) found a negative correlation between radial growth and August temperature, and a positive correlation with early spring rainfall of the current year. Schumacher and Day (1939) found that the effect of precipitation on annual ring width was variable between several sites in Florida.

After a rather long period devoid of dendroclimatological research on longleaf pine, Zahner (1989) found that longleaf pine radial growth was negatively related to the severity of drought in southern Alabama. In southern Mississippi, Devall *et al.* (1991) developed a chronology from 1921 to 1987 and found that current August rainfall, September temperature, and February Palmer Drought Severity Index (PDSI) were the best predictors of radial growth. Some of these factors, such as February PDSI, were not consistently significant influences on growth throughout the study period, however. Devall *et al.* (1991) also noticed an increase in growth after Hurricane Camille moved through the area in 1969.

West *et al.* (1993) surmised that CO_2 fertilization rather than trends in precipitation or temperature may have caused an increase in longleaf pine growth rates in southern Georgia during the late 20th century. Later, Meldahl *et al.* (1999) conducted a comprehensive dendroclimatological study in southern Alabama, examining earlywood and latewood widths and their correlation with monthly rainfall and temperature. They concluded that the most important factor driving total ring width was current growing season rainfall, particularly in March and September. Second, high temperatures generally had a negative effect on tree growth, particularly in February through April. Third, latewood widths were much more variable than earlywood widths and generally had higher correlations with climate variables (Meldahl *et al.* 1999).

Foster and Brooks (2001) found significant correlations between tree growth and precipitation in the current spring and summer on xeric sites in west-central Florida, and with previous summer precipitation on intermediate sites. High summer temperatures in the previous summer were also significantly related to growth rates. Similarly, Atchley

(2004) reported a positive tree-growth response to spring precipitation for longleaf pine at the Appalachicola Bluffs and Ravines Preserve, Florida. The most recent dendroclimatological study that used longleaf pine was conducted in southern Georgia (Grissino-Mayer, unpublished data) and showed a strong relationship between total ring width and winter/spring rainfall. None of these studies provided a comprehensive analysis of the climate response of longleaf pine across the Coastal Plain. Research from a multitude of sites is necessary to fully understand the climate/pine growth relationship, as subtle differences in tree growth occur because of site heterogeneity (Grissino-Mayer and Butler 1993). Moreover, none of the published studies attempted any climatic reconstruction using longleaf pine ring widths as a climate proxy, nor do the published records extend into the past farther than about two centuries.

1.3.4 Objectives and Justification

The purpose of this study is to extend our knowledge of past climate in the Southeastern Coastal Plain region of the Southeastern U.S. using tree-ring data as a proxy. This study takes advantage of the long-lived character of longleaf pine and the persistence of its resinous wood on forest floors to develop climate reconstructions in three major sub-regions of the Coastal Plain. Not only will these reconstructions be some of the longest ever developed in the Coastal Plain, but an analysis of past climate relationships across the vast expanse of the region will incorporate a spatiotemporal view on regional climatic history. In addition, the wide range of the study areas allows comparisons of the climatic response of longleaf pine across its range, particularly along an east-west gradient.

I have seven specific objectives for the dendroclimatic research:

1) Develop three longleaf pine master chronologies from eastern Texas, the Florida Panhandle, and coastal South Carolina.
2) Determine the climatic factors that most influence tree growth at these sites.
3) Compare the climatic response of longleaf pine trees among the different sites.
4) Reconstruct long-term climate using tree-ring widths as a proxy.
5) Examine trends in past climate at various temporal scales.
6) Examine how disturbances may have affected the accuracy of the climate reconstruction.
7) Use the reconstructed climate variables to investigate fire history and possible relationships with interhemispheric climate teleconnections.

1.4 Studies on Interhemispheric Climate Linkages

1.4.1 Introduction

The oscillatory dynamics of the global climate system drive long temporal lags in the transfer of energy throughout the oceans and the atmosphere (Swetnam *et al.* 1999). Large-scale coupled interactions of the oceans and atmosphere can affect areas far removed from the region where these interactions occur, and these remote associations are known as teleconnections (Caviedes 2001). Teleconnections have a marked effect on climate in some regions of the United States, and a greater understanding of these effects can improve long-range climate forecasts (Ropelewski and Halpert 1987; Latif and

Barnett 1996). The variation in teleconnections between the tropical Pacific and other regions and how they are modulated on various timescales is not well understood (Noren *et al.* 2002). However, links between regional climate parameters and various teleconnections such as ENSO, PDO, NAO, and AMO have been demonstrated for many areas of the United States. In the past two decades, research on the effects of ENSO and PDO, in particular, on North American climate has increased dramatically (Quinn *et al.* 1987; Ropelewski and Halpert 1987; Kiladis and Diaz 1989; Latif and Barnett 1996; Rajagopalan *et al.* 2000; Lau *et al.* 2004).

The relationships between United States climate and El Niño have been documented in several regions (Vega *et al.* 1998). El Niño refers to the occasional "anomalous" warming of the eastern tropical Pacific Ocean, but is commonly linked to a basin-scale warming extending from the coast of South America to the International Date Line (Trenberth and Hoar 1996). In contrast, La Niña is a decrease in sea-surface temperature of the eastern equatorial Pacific Ocean with no shifting of the active center of atmospheric convection from the western equatorial Pacific (Sheppard *et al.* 2002). The primary response in the atmosphere coupled to El Niño is the Southern Oscillation, a variation in surface pressure over Indonesia and the tropical South Pacific (Trenberth and Hoar 1996). The resultant shifts in Pacific sea surface temperatures (SSTs) and pressure systems affect both the Pacific basin and continents far-distant from the equatorial Pacific Ocean. The reason for this downstream effect is that El Niños deflect the path of jet streams, particularly in the wintertime when the north-south contrast in temperature is most pronounced and the maximum pressure anomalies occur (Kiladis and Diaz 1989; Swetnam and Betancourt 1990; Nash 2002). Typical ENSO events persist for 16 to 18 months (Mantua and Hare 2002). In addition to the Great Plains and mid-Atlantic, the Southwest region of the U.S. is one of several regions in North America that is affected by ENSO events (Ropelewski and Halpert 1986; Cole and Cook 1998). In the southwestern U.S., wetter conditions prevail in ENSO years, and La Niña years are predominantly drier (D'Arrigo and Jacoby 1991).

Because these climate parameters also affect tree growth to a large degree, dendrochronology has been utilized to help further our understanding of these relationships. The four wettest years in a 1000-year reconstruction of precipitation in northwestern New Mexico were interpreted as ENSO events from instrumental and historical data (D'Arrigo and Jacoby 1991). Correlation analyses also revealed significant relationships between the Southern Oscillation index and tree-ring chronologies, with the highest correlations in winter (December-February) (D'Arrigo and Jacoby 1991). A network of earlywood and total ring-width chronologies from the southwestern U.S. and Mexico exhibited some of the strongest correlations with ENSO indices of any available tree-ring chronologies worldwide (Stahle *et al.* 1998). These chronologies were used with chronologies from Indonesia to reconstruct winter Southern Oscillation Index (SOI) from 1706 to 1977 (Stahle *et al.* 1998). Allan and D'Arrigo (1999) used this reconstruction to reveal the existence of persistent ENSO sequences of three or more years at various times since 1706. Besides these tree-ring studies in the Southwest, where trees are most sensitive to precipitation, other research has shown the effects of ENSO in transitional areas. In the Colorado Front Range, trees clearly respond to ENSO events, but the response varies with the type of event and tree species (Woodhouse 1993). Tree-growth response was more consistent with La Niña events than El Niño events in the Colorado Front Range (Woodhouse 1993).

Other studies have documented historical changes in the nature of ENSO teleconnections in the United States. Using a tree-ring reconstruction of PDSI for the United States and a 130-year record of the SOI, Cole and Cook (1998) discovered that the influence of ENSO on U.S. moisture balance was more extensive before 1910. Also, the sign of the ENSO-PDSI correlation has shifted over time in the mid-Atlantic states, and a bipolar correlation structure exists for certain periods between the mid-Atlantic and the southwest region (Cole and Cook 1998). An increase in the frequency of winter SOI extremes was detected in tree rings from the southern Great Plains and Mexico, and these findings may reflect real changes in the extratropical influence of the SO over the southern United States (Stahle and Cleaveland 1993). These findings demonstrate the inherent instability in the effects of ENSO through time in many regions of the U.S. and the complexity of these extratropical effects (Stahle and Cleaveland 1993). An investigation of the relationships between La Niña and drought in the U.S. revealed that La Niña events tend to trigger drought conditions that linger due to additional land-surface feedbacks (Cole *et al.* 2002). Thus, the effects of atmospheric teleconnections can be amplified by other climate controls, further complicating the ability to discern their actual influence.

Although ENSO variability has a tremendous influence on climate in certain regions of the U.S., other teleconnections have been shown to be important as well. Decadal variations in the ocean and atmosphere in the North Pacific produce climate anomalies downstream over North America in a similar fashion to ENSO (Latif and

Barnett 1996; Mantua *et al.* 1997). The PDO, which modulates the impacts of ENSO, is difficult to distinguish from ENSO because the winter SOI is significantly correlated with PDO (Cole and Cook 1998; Cleaveland *et al.* 2003). The PDO is defined as the leading mode of variations in monthly anomalies of Pacific SST north of 20 degrees latitude, and this teleconnection is much less well understood than ENSO (Mote *et al*. 2003). The period of each phase is irregular and spans several decades (20–30 years), so only two complete oscillations have been observed in the instrumental record (Mote *et al.* 2003). The PDO index is positive when northeastern Pacific Ocean temperatures are warm, and central and western North Pacific temperatures are cool (Mantua *et al.* 1997; Sheppard *et al*. 2002). Unusually low sea-level pressure occurs over the northern Pacific Ocean during strong positive phases in the winter months (Sheppard *et al.* 2002). Hence, winter precipitation is significantly correlated with PDO in many areas of western North America (Mantua *et al.* 1997).

Positive phases of the North Pacific Index have been related to climate conditions in the Pacific Northwest, western Canada, northern Great Plains, and the Midwest (Lau *et al.* 2004). Tree-ring studies have documented the influence of PDO on tree growth in some of these areas. Significant relationships between tree growth and winter PDO have been documented in mountains of Washington and Oregon, and these relationships are believed to be related to changes in snowpack depth (Peterson and Peterson 2001). D'Arrigo *et al*. (2001) found a positive relationship between PDO and temperatures in the Pacific Northwest and Alaska. Tree-ring records from Baja and Southern California show the influence of PDO and a dominant bidecadal mode that appears to coincide with the circulation time of the Pacific gyre (Biondi *et al.* 2001). Patterns of tree growth roughly corresponding to PDO phases were noted in trees from British Columbia and Yosemite National Park, California (Kadonaga *et al.* 1999). Droughts in the interior Pacific Northwest have been linked to warm phases of the PDO, when a blocking high is present off the northwest coast of the continent (Knapp *et al.* 2004). The PDO appears to produce drought anomalies in the mid-Atlantic states, particularly when PDO variance is strong (Cole and Cook 1998).

1.4.2 Research in the Southeast

In the southeastern U.S., studies have shown a strong connection between ENSO and seasonal rainfall and temperatures (Vega *et al.* 1998). In general, the studies of the Southeast found a pattern of cool, wet winters in El Niño years, and dry, warm winters during La Niña events (Douglas and Englehart 1981; Ropelewski and Halpert 1986; Sittel 1994). The largest precipitation and temperature anomalies occur from October through April in this region (Sittel 1994). Milder, drier winters in the Southeast may be linked to a weakened and northward displacement of the jet stream during La Niñas that decreases storm activity (Douglas and Englehart 1981). In contrast, the midlatitude jet is displaced toward the equator during El Niño, causing increased frontal precipitation in the winter (Ropelewski and Halpert 1986; Schmidt *et al.* 2001). Moreover, El Niño winters are characterized by the advection of moisture from the tropical Pacific by the subtropical jet stream (Ropelewski and Halpert 1986). During El Niño summers, tropical storm development is reduced, while tropical storms are enhanced in La Niña summers (Bove *et al.* 1998). As a result, most of the summer precipitation in El Niño summers comes from localized convective storms and not hurricanes (Schmidt *et al.* 2001).

Winter and summer in the Southeast represent the two extremes of the annual cycle when the region is more susceptible to subtle changes in the climate system (Burroughs *et al.* 1996). During the transitional periods of fall and spring, the chaotic short-term changes usually mask the slowly varying components of climate (Burroughs *et al.* 1996). These general trends do not always hold true across the entire region, and teleconnection effects are particularly diverse in Florida. The effects in winter and summer are magnified or negligible in some parts of the state for certain phases, or fall and spring rainfall can be significantly affected (Schmidt *et al.* 2001).

For example, while winter precipitation in Florida is strongly affected by ENSO phase, the effects are most pronounced in southern Florida (Schmidt *et al.* 2001). El Niño events have been statistically linked to wet winters in southern Florida, and dry conditions during La Niña events (Douglas and Englehart 1981). Hanson and Maul (1991) found that rainfall is anomalously high in both the winter and spring in Florida during ENSO. Likewise, Schmidt *et al.* (2001) determined that precipitation during spring in the panhandle of Florida is elevated during ENSO. In many respects, however, precipitation patterns in the Florida panhandle are more closely related to the other Gulf of Mexico coastal states (Texas, Louisiana, and Mississippi) than the rest of the peninsula. Summer precipitation is elevated in the panhandle during La Niña, and this pattern is not evident in the rest of the state (Schmidt *et al.* 2001).

Studies have used this knowledge of the relationship between climate parameters and ENSO to examine the corresponding effects of ENSO on vegetation in the Southeast. Researchers have seen a clear relationship between ENSO-related precipitation events and southeastern vegetation growth using crop yields (Hansen *et al.* 1998). Corn yields in

Florida, Alabama, Georgia, and South Carolina tend to be high in La Niña years because June rainfall is slightly higher during those years (Hansen *et al.* 1998). Analysis of vegetation vigor in the North and South Carolina and Georgia using satellite imagery revealed a similar trend, with increased vegetation vigor in La Niña years and a decline in vigor during El Niño (Mennis 2001). However, the influence on vegetation vigor was weak and subservient to other, probably local, factors (Mennis 2001). Peters *et al.* (2003) expanded on previous research using satellite imagery by studying the entire Southeast. They determined that from 1989–1999, ENSO had a similar influence on vegetation conditions along the Gulf Coast and the interior portions of the Southeast (Peters *et al.* 2003). Moreover, neutral ENSO phases provide optimal climate conditions for vegetation in the Southeastern U.S. (Peters *et al.* 2003).

The effects of teleconnections on vegetation in the Southeast have also been studied using dendrochronology. An ENSO influence on tree growth near the Gulf of Mexico seems probable because the effects of ENSO on rainfall and temperature extend into the early spring growing season, and trees in this region may break dormancy as early as February during warm winters (Stahle and Cleaveland 1993). In addition, a preconditioning effect on cambial activity in the growing season may be present because of soil moisture recharge (depletion) during ENSO (La Niña) events (Stahle and Cleaveland 1993). However, the results of dendrochronological studies of teleconnections in the Southeast have been mixed.

ENSO had little influence on summer PDSI reconstructions using baldcypress chronologies in the Southeast region (Cleaveland *et al.* (1992). In like manner, Stahle and Cleaveland (1992) were unable to detect any statistically significant correlations between reconstructed spring rainfall data from North and South Carolina and Georgia and the Pacific/North America (PNA) pattern, ENSO, or NAO. Presumably, these tree-ring reconstructions showed little to no relationship with these circulation phenomena because they are most strongly teleconnected with the southeastern U.S. during the winter, as opposed to spring and summer (Stahle and Cleaveland 1992). Therefore, baldcypress may not reflect the precipitation patterns because radial growth begins in the late spring (Cleaveland *et al.* 1992). Farther westward, an ENSO index created from tree-ring chronologies in Texas, Oklahoma, Arkansas, and Missouri showed a clear relationship with Pacific sea level pressures (Cleaveland *et al.* 1992).

In a more recent study using dendroclimatological techniques, the response of sand pine trees to ENSO phase differed between inland and coastal sites in Florida (Parker *et al.* 2001). Sand pine growth at inland sites on the Florida panhandle exhibited no relationship to ENSO phase, while coastal sand pines showed a clear response in growth. Furthermore, latewood width series showed no significant relationship to ENSO phase for both inland and coastal sites. Presumably, ENSO phase primarily affects winter and spring precipitation in this area, so only earlywood widths record an ENSO signal (Parker *et al.* 2001).

Because the results of dendroclimatological studies concerning ENSO and other teleconnections have been inconsistent in the Southeast, further studies are warranted to determine specific local effects on trees within the region. While a strong, consistent climatic response to ENSO events has been demonstrated in some areas, more emphasis should be paid to areas with variable responses to ENSO (Woodhouse 1993), such as the Southeastern Coastal Plain. While Texas and southern Florida have shown some consistency in ENSO response, the picture in the remainder of the Coastal Plain is less certain. Moreover, Cleaveland *et al.* (1992) state that more climate sensitive tree-ring chronologies are needed for the Gulf coastal states to test for the existence of an ENSO signal in Gulf coast trees. The spatial and temporal coverage of available chronologies is far from complete, and many old-growth forest remnants remain to be sampled (Stahle and Cleaveland 1993). The response of trees to teleconnections may vary among different tree species (Woodhouse 1993), so long chronologies from a variety of species are desirable. Also, proxy data from many different areas are needed to distinguish large-scale variability from local variability (D'Arrigo and Jacoby 1991).

1.4.3 Objectives and Justification

Building on the tree-ring chronologies developed in the dendroclimatological portion of the research, I will examine the effects of interhemispheric teleconnections on longleaf pine growth across the Coastal Plain. Because of the far-reaching effects of ocean-atmospheric teleconnections, both the Atlantic and Pacific Ocean regions may cause varied effects in a region as large as the Coastal Plain. Because our knowledge of their effects in the Southeast is limited, this analysis includes a broad range of known teleconnections, including ENSO, PDO, AMO, and the North Atlantic Oscillation (NAO).

I have two specific objectives in this portion of the research:

1) Determine the effects of atmospheric teleconnections on tree growth based on records of teleconnection indices (e.g. sea-level pressure, sea surface temperatures).

2) Explain the relative climatic effects of teleconnections in the different subregions of the Southeastern Coastal Plain.

1.5 Dendropyrochronological Research

1.5.1 Introduction

Despite the excellent record of fire history that fire scars can provide, the only region in the world where extensive networks of century-scale climate and fire reconstructions have been created with annual resolution is the southwestern U.S. (Grissino-Mayer and Swetnam 2000). The dating of fire scars to the exact year of formation was not common practice until the early 1980s, so the field of dendropyrochronology is essentially only a few decades old (Madany *et al.* 1982; Dieterich and Swetnam 1984). In addition to providing valuable information on past fire frequency, extent, and seasonality, fire history studies have also linked fire activity to rainfall and temperature, ocean-atmospheric teleconnections, and anthropogenic activity.

Composite fire reconstructions for the Southwest and other regions have shown that fires that occur synchronously across the region are related to regional climatic factors (Swetnam and Betancourt 1990; Swetnam 1993; Swetnam *et al.* 1999). Fire activity in the giant sequoia (*Sequoiadendron giganteum* (Lindley) Buchholz) groves of the Sierra Nevada, California was related to precipitation and summer temperatures (Swetnam 1993). Likewise, summer precipitation amounts and lightning activity in the Blue Mountains of Oregon and Washington affected fire frequency (Heyerdahl *et al.* 2001). Weisberg and Swanson (2003) also studied the fire history in Washington and Oregon and postulated that periods of cool climate (1650–1800) were associated with reduced fire activity, while warm periods (1801–1925) promoted widespread fires. Studies in northwestern New Mexico demonstrated that wildfires are influenced by climate on interannual to century timescales (Grissino-Mayer and Swetnam 2000). For example, the cool and dry conditions during the Little Ice Age (AD 1400–1800) promoted frequent fires, while warm conditions and increased summer rainfall after 1800 caused fire frequency to decrease (Grissino-Mayer and Swetnam 2000). Several studies in the Southwest have demonstrated that wet conditions prevail several years prior to fire events, allowing fine fuels to build, followed by dry conditions during the year of fire (Baisan and Swetnam 1990; Swetnam 1993; Grissino-Mayer and Swetnam 2000).

Several researchers have found that regional fire activity is related to extreme phases of ocean-atmospheric oscillations (Swetnam and Betancourt 1998; Swetnam *et al.* 1999). In the San Juan Mountains of Colorado, fire activity in the mid-1700s is believed to be related to weakened ENSO activity and an extended series of cool-phase PDO events (Grissino-Mayer *et al.* 2004). El Niño conditions in the Southwest have been shown to cause increased precipitation and a reduced incidence of fire (Swetnam and Betancourt 1992). Furthermore, changes in fire seasonality have been linked to changes in ENSO activity in New Mexico (Grissino-Mayer and Swetnam 2000). Variations in fire frequency in the Colorado Front Range are strongly connected to ENSO events (Veblen *et al.* 2000). Dry springs associated with La Niña events are conducive to widespread fire, while wet springs during El Niño years produce abundant fine fuels that produce a peak in fire occurrence several years later (Veblen *et al.* 2000).

While the effects of 20th century fire suppression have been well documented in many areas, fire-scar studies of fire history have revealed other anthropogenic effects as well. In the 19th century, livestock grazing in the American Southwest reduced fire frequency because of a reduction in fine fuels covering the ground (Swetnam and Betancourt 1992; Swetnam and Baisan 1996; Grissino-Mayer and Swetnam 2000). Livestock grazing also affected fire frequency in the late 1800s in mountains of the Pacific Northwest (Heyerdahl *et al.* 2001). Early settlers in the Colorado Front Range increased fire frequency by intentional burning in the mid-1800s, and livestock grazing and fire suppression decreased fire activity beginning in the late 1800s (Veblen *et al.* 2000).

With regard to anthropogenic influences in presettlement times, the influence of Native Americans on western fire regimes is a subject of controversy. Some researchers believe it is impossible to quantitatively assess Native American effects on fire regimes without data on fire spread according to ignition source (Veblen *et al.* 2000). Other researchers have used available evidence such as fire frequency and known population centers to infer the influence of Native Americans. No compelling evidence was found that Native Americans influenced fire regimes in the southern San Juan Mountains of Colorado (Grissino-Mayer 2004). However, Native American burning in western Montana seems to have affected fire frequency before European settlement commenced (Barrett and Arno 1982). Fire intervals before settlement were shortest near Indian-use zones, suggesting Indian-caused fires contributed significantly to fire regimes in the mountains of Montana (Barrett and Arno 1982).

1.5.2 Research in the Southeast

In the Southeastern Coastal Plain, fire history research based on tree-ring data is scant, and until the past two decades, few fire history studies using fire scars have been conducted in the eastern U.S. as a whole (Frost 2000). Remnant wood, which is critical to the success of this research, rots more quickly in the humid climates of the East, particularly in hardwoods (Harmon 1982), but several recent studies in the southeastern U.S. have shown the ability to reconstruct fire history for several hundred years using fire scars.

A considerable body of research has been conducted in the oak and pine forests of Missouri, Oklahoma, and Arkansas, and human settlement proved to be an important factor that could influence the fire regime in these areas. In the Missouri Ozarks, the fire return interval in an oak savanna was approximately one fire every 6.4 years, according to a fire-scar chronology dating to the 1700s (Guyette and Cutter 1991). Fire was frequent in the pine forests of southeastern Oklahoma prior to 1890, with fires occurring as frequently as once every 3.5 years (Masters *et al.* 1995). Fire suppression that followed settlement decreased the fire frequency substantially and caused the encroachment of midstory hardwoods. Similarly, fire return intervals decreased from about one fire every 2 years to every 24 years after settlement in oak-hickory ridges in Missouri because of the reduction in fuels from land clearing (Cutter and Guyette 1994). Furthermore, growing season drought seemed to have little influence on whether or not a fire occurred in southern Missouri (Cutter and Guyette 1994). In the Boston Mountains of Arkansas, fire frequency in shortleaf pine stands (*Pinus echinata* Mill.) may have been influenced by human population densities (Guyette and Spetich 2003). Most of the fires in this study occurred during the dormant season, and the vast majority of fires were believed to have resulted from anthropogenic ignitions (Guyette and Spetich 2003). Fire intervals ranged from 1.4 to 16 years in these forests prior to the commencement of fire suppression in the early 1900s (Guyette and Spetich 2003).

In addition to the fire history research conducted in the western limits of the Southeast, several fire history studies have documented past fire regimes in the central and southern Appalachians. Fires in the Ridge and Valley Province in eastern West Virginia occurred once every 7 to 15 years prior to the fire control era, and the reduction of fire halted the recruitment of red oak (*Quercus rubra* L.) in the area (Schuler and McClain 2003). Sutherland *et al.* (1995) found that surface fires predominated in the southwestern Virginia highlands with occasional stand-replacing fires. Fire intervals during Euro-American settlement (1850s to 1940) in the western sections of the Great Smoky Mountains National Park (GSMNP) were similar, averaging about 13 years between fires (Harmon 1982). Armbrister (2002) continued the research in GSMNP by reconstructing fire regimes in table mountain pine stands (*Pinus Pungens* Lamb.). Humans were believed to be the major cause of fire during the period of Euro-American settlement in the GSMNP, and after 1940, fire suppression virtually eliminated all fires (Harmon 1982). In addition to these fire-scar studies in the Appalachians, research using pollen and charcoal has documented that Native Americans substantially affected the fire regimes in the Blue Ridge escarpment of North Carolina and the northern Cumberland Plateau (Delcourt and Delcourt 1997; Delcourt *et al.* 1998).

While all the fire-scar studies mentioned thus far from the Southeast have been outside the Coastal Plain, one recent study examined the fire history of a barrier island slash pine savanna off the coast of northern Florida since 1866 and concluded that fire frequency was influenced by turpentining operations (Huffman *et al.* 2004). When turpentining operations occurred, fires were excluded from the stand, while a fire interval of approximately 4 years was observed when turpentining activities were not in progress (Huffman *et al.* 2004). Furthermore, most of the fires occurred in the middle position of the growing season, and lightning was probably the major source of ignition (Huffman *et al.* 2004).

Beyond these examples of fire-scar research, other studies using alternate methodologies have examined relationships between fire and climate in the Southeast, with particular emphasis on teleconnections. Statistically significant relationships between El Niño events and reduced fire activity have been observed for the southeastern U.S. (Simard *et al.* 1985). The decrease in fire activity has been attributed to increased precipitation in the southern winter/early spring fire season during ENSO events (Rasmusson and Wallace 1983; Simard *et al.* 1985). Similarly, Brenner (1991) found that fire activity in Florida was below average in El Niño years and above average in La Niña years. One study that was not focused on fire but nevertheless, has potential ramifications for fire history studies in the Southeast involved determining the relationship between wintertime lightning and El Niño in the Southeast. Increased wintertime lightning in the southeastern U.S. during 1997–1998 was directly attributed to ENSO phase and the stronger than normal upper level jet stream (Goodman *et al.* 2000).

1.5.3 Fire Ecology Research and Longleaf Pine

The longleaf pine forest and its fire ecology in the lower South have been studied perhaps more than any other forest type in the United States (Komarek 1974), although recent decades have seen increased levels of research in western forest types (Swetnam 1993; Heyerdahl et al. 2001; Grissino-Mayer and Swetnam 2000). The importance of fire in longleaf pine ecosystems has long been recognized (Harper 1911; Chapman 1932; Heyward 1939; Wahlenberg 1946). Renewed interest in restoring longleaf pine stands in the Southeast has sparked research on the importance of fire and its management. Longleaf pine forests are the natural habitat of numerous threatened or endangered animals, and over 100 species of rare plants are associated with many longleaf pine forests (Simberloff 1993; Smith *et al.* 2000).

No research has been published on fire history in the longleaf pine ecosystem using tree-ring data from longleaf pines, although extensive studies have been conducted on the effects of fire using forestry and ecological techniques. Many studies by foresters and biologists have examined the effects of fire and fire exclusion in longleaf pine stands (Gilliam and Platt 1999; McCay 2000; Provencher *et al.* 2001). Numerous recent studies have examined the effects of various types of prescribed burning on longleaf pine forests (Bruce 1947; Robbins and Myers 1992; Glitzenstein *et al.* 1995; Haywood *et al.* 2001; Glitzenstein *et al.* 2003; Kush *et al.* 2004; Varner *et al.* 2005). The major objective of prescribed burning programs in pine-dominated habitats is to prevent midstory hardwood development and maintain the herbaceous ground cover (Platt *et al.* 1991; Streng *et al.* 1993; Tucker *et al.* 2003). Various applications of fire frequency, seasonality, and intensity of prescribed burns have been used to determine the effects of fire on longleaf pine growth, reproduction, and vegetational assemblages. While many of these studies speculate on the historical fire frequency in past centuries, the estimates are usually based on historical accounts (Wahlenberg 1946; Komarek 1974; Christensen 1981; Pyne 1982) and not on tree-ring data. Moreover, the relatively short time frames of many of the forestry studies are inadequate to evaluate the dynamics of some ecosystems components such as long-lived trees (Swetnam *et al.* 1999). However, the value of field experimentation with fire in longleaf pine forests is considerable, and the merging of historical reconstructions using fire-scar data with the known short-term dynamics of fire activity provides converging lines of evidence in the study of longleaf pine fire history. Thus, forestry experimentation helps to properly interpret historical information and aids our overall understanding of long-term forest dynamics (Swetnam *et al.* 1999).

The most comprehensive study of presettlement fire regimes in the Southeast utilized what little fire-scar data were available for the Southeast in developing historic fire frequency maps (Frost 2000). This study used the findings of fire history studies, historical vegetation records, lightning ignition data, remnant natural vegetation, fire frequency indicator species, and "land surface-forms" to develop a map of presettlement fire frequency regimes in the United States. The map represents a window of time ranging from around the mid 1500s to the late 1800s (Frost 2000). This synthesis used all existing fire-scar chronologies for constructing the map because of their value as actual data points on the landscape. Despite the fact that Frost valued and employed these chronologies, very few fire-scar chronologies were available for the Southeast when he developed his map. Clearly, the development of fire-scar chronologies using longleaf pine and other prominent species in the Southeastern Coastal Plain is necessary to further our understanding of fire history in this region.

1.5.4 Objectives and Justification

This study helps to fill a large gap in fire history studies in the Southeastern Coastal Plain. As with the climate portion of the research, comparisons of historic fire regimes in several areas across the Coastal Plain can reveal differences and similarities not readily evident in forest-plot experimentation. Obtaining precise temporal information on how often and in what seasons historic fires occurred has been problematic in longleaf pine forests because of the paucity of fire-scar data. Although longleaf pine trees with conspicuously fire-scarred bases are rare, fire scars can sometimes be found embedded in cross-sections where the wood has healed over the scars, masking the underlying evidence of fire. Remnant stumps and logs are abundant in some areas of the Southeast, and uncovering this evidence will provide some of the most definitive information available on historic fire regimes in longleaf pine ecosystems. Providing geographic data points of actual fire events helps to definitively confirm the minimum frequency and seasonality of fires in an area.

A great deal of controversy exists concerning the relative influence of lightning versus Native American ignitions in the history of the Southeastern Coastal Plain, and these conflicting views will be discussed in detail in Chapter 6. Assessing the seasonality of fires will aid in determining whether natural or anthropogenic forces were igniting fires. The vast majority of dormant season fires were probably anthropogenic, because virtually all lightning ignitions occur during the spring and summer growing season (Komarek 1964).

Fire history data can help land managers better customize their prescribed fire plans to meet land management goals. Both fire seasonality and fire frequency information of historic fire regimes will help land managers assess prescribed fire strategies in light of fire regimes in the past. Prescribed fire experiments are often limited in time, so the long-term effects of burning for more than several decades cannot be determined conclusively. Fire history reconstructions that span several hundred years may help fill this information void.

The specific objectives of the fire history study are threefold:

1) Reconstruct fire history at three sites in the Southeastern Coastal Plain.
2) Analyze and explain the changes in fire regimes over the period of record.
3) Assess the relative influence of natural and anthropogenic forces that may have shaped the historic fire regimes by examining fire seasonality and frequency.

1.6 Organization of the Dissertation

The remainder of the dissertation consists of six chapters. Chapter 2 details the important characteristics of longleaf pine, emphasizing growth characteristics and reaction to disturbances. In Chapter 3, I provide a geographical description of the three major study areas in the Southeastern Coastal Plain to include the land use history as it may have affected fire regimes and tree growth within the stands. Chapter 4 provides an in-depth examination of how climatic variables affect ring width in longleaf pine.

Climatic reconstructions for each of the study sites are also presented in this chapter. Chapter 4 concludes with a comparison of the growth response of longleaf pine to climate among the various sites and the utility of the climate reconstructions for assessing past climate. Chapter 5 continues the climatic theme and focuses on the effects of interhemispheric teleconnections on longleaf pine growth. In Chapter 6, I discuss the fire history of these sites, focusing on how natural and anthropogenic forces may have affected fire regimes over the past several centuries. I summarize the major findings of the dissertation in Chapter 7 and suggest recommendations for future research. The Appendices contain details of the chronologies and fire-scarred samples.

Chapter 2

Ecology and Biogeography of Longleaf Pine

"The forests of pine are not only useful but beautiful. The characteristic moan of the winds in their branches, their funereal aspect, almost limitless extent, and the health-giving influences which attend their presence all contribute to make the pine an object of peculiar interest to the people of the Southern States."

- Francis P. Porcher, Surgeon P.A. Confederate States, 1863

2.1 Introduction

Longleaf pine forests may have been the dominant vegetation on upland Coastal Plain sites since the Hypsithermal Interval 5000 years ago (Delcourt 1980; Platt *et al.* 1988; Watts *et al.* 1996). When the first Europeans arrived on the North American continent, a vast belt of forested uplands dominated by longleaf pine stretched along the Coastal Plain from southern Virginia to east Texas (Wahlenberg 1946; Hickman 1962; Delcourt 1980). Longleaf pine was also present in mixed-species stands in wetland areas, with the total areal extent of the species encompassing approximately 37 million ha (Frost 1993). In the postsettlement period, the distribution of longleaf pine has been reduced to 1.3 million ha, a difference of over 95% (Myers 1990; Frost 1993). Although the range of this unique vegetative community has been drastically reduced since presettlement times because of logging and fire suppression, the importance of maintaining longleaf pine forest and its associated species has received renewed interest over the past several decades.

Many endangered species inhabit longleaf pine forests, and the application of the Endangered Species Act has made the management of longleaf pine a key consideration in public lands of the Coastal Plain (Early 2004). Furthermore, in some longleaf pine savannas, the small-scale diversity of plant species is among the highest in North America, which emphasizes the need to preserve these ecologically unique areas (Walker and Peet 1983). Moreover, the economic benefits of longleaf pine forests are being more widely recognized. Landowners can lease their property for fee hunting for deer, turkey, and quail that thrive in these open forests (Landers *et al.* 1995). Longleaf pine straw is becoming a valuable and major product for landscaping purposes. The trees, once established, are a low-risk species to manage, and the wood is of high commercial quality (Landers *et al.* 1995). Finally, conservationists feel that the restoration and conservation of a diminished ecosystem represents wise stewardship. To many involved in the restoration efforts, longleaf pine forests possess ethereal beauty and should be preserved for future generations to enjoy.

2.2 Environmental Conditions

2.2.1 Range of the Species

Longleaf pine still occurs over much of its former range, albeit in small pockets (Landers *et al.* 1995). The native range of longleaf pine and its associated communities extends from southeastern Virginia south and westward to the Trinity River in eastern Texas (Hickman 1962; Frost 1991) (Figure 2.1). This belt ranges from 160 to 320 km wide and seldom extends over 240 km from the coast (Wahlenberg 1946). The boundary along this belt in the presettlement forests was remarkably distinct in many areas, with a transition zone to other forest types less than 1.6 km wide (Wahlenberg 1946). The most conspicuous break in the east-west belt is the Valley of the Mississippi River, which is a

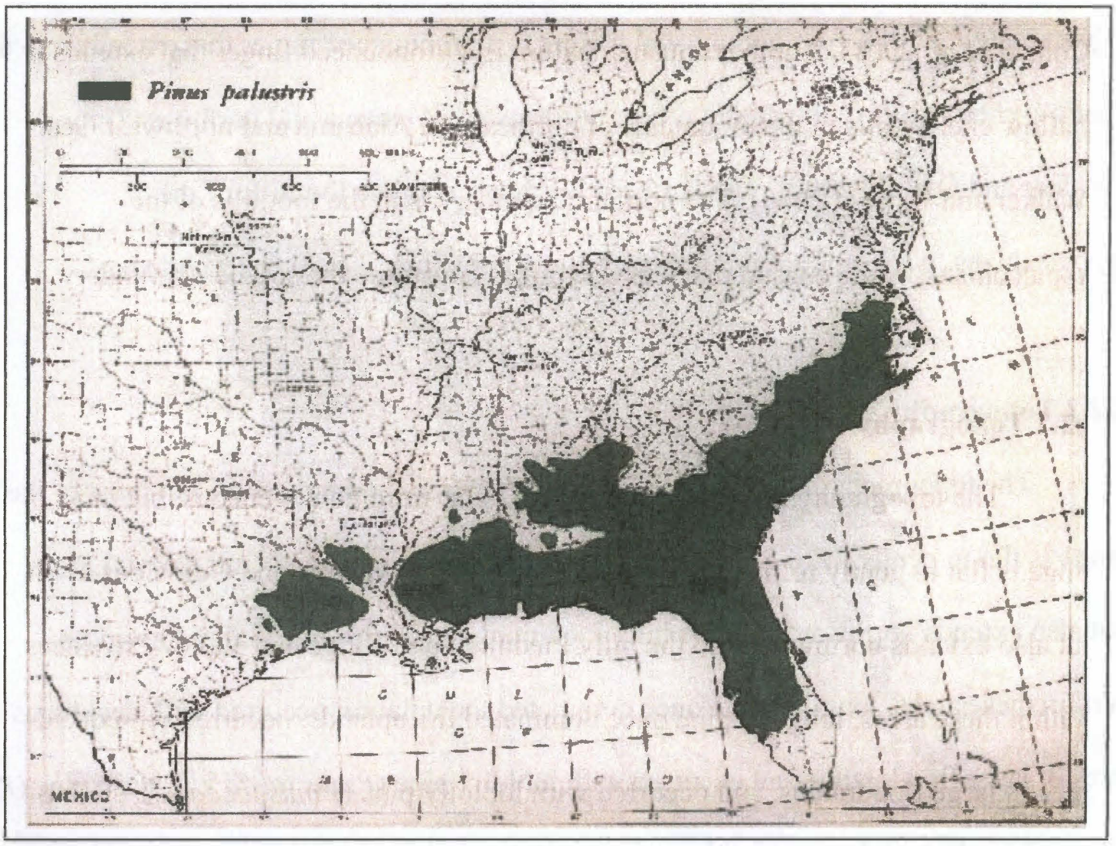


Figure 2.1 Native range of longleaf pine.
(Source: http://www.sfws.auburn.edu/sfnmc/class/longmap.jpg)

primarily deciduous area that separates pine habitat to the east and west by 100 km (Conner *et al.* 2001). Another unusual feature is a pronounced finger that extends into the shallow cherty soils in the mountains of northeastern Alabama and northwest Georgia (Walker and Oswald 2000). The northern boundary is in the foothills of the Appalachians, while coastal marshes and dunes constitute the southern boundary.

2.2.2 Topography

The topography in the longleaf region is far from homogeneous, but most of the range is flat to gently rolling. The species inhabits the Atlantic and Gulf Coastal Plain, but also extends northward into the hilly Piedmont and Ridge and Valley Provinces. Within these areas, longleaf pine once dominated the uplands, occurred with deciduous trees in large floodplains, and occurred with loblolly pine (*Pinus taeda* L.), slash pine (*P. elliottii* Engelm), and mixed hardwoods in minor riparian areas and on other moist sites (Croker and Boyer 1975). Elevations range from 600 m in northern Alabama to near sea-level along the Gulf of Mexico coastline (Snyder *et al.* 1977; Meldahl *et al.* 1999).

The majority of longleaf pine forests are found at elevations below 200 m (Boyer 1990). In these areas of low elevation, the soils are typically underlain by marine and fluvial terraces composed of coarse sands (Walhenberg 1946). In the lowest areas, known as flatwoods, the water table is near the surface, creating moist conditions (Boyer 1990). Despite the lack of relief in low elevation areas of the lower Coastal Plain, a difference of one meter or so in elevation can determine the difference between a wet site and a mesic site, so subtle changes in topography can be significant (Walker 1999). For example, pocosins, common from Virginia to northern Florida, are wetland depressions that may be separated from dry uplands by a few meters in elevation (Richardson *et al.* 1981).

The highest ridges in the Coastal Plain, known as sandhills, are often capped by sands and gravels of the Lafayette formation, and longleaf pine trees tend to predominate where sands and gravels form deep layers over older rock strata (Mohr 1901; Wahlenberg 1946). At the highest elevations in Alabama and Georgia, the underlying strata in longleaf pine forests are composed of siliceous slates and quartzites. The dry, rocky mountain ridges support scattered populations of longleaf pine on thin soils. Where the parent material is composed of gneissic rocks and clayey slates, shortleaf pine (*Pinus echinata* Mill.) and loblolly pine are more common than longleaf pine (Pessin 1940).

2.2.3 Soil Conditions

Though the climate is fairly uniform across its known range, the soils in which longleaf grows are quite diverse. Deep, sandy soils are dominant in longleaf pine regions, but this pine is found on all but the most inundated soils of the southeastern U.S, where floods may kill seedlings (Wahlenberg 1946). In fact, the Latin species name *palustris* means “swamp,” as the species was named from longleaf pine trees growing in seasonally wet soils along the Atlantic coast (Walker and Oswald 2000). Soils of the longleaf pine ecosystem vary from mesic, even wet, Ultisols to rather xeric Entisols (Christensen 1993a). In general, longleaf pine grows in siliceous soils that are low in fertility, rather than calcareous soils (Wahlenberg 1940).

Ultisols are the most dominant soil order in the range of longleaf pine, and the Ultisols most commonly associated with longleaf pine include Typic Paleudults and

Plinthic Paleudults (Boyer 1990). Spodosols are prevalent in low-lying moist flatwoods, particularly in the lower Coastal Plain in Florida and southerly portions of the Atlantic Coast. Spodosols form in quartz-rich sands that have a fluctuating groundwater table (USDA 1988). Another soil type that commonly forms in poorly drained parts of the landscape is Alfisols, moist mineral soils with no mollic epipedon or oxic or spodic horizons (Brady 1990). Within the range of longleaf pine, Alfisols are most common in the West Gulf Coastal Plain in east Texas.

Some of the driest soils in the Coastal Plain are deep, sandy Entisols that range from 3 m above sea level in Florida to almost 185 m in Georgia and the Carolinas (Boyer 1990). Longleaf pines are well-suited to xeric conditions and are a hardier tree in dry environments than all other deciduous trees except the turkey oak (*Quercus laevis* Walt.) (Earley 2004). The ability of longleaf pine to thrive in dry sites is also related to the extreme depth of its taproot and its narrow and waxy needles that limit water loss (Earley 2004). The taproot may extend to a depth of 2.4 to 3.7 m or more in mature trees (Boyer 1990).

Its apparent penchant for poor soils belies its ability to thrive in response to soil enrichment, indicating that its natural range on mostly poor soils is related to an ability to withstand unfavorable ecological conditions and fire disturbance (Wahlenberg 1946). The capability of longleaf pine to thrive in poor soils gives it a competitive edge over many species, particularly on dry sites. Raw humus formation is rare in the longleaf region regardless of stand composition, so low soil moisture often limits growth more than low soil nutrients (Heyward and Barnette 1936; Heyward 1939).

2.2.4 Climate

The climate across the region is predominantly warm-temperate with heavy summer rainfall and mild winters (Croker 1968). Precipitation ranges from 113 to 164 cm annually, with frequent summer thunderstorms and occasional hurricanes offsetting large losses of moisture from infiltration in sandy soils and transpiration during the long growing season (Wahlenberg 1946; Croker 1968). The western boundary of longleaf pine in Texas represents the limit of longleaf pine's ability to survive in dry conditions (Schmidtling and Hipkins 1998). Mean annual temperature ranges between 16° C and 23° C, with a minimum and maximum temperature of – 23° C and 41° C, respectively (Wahlenberg 1946; Croker 1968). The frost-free period averages from 200 to 300 days between the northern and southern portions of the range (Fowells 1965).

Temperature seems to have a strong influence on the range of longleaf pine. Entire flowering crops can be destroyed by March frosts as severe freezes in the flower stage can be very damaging (Wahlenberg 1946). In addition, cotyledonary seedlings are subject to damage by freezing temperatures and frost heaving (Wahlenberg 1946). Where snowstorms are heavy, longleaf pine cannot survive because of the inability to withstand heavy snow loads on its branches (Wahlenberg 1946). The northern limits of longleaf pine probably represent the limit of its tolerance to low temperatures, heavy snowfall, and/or ice accumulation. The minimum temperature necessary to injure the cambium of central Gulf Coast longleaf pines is not known, because few studies have been conducted on cold tolerance (Wells and Wakely 1970). In the cold winter of 1962–1963, the temperature reached near record lows in east Texas and South Carolina, but no visible freeze injury occurred in longleaf pine plantings (Wells and Wakely 1970).

2.3 Reproduction and Growth

The species is similar to other southern pines in reproductive and growth characteristics. Longleaf pine is monoecious and anemophilous. Although the longleaf pine is normally cross-pollinating, some self-pollination occurs, and seed yields and survival rates are lower in hybrids (Snyder *et al.* 1977). The only named southern pine hybrid is the Sonderegger pine (*Pinus sondereggeri* H.H. Chapm.), a cross between longleaf and loblolly pine (Chapman 1922).

Longleaf pines produce seed by masting, and for cone production to occur, trees must normally be greater than 30 cm dbh (Rathbun 1993). Seed production is sporadic, with abundant seed crops occurring at 10-yr average intervals (Walker and Oswald 2000). Longleaf pine seeds fall from the end of September to December and normally germinate best on mineral soil exposed by fires during the growing season (Earley 2004). The large longleaf seeds contain enough moisture and nutrients to sprout almost immediately in the fall on fire-cleared mineral soil, and the seedlings begin root growth before winter (Wahlenberg 1946). The seeds and the succulent seedlings are particularly susceptible to consumption by birds and small mammals, as well as feral pigs.

A distinguishing feature of longleaf pine during its lifespan is the “grass stage” of growth (Figure 2.2). The stem above the cotyledon does not elongate quickly as in most other pines (Boyer 1990). Unlike other North American trees, longleaf pines demonstrate temporary nanism in which seedlings remain in a stemless condition from 2 to 25 years before beginning significant height growth (Walker and Oswald 2000). During the grass stage, longleaf pine does not produce annual rings (Pessin 1934).

Figure 2.2 Grass stage seedlings of longleaf pine at Eglin Air Force Base.

Young seedlings are particularly susceptible to drought in sandy soils with low moisture holding capacity (Collier 1964). To survive in dry conditions, young trees grow a deep taproot that may extend up to 2.4 m long in length in an 11-month period (Earley 2004). The long taproot allows the tree to survive more easily in dry environments, anchors the tree in sandy soils, and stores food for subsequent growth (Earley 2004). Height increases much more rapidly than stem diameter after grass-stage plants reach a basal diameter of 2 to 3 cm (Platt *et al.* 1988).

Normally, height and diameter growth increase rapidly after the first three to six years. Twenty-five year-old trees average 13.7 m in height and 15.2 cm in diameter (Harlow and Harrar 1968). As the trees draw on the nutrients stored in their taproots, they may grow as much as 0.9 m in a single year (Earley 2004). This rate of height growth equals or exceeds that of other major southern pines (Boyer 1990). The timing and extent of height growth is closely tied to competition within the stand, as height growth of longleaf pines is sensitive to competition for light or moisture. Even though seedlings can survive for years beneath a pine overstory, growth is slow until the seedlings are released from overstory competition (Boyer 1990).

Trees that survive to sexual maturity have expected life spans of one or more centuries (Wahlenberg 1946; Platt *et al.* 1988). After trees approach 30 cm dbh, growth declines rapidly (Platt *et al.* 1988). The combination of slow growth and low mortality among trees in the 30–50 cm diameter class results in life spans for longleaf pine that approach 500 years (Platt *et al.* 1988). Longleaf pines rarely reach their biological potential age because of frequent disturbances such as hurricanes, tornadoes, lightning strikes, and wildfire (Brockway and Lewis 1997). The growth forms of longleaf pine are highly variable and dependent on site conditions. Longleaf pine might grow tall in one setting, but be short and squat in another (Early 2004) (Figure 2.3). Typically, trees in moist sites tend to have larger diameters and greater heights than those in more xeric settings. Moreover, disturbances such as fire can significantly affect stand dynamics and growth rates (Boyer 1987).

2.4 Stand Characteristics and Disturbances

Old-growth longleaf pine stands tend to be uneven-aged, indicating that the virgin forest was not simply a homogeneous stand of old growth trees (Chapman 1909; Wahlenberg 1946; Truett and Lay 1984; Platt *et al.* 1988). Young, even-aged stands of longleaf pine can develop a diverse size distribution over a short period because of the grass stage (Boyer 1990). Because annual rings are not produced in the grass stage, the ring counts on these trees will indicate a difference in age when the trees are actually from the same cohort.

Recruitment occurs frequently, but juvenile mortality is high (Platt *et al.* 1988). Disturbances such as tornadoes, hurricanes, ice storms, and beetle outbreaks can produce large open areas by treefall, and these gaps are important in longleaf pine recruitment (Chapman 1909; Wahlenberg 1946; Platt *et al.* 1988). The trees that are most susceptible to damage by disturbances are those that have been wounded or weakened by competition or drought (Wahlenberg 1946). Longleaf pine is generally less vulnerable to most damaging agents, but disturbances caused by wind, ice, earthquakes, and biotic agents can have significant effects (Boyer 1990).

Figure 2.3 Comparison of growth of longleaf pine trees of similar age. Left photo is mesic flatwoods, right photo is xeric sandhills.

2.4.1 Wind Disturbances

Longleaf pine is better able to withstand wind injuries than other southern pines because of its deep taproot and widespread lateral root system (Touliatos and Roth 1971; Gresham *et al.* 1991; Provencher *et al.* 2001a). However, wind is a significant stand disturbance event throughout much of the range of longleaf pine, and thunderstorms, tornadoes, and hurricanes can cause considerable damage. Wind can cause trees to be uprooted (windthrown), or their stems or branches to snap (Putz *et al.* 1983). Because of the strength of longleaf pine roots, strong winds normally break longleaf pines rather than uprooting them (Wahlenberg 1946). Tornadoes and associated thunderstorms can affect large areas, although tornadoes tend to touch down sporadically.

Whereas tornado paths are, on average, about 250 m wide and 8 km long, hurricanes are much larger-scale disturbances and produce damaging sustained winds. Return intervals for hurricanes on the lower Coastal Plain are generally 50 years or less (Oliver and Larson 1990; Platt and Rathbun 1993; Palik and Pederson 1996). In some areas, the return interval is almost 6 years, meaning that some trees could be exposed to as many as 17 hurricanes in a century (Purvis 1973; Gresham *et al.* 1991). Hurricane-force winds, which exceed 125 km per hour, tend to cause greater breakage and mortality in taller trees, especially if the boles have little taper (Touliatos and Roth 1971). Tall, slender longleaf pines with extensive crowns are particularly vulnerable to hurricanes, but small longleaf pines can also sustain heavy crown damage (Platt and Rathbun 1993; Gresham *et al.* 1991).

The damage created in longleaf pine forests by hurricane winds has been well documented. As early as 1528, Alvar Nuñez Cabeza de Vaca, a Spanish explorer, described hurricane damage in peninsular Florida as being so destructive that the fallen trees made marches through the forest "laborious" (de Vaca 1983). In 1752, a destructive hurricane downed huge stands of pines within a 50 km radius of Charles Town (now called "Charleston"), South Carolina (Fraser 1989). In 1989, Hurricane Hugo damaged more than 90% of South Carolina's timberland in six counties, and the volume of longleaf pine in South Carolina fell by 25% (Sheffield and Thompson 1992). In Mississippi, Hurricane Camille, a Category 5 storm, struck the Harrison Research Natural Area and damaged almost two-thirds of all trees. As much as 75% of pine trees larger than 22 cm in diameter sustained substantial damage in Harrison County, Mississippi (Van Hooser and Hedlund 1969; Touliatos and Roth 1971). In southern Georgia in 1985, Hurricane Kate's winds caused snapped crowns and tip-ups of longleaf pine, destroying almost 20% of the trees of the larger size classes in the Wade Tract, an experimental longleaf pine forest (Platt and Rathbun 1993).

Hurricanes and other damaging winds have significant effects on stand dynamics. For those trees that survive the storm but are heavily damaged, growth tends to be suppressed or reaction wood is formed because of leaning (Noel *et al.* 1998). If fire moves through the forest after a wind disturbance event, downed logs and tree crowns provide fuel for fires that may kill living trees next to the woody debris (Glitzenstein and Harcombe 1988; Platt and Rathbun 1993). The death of older, larger trees creates gaps for the recruitment of longleaf pine seedlings, but these seedlings can only reach maturity if they are able to compete with other saplings (Glitzenstein and Harcombe 1988; Noel *et al.* 1998).

The survivors that sustain little damage from wind may undergo a growth release for two reasons. First, the surviving trees have less competition because of the death of adjacent trees. Second, the nutrient pool in the forest floor is increased by the additional biomass blown onto the ground or by windthrow in which trees are uprooted (Waring and Schlesinger 1985; Blood *et al.* 1991). Windthrow overturns the soil and incorporates organic matter into the soil, increasing the availability of nutrients, moisture, and oxygen to roots (Oliver and Larson 1990). A period of rapid growth in east Texas longleaf pine forests during the late 1800s has been attributed to hurricanes that moved over the Big Thicket in 1886 and 1896 (Glitzenstein *et al.* 1986). The Galveston, Texas hurricane of 1900 may have had a similar effect in the early part of the century (Glitzenstein *et al.* 1986). Besides the effects of wind, salt damage from hurricanes can occur in forests near the coast, but longleaf pine is one of the most resistant trees in the Coastal Plain to salt intrusion (Touliatos and Roth 1971). Lightning associated with strong wind events such as thunderstorms and hurricanes is one of the leading causes of mortality for the taller and more isolated trees (Wahlenberg 1946; Platt *et al.* 1988; Boyer 1990). Damage from lightning attracts bark beetles (*Ips* spp.) and causes decay, making lightning-struck trees more prone to death from windfall (Wahlenberg 1946).

2.4.2 Ice storms

Another significant disturbance that affects longleaf pine forests is ice storms, which occur more often in the eastern U.S. than anywhere on earth (Bennett 1959). Although ice storms are most prevalent in the Northeast, they are often most destructive in the southern states (Oliver and Larson 1990). In the lower Coastal Plain, only one or two ice storms may occur in a 27 year period, but these events are particularly injurious to southern pines (Bennett 1959). The most damaging ice events in the Coastal Plain occur as freezing rain or drizzle, and in the Southeast, these phenomena are typically associated with warm fronts (Gay and Davis 1993). Freezing precipitation events often begin during a transitory period between the occurrence of rain and snow, so these events normally happen when temperatures are slightly below freezing (Bair 1992). Freezing rain occurs when temperatures at cloud level are below 0^{o} C, and supercooled water droplets fall from the clouds. If the precipitation freezes in mid-air, the tiny pellets fall as sleet, which does little damage to trees (Reihl 1972). If the layer of subfreezing air near the ground is not thick enough to allow the supercooled droplets to freeze, the drops will strike ground surfaces before changing state (Lutgens and Tarbuck 1992). When the droplets strike a surface that is below freezing, they freeze and form a layer of ice called glaze (Reihl 1972; Bair 1992). Large, supercooled droplets tend to spread out over surfaces before freezing and are more damaging to trees than small droplets that form rime, a granulated coating of ice (Bair 1992). The thickness of glaze is usually about 3 cm thick but may reach a maximum thickness of about 20 cm (Oliver and Larson 1990).

Ice damage to trees occurs when glaze accumulates on foliage and bark surfaces, and the added weight can snap or bend branches and main stems (Geiger 1965). Because evergreen trees contain more surface area for adherence of ice, they are more heavily weighted down by ice than deciduous trees (Oliver and Larson 1990). For example, an evergreen tree 15 m high with an average crown width of 6 m may be coated with as much as 4.5 metric tons of ice during a severe ice storm (Bair 1992). Damage to trees is especially acute if the duration of the weight load is prolonged or accompanied by wind and if the trees are tall and slender (Brender and Romancier 1965; Van Lear and Saucier 1973). Heavy, wet snow can cause similar problems of overloading, but the damage is generally less severe (Lafon 2000). Compared to other southern pines, longleaf pine is particularly susceptible to damage by glaze ice because its dense, persistent foliage and long needles accumulate a large ice load (McKellar 1942; Wahlenberg 1946). Glaze ice storms can bend young longleaf pine trees up to about 15 cm in diameter (Wahlenberg 1946). Glaze ice normally thaws within a few hours, but in some instances, the ice persists for days or even weeks (Burroughs *et al.* 1996).

Descriptions of several ice storm events in the Coastal Plain are contained in the historical record. In 1690, Spanish explorers near the Sabine River in Louisiana described a late fall snow and ice storm that caused thousands of trees in the surrounding countryside to fall, killing many of the party's mules and horses (Truett and Lay 1984). In 1835, a disastrous freeze and ice storm affected northern Florida and the Carolinas, killing many trees (Lyell 1849; Harper 1958). During this rare arctic outbreak, the temperature dropped to – 21.7° C, the wind blew severely for ten days, and the St. John's River in Florida was partially frozen (Harper 1958). Lyell (1849) postulated that the impact of this winter storm would influence the composition of Atlantic coast forests for a century.

Researchers have documented the damage to trees in more recent ice events in the 20th century. A severe glaze ice storm in January 1940 damaged over 50% of 11-year-old longleaf pines near Athens, Georgia, and 24% of the trees were killed (McKellar 1942). A sleet and snow storm in January 1944 in northeast Louisiana severely damaged half of the longleaf pine trees 15 m high and 30 years old (Wahlenberg 1946). In February 1969, tens of thousands of trees were uprooted or broken in the Sandhill region of South Carolina near Cheraw (Hebb 1972). Only 59% of longleaf pines in Sandhill State Forest Park survived the ice storm (Hebb 1972). In January 1973, a severe ice storm damaged 57% of longleaf pines near Holly Hill, South Carolina, completely breaking off the tree tops or toppling the trees (Van Lear and Saucier 1973). These examples illustrate that, although ice storms are not particularly frequent in the Coastal Plain, when they occur, their effects can be severe and widespread.

2.4.3 Earthquakes

Although high-magnitude earthquakes seldom occur in the eastern United States, earthquakes have been known to significantly affect tree growth and even cause tree mortality (LaMarche and Wallace 1972; Jacoby *et al.* 1995; Jacoby 1997). The New Madrid earthquakes of A.D. 1811–1812 in the central U.S. greatly affected the growth of baldcypress trees in the vicinity of Reelfoot Lake in northwestern Tennessee (Van Arsdale *et al.* 1998). The shaking of the ground cracks tree stems and disrupts root systems if the event is of sufficient magnitude (Jacoby 1997; Arsdale *et al.* 1998). Although no studies have been conducted concerning longleaf pine and earthquake effects, the characteristically long taproot and main stem of the longleaf pine would undoubtedly experience considerable stress in a large earthquake. The 1886 earthquake centered near Charleston, South Carolina, caused over 12,000 chimneys to be sheared off at the roof line (Fraser 1989). The damage to trees from this earthquake has not been documented, but the stresses that caused structures to fail could likewise have injured trees.

2.4.4 Biotic Disturbances

The biotic agents that affect longleaf pine include animals and various diseases. Birds and mammals influence the reproduction of longleaf pines by consuming the seeds and seedlings. Mice, squirrels, and numerous bird species feed on the seeds, more so than other southern pines (Wahlenberg 1946). Feral hogs, livestock, pales weevil (*Hylobius pales*), pocket gophers, and ants consume the seedlings.

Few pathogenic agents, except brown spot needle blight, have a significant effect on longleaf pine. Brown spot is caused by a fungus (*Mycosphaerella dearnessii* Barr.) and is the major disease that afflicts grass-stage seedlings (Kais *et al.* 1981; Christensen 1981; Platt *et al.* 1988; Boyer 1990). The needles become infected in the second or third year after germination and subsequently turn brown. If left unchecked, brown spot can cause severe defoliation and mortality in seedlings. Other diseases that have a minor effect on longleaf pines are pitch canker (*Fusarium moniliforme* var. sub *glutinans*), annosus root rot (*Heterobasidion annosum*), heart rot (*Polyporus* spp.) and cone rust (*Cronartium strobilinum* Arth.) (Wahlenberg 1946; Boyer 1990). These diseases make longleaf pines more susceptible to windthrow or, in the case of cone rust, affect reproduction. Longleaf pine is fairly resistant to fusiform rust (*Cronartium quercuum* f. sp. *fusiforme* Berk.) and pests such as the southern pine beetle (*Dendroctonus frontalis* Zimmerman) (Boyer 1990).

2.5 Fire and Longleaf Pine

The ability of longleaf pine to prosper in conditions of frequent fire is very well documented. No other tree species in the southeastern U.S. equals the ability of longleaf pine to thrive and regenerate abundantly where fire may occur several times per decade, even where surface fires are relatively intense (Boyer 1987; Glitzenstein *et al.* 1995; Conner *et al.* 2001). Fire is essentially a requisite for the regeneration and perpetuation of longleaf pine (Croker and Boyer 1975). Many ecologists believe that the longleaf pine ecosystem is a fire "steady state" assemblage or fire climax that represents a successional stage that owes its long-time occupancy of extensive areas to frequent fires (Wahlenberg 1946; Watts 1971). Interestingly, fire can be quite lethal to mature longleaf pines when fire has been excluded for several decades and deep organic layers and vegetation in understory and middle story strata build up around the trees (Varner *et al.* 2005).

Fire is thought to be essential for the successful germination of longleaf pine seeds, but the value of fire for reproduction was not fully understood until the 1930s (Chapman 1932). For example, in 1899, forester A. Schenck (1998) was "nonplused" to find extensive regeneration in a longleaf pine stand in western Florida "on land badly and continually burned over." Our knowledge of the relationship between longleaf pine and fire has since increased substantially, and the importance of fire in longleaf pine regeneration is well understood. Fire reduces the competition from trees and shrubs and exposes mineral soil for the establishment of longleaf pine seedlings in the late fall (Provencher *et al.* 2001b). Fire is important for seed germination, as the exceptionally large wings of longleaf propagules keep seeds from penetrating heavy grass and litter; so fire is necessary to burn away the obstructing vegetation (Platt *et al.* 1988).

Once seedlings establish, longleaf pine is exceptionally fire resistant. Juveniles are resistant to fire as early as two years following germination, and once in the grass stage, juveniles tend to have low mortality from fire (Croker and Boyer 1975; Gilliam and Platt 1999). In the grass stage, the single large bud on each seedling is shielded from heat by the sheath of needles during the grass stage (Walker and Oswald 2000). The water in the needles is vaporized, and the steam generated dissipates heat which protects the terminal bud (Means 1985) (Figure 2.4). Fire also checks the progress of brown spot needle blight in the grass stage by acting as a sterilizing agent that consumes the infected needles (Wahlenberg 1946; Grelen 1983).

When seedlings emerge from the grass stage, they are more prone to injury by fire because the thin bark does not provide sufficient protection to the cambium (Walker and Oswald 2000). Saplings in the early stages of height growth are susceptible to damage by fire up to a height of approximately 0.6 to 0.9 m (Boyer 1990). The rapid height increase when seedlings emerge from the grass stage reduces the possibility of fire-induced mortality in the vulnerable sapling stage (Platt *et al.* 1988). Once longleaf pines are larger than 10 cm dbh, they are not easily killed by low- to moderate-intensity surface fires because of the growth of protective bark that armors the cambium (Palik and Pederson 1996; Earley 2004). The threshold thickness of bark for effective insulation of the vascular cambium is approximately 2.5 cm in longleaf pine (Hare 1965). Pine bark has natural qualities of insulation because it is thick and porous, but longleaf pine bark provides particularly effective protection from fire (Sutton and Sutton 1985). Sheathed with thick plates of bark, longleaf pines dissipate the heat of low-intensity fires away from the cambium by flaking off the bark as it burns (Means 1985). On older trees, the mounding of bark around the base of the tree is strikingly conspicuous (Figure 2.5). Because of the protective bark, longleaf pine trees do not scar readily from fire alone, except in trees surrounded by slow-burning woody debris (Wahlenberg 1946). Most scars

Figure 2.4 Grass-stage seedling with apparent fire damage to lower needles and needle tips but little-damaged interior needles.

Figure 2.5 Thick plates of bark armor the base of a mature longleaf pine (note flaking of fire-singed bark).

are initially produced by logging bruises, tree fall, turpentining, and turpentine beetles (Wahlenberg 1946).

When fire is excluded from longleaf pine ecosystems, the forests tend to give way successionally to mixed hardwood forests (Watts 1971; Gilliam and Platt 1999; Provencher *et al.* 2001a). Fire does not, however, eliminate scrub oaks (*e.g.* turkey oak (*Quercus laevis* Walt.) and blackjack oak (*Quercus marilandica* Muenchh.)) on well-drained sandy sites (Heyward 1939). Longleaf pine is particularly sensitive to competition from hardwoods during the grass stage (Platt *et al.* 1988). The presence of competitor species slows growth and makes juvenile longleaf pines more susceptible to fire and diseases, such as brown spot needle blight (Chapman 1932).

When fires are allowed to ignite and spread naturally, the resinous, flammable needles shed by longleaf pines provide abundant fuel for surface fires. The longleaf pine needles are the longest among the southern pine, and they rest loosely on bunch grass crowns, allowing them to air-dry readily. One much-debated hypothesis states that natural selection may favor the production of litter that is recalcitrant in order to maintain a fire cycle that is favorable to successful reproduction (Mutch 1970). The tendency of longleaf pine to promote frequent ground fires by the frequent shedding of incendiary needles may have contributed to the long-term presence of environmental conditions that favor longleaf to the exclusion of other, less fire tolerant species (Platt *et al.* 1988). Because longleaf pine has more abundant needle litter per basal area than shortleaf and loblolly pine stands, the intensity, rate of spread, and flame length in longleaf pine stand fires is generally greater than in other southern pine stands (Roberston and Ostertag 2003). The longleaf pine needles, 20 to 46 cm long, normally persist for two seasons before falling from the tree (Harlow and Harrar 1968). Needlefall occurs year-round but is heaviest in fall and winter (Wahlenberg 1946). In addition to the large quantities of pine needles, dead grass and live herb loads are also generally more abundant in longleaf pine forests than in shortleaf or loblolly pine forests because the canopy is often discontinuous (Robertson and Ostertag 2003).

Pineland threeawn, or wiregrass (*Aristida stricta* Michx.), found in 90% of the understories of longleaf pine communities, is extremely flammable (Earley 2004). Most of the cells in the live leaves are woody and fibrous, making the entire plant highly flammable (Earley 2004). Not only is wiregrass fire-inducing, but it is also resistant to fire. Wiregrass has relatively narrow blades and hardened leaf bases that protect the growing tip of the rhizome from high temperatures, allowing the plant to survive and resprout after fire (Earley 2004). Thus, longleaf pine and its associates seemingly maintain a self-reinforcing fire regime through the production of plant material that burns readily (Earley 2004).

2.6 Associated Plant Species

Like wiregrass, other plant species within the longleaf ecosystem thrive under conditions of frequent fire. The frequent fires reduce competition for light and reduce leaf litter deposition, allowing for high species richness on the forest floor (Earley 2004). Interestingly, some longleaf pine forests with discontinuous canopy and mesic settings support the greatest small-scale plant species richness in North America (Walker and Peet 1983). The great plant diversity of the longleaf pine system lies not in the tree species but in the herb layer (Earley 2004). For example, in the 81 ha Wade Tract in southern

Georgia, nearly 400 plant species are found in the ground cover (Earley 2004). An average of 35 plant species/m^2 was found in the Green Swamp of southeastern North Carolina (Walker and Peet 1983).

Most of the areas in the Southeastern Coastal Plain lack detailed presettlement land surveys (Lorimer 2001), but historical accounts describe the vegetation at the time of first Euro-American contact. Early explorers described the longleaf pine forests of the Coastal Plain uplands as open and park-like and as having grassy "savannas" interspersed with pines (Lyell 1849; Harper 1958). The open nature of these forests was probably created by natural and human-caused wildfires (Christensen 1981; Pyne 1982). Numerous herbaceous plants that are fire resistant are prevalent in the longleaf region, but the dominant herbaceous species are bunch grasses. Wiregrass is common in the eastern portion of the longleaf belt, whereas bluestem grass (*Adropogon* spp.) and *Panicum* grass predominates in the western areas (Wahlenberg 1946; Delcourt 1980; Eyre 1980). Many rare herbaceous plants in the longleaf pine ecosystem are fire dependent, such as the Venus flytrap (*Dionaea muscipula* Ellis) (Frost 2000). Fire dependent plants are those that may have gone extinct without fire in the presettlement landscape (Frost 2000).

Other understory associates include several species of oak including blackjack oak, bluejack oak (*Quercus incana* Bart.), sand post oak (*Quercus stellata* var. *maragaretta* (Ashe) Sarg.), and turkey oak. All of these oak species have shrubby growth habits (Wahlenberg 1946). The oak species are less prevalent to absent where fire is more frequent, but they all possess some resistance to fire. Turkey and bluejack oaks will sprout after a winter fire seems to have killed them (Earley 2004). Other pine species that may co-occur with longleaf include slash pine, loblolly pine, and shortleaf pine. In dry, sandy areas, saw palmetto (*Serenoa repens* Bart.) is found, and on the driest sites, sand pine may be present (*Pinus clausa* Chapm. ex Engelm) (Wahlenberg 1946). Associated shrubs include wax myrtle (*Myrica cerifera* (L.) Small), blueberry (*Vaccinium* spp.), and inkberry (*Ilex glabra* (L.) Gray), and yaupon (*Ilex vomitoria* Ait.).

2.7 Post-settlement Influences on Longleaf Pine Forests

2.7.1 Lumbering and Naval Stores Industries

The turpentine and logging industries led to the downfall of the original longleaf forests. The most rapid and extensive changes in longleaf pine forests occurred during the last 500 years from the influence of European settlement in the Southeast (Frost 1993). Longleaf pine dominated forests in the Southeast at the time of European settlement, and these trees were immediately recognized as an important resource (Watts *et al.* 1996). The effects of Anglo-American settlers on longleaf forests began in the 1500s and gradually spread southward and westward from Virginia to Texas. From the time of earliest arrival to each area, the settlers began to exploit the wealth of virgin timber throughout the Coastal Plain. One of the first industries to affect the Coastal Plain forest was the naval stores industry.

2.7.1.1 Naval Stores

The advent of the naval stores industry in Virginia in 1608 was the beginning of the demise of the longleaf pine forest in the Southeast (Frost 1993). Longleaf pine was a mainstay of the naval stores industry in the United States for centuries, and the industry began in 1608 when John Smith first exported tar and pitch from Jamestown (Frost 1993). Naval stores was the name given to tar, pitch, and turpentine, and in the Southeast, naval stores were produced almost exclusively from longleaf pine (Frost 1993). Naval stores consist of two major types, wood and gum. Tar and pitch were wood naval stores that were used extensively as caulking on ships and insulating ropes against moisture, hence the term "naval stores" (Perry 1968). The Constitution, the colonial ship known as "Old Ironsides," was sealed with longleaf pine resin (Walker 1991). The making of pitch and tar was one of the first widespread industries in America. In early naval stores production, tar and pitch were produced by burning the "lightwood" of a dead tree or limb (Earley 2004). The wood was burned slowly in earth-covered mounds called tar kilns until the resinous matter was forced out (Perry 1968).

"Lightwood" or "fatwood" is the name given to the dense heartwood of the longleaf pine, and "lightwood" is so named because the wood burns brightly (Hawley 1921). The heartwood in remnant snags, stumps, and logs of longleaf pine is seemingly impervious to decay and saturated with resin (Earley 2004). For this reason, dead longleaf pine trees were sometimes used in maritime construction because of the quality of the remnant wood and its resistance to water (Smith *et al.* 2000). Moreover, "dead-head" logs that sank to the bottom of Coastal Plain rivers during the historical logging boom are still in demand today because the wood has resisted deterioration. In the 1900s, the lightwood from remnant stumps was in high demand for "wood rosin" produced in wood distillation plants (Hawley 1921). Because longleaf pine stumps were harvested extensively throughout the Southeast in the 20th century, these stumps are rather rare in the Coastal Plain today, despite the fact that longleaf pine was once widespread (Hawley

1921). While wood naval stores depleted the supply of dead longleaf pines, gum naval stores affected the living trees.

Gum naval stores are produced by tapping living pine trees and collecting the "gum" or resin that exudes from a network of resin ducts in the trees (Coppen and Hone 1995). A square inch of sapwood surface in tangential sections of longleaf contains 300 to 400 rays with resin ducts (Wahlenberg 1946). Resin was extracted from mature trees by chopping into the base and collecting the sap in a cup or cavity (called a "box") in the base of the trunk (Perry 1968; Loughmiller and Loughmiller 1977; Butler 1998). Boxes were normally cut about 25 cm above the ground approximately 8 cm wide and 33 cm long (Hickman 1962). The minimum size of tree for turpentining was generally 25 cm in diameter, and depending on the size of the tree, workers would cut or "box" on two to four sides of the trees about a meter above the collection point (Loughmiller and Loughmiller 1977: Frost 1993; Earley 2004). The lower portion of the cut-out area was called a "catface" while the entire surface was called a "face" (Grissino-Mayer *et al.* 2001). Chipping of the catface (removal of bark and cambium in diagonal streaks) began in the spring when the resin began to flow and continued into late fall (Figure 2.6). New streaks had to be chipped into the catface every week to enable the resin to continue to flow, so the catface gradually progressed up the trunk (Hickman 1962). If the wound was not kept fresh by chipping, the severed parenchyma cells would dry and clog with hardened gum (Wahlenberg 1946).

About once every three weeks, dippers emptied the boxes into barrels for transportation to distilleries (Hickman 1962). The resin was distilled in a manner similar to distilling whiskey to produce rosin and turpentine (Perry 1968; Coppen and Hone

Figure 2.6 Turpentining operations in Florida in the early 1950s. The slanted wounds on the tree were created by the chipping process, and the wounded area is known as a catface. A cup is used to accumulate gum from the working face. The worker is using a combination bark pulling and acid-treating tool that helps stimulate production while preserving the tree for future uses.

1995). Rosin can be converted into a variety of derivatives such as adhesives, chewing gums, soaps, detergents, printing inks, and synthetic rubber (Coppen and Hone 1995). Turpentine is sometimes used in whole form as a solvent for paints and varnishes or as a cleaning agent, but its derivatives are also used in fragrances, flavoring, and synthetic pine oil (Coppen and Hone 1995). Synthetic pine oil is used in disinfectants, cleaning agents, and other products with a pine odor such as citronellol and menthol (Coppen and Hone 1995).

Because the resin exposed on the catfaces is highly flammable, much effort was expended to reduce the possibility of fire in turpentining orchards. The boxes were natural fire traps, and once fire entered a turpentining orchard, trees were usually killed as the fires could not be readily extinguished (Hawley 1962). One of the first steps in developing an orchard was to burn as much of the undergrowth as possible (Averit 1921). Initially, fire suppression was practiced in the orchards, but forest managers decided that keeping fire out of the stands would result in more devastating fires in the future (Recknagel 1913). While turpentining operations were in progress, flammable material was hoed away from the base of trees being tapped for resin, and typically, workers burned the raked material annually (Heyward 1939; Hawley 1962).

Longleaf pine is the most resinous southern pine, so it was a leading source of rosin and turpentine for hundreds of years (Perry 1968; Earley 2004). An average pine tree could continue to produce sap profitably for 10 to 12 years, but turpentine orchards were normally abandoned after 4 or 5 years (Averit 1921; Hickman 1962). Although turpentining operations did not normally kill the trees, some 20 to 50% would die when care was not taken to preserve the trees (Meredith 1921).

During the early Colonial Period, naval stores were not a particularly important export, but beginning in 1705, these products became a major export with increasing demand from England (Perry 1968). In the late colonial period, North Carolina was the major source of naval stores for England (Hickman 1965). The industry declined after the Revolutionary War as the market for the products collapsed (Hickman 1965). The introduction of the copper still in 1834 made the process of producing "spirits of turpentine" more cost efficient and initiated a commercial bonanza that swept south and westward into Texas (Frost 1993). Moreover, the discovery of new uses for spirits of turpentine and better transportation networks helped the expansion of the industry (Perry 1968). In conjunction with the expansion of the turpentining industry was the decline of tar and pitch production, which were replaced by petroleum-based products in the mid-1800s (Grissino-Mayer *et al.* 2001). By the 1850s, naval stores were the South's third leading export, and North Carolina was the world's leading supplier (Perry 1968; Frost 1993). The Civil War disrupted the naval stores industry for over a decade because of Union blockades of exports (Perry 1968). When the industry began to recover, the heart of the turpentine production methodically migrated through the Coastal Plain, progressing through South Carolina (1879–1888), Georgia (1889–1899), and Florida (1909–1919). Alabama, Louisiana, and Texas also were engaged in the turpentining industry, but these states were of lesser importance (Perry 1968).

Through the 19th and well into the 20th century, the demand on the world market for forest products including wood and naval stores was very high (Derr 1989). The industry reached its height in the early 1900s, but after World War I, the demand for naval stores in the U.S. declined as new petroleum-based solvents and various synthetics became more popular (Smith *et al.* 2000; Derr 1989). As late as 1941, however, Florida was still producing 20% of the world's turpentine and rosin (Derr 1989). The turpentining industry is now concentrated in the areas where second-growth trees are large enough to produce sufficient turpentine. Most recently, Georgia produced the majority of gum resin in the United States (Grissino-Mayer *et al.* 2001), but the commercial turpentine industry is virtually nonexistent today.

2.7.1.2 Logging Industry

"A stumppocked scene of profound and peaceful desolation, unplowed, untilled, gutting slowly into red and choked ravines beneath the long quiet rains of autumn and the galloping fury of vernal equinoxes."

- William Faulkner, Light in August, 1932

As the turpentining industry passed from the Atlantic seaboard westward to Texas, the logging industry usually followed closely behind in pursuit of the excellent timber (Loughmiller and Loughmiller 1977). Longleaf pine is highly valued among the Southern pines for its durability, strength without brittleness, ability to hold nails firmly, and resistance to splintering, abrasion, and mechanical wear (Collier 1964). The wood resists decay and is practically immune to termites. In old-growth forests, particularly on dry sites, longleaf pines tended to grow slowly, producing a compact and narrow grain of closely-spaced rings (Earley 2004). The great strength of the wood is caused by the high percentage of latewood (Wahlenberg 1946). Furthermore, old-growth longleaf has a very high proportion of heartwood relative to sapwood (Loughmiller and Loughmiller 1977; Earley 2004). Finally, the species prunes well so that lower sections of the bole are largely free of branches (Boyer 1990). All of these qualities make the longleaf pine a very desirable tree in the logging industry and an excellent material for construction and furnishings. Longleaf pine wood was valuable for masts and spars, structural timbers, siding, and decks (Maxwell and Baker 1983). Wharves in practically every port from New York to New Orleans were built using longleaf pine (Wahlenberg 1946). Other major uses of the timber included railroad cars, railroad ties, paving blocks, and farming implements (Wahlenberg 1946).

Longleaf pine timber has been prized in the United States from the Colonial Period, and cutting of longleaf pine trees dates from earliest settlement. George Washington's Mount Vernon mansion was built from the heartwood of longleaf pine, and the keel of the U.S.S. Constitution, the world's oldest commissioned warship, was made with a single heart pine timber (Walker 1991). Romans (1999) described the longleaf pine timbers in the Floridas in the 1770s as of "superior quality…acknowledged without rival." The early colonists cut straight, tapering longleaf pines for masts and spars on sailing vessels, principally for use by European navies (Hickman 1962). Early logging was conducted by hand, and stock animals were used to transport the logs to the mill or river course. Boards were cut manually by sawyers over a saw pit or elevated trestle (Hickman 1962). The first water-powered sawmills were not constructed until the early 1700s in Louisiana and the Cape Fear region of North Carolina (Frost 1993). These early sawmills used straight-blade reciprocating saws that produced a similar action to the "pit" saws (Frost 1993). Because of the limitations of transportation and the sites for sawmills, commercial exploitation of longleaf pine timber was largely confined to zones around navigable streams in coastal areas (Frost 1993). One of the first pine sawmills in Georgia was built in Savannah in 1744 (Collier 1965). Spain invaded the Pensacola area of Florida in 1781 solely to gain control of its timber, and the Spanish built a sawmill near Pensacola in 1798 (Collier 1965). Commercial logging remained a minor industry in the Southeast through the Civil War, when both the lumber and turpentining industries virtually ceased because of Union blockades (Derr 1989). Furthermore, invading Union troops often destroyed sawmills throughout the South (Hickman 1962).

The first extensive logging in the longleaf pine forests began after the Civil War with the expansion of the railroads and development of steam skidders and steam-powered sawmills (Wahlenberg 1946; Frost 1993; Earley 2004). Furthermore, the circular saw and band saw replaced the reciprocating saws in the sawmills, greatly increasing production because of the continuous cutting edge (Maxwell and Baker 1983). By the late 1800s, kiln-drying of lumber had been developed to speed the drying process and reduce weight for shipping (Hickman 1962). Also, in the 1880s, the more efficient crosscut saw replaced the ax as the basic tool for felling trees (Hickman 1962). The demand for lumber in the northern United States and Europe steadily increased during Reconstruction, and the logging industry grew tremendously in the longleaf pine region (Derr 1989). By 1880, the annual cut of longleaf pine was estimated at 4.7 million m^3 (2 billion board feet) throughout eight states, and logging peaked in 1907, with an estimated 30.7 million m^3 (13 billion board feet) logged (Wahlenberg 1946).

As in the turpentining industry, the movement of the logging industry proceeded from the Atlantic Coast south and westward to Louisiana and Texas. Logging companies acquired and exploited vast amounts of land. In Florida and Alabama, individuals such as Weyerhauser and Sullivan each held land over 60,000 ha in size (Smith *et al.* 2000). One of the largest holdings was in the Kirby Lumber Company organized in 1901 and centered in Beaumont Texas. J.H. Kirby operated 11 sawmills in the region and controlled over 100,000 ha of pinelands (Collier 1965; Maxwell and Baker 1983). Large areas were clear-cut without leaving a single seed-producing longleaf pine tree in the "cut-and-get-out" lumberman era from the late 1800s to around 1930 (Williams 1989; Walker and Oswald 2000). In Mississippi and Louisiana, merchantable trees as small as 20 to 25 cm dbh were cut down (Wahlenberg 1946). From 1870 to 1930, virtually all the virgin longleaf pine timber was removed from the South (Frost 1993). In 1935, only 9% of the longleaf pine area in the flatwoods and rolling uplands from South Carolina to Louisiana was old growth (Wahlenberg 1946). By the 1930s, the longleaf pine forests in Florida had been largely exhausted (Derr 1989). Logging in second-growth longleaf pine began during World War II and continues today as this age class has matured (Landers *et al.* 1995).

2.7.2 Pine Plantations

Since the early 1900s, pine plantations of loblolly, slash, or shortleaf pine were developed in many areas formerly occupied by longleaf pine (Schwartz 1994). The advent of the pulp and paper industries in the 1930s made longleaf pine an undesirable tree for silviculture when compared to loblolly and slash pine (Landers *et al.* 1995; Earley 2004). Loblolly and slash pines mature more quickly and are considered easier to manage, although this fact is being increasingly debated (Landers *et al.* 1995). Longleaf pines were seen as too difficult to grow in pine plantations because its delayed period of seedling height growth is not compatible with maximizing yields in pulpwood rotations

(Brown and Kirkman 1990; Earley 2004). The emphasis of the pulp and paper industry is on wood fiber production, and longleaf pine is not particularly suited for highly productive plantations with short rotations. Since 1940, the remaining longleaf pine acreage has been reduced by as much as 90% in some states (Smith *et al.* 2000).

2.7.3 Hogs in the Coastal Regions

While the lumber industry destroyed much of the mature trees, feral hogs helped to thwart the growth of new seedlings (Frost 1993). From the time of early colonial settlements, the Atlantic and Gulf pine forests were occupied largely by herdsmen, whose cattle, horses, mules, goats, sheep, and hogs ranged freely on the excellent forage (Earley 2004). The same habitat that supported the large populations of grazers and browsers in the Southeast was used by the Europeans to support their livestock (Pyne 1982). One of the most significant effects of cattle grazing in the Southeast was the reduction of native perennial grasses that depleted the natural fuel for fires (Sitton 1995).

Although sheep and goats consumed or damaged many young seedlings, feral hogs wreaked the most havoc on young longleaf pines. Hernando de Soto first introduced swine to the South in 1539, and English settlers brought hogs with them as starter livestock (Bakeless 1961; Frost 1993). On the open range, hogs had the ability to increase from a handful to thousands in only two to three years (Frost 1993). The entire Coastal Plain of Virginia and parts of North Carolina were probably saturated with hogs by 1730 (Frost 1993). Farther south, the coastal regions of Alabama were teeming with hogs by 1840 (Frost 1993).

Hogs grazed voraciously on longleaf pine seeds and seedlings throughout the Coastal Plain, drastically lowering the seedling population (Bruce 1947; Frost 1993). Feral hogs seemed to favor the luscious cortex of the main taproot, and the root starch content of the seedlings is highly nutritious (Foster 1916; Frost 1993). Hogs have been known to kill 200 to 400 longleaf pine seedlings per day, so that a single hog could decimate almost 0.5 ha in one day (Wahlenberg 1946). Not only were hogs destructive to pine seedlings, but they also created conditions for more intense and destructive fires when they loosened and dried out the soil (Schwarz 1907).

When the feral hog population was at its height in the 1800s, 10,000 to 40,000 hogs roamed the open range in every settled county in the longleaf region (Frost 1993). Most of the southeastern United States was open range until the early 1900s when stock laws began to take effect (Platt *et al.* 1988). Most southern states, however, did not pass livestock laws until the mid-20th century (Earley 2004). While hogs continue to run wild in parts of the Coastal Plain, their numbers have been reduced considerably (Frost 1993).

2.7.4 Fire Suppression

"Forest fire control...and prescribed burning...are Siamese twins...quarrels between Siamese twins are both uncomfortable and unprofitable."

- H.H.Chapman, forester, 1947

Adding to the adverse effect of hog grazing on longleaf pine regeneration were many decades of fire suppression in the first half of the 20th century (Frost 1993). Woods burning was common and largely unregulated in the Coastal Plain until the early 1900s (Waldrop *et al.* 1992). During the period 1910 to 1930, modern fire laws and the suppression of wildfires became widespread in the South (Maxwell and Baker 1983; Frost 1993). Motorized fire-fighting equipment came into use extensively in the 1940s and nearly all of the southeastern United States was under effective fire suppression by 1950 (Little 1979; Frost 2000). Aiding the fire suppression efforts was an increasingly dense network of artificial fire breaks throughout the region. Artificial fire breaks include roads, agricultural fields, and urban areas, and these breaks serve to compartmentalize and limit the spread of fire.

Without fire to destroy the competing vegetation, the original longleaf forests were invaded by deciduous shrubs and arborescent hardwood species (Croker 1968; Delcourt and Delcourt 1977; Gilliam and Platt 1993; Glitzenstein *et al.* 2003). Longleaf pine lost its competitive edge when fire was eliminated, particularly on fertile soils, because longleaf pine seedlings seem to be more sensitive to competition than any other southern pine (Boyer 1987; Earley 2004). Other southern pine species that grew faster than longleaf pine attained dominance in former longleaf forests. For example, in parts of southern Georgia, shortleaf and loblolly pines have taken over in most areas, and wiregrass and longleaf pine are absent (Robertson and Ostertag 2003). In the Florida panhandle, sand pine has encroached where fire has been suppressed in longleaf pine forests (McKay 2000). Slash pine has also replaced longleaf pine along the Gulf and Atlantic coasts (Walker and Oswald 2000). The reproductive success of longleaf pine is also lowered because of the chemical effects of fire suppression. Important nutrients such as phosphorous are typically more available after fires, and the absence of fire reduces soil nutrients and organic matter in surface horizons (Heyward 1937; Christensen 1993a).

By the 1950s, the deleterious effects of fire suppression on longleaf pine forests began to be noticed. Not only did fire suppression inhibit longleaf pine reproduction, but it resulted in the accumulation of more fuel and more intense fires that were difficult to control (Christensen 1981). Recognizing the adverse effects of fire suppression, land managers have implemented prescribed burning as standard management practice in longleaf pine forests. For example, the Big Thicket Fire Management Plan (BTFMP) for the Big Thicket National Preserve, Texas, stipulates the use of prescribed fire as an important measure in restoring longleaf pine stands and for long-term maintenance (BTFMP 2004). Similar measures have been implemented by the Nature Conservancy at Sandy Island, South Carolina (Leslie 2004).

The use of prescribed fires in southern forests has helped longleaf pine to expand its range and restore this fire-dependent ecosystem (Walker and Oswald 2000). Prescribed burning reduces fuel loads to decrease the threat of wildfires, fire temperatures, and favors pines over oaks. Also, periodic burning favors herbaceous plants over shrubs so larger and more nutritious amounts of succulent browse is available for wildlife (Little 1979; Lewis *et al.* 1982; Platt *et al.* 1991; Streng *et al.* 1993; Brockway and Lewis 1997; Tucker *et al.* 2003). Plant community changes as a result of prescribed fire are dependent on the frequency and season of burn (Waldrop *et al.* 1992; Provencher *et al.* 2001b). Prescribed fire as frequently as fuels will allow has resulted in high levels of species richness in longleaf pine flatwoods and wet savannas (Brockway and Lewis 1997; Glitzenstein *et al.* 2003). Although volume growth loss can occur when prescribed fire is frequent, the positive effects of reduced competition and better reproduction seem to outweigh the undesirable effects (Boyer 1987).

2.7.5 Preservation and Restoration

The first national efforts in conservation and reforestation of the southern pine forests came during the 1930s with Franklin D. Roosevelt's New Deal measures. The National Recovery Administration's new codes for the lumber industry stressed preservation of young trees during logging, restocking, selective cutting, and sustained-yield programs (Maxwell and Baker 1983). State and federal Forest Service agencies acquired large areas of land to promote sustained yield of timberlands and for public enjoyment. Unfortunately, much of the emphasis on restocking was placed on the other southern pines, such as loblolly pine, and not on longleaf pine.

Within the past two decades, renewed interest in the importance of longleaf pine ecosystems has resulted in the reintroduction of longleaf pine to parts of its historic range and the preservation of existing stands on public lands (Means 1996; Smith *et al.* 2000; Provencher *et al.* 2001b). Longleaf pine forests are the natural habitat of 18 declining, threatened, or endangered terrestrial vertebrates, including the red-cockaded woodpecker (*Picoides borealis* Vieillot) and Bachman's sparrow (*Aimophila aestivalis* Lichtenstein) (Liu *et al.* 1995), so the preservation of this habitat is vital for their survival (Simberloff 1993; Smith *et al.* 2000). In addition, 191 species of rare plants are associated with wiregrass that is common to many longleaf pine forests (Smith *et al.* 2000). Recognizing the ecological and economic value of longleaf pine ecosystems, the "Longleaf Alliance" was formed at Auburn University in Alabama to emphasize education, research, and recovery of longleaf pine forests (Longleaf Alliance 1996).

Private, state, and federal land managers are involved in restoration of these valued habitats (Kush *et al.* 2004). The Department of Defense has made the retention and restoration of the longleaf forest ecosystem a major priority. Military bases in Florida, Alabama, Georgia, and the Carolinas all have longleaf conservation programs that are tied to the protection of endangered or threatened species. These efforts include prescribed fire programs, removal of hardwood understory, and the planting of longleaf pine seedlings (Figure 2.7). Beginning in the 1980s, the U.S. Forest Service developed new silvicultural techniques that helped private landowners to grow longleaf pine trees (Early 2004). Since the 1990s, the U.S. Department of Agriculture has encouraged the planting of longleaf pine on designated cropland by granting federal subsidies (Smith *et al.* 2000).

Not only is there renewed interest in longleaf pine for ecological reasons, but its resistance to insects and diseases and its high quality solid-wood forest products has generated increased demand in the forestry industry (Barnett and Pesacreta 1993). The high-value products from relatively long rotations of longleaf pine complement the high yield, intensive plantations of loblolly and slash pine (Landers *et al.* 1995). Besides excellent lumber and turpentining products, longleaf pine produces several other special forest products of economic importance. The long needles have several uses. First, distillation of the green pine needles yields oils with a pleasing scent that can be used in air fresheners and for aromatherapy (Wahlenberg 1946). Second, the dry needles are also used as mulch for gardeners and landscapers. In 2002, pine straw was a $50–$55 million dollar-per-year industry in North Carolina (Earley 2004). Third, the long, lustrous needles have many decorative uses including basketry, mat weaving and, along with the cones, Christmas ornaments (Earley 2004). Finally, longleaf pine straw can be used as a sanitary litter in poultry houses (Wahlenberg 1946).

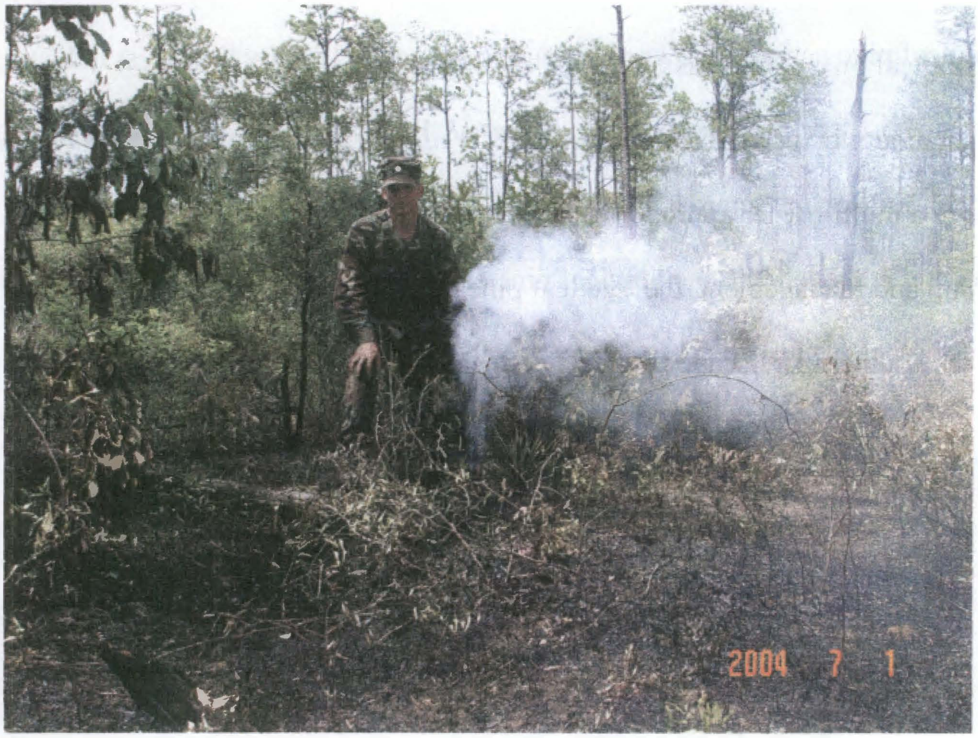


Figure 2.7 Prescribed burning on Eglin Air Force Base, Florida.

Restoration efforts may expand the current range of the species, but the historic spatial extent and dominance of longleaf pine will never be fully recovered. Today, about 31% of longleaf pine acreage is owned by public agencies, 18% by the forest industry, and the remainder by private owners (Landers *et al.* 1995). As such, effective restoration will require a multi-owner approach to landscape management. Through wise stewardship and management, the longleaf pine ecosystem can be reestablished in many areas of the southern landscape (Landers *et al.* 1995).

Chapter 3

Description of Study Areas

"A level open, airy pine forest, the stately trees shatteringly planted by nature, arising straight and erect from the green carpet, embellished with various grasses and flowering plants."

- William Bartram, botanist, 1791

3.1 Introduction

I collected samples from three major field sites: Big Thicket National Preserve in eastern Texas, Eglin Air Force Base (EAFB) in the Florida Panhandle, and Sandy Island in eastern South Carolina (Figure 3.1). I selected these sites because of the availability of living old-growth pines and remnant pieces of wood (stumps and logs), and because they had not been previously sampled for the development of longleaf pine tree-ring data sets. As all of these sites are located in the Coastal Plain, a degree of similarity exists in the topography, geology, climate, soils, and vegetation. I will begin by first describing the Coastal Plain in general, followed by site descriptions of the Big Thicket, Eglin, and Sandy Island sites in greater detail. These site descriptions will focus only on the major field sites where I examined historical climate and fire regimes. Additional sites that were sampled include Pine Park near Hemphill, Texas, the George Russell property near Livingston, Texas, and the Francis Marion National Forest Preserve and Poinsett Electronic Combat Range in eastern South Carolina. The George Russell property in San Jacinto County contains the only documented stand of longleaf pines west of the Trinity River and is believed to represent the western limit of the range of longleaf pine.

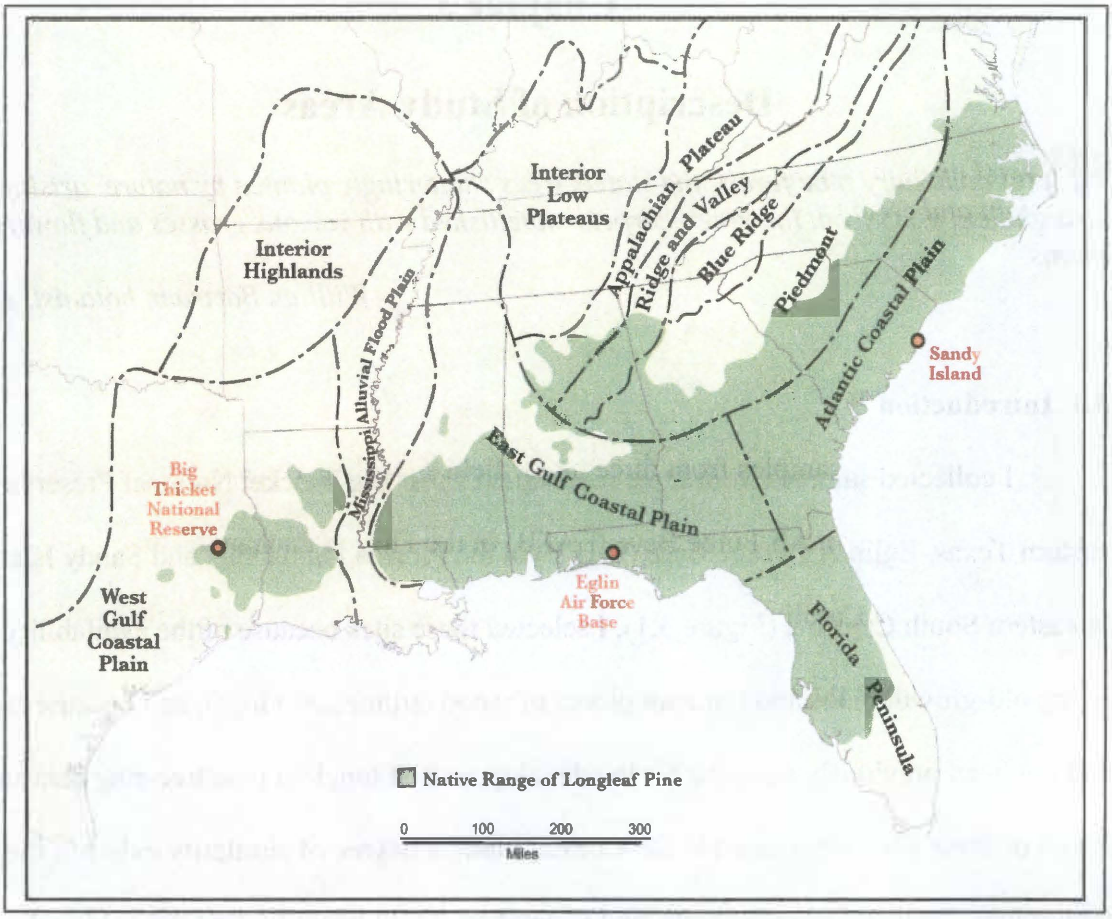


Figure 3.1 The Coastal Plain and major sub-regions. The native range of longleaf pine is shaded in green. Major study sites are shown in red.

3.2 The Coastal Plain

3.2.1 Geomorphology

The Coastal Plain is a 160 to 320 km wide belt of elevated sea bottom that extends from the Atlantic seaboard along the Gulf Coast and westward into Mexico (Bennett 1921; Hunt 1967). This curving swath of land exhibits low topographic relief that ranges from sea level to generally less than 90 m in elevation (Welch and McCart 1963). Bays and estuaries are found along the coastlines (Walker 1999). The Coastal Plain is generally divided into three major sub-regions that include the Atlantic Coastal Plain, the East Gulf Coastal Plain, and the West Gulf Coastal Plain (Fenneman 1938) (Figure 3.1).

The Atlantic Coastal Plain in the vicinity of the Carolinas is marked by a series of broad marine and step-like terraces that parallel the ocean (Walker and Oswald 2000). The uppermost terrace on the Atlantic portion of the Coastal Plain is known as the Fall Line because of the abrupt change in the gradients of rivers (Walker and Oswald 2000). The East Gulf Coastal Plain is characterized by alternating cuestas and lowlands and terraces that parallel the coast along the outer margin (Thornbury 1965). Similarly, the West Gulf Coastal Plain contains a series of low ridges and valleys, but the cuestas are not as well-developed as in the East Gulf Coastal Plain (Thornbury 1965; Walker and Oswald 2000). The West Gulf Coastal Plain terminates inland in Central and South Texas at the escarpment formed by the Balcones fault zone, which marks the edge of the Edwards Plateau (Hunt 1967; Swanson 1995).

3.2.2 Geology

The sedimentary deposits that underlie this region of low topographic relief represent various onshore, offshore, and nearshore environments. Soils of the Coastal Plain are underlain by loose material that was moved from the Piedmont and deposited under the Atlantic Ocean that once covered the area (Welch and McCart 1963). The underlying sediments of the region are geologically young and consist of sands, gravels, clays, and marls (Walker and Oswald 2000). Cretaceous formations form the inland belt of geologic formations, Tertiary formations are intermediate, and the coastal belt is of Quaternary age (Hunt 1967). The Cretaceous and Tertiary formations in the East and West Gulf Coastal Plains are thicker than those along the Atlantic Plain, but are more folded and faulted (Hunt 1967). The thickness of sediments along the Atlantic Coast ranges from 30 m to several hundred meters thick, while sedimentary deposits on the Gulf Coastal Plain are up to 9,000 m thick (Sutton and Sutton 1985). During the last 2–3 million years, the surface of the Coastal Plain has been reworked considerably by fluvial and coastal processes, and the areal extent has varied with changes in sea level (Christensen 2000).

3.2.3 Soils

Most of the southeast Coastal Plain is dominated by Ultisols (Brady 1990; Markewich *et al.* 1990; Walker 1999), but a wide variety of less common soil types exist across the breadth of the region. For example, Entisols such as Psamments are common in drier upland areas where the parent material consists of more than 95% quartz sand (Christensen 1981; Markewich *et al.* 1990). Regardless of soil type, Coastal Plain soils are comparatively infertile (Christensen 1981). Coastal Plain soils are typically acidic and low in organic matter and soluble nutrients (Walker and Oswald 2000). Pedogenesis generally begins in siliceous sedimentary parent material (alluvium, marine sands and clays, or dune sands) that is typically coarse-grained (Markewich *et al.* 1990). Soils are typically as thick as 2 to 8 m and have high sand content throughout (Markewich *et al.* 1990). Interestingly, Coastal Plain hills are often capped by deep sands that essentially armor the surface from erosion because of their high infiltration capacity (Markewich *et al.* 1990).

3.2.4 Climate

The climate across the Coastal Plain is fairly uniform, except the growing season rainfall is more deficient west of the Mississippi River Valley because of the slightly higher summer temperatures (Croker 1968; Marks and Harcombe 1981). The humid subtropical climate supports an annual total rainfall from 117 to 165 cm, with slightly more rainfall falling in summer than in winter (Walker 1999; Walker and Oswald 2000). Winter rainfall is produced primarily by mid-latitude cyclones, and summer rain is normally produced by convective thunderstorms (Christensen 2000). The abundant rainfall leaches soluble bases, plant nutrients, and colloidal material in the soil downward, which contributes to the generally poor nutrient and organic content of the soil (Overing *et al.* 1995). Thunderstorms occur on average 50 or more days a year, primarily in the summer months, and lightning strikes associated with these storms can cause wildfires (Komarek 1968). Tropical storms and hurricanes are common, particularly in August and September. Tropical storms provide approximately 10% of total summer and fall precipitation over much of the southeastern U.S. (Court 1974). Droughts that last several months are not uncommon in the Coastal Plain, and these dry conditions make the Coastal Plain forests more susceptible to wildfires and beetle attacks, particularly in hot weather (Walker and Oswald 2000).

Mean annual temperature ranges from 16 to 23° C (Croker 1968), and the growing season is long, averaging 240–260 days over much of the region. The warm temperatures speed the progress of chemical reactions and soil formation processes. During the warm summer months, actual evapotranspiration is often lower than potential evapotranspiration because of diminished soil reserves (Christensen 2000). Although warm temperatures are predominant, extreme cold spells accompanied by snow and ice storms occur on rare occasions, and these events can severely damage or kill natural vegetation. Seasonal temperature variations increase inland, and the frost-free season is longer near the coast (Christensen 2000).

3.2.5 Vegetation

Much of the Coastal Plain is covered by the Southeastern Pine Forest, which extends from eastern Texas to the New Jersey coast (Hunt 1967; Walker 1999). Loblolly (*Pinus taeda* L.), shortleaf (*Pinus echinata* Mill.) longleaf (*Pinus palustris* Mill.), and slash (*Pinus elliottii* Engelm.) pines are widespread, as are various species of oak (Orne 2002). Longleaf and slash pines dominate on sandy soils. Turkey oak (*Quercus laevis* Walt.) and other scrub oaks are commonly present in longleaf pine forests on xeric sites (Walker and Oswald 2000). Paludal wetlands such as pocosins and bogs are occasionally present in the uplands, and these areas typically contain a dense cover of shrubs and scattered emergent trees (Christensen 2000). Upland hardwood forests and alluvial wetlands also occur in the Coastal Plain, but tend to have a very low concentration of longleaf pine (Christensen 2000).

3.3 Big Thicket National Preserve, Texas

> *"...it is a striking phenomenon, this breaking up and gradual dwindling away of so vast and vigorous a forest – that breaks upon the dry plains."*
>
> *William L. Bray, forester, 1904*

Established in 1974, the Big Thicket National Preserve (BTNP) is located in Southeast Texas between the Neches River to the east and the Trinity River to the west (Figure 3.1). The preserve is known for its biological diversity, which ranges from dry oak woodlands to wet floodplain forests and swamps (Marks and Harcombe 1981). The preserve consists of several land units along creeks and rivers, and the Turkey Creek Unit was the location for my study site (Figure 3.2). The Turkey Creek Unit is located in Tyler County near Warren, Texas and is near the western limit of longleaf pine in Gonzales County, Texas (Critchfield and Little 1966).

3.3.1 Geology, Soils, and Topography

BTNP lies within the West Gulf Coastal Plain. The land surface in the Turkey Creek unit is gently rolling with sandy uplands grading to the broad flat floodplain that borders Turkey Creek. The Bentley formation that underlies the area is of Pleistocene origin and comprises fluvial to marine gravels, sands, silts, and clays (Bernard and LeBlanc 1965). The field site within the Turkey Creek Unit is located on the deep sand

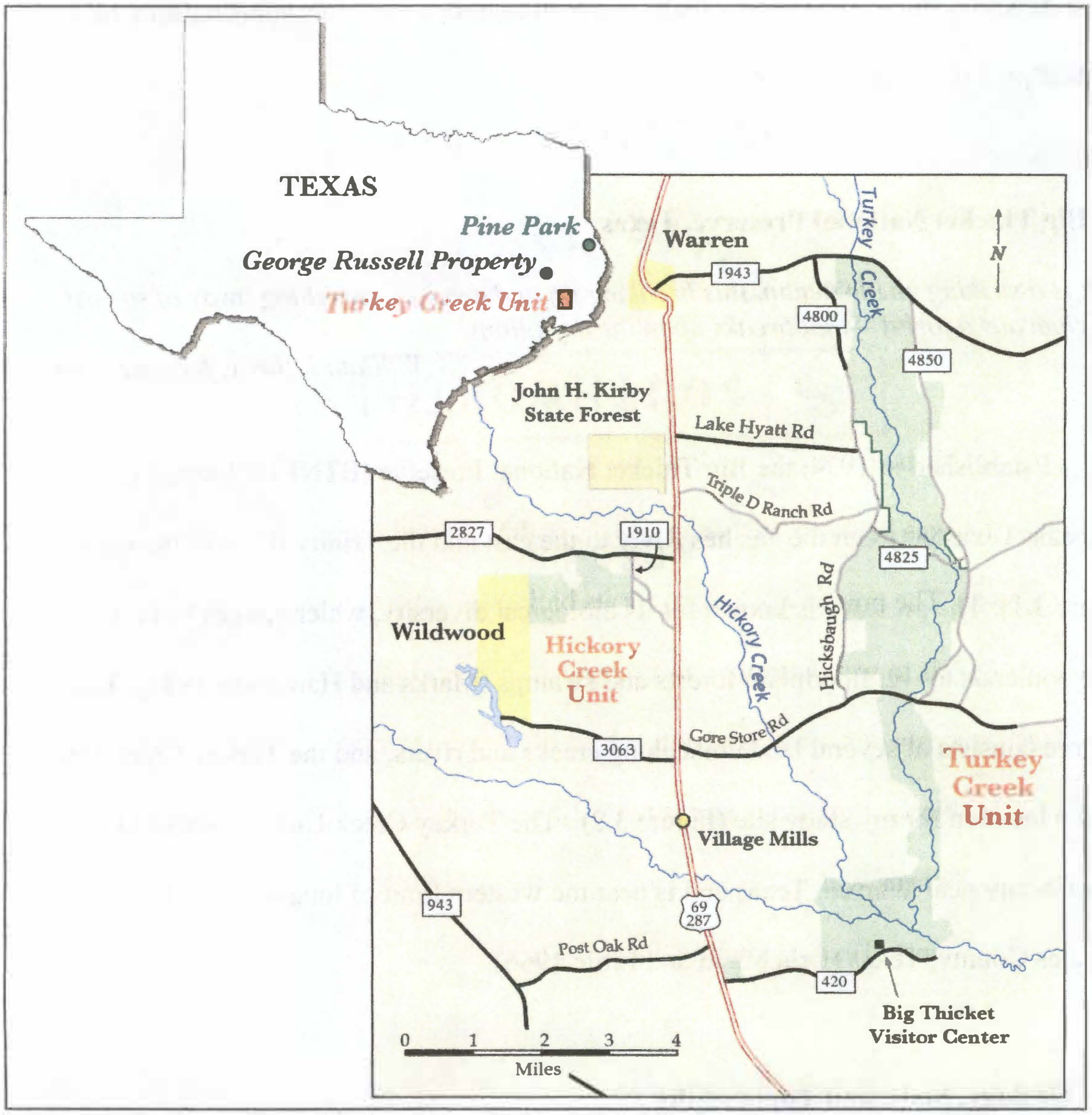


Figure 3.2 East Texas study sites.

deposits of an old stream terrace, and Alfisols are common on the slopes and uplands (Marks and Harcombe 1981). The dominant soil association at the study site is Bienville loamy fine sand, a Psammentic Paleudalf that is somewhat excessively drained and up to 203 cm thick (Deshotels 1978). The soil profile includes an argillic B horizon, and crayfish krotovina are present near small ephemeral creek beds (Deshotels 1978). The loamy soil permits moderate water movement and adequate levels of water retention.

3.3.2 Climate

Compared to the rest of the Southern Mixed Hardwood Forest, the Big Thicket is slightly warmer and drier (Marks and Harcombe 1981). The average July temperature is as much as 2 $^{\circ}$ C warmer than most of the rest of the southeastern U.S., and the average annual water deficit is as much as 17 cm higher than the other parts of the Southeast (Marks and Harcombe 1981). Rainfall is more abundant in the winter than in the summer in the Big Thicket, but the difference is not appreciable (Walker and Oswald 2000). Precipitation averages 132 cm annually, and the average annual temperature is 19.5° C (Glitzensten *et al.* 1986). The growing season is March through November, and freezing occurs on average only 16 days per year (Glitzenstein and Harcombe 1988). Snowfall is rare and occurs in only 20% of winters (Trenchard 1977). Hurricanes and tropical storms are frequent, as in other areas close to the Gulf of Mexico, and the frequency of tornadoes is particularly high (Simpson and Lawrence 1971). The tornado density is as high as 5.8 tornadoes 10,000 km^{-2} year^{-1} in the Big Thicket area (Glitzenstein *et al.* 1988).

3.3.3 Vegetation

The Big Thicket area lies within a region known as the Piney Woods of east Texas (Chambers 1930), and the vegetation is diverse, reflecting variations in soil texture, topography, and disturbance regimes (Marks and Harcombe 1981). The vegetation at the Turkey Creek site is characteristic of the dry upland forest plant communities (Harcombe *et al.* 1991) and is dominated by a mixture of pines and oaks (Figure 3.3). This forest is very similar in composition and structure to longleaf pine-turkey oak sandhill forests of the east Gulf Coast, except for the absence of turkey oak and wiregrass (Harcombe *et al.* 1991). The overstory vegetation is instead dominated by southern red oak (*Quercus falcata* Michx.), post oak (*Quercus stellata* Wang.), black hickory (*Carya texana* Buckl.), mockernut hickory (*Carya tomentosa* Nutt.), longleaf pine, shortleaf pine, and loblolly pine. The understory includes American holly (*Ilex opaca* Ait.), flowering dogwood (*Cornus florida* L.), common sassafras (*Sassafras albidum* Nutt.), yaupon (*Ilex vomitoria* Ait.), southern wax-myrtle (*Myrica cerifera* L.), Japanese honeysuckle (*Lonicera japonica* Thunb.), and pinehill bluestem (*Schizachyrium scoparium* var. *divergens* (Hack) Gould) (Deshotels 1978; Peacock 1994).

A pine savanna wetland ecosystem is adjacent to the study area, and some of the trees sampled were in the transition area between the drier uplands and the savanna. A local hardpan creates limited drainage and higher soil moisture content (Streng and Harcombe 1982; Peacock 1994). Such wetland savannas within upland pine forests are referred to as pitcher plant bogs because of the presence of pitcher plants (*Sarracenia alata* Wood) (Nixon and Ward 1986). A diverse herbaceous layer dominated by sedges and grasses is characteristic of this savanna (Harcombe *et al.* 1991) (Figure 3.4).

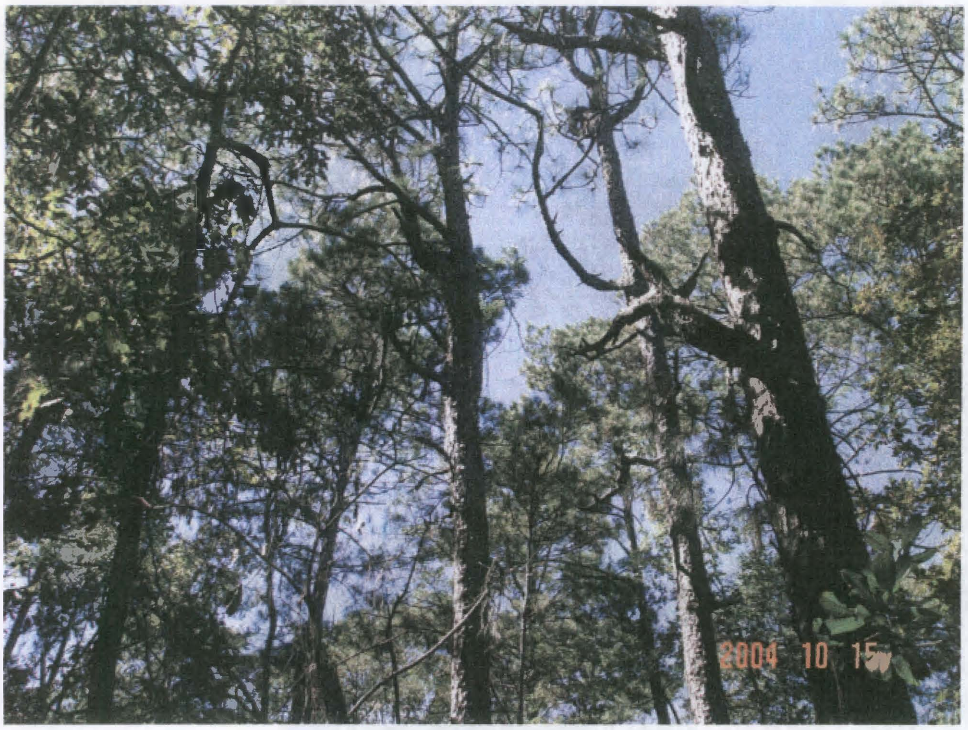


Figure 3.3 Mixed pine-oak overstory on the Turkey Creek study site.

Figure 3.4 Pitcher Plant Bog adjacent to the Big Thicket study site.

3.3.4 Land Use History

3.3.4.1 Presettlement Period

Scafale and Harcombe (1983) state that the presettlement vegetation of the area was similar to other parts of the southeastern Coastal Plain. Longleaf pine forests dominated the dry uplands (Figure 3.5), oak-pine and beech-magnolia forests were found in the intermediate zones, and southern floodplain forests occupied major floodplains. The mesic lowlands contained more hardwoods because fires stopped at the edge of the wet bottoms (Lay 1987). Early explorer accounts of east Texas forests, such as those of Bartram in the late 1700s, tend to validate these findings (Harper 1958; Truett and Lay 1984; Walker 1991).

The earliest maps of the vegetation of the west Gulf Coastal Plain indicate that most of the area was longleaf pine forest (Bray 1907; Harper 1920). The Texas pine forest was the westernmost extension of the great trans-Mississippi evergreen forest that extended into Arkansas, eastern Oklahoma, and Louisiana (Maxwell and Baker 1983). The original longleaf pine forest consisted of nearly 1.3 million hectares in southeast Texas and resembled an arrowhead thrusting its point from the Sabine River in the east to the Trinity River in the west (Cozine 1976).

The earliest residents of the Big Thicket area were the mound-building Caddo Indians in the north and the Atakapans in the south, and these tribes likely moved into the region thousands of years ago (Martin 1966; Abernethy 1977). The Big Thicket was also the common hunting grounds for many tribes from as far away as Colorado (Abernethy 1977). However, the prevailing view is that the Big Thicket was not densely settled by early Indians (Gunter 1993). The entire Caddoan group in Texas and Louisiana is

Figure 3.5 The upland pine forest in Tyler County in 1907 (Texas Forestry Association Museum, Thompson-Ford Photo Collection).

estimated to have totaled only 8,500 in 1690, and how many of these lived in Texas is not clear (Swanton 1952; Chambers 1941). In light of these figures, the Caddoans probably had a minor impact on the forest (Collier 1964).

The Caddo Indians were farmers that tilled small fields in the river bottoms and hunted game in the forests (Phelan 1976). As with most Native Americans of the Southeast, the cultivation of maize, beans, melons, tobacco, sunflowers and other crops was supplemented with wild foods such as fish, deer, turkey, nuts and berries (Wilson 1999). Only 200 years before the arrival of the Anglo-Americans, the Caddoes had been a rich theocracy, but the tribe collapsed in the late 1700s because of exposure to diseases borne by missionaries and settlers (Phelan 1976; Sitton 1995). By the late 1700s, the closely-associated Alabama and Coushatta tribes from Louisiana began moving into the northern and western fringes of the Big Thicket, and these Indians inhabited the area for several decades (Martin 1966; Abernethy 1977). Alabamans had established several villages in northwestern Tyler County by 1830 (Martin 1966). Their livelihood consisted of farming, hunting and trading. By the 1830s, the Alabamans had reached their peak population in east Texas, but Euro-American settlers that moved into the area drove them out within a decade (Gunter 1993).

3.3.4.2 Postsettlement and Logging

The first Europeans to arrive in the Big Thicket area were Spanish explorers in the 1600s, and Spanish priests established missions to the Indians in the early 1700s (Maxwell and Baker 1983). These missions were abandoned after several years, and no Mexicans settled in the Big Thicket, despite the push by the government to settle the area.

Therefore, in the early 1800s, the forests had not changed since the earliest explorers had visited the area (Walker 1991). The first Anglo-Saxon settlers arrived in east Texas in the 1820s after the Republic of Mexico was established, but the main influx arrived in the region after the Texas Revolution in 1836 (Collier 1964; Walker 1991; Sitton 1995). The new settlers built cabins on the higher elevations, and their way of life consisted of hunting deer and bear and raising corn, sweet potatoes, and cane (Abernethy 1977). Plantation farming was not undertaken because of the poor quality of the deep sandy soil (Chambers 1930). Unfenced forest supported a livestock industry of cattle, goats, hogs, and sheep, and seasonal burning of the woods to enhance forage was common (Chambers 1930). In Tyler County, most of the rural people in the late 1800s were stockmen-farmers (Sitton 1995).

After the Civil War, the Piney Woods region developed into a mosaic of relatively small farms among great timbered landholdings (Maxwell and Baker 1983). "Timber barons" amalgamated large personal landholdings after 1880 (Collier 1964). In 1924, only 6% of Tyler County was tilled (Siecke *et al.* 1924). About 80% of Tyler County was owned by logging companies (Gunter 1993).

The first extensive logging in the area began in the 1850s, but not until the arrival of extensive railroads in the 1880s did the clearing of the Piney Woods begin in earnest (Gunter 1993). In fact, by the mid-1870s, the great pine forests of East Texas were still virtually untouched (Maxwell and Baker 1983). By the early 1900s, however, most of the wage earners in the area were engaged in lumbering, sawmilling, and the operation of turpentine camps (Chambers 1930). Logging was conducted primarily by clear-cutting, and essentially every tree that could be sold was removed in logged areas, leaving a barren wasteland of stumps (Gunter 1993). Seldom were any seed trees left to produce new growth of pine trees. Lumbering reached its peak of production in east Texas in 1907, and by 1917, only about 14% of the virgin timber remained (Foster *et al.* 1917; Schmidly 2002). Within about 50 years of heavy logging, the extensive pine forests of east Texas were virtually exhausted (Siecke *et al.* 1924).

In some areas, turpentining operations preceded logging by a period of two to three years (Chambers 1930). Tyler County was one of the seven east Texas counties engaged in turpentining, and about 2,000 to 3,200 ha were involved (Collier 1964; Foster *et al.* 1917). The peak of turpentining operations in Texas was about 1908–1909 (Collier 1964). My study site was turpentined and logged in the 1920s to 1930s. Evidence of turpentining and logging exists from the numerous box cuts, cut stumps, and remnant snags throughout the study site (Figure 3.6). In their study of the stand history in the Turkey Creek Unit, Harcombe *et al.* (1991) determined that the area around the study site had not been logged before 1929–1930.

Regeneration, after turpentining and logging, favored oaks and other pines at the expense of longleaf pine (Harcombe *et al.* 1991). While residual stands of longleaf pine still remain, the forest is now mixed with shortleaf and loblolly pines and a hardwood-dominated understory (Harcombe *et al.* 1991). The natural regeneration of longleaf pine forests was hindered by a lack of seed trees. In addition, hogs, goats and other livestock ranged upon the land and devoured young longleaf pine seedlings (Siecke *et al.* 1924; Chambers 1930; Maxwell and Baker 1983). Not until the 1950s was open range outlawed in the area (Abernethy 1977). The suppression of fire in the area began in 1925 with the establishment of forest protection divisions, which also slowed the regeneration

Figure 3.6 Turpentined face is still visible on face of standing snag at Big Thicket study site. The scarred area is outlined with a dotted line.

of longleaf pine and encouraged the growth of new pine and hardwood species (Big Thicket Fire Management Plan (BTFMP) 2004).

Prior to the establishment of the Big Thicket National Preserve by the National Park Service (NPS) in 1974, the area was still being used primarily for timber and pulpwood production (Deshotels 1978). Two southern pine beetle outbreaks occurred in the Turkey Creek Unit in 1976 and 1982, resulting in the mortality of significant portions of mature pine forests. These invasions once again opened the canopy, encouraging brush (particularly yaupon) growth (BTFMP 2004). Since 1980, the NPS has used prescribed burning in an attempt to restore the natural vegetation to the Turkey Creek Unit (BTFMP 2004).

3.3.4.3 Fire in the Big Thicket

The earliest Native Americans in east Texas augmented the natural ignitions created by lightning. The Caddos hunted deer in the fall and turkey year round, and fires helped to promote the "edge effect" by encouraging the sprouting of new herbaceous growth (Williams 1989; Sitton 1995). The Native Americans also set periodic fires to clear stubble from cultivated fields, to eliminate pests around villages, and to clear the undergrowth for ease of movement and to drive game (Sitton 1995). Research has indicated that fire was fairly frequent in the Big Thicket area until the 1900s (Streng and Harcombe 1982). In the Hickory Creek unit of the Big Thicket, adjacent to Turkey Creek, the area likely had once been an open savanna dominated by longleaf pine and various prairie grasses, and the presence of prairie was probably due to frequent fire. Much of the

Hickory Creek unit grew into closed forest after cessation of fire in 1957 (Streng and Harcombe 1982)

Like the Native Americans who preceded them, the early Euro-American settlers continued the practice of setting fires for essentially the same reasons (Sitton 1995). Settlers used fire to improve the forage for their open range livestock, eliminate chiggers, ticks and snakes, and to smoke out bears (Maxwell and Baker 1983; Sitton 1995). Euro-American stockmen from 1830 to 1850 typically set fires in the late winter and early spring to recycle nutrients and encourage new growth (Sitton 1995). Fires also helped to herd cattle by causing them to congregate in burnt-over areas. Fires destroyed fence posts and, thus, helped enforce the local custom of the free range (Sitton 1995). Such seasonal burning did not significantly damage the longleaf pine forest and prevented more destructive fires in the late summer when the forest was dry (Maxwell and Baker 1983). When the lumber companies began logging extensively, fire was used by the locals to retaliate against lumber companies that had seized their land (Gunter 1993; Sitton 1995).

Anthropogenic fires continued in the early 1900s, and many were deliberately set (Foster 1916a; Siecke et al. 1924). The understory in many forested areas of eastern Texas was sparse because of annual or biannual burning by settlers (Bray 1904). Fires were set to clear land or protect fences and buildings, and were allowed to burn in any direction away from the owner's property (Foster 1916b). Some fires were started simply to observe the excitement of the burn. Railroad section foremen frequently left piles of ties burning along rights of way and allowed the fires to burn unchecked (Foster 1916b). Spark arrester laws for lumberman were not enacted until 1923 (Siecke et al. 1924).

Reports document that early 20th century burning was indeed widespread in east Texas. Before World War II, about 5% of the forested area of Texas burned each year (Texas Forest Service 1957). In the spring of 1916, a particularly dry year, more than half the total forest area of east Texas had been burned over within the past 60 days (Foster et al. 1917). At least 75% of Tyler County burned each year (Foster et al. 1917).

When the Big Thicket National Preserve was first established in the 1970s, the sole focus was fire suppression (BTFMP 2004). Southern pine beetle outbreaks in 1976 and 1982 resulted in significant mortality of mature pine forests, and pile burning was conducted beginning in the late 1970s as part of southern pine beetle control work. Later, one of the major objectives of fire management was to restore and maintain fire's function to promote a natural system on a landscape scale, with the restoration of longleaf pine forests as a high priority (BTFMP 2004). The importance of fire in maintaining species diversity and the natural patterns of succession was also recognized. To implement this new approach, prescribed burning began in the early 1980s for restoration purposes. In the vicinity of the Turkey Creek study site, nine prescribed burns have been conducted between the early 1980s and 2003 (BTFMP 2004).

3.4 Eglin Air Force Base, Florida

EAFB is located in the Florida Panhandle north of Choctawhatchee Bay and extends through three counties, making it the largest forested military reservation (187,555 ha) in the United States (Department of Defense (DoD) 1993). The installation is also well known for its large stands of old-growth longleaf pines and comprises 2,000 ha of old-growth forest, the largest contiguous tract in the U.S. (Means 1996; Smith *et al.* 2000).

3.4.1 Geology, Soils, and Topography

EAFB lies within the East Gulf Coastal Plain and is characterized by gently rolling sandhills in the north, grading to low-lying flatwoods and marshes near the coast. Portions of the Western Highlands and Gulf Coastal Lowlands physiographic provinces of Florida lie within the boundaries of the base (Vernon and Puri 1964; Schmidt 1997). The Western Highlands are separated from the Gulf Coastal Lowlands by the south-facing Cody Escarpment, the most persistent topographic break in Florida (Overing *et al.* 1995; Schmidt 1997). The Westerns Highlands is composed of gently sloping plateaus separated by large stream valleys. These highlands are the dissected sedimentary remains of fluvial, deltaic, and shallow-water marine systems (Schmidt 1997). The hills have been modified by stream dissection and limestone dissolution, and erosional relief in the highlands reaches 30.5 m (Schumm *et al.* 1995). The underlying bedrock consists of the Bruce Creek and Chickasawhay Limestone, permeable carbonate rock of Miocene age (Overing *et al.* 1995).

Two of the sites at EAFB are located in the Western Highlands (Figure 3.7). The first site (Donut) is located in the Patterson Natural Area on the west-central portion of the base northwest of Ft. Walton Beach. The natural area was originally a 375 ha tract that was set aside for preservation by the U.S. Forest Service prior to World War II and the establishment of Eglin AFB (Means 1996). The Patterson Natural Area has expanded to over 1500 ha and contains numerous longleaf pine trees greater than 200 years old

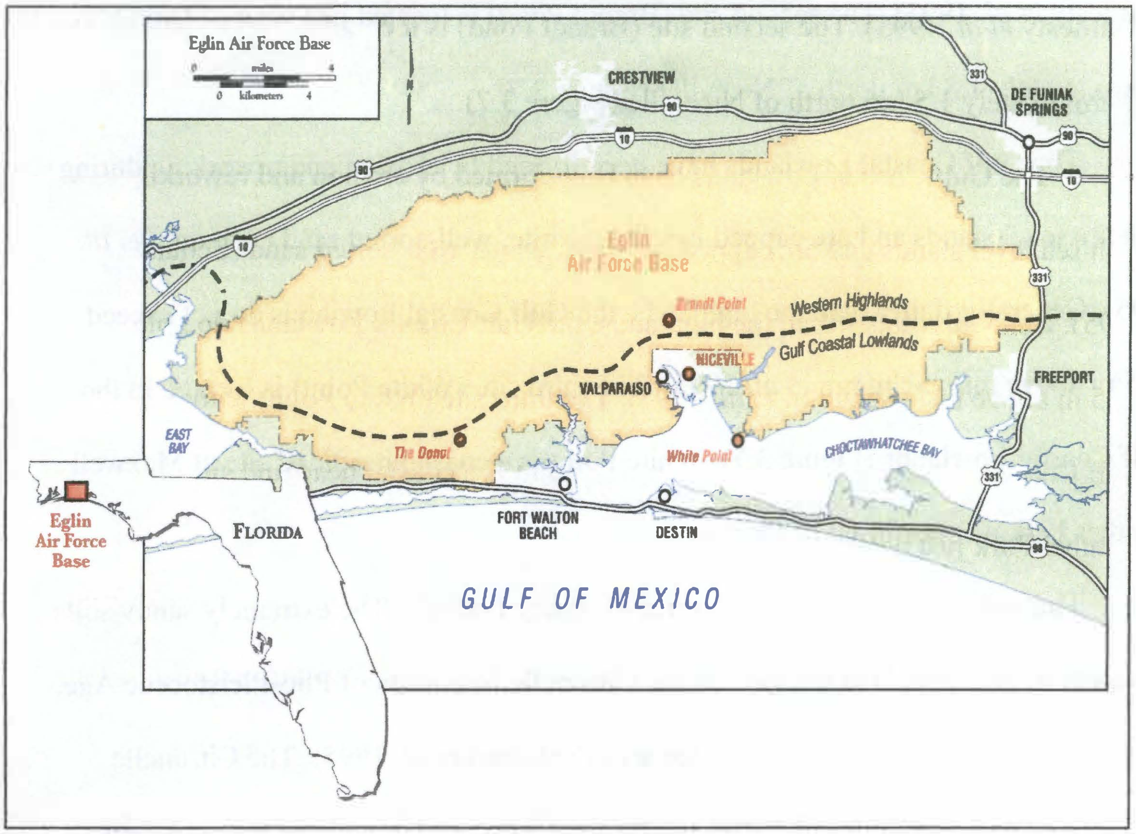


Figure 3.7 Map of Eglin Air Force Base and study sites.

(Hardesty *et al.* 1993). The second site (Brandt Pond) is located just west of Brandt Pond, approximately 1.5 km north of Niceville (Figure 3.7).

The Gulf Coastal Lowlands have been formed by erosion and reworking during high sea level stands and are capped by clean, white, well-sorted sand (Schumm *et al.* 1995). Generally flatter than the highlands, the Gulf Coastal Lowlands do not exceed 30.5 m above msl (Schumm *et al.* 1995). The third site (White Point) is located in the Gulf Coastal Lowlands (Figure 3.7). White Point is a coastal headland site at Maxwell Gunther Park just northeast of Destin.

The soil types on EAFB are primarily sandy Entisols. The extremely sandy soils prevalent in the uplands developed on the Citronelle formation of Plio-Pleistocene Age, the primary surficial geologic unit in the area (Schumm *et al.* 1995). The Citronelle Formation consists of unfossiliferous quartz sand, clay, and gravel and has scattered limonite beds, lenses, and pavements (Vernon and Puri 1964). This formation is over 53 m at its deepest point on EAFB, and the formation slopes gently southward toward to the coast (Schumm *et al.* 1995). The Citronelle Formation is overlain by siliciclastic surficial sediments composed of unconsolidated quartz sand (Clark and Schmidt 1982; Scott 1997).

The Lakeland sands are the most prevalent soil series in the uplands of EAFB (Overing *et al.* 1995). Lakeland soils are classified as thermic, coated Typic Quartzipsamments. These soils are particularly deep, up to 2 m or more in most locations (Overing *et al.* 1995). Digging animals such as gopher tortoises (*Gopherus polyphemus*) and ground-dwelling beetles (*Peltotrupes youngi*) turn over the soils and prevent horizon development (Myers 1990). The sand is almost pure quartz that is highly resistant to weathering (Overing *et al.* 1995) and represents some of the driest, least fertile soils in the state of Florida (Myers 1990). Because the soil is very coarse grained, the infiltration capacity is exceptionally high and can exceed 50 cm/hr. In contrast, the average infiltration rate for the Coastal Plain is only 13–28 cm/hr (Markewich *et al.* 1990). The rapid infiltration limits runoff and deters soil erosion, so the sand essentially armors the surface (Markewich *et al.* 1990). The dry conditions are exacerbated by high levels of radiation because of the sparse canopy cover and a high soil albedo (Christensen 1981).

In contrast to the highlands, the soils of the Coastal Lowlands are able to hold more moisture. At White Point, the soils are primarily of the Chipley series, a thermic coated Aquic Quartzipsamment. Like the Lakeland series, these soils are very coarse and deep, but a seasonal high water table exists at a depth of 51 to 102 cm for 2 to 4 months during most years. In addition, a higher percentage of silt and clay is found at depth (Overing *et al.* 1995).

3.4.2 Climate

The climate at EAFB is humid subtropical with warm, humid summers and mild winters. Annual precipitation averages 158 cm, and the wettest months are June through September when thunderstorms are frequent (Overing *et al.* 1995). The average number of days with thunderstorms is between 60 and 70 in the vicinity of EAFB. Winter rains are typically more gentle and associated with winter frontal passing. Dry weather periods are most common in the spring and fall (Overing *et al.* 1995). The influence of the Bermuda high pressure area creates subsidence that keeps convective clouds from building during these seasons (Chen and Gerber 1990). Over 100 tropical storms and hurricanes made landfall within 110 km of EAFB between 1871 and 1985 (NOAA 1994).

The mean annual temperature is 18.3° C, and approximately 275 freeze-free days occur per year (DoD 1995). The warm temperatures contribute to some of the highest rates of evapotranspiration in the eastern U.S. (Ware *et al.* 1993). The moderating effect of the Gulf of Mexico on local temperatures is strong along the coast but diminishes quickly a few miles inland (Overing *et al.* 1995). As a consequence, the northern portions of EAFB have a more continental climate, and these interior areas are much more likely to record below-freezing temperatures (Henry *et al.* 1994).

3.4.3 Vegetation

Early historical accounts indicate that longleaf pine was abundant in the Florida panhandle during presettlement times (Harper 1914; Harper 1958). The earliest public land surveys in northern Florida in 1822 and later in 1914 (Harper 1914) showed that longleaf pine was by far the dominant pine in the region (Schwartz 1994). In the earliest silvical report of the area, the vegetation of the area is described as virgin longleaf forest with blackjack oak and turkey oak in the understory (Florida National Forest 1911).

Today, approximately 78% of EAFB consists of sandhills dominated by longleaf pine (Department of Defense 1993; Tucker *et al.* 2003). The Donut site in the Western Highlands falls within the "Southern Xeric Longleaf Pine Woodlands" classification (Peet and Allard 1993) (Figure 3.8). The xeric conditions in the sandy uplands limit the type of tree species that thrive in this area. The result is a rather open understory with little organic accumulation at the surface. The natural vegetation of these woodlands

Figure 3.8 Southern Xeric Longleaf Pine Woodland at the Donut site.

includes longleaf pine, turkey oak, bluejack oak, sand post oak, saw palmetto, and scattered clumps of wiregrass (Peet and Allard 1993; Overing *et al.* 1995). All of these species are adapted to the dry conditions and frequent fires that have historically spread throughout the area.

The Brandt Pond site appears more mesic at present than the Donut site and is characterized by a denser midstory of oaks and more scattered longleaf in the overstory (Figure 3.9). The dense midstory is likely related to fire suppression at the site since 1972 (C. Avery, pers. comm.). This site falls under the Southern Subxeric Longleaf Woodland (Peet and Allard 1993). The heavy carpet of deciduous leaf litter and the presence of numerous hardwoods are indicative of infrequent fire. Herbaceous plants are scarce on the forest floor, but deer lichen (*Cladina evansii* (Abbayes) Hale & W.L. Culberson) is prevalent. Because this area is near a highway and populated areas, fire suppression has occurred in the area. The White Point site lies within the Southern Longleaf Flatwoods near sea level. The water table is closer to the surface in the flatwoods than in the xeric uplands (Earley 2004). The vegetation is moderately denser than the other sites and includes essentially the same species but is shrubbier. Huckleberry (*Gaylussacia* spp.) and wax myrtle (*Myrica cerifera* L.) are more common.

3.4.4 Land Use History

3.4.4.1 Presettlement Period

In the late pre-Columbian period, the Pensacola culture inhabited northwest Florida from Choctawhatchee Bay (bay of the Choctaws) west to Mobile Bay (Milanich 1994). These people primarily inhabited coastal locations, and the economy consequently

Figure 3.9 Vegetation at the Brandt Pond site. Deer lichen and deciduous leaves cover the ground.

centered on coastal resources such as shellfish (Thomas and Campbell 1993; Milanich 1994; Wilson 1999). In the early 1700s, the Florida Indians were decimated because of James Moore's Indian raids into Florida (Hudson 1976). The Lower Creeks were believed to have invaded the area in the mid-1700s after the indigenous inhabitants had been enslaved or killed (Hudson 1976). The livelihood of the Indians included farming in the major floodplains and hunting (Romans 1999). The women cultivated maize, millet, squash, beans, melons and tobacco, while men hunted turkey, bear, deer, and opossum (Yenne and Garrant 1994). In the 1770s, the Indians of Florida became known as the Seminoles, and they were defeated in a series of wars that ended in the mid-1800s. In 1832, the Seminoles were pushed into the Everglades (Yenne and Garrant 1994). The Seminoles relied heavily on a diet of fish, but also gathered nuts, berries, and other foraged vegetables (Yenne and Garrant 1994).

3.4.4.2 Postsettlement and Logging

Although European settlers arrived in northern Florida over four hundred years ago, evidence suggests that these settlers did not substantially alter the vegetation until the early 1900s (Schwarz 1994). Spain had occupied portions of the Florida panhandle from the late 1500s, but most settlements were located along the coast (Gannon 1993). Pensacola, southwest of EAFB, was established permanently in 1698 (Gannon 1993). Spanish missions in the panhandle were small and probably had little impact on the surrounding land (Tebeau 1980). Until the cession of Florida to the United States in 1821, the Spanish blocked settlement of the Gulf Coast interior (Frost 1991). After the Spanish ceded Florida to the United States in 1821, settlers of Scottish descent settled in the

EAFB area (Tebeau 1980; Overing *et al.* 1995). Because the soil was poor, farming was not common (McCay 2000). However, livestock grazing by cattle, hogs, and sheep was widespread in the area, particularly from the early 1900s until 1932 when the Forest Service stopped grazing (Earley 2004; McCay 2000). As in east Texas, stockmen burned the land every year to enhance the growth of forage for their open-range livestock and to clear undesirable hardwoods (Eldredge 1911; Pyne 1982).

Although the Spanish operated a sawmill near Pensacola as early as 1798, logging operations were not extensive in the panhandle until well into the 19th century (Collier 1965). By the late 1800s, a thriving timber industry was in place (Overing *et al.* 1995). Early in the 1890s, the completion of the Pensacola and Atlantic Railroad across the Appalachicola River opened the Panhandle's longleaf forests to large-scale commercial logging (Derr 1989). By 1909, nearby Pensacola was a major center of the lumber industry (Walker 1991).

In addition to timber operations, turpentining was also a major industry during this period, and turpentining preceded logging on most of the area around EAFB. In fact, Florida was the leading state in the naval stores industry in the early 1900s (Gamble 1921b), and a large portion of the area currently occupied by EAFB was engaged in the turpentining industry. The Choctawhatchee National Forest (CNF), occupying the western two thirds of the current EAFB, listed turpentining as a major objective (Eldredge 1911). Twenty-six turpentine companies worked within the boundaries of the forest or adjacent lands (Earley 2004). Established in 1908, the CNF had been surveyed in the 1890s and contained most of the untimbered longleaf left in Florida (Earley 2004). Although most of the trees were between 150 and 300 years old, their diameters were barely large enough for turpentining (25.4 cm) (Earley 2004). Only five turpentine companies survived until 1931 because of overproduction (Earley 2004). Turpentining activities and logging occurred throughout the early 1900s, but turpentining operations ended by 1948, almost a decade after the CNF was transferred to the War Department for use as an air base (EAFB 1949; Overing *et al.* 1995; Walker and Oswald 2000).

Logging typically occurred after turpentining operations were complete. The CNF management plan involved turpentining the trees for 15 years, then cutting the trees using the seed tree method, leaving 7–15 seed trees per hectare for regeneration (DoD 1993; Tucker *et al.* 2003; Earley 2004). Between 1890 and 1913, vast quantities of longleaf pine timber were shipped out of Pensacola harbor (Derr 1989). Timber operations slowed considerably with the advent of World War I. By 1949, only 10% of the longleaf pine forests at EAFB had survived logging (Eglin Air Force Base 1949). However, logging of longleaf pine continued through the 1980s (Hardesty *et al.* 1993). In addition to harvesting living trees, 400,000 tons of longleaf stumps were also removed from EAFB from 1961 to 1990 to accommodate the wood distillation industry (Hardesty *et al.* 1993). Two of the three sites sampled at EAFB appeared to have been logged during the turpentining and logging bonanza of the early 1900s.

3.4.4.3 Fire at EAFB

As in the Big Thicket, Native Americans are suspected to have augmented natural ignitions with human-caused fires for hunting and other reasons. When Florida was acquired from Spain and settlers moved into the area, burning the pinelands about once a year was believed to have been common to control hardwoods, clear land, and support cattle grazing (Pyne 1982; Schwartz 1994). Survey records from the 19th century from northern Florida also indicate that fires were generally more frequent than they are today (Delcourt and Delcourt 1977a).

The practice of burning was stopped when institutionalized fire suppression policies were enacted in 1927 to protect turpentined trees, and early records indicate near total elimination of natural fire by the late 1940s (U.S. Forest Service 1931; DoD 1993; C. Avery, pers. comm.). The residual seed trees left after logging initially failed to successfully regenerate longleaf pines in these forests, largely because of fire suppression (Earley 2004). Without fire, seeds could not easily germinate because bare mineral soil was not exposed, and hardwoods had a competitive advantage over longleaf pine trees. Non-serotinous sand pine (*Pinus clausa* (Chapm. ex Engelm.) Vasey ex Sarg.) began to encroach from the south into many areas of EAFB by 1920 and has since replaced large areas of former longleaf forest (McCay 2000). Fire suppression practices have also allowed the development of a dense hardwood midstory in many areas (Hardesty *et al.* 1993; Tucker *et al.* 2003). Despite the emphasis on fire suppression, wildfires were not infrequent near bombing ranges since the mid-1940s (Hardesty *et al.* 1993).

EAFB forest managers began an extensive controlled burning program in 1976, and introduced growing season fire in 1989 (DoD 1993). Current forest management practices on EAFB include prescribed burning or mechanical removal of hardwoods to restore natural communities, such as the former longleaf pine forest in the upland areas (DoD 1993; Smith *et al.* 2000; Provencher *et al.* 2001). The typical fire rotation for prescribed burning at EAFB is 4 years, but the interval varies by site (C. Avery, pers. comm.). The Donut has received five prescribed burns since 1990, and most of these fires were in the dormant season (C. Avery, pers. comm.). At Brandt Pond, however, no prescribed burns have occurred since 1972, possibly because of the proximity of the site to a major highway (C. Avery, pers. comm.)

Presently, the typical fire season in Florida is from December through May, and most wildfires are caused by humans (Brenner 1991). Today, nearly 80% of all wildfires on EAFB, for example, are caused by bombing and strafing missions (C. Avery, pers. comm.). From 1981 to 1991, the peak of fires in Florida was in February, and the maximum acres burned occurred in May (Brenner 1991). The month with the largest number of lightning-ignited fires in that period was July, when thunderstorms are most frequent (Brenner 1991).

3.5 Sandy Island, South Carolina

Sandy Island is located in Georgetown County in northeastern South Carolina. The island is situated between the Waccamaw and Great Pee Dee Rivers and is accessible only by boat. The island is managed by the Nature Conservancy, but a few residents still occupy the southern end of the island. The study area is located on the northern half of the island, where the elevation is highest and longleaf pines are more prevalent (Figure 3.10).

3.5.1 Geology, Soils, and Topography

Sandy Island is situated in the Atlantic Coast Flatlands of the Atlantic Coastal Plain and has the highest relief in the local area. The highest point in Georgetown County, at 21.9 m, is located on the northern portion of the island (Stuckey 1982). The

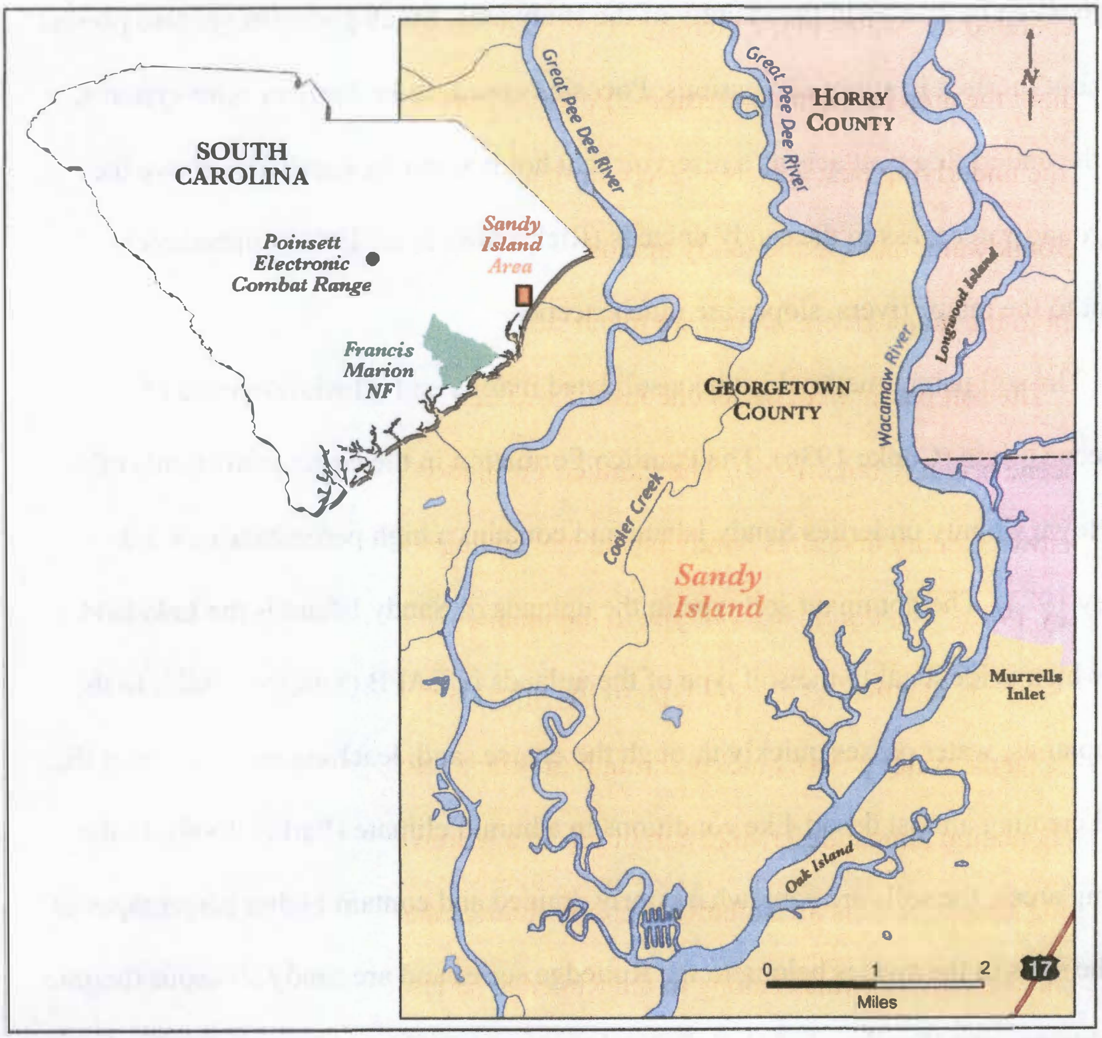


Figure 3.10 Sandy Island and South Carolina study sites.

terrain is level to gently sloping and is characterized by east-west trending low ridges of sand separated by swales in the vicinity of the study area. Small pocosins are also present throughout the area in slight depressions. Pocosins appear to be Tertiary mire systems, where the underlying peat acts as a reservoir that holds water by capillarity above the main groundwater mass in the sandy uplands (Richardson *et al.* 1981). Immediately adjacent to the major rivers, slopes are much steeper.

The soil parent material is unconsolidated marine and alluvial deposits of Pleistocene origin (Cooke 1936). The Pamlico Formation in the eastern two-thirds of Georgetown County underlies Sandy Island and contains a high percentage of sand (Stuckey 1982). The dominant soil type in the uplands of Sandy Island is the Lakeland sands, which is identical to the soil type of the uplands in EAFB (Stuckey 1982). In the sandy uplands, water passes quickly through the coarse sand, leaching nutrients from the soil and creating almost desert-like conditions in a humid climate (Earley 2004). In the low-lying areas, the soils are somewhat poorly drained and contain higher percentages of clay. The soils in the swales belong to the Rutledge series and are sandy siliceous thermic Typic Humaquepts (Stuckey 1982). Soils tend to be saturated in pocosin areas where peat may accumulate at depth, forming Histosols (Earley 2004).

3.5.2 Climate

The climate of the area is warm-temperate with mild winters and hot humid summers, reflecting the maritime influence and close proximity to the Gulf Stream. Precipitation averages 130 cm/yr, and 60% usually falls in April through September (Stuckey 1982; NOAA 1985). Annual precipitation patterns are highly variable, however, due to the episodic occurrence of tropical storms and hurricanes (Blood *et al.* 1991). These storms strike the South Carolina coast approximately once every 2 to 6 years (Gentry 1971; Purvis 1973) and may account for 25% of the annual rainfall (Michener *et al.* 1990). The average number of days with thunderstorms is 50–60 in the vicinity of Sandy Island (USDA 1941). For the period 1951–1980, monthly mean January and August temperatures are 8° and 23° C, respectively (NOAA 1981). Because of warm winter temperatures, 90% of winters have recorded no measurable snowfall (Stuckey 1982).

3.5.3 Vegetation

The native vegetation in Georgetown County on better-drained soils was mainly loblolly pine, slash pine, longleaf pine, oak, and hickory (Stuckey 1982). In the late 1700s, Bartram described the vegetation of the uplands near Charleston, South Carolina as being mostly longleaf pine with some loblolly and slash pine (Walker 1991). The vegetation of the uplands on Sandy Island is similar to the vegetation of the Sandhill region of South Carolina which is typically xeric sandhill scrub. The dominant native trees of the sandhills are longleaf pines and turkey oak, the indicator species for the xeric sandhill scrub community (Edgar 1998). The north end of the island, in particular, supports an overstory dominated by longleaf pine with turkey oak in the understory (Figure 3.11). These two species are practically the only vegetation in the highest portions of Sandy Island, and the forest is very open and park-like. Wiregrass is present but extremely sparse on the forest floor. Small shrubs such as dwarf huckleberry (*Gaylussacia dumosa* (Andr.) Torr. & Gray), dwarf live oak (*Quercus minima* Sarg.), and


2005 6 28

Figure 3.11 Upland vegetation at Sandy Island.

staggerbush (*Lyonia mariana* L.) also exist in the understory. As the topography grades toward the low elevations near the rivers, the vegetation more closely resembles that of the Outer Coastal Plain. Here, longleaf pine is absent, and oaks, principally live oak (*Quercus virginiana* Mill.), dominate the overstory. Vegetation in the swales is exceptionally thick with a variety of oaks and shrubs. The pocosins are non-longleaf communities densely thicketed with evergreen shrubs over a peaty soil (Earley 2004). Fetterbush (*Lyonia lucida* Lam.) dominates in the pocosin areas, and pond pine (*Pinus serotina* Michx.) is also present.

3.5.4 Land Use History

3.5.4.1 Presettlement Period

The native people of Georgetown County were mainly hunters and fishers of the Siouan tribes, and included the Santees, Sampits, Winyaws, Peedees, and the Waccamaws (Rogers 1970; Lerch 2004). The Siouans were Woodlands people who hunted with bows and arrows (Edgar 1998). In addition to foraging, these tribes engaged in intensive agriculture and mound-building (Lerch 2004). The Native Americans probably did not engage in farming on the uplands of Sandy Island because of the impoverished condition of the soil. The Waccamaw, Peedee, and Winyaws tribe likely inhabited the Sandy Island area, as this tribe was known to range from Winyah Bay up the Waccamaw River and its tributaries (Lerch 2004). Prior to European contact in 1521, the Indian population in South Carolina was probably between 17,000 and 30,000 (Edgar 1998), but by 1600, the population was estimated at only 15,000 because of diseases transferred from Spanish missionaries. The remaining tribesmen in South Carolina had virtually disappeared from the area by 1755 because of enslavement and an inability to adjust to agricultural labor (Rogers 1970; Hudson 1976; Lerch 2004).

3.5.4.2 Postsettlement and Logging

> *"The towering dark old pines,*
> *Destroyed once, their fate is sealed,*
> *They ne'er will be replaced."*
>
> *- A.R. Black, 1878, reference to mill timber in the Carolinas*

The first Europeans in Georgetown County were the Spaniards who arrived in the early 1500s, but their settlement was short-lived (Stuckey 1982). In the early 1700s, English colonists moved in from the south, and the city of Georgetown was established in 1729, the same year South Carolina became a crown colony (Hudson 1976; Stuckey 1982).

One of the earliest uses of the longleaf forests in South Carolina was for naval stores. The longleaf pine forests of South Carolina were harvested for tar, pitch, turpentine, and timber from as early as 1682 (Carroll 1836; McKay 1909). The practice in South Carolina was to select already fallen trees rather than green trees (Edgar 1998). By 1720, South Carolina produced more naval stores than any other colony (Edgar 1998). The peak of naval store production in coastal South Carolina occurred between 1732 and 1738 (Rogers 1970). Because of overproduction in naval stores, the industry declined in South Carolina shortly thereafter (Perry 1968).

Rice agriculture was another activity that continued from the 1700s through the Civil War. While rice cultivation was fairly widespread in the Charleston area in the early

1700s, rice was not planted on Sandy Island until much later (Lawson 1714). The wetland portion on the eastern side of Sandy Island was converted to rice plantations in the 1800s. The peak of rice production in Georgetown County occurred between 1850 and 1860, when the Georgetown district was the leading rice-producer in the U.S. (Rogers 1970; Edgar 1998). After the Civil War, the rice plantations gradually ceased production with the loss of slave labor.

Forest-related industries became the next major industry and remain a major industry in Georgetown County at present (Stuckey 1982). The destruction of the Carolina pine forests was greater in the 50 years following the Civil War than in all the 200 years preceding it (Gamble 1921c). In the 1870s, the Franco-Prussian War stimulated a need for naval stores, and the industry experienced resurgence in South Carolina. It was not until the early 1870s that Charleston became a leading market in naval stores (Gamble 1921a). From 1870 to 1890, production in South Carolina was at its peak to meet the large demand (Gamble 1921a). In 1883, Georgetown County was still exporting lumber, rosin, tar, and spirits (Rogers 1970). By 1903, production from Charleston had dwindled considerably when the naval stores industry was no longer important (Gamble 1921a).

As in other areas of the Coastal Plain, logging typically followed turpentining operations. Charleston was a major center for the lumber industry in 1909 (Walker 1991). Dating of turpentine scars from Sandy Island in this study indicates that turpentining operations occurred in the 1890s in the study area. The island was turpentined and logged, as revealed by the numerous stump remnants where the box cut is still visible on the decaying surface of the stump. Virtually all the old growth trees that were turpentined have been logged, although a few scattered trees that were box-cut for turpentining are still living (Figure 3.12).

3.5.4.3 Fire at Sandy Island

According to early accounts, the Native Americans living along the Atlantic Coastal Plain set fires as Verrazano reported in 1524 seeing “great fires because of the numerous inhabitants” (Wroth 1970). Very little is known about the fire history of Sandy Island, but Native Americans and slaves are suspected to have set fires on the island (M. Leslie, pers. comm.). In the past 70 years, only two known lightning-ignited fires are known to have occurred on Sandy Island, in 1962 and 2004 (M. Leslie, pers. comm.). The only known anthropogenic fire originated from a “debris burn” in the village on the south end of the island, and this fire converted a mature longleaf stand into a turkey oak barren (F. Long, pers. comm.). The exact year of this fire and its extent are not known.

The South Carolina Department of Transportation (SCDOT) purchased Sandy Island in 1997. A large portion of Sandy Island is now managed by the Nature Conservancy through a contract with SCDOT. The Nature Conservancy conducts periodic prescribed burns to maintain the integrity of the natural longleaf pine ecosystem. Of the 1,210 ha in the upland, 180 ha were burned under prescription from 1999 to 2001, and an additional 400 ha were burned in 2002 and 2003 (M. Leslie, pers. comm.). Approximately one half of the upland remains unaffected by the prescribed burn program (M. Leslie, pers. comm.).

Figure 3.12 Longleaf pine that survived turpentining on Sandy Island. Two box cuts can be seen near the base of the tree. Diagonal streaks on the catface show evidence of the chipping process. The age of this tree is not known because the heartrot has decomposed the inner portion of the tree. This specimen may be the only living tree on Sandy Island that was tapped for turpentine. Also, living trees with preserved box cuts are rare in the Southeast.

Chapter 4

Climate Analysis and Climate Reconstruction

4.1 Site Selection

The rationale for selecting the sites described in Chapter 3 was based on two of the overarching objectives of the study, which were to develop long tree-ring chronologies from longleaf pine trees in the Coastal Plain and to reconstruct climate based on these reconstructions. First, the sites had to lie within the three major sub-regions of the Southeastern Coastal Plain to determine if differences in the tree-growth response to climate exist across the region. Second, the sites had to be accessible, and land managers had to allow some destructive sampling using a chainsaw. Third, old-growth living trees as well as remnant stumps were needed. Old growth is a not a well-defined concept (McKelvin 1996), but for this study, stands with trees greater than 150 years of age were considered old growth. At my sites, trees exceeding this age generally provide an adequate overlap with remnant wood for crossdating. Once I identified general areas based on these criteria, I consulted with land managers and researchers familiar with the area to locate old-growth stands of trees.

4.2 Methods

4.2.1 Field Methods

At each site, we collected over 40 cores (two cores per tree) from living longleaf pine trees, targeting the oldest-looking trees using the criteria developed by Stahle (1996). Cores were extracted with an increment borer inserted as close to the ground as possible to maximize the number of rings in each sample (Grissino-Mayer 2003) (Figure 4.1). We also collected more than 20 cross sections per site from logs, snags, and stumps using a chain saw (Figure 4.2). Collecting a large number of samples is necessary to elucidate the strongest climate signal and to help reduce noise, as changes in climate do not alter cambial growth similarly in every tree in a stand. The lack of a common growth response within a stand can be attributed to differences in crown size, exposure, depth of rooting, physiological preconditioning, and other non-climatic factors (Kozlowski 1971).

4.2.2 Laboratory Methods

4.2.2.1 Sample Preparation and Measuring

In preparation for sanding, I dried and mounted each core in standard wooden core mounts. For the cross-sections, I mounted fragile pieces on plywood or cardboard, and then cut all cross-sections with a bandsaw to expose a surface for sanding. Next, I prepared the cores and cross-sections for measuring using successive sandpaper grit sizes from ANSI 40-grit (500–595 μm) to ANSI 400-grit (20.6–23.6 μm) sandpaper (Orvis and Grissino-Mayer 2002). Some of the samples required additional finishing with steel wool to remove excess resin to help distinguish the tree-ring structure at standard 7–10X magnification.

4.2.2.2 Crossdating and Master Chronology Development

Crossdating is the method of matching patterns of narrow and wide rings among trees to identify the exact year that each ring was formed (Fritts 2001). I visually crossdated the samples using the extreme-ring match-mismatch method (Phipps 1985)

2004 6 28

Figure 4.1 Coring longleaf pines with an increment borer at White Point, Eglin Air Force Base.

Figure 4.2 Collecting cross sections from stumps on Eglin Air Force Base.

and labeled the cores and cross-sections according to the techniques described by Stokes and Smiley (1996). The identification of extremely wide or narrow "marker rings" assisted in the crossdating process. Next, I measured the total ring widths to 0.001 mm precision using a Velmex movable stage micrometer and the MeasureJ2X program.

To develop a master chronology for each site, I first verified my visual crossdating by entering all the series separately into COFECHA (Holmes 1983; Grissino-Mayer 2001a). COFECHA checks crossdating accuracy by correlating successive time segments with a master chronology from the remaining series. For each series, I used a 50-year segment length lagged 25 years because of the long length of the tree-ring series. If the COFECHA output showed that the rings were dated incorrectly, I visually verified and corrected the dating as necessary. I examined Parts 5 and 6 in the COFECHA output to help identify missing and/or false rings. Part 5 of the COFECHA output shows the correlation of each tree-ring series with the master, and Part 6 provides important information for diagnosing segments with potential dating problems (Grissino-Mayer 2001a). I checked flagged segments to ensure no measurement errors occurred.

Because raw ring-width series possess nonclimatic growth trends related to the increasing age and size of the tree or to changes in competition in the surrounding forest, all series must be adjusted in a process called standardization. Standardization is necessary to remove age-related growth trends that result from physiological effects or stand dynamics (Cook 1985; Fritts 2001). The chronologies produced in the standardization process are an index of ring-width values with a mean of one and relatively homogeneous variance through time (Fritts 2001).

To standardize the tree-ring measurement series, I entered the measurement data into the program ARSTAN (Cook 1985). ARSTAN computes ring-width indices by dividing the ring-width value by the value computed by a cubic smoothing spline fit to each series with a 50% cutoff wavelength (Cook and Peters 1981; Cook and Holmes 1986). The smoothing spline can be thought of as a series of piecewise cubic polynomials with a knot at each data-point abscissa. In effect, the spline is a centrally-weighted moving average on the data, and splines work better than polynomials at approximating functions that are episodic, such as tree-ring series (Cook and Peters 1981). Master chronologies were developed for each site in Texas, Florida, and South Carolina. I developed combined master chronologies for each larger site by combining series from each site into a composite chronology. Two longleaf pine chronologies previously developed for the Big Thicket area (Glitzenstein, unpublished data) were used in the composite chronology for Texas. A separate longleaf pine chronology developed for Lake Louise, Georgia (Grissino-Mayer, unpublished data) was also used in the climate analysis.

4.2.2.3 Earlywood and Latewood Chronology Development

On a limited number of samples from South Carolina and Texas, earlywood widths (EWW) and latewood widths (LWW) were measured in addition to total ring width (TRW). Earlywood is the light-colored wood produced in the early part of the growing season, while latewood is the darker, denser wood produced in the latter portion of the growing season (Fritts 2001). Earlywood cells are large and thin-walled, while latewood cells are smaller and thick-walled (Oliver and Larson 1990). Longleaf pine rings have the most distinct seasonal banding of any of the southern pines (Wahlenberg 1946), which facilitates the measuring process. Measuring EWW and LWW was not attempted until each tree ring was marked and dated to the exact year of formation. This procedure ensured a cross-check of TRW measurements and also minimized wasted effort, as only those samples that statistically crossdated with the master chronology were measured for earlywood and latewood information. Measuring EWW and LWW is rather cumbersome and time-consuming because the measurement time is doubled, and the data must be manipulated in a series of formatting conversions to obtain the final product.

When EWW and LWW are measured, the procedure using Measure J2X software is the same as with TRW, but the total amount of years are doubled in the output file. Because the software does not distinguish EWW/LWW from TRW, the file must be converted using three software programs in sequence. First, the UNCON program converts the Measure J2X file from decadal to TRIMS ("Tree Ring Incremental Measurement System") format in single column. Next, the DIVIDER program separates the single columns into earlywood, latewood, and TRW files. Finally, the CONVERT5 program converts the three sub-files back into decadal format so that all files are in the format of the original master chronologies of TRW. EWW and LWW master chronologies were developed for South Carolina and Texas using the techniques described above.

4.2.2.4 Instrumental Climate Data

After building the master chronologies for TRW, EWW, and LWW, I examined the climate-tree growth relationship using divisional climate data from the National

Climatic Data Center online database (NCDC 2004). The period for the analysis ranged from 1895–2003. I used regional data rather than single-station data because regionally averaged data tend to provide better calibration and verification statistics than single station data (Blasing *et al.* 1981). First, single-station data are generally noisier measures of climate than climate divisions because of their unique microclimates and recording histories (Cook *et al.* 1995). Second, the single-station data cover shorter periods and have an abundance of missing data. Finally, because regional climatic series have less variance than individual records, there is less total variance to estimate and less potential variance in regression models (Cook *et al.* 1995). For the Texas chronologies, I used the climate data developed for NOAA Climate Division Four for Texas. For the Florida chronologies, I averaged the data from Climate Division 1 for Florida and Climate Division 7 for Alabama because of the proximity of EAFB to the border between these states. Other studies have used a two-state average of climate data in areas that may be climatically diverse (Blasing *et al.* 1988). Data for Climate Division Four of South Carolina was used for the remaining chronologies.

The climatic variables used in the climate-response analysis included monthly average temperature, monthly total precipitation, the Palmer Drought Severity Index (PDSI), and the Palmer Hydrological Drought Index (PHDI). PDSI and PHDI are used by the National Weather Service to monitor drought and wetness conditions in the United States and are excellent measures of moisture conditions on the ground during the growing season (Dai and Trenberth 1998; Stahle *et al.* 1998). PDSI is frequently used in dendroclimatic studies and is often significantly correlated with tree-ring indices in the eastern United States (Cook *et al.* 1988; Cleaveland *et al.* 1992; Grissino-Mayer and

Butler 1993; Cook *et al.* 1995; Lafon 2000). PDSI is a monthly meteorological index that describes the severity of wet and dry spells and integrates temperature, precipitation, and evapotranspiration as an estimate of soil moisture availability (Palmer 1965; Orwig and Abrams 1997). This index is essentially a weighted average of soil moisture conditions for the current and preceding months; hence, a strong month-to-month autocorrelation exists in the index that depicts how soil moisture conditions slowly change over time (Stahle and Cleaveland 1988). The index may range from – 6 (very dry) to + 6 (extremely wet), with zero values considered normal conditions (Palmer 1965; NCDC 2004). Values greater than + 4 and less than – 4 are generally considered extreme climatic conditions (Meldahl *et al.* 1999). Because all precipitation is treated as rain in computing the index, the timing of PDSI and PHDI is more accurate in the Southeastern Coastal Plain than in areas where snowfall is more common (Hayes 1996).

PHDI is an adaptation of the PDSI that approaches real time and is therefore a hydrological index used to assess long-term moisture supply (NCDC 2004; Hayes 1996). Unlike the PDSI, the PHDI does not take into account long-term moisture trends because it is based on moisture inflow (precipitation), outflow, and storage (Karl and Knight 1985). PHDI approximates true subsurface hydrologic characteristics but reacts more slowly to changes in weather conditions than PDSI (Grissino-Mayer and Butler 1993). The PHDI only changes sign when the ratio of moisture received to moisture required to end a dry or wet period is equal to 100% (Karl and Knight 1985). The values for PHDI are similar in range and sign (i.e., negative values indicate drought) to PDSI.

4.2.2.5 Statistical Analysis of Climate Response

Correlation analysis is a useful first step in determining the relationship between tree growth and climatic variables (Gholz 1982). In this chapter and those that follow, tree growth refers to "radial" tree growth unless otherwise stated. The correlation coefficient (*r*) is a parametric association between two samples (Cook *et al.* 1995). I computed Pearson correlation coefficients between annual growth indices and the four climate variables (average temperature, total precipitation, PDSI, and PHDI) for a 24 month period (previous January – current December). I used monthly and seasonal climate variables in the computations. The seasonal groupings were defined as three-month periods and included winter (December–February), spring (March–May), summer (June–August), and fall (September–November). Seasonal climate variables were computed by summing the values of the corresponding months. I included prior year climate because both the previous and current growing season conditions and the dormant season can affect the amount of carbon fixed and subsequently used for tree-ring growth (Kozlowski 1979; Grissino-Mayer and Butler 1993; Foster and Brooks 2001; Fritts 2001). For example, stored food reserves from the previous year can ameliorate the effects of unfavorable climate conditions in the current year (Stahle and Cleaveland 1992). The two-year period was selected because longleaf pine trees retain their needles for about two years, and needles affect photosynthesis and tree growth (Wahlenberg 1946).

4.2.2.6 Developing Climate Reconstructions

I selected the climate variable with the highest correlation coefficient with the tree-ring indices to perform the reconstruction. I divided the full period of instrumental climate record (1895–2003) into half-sample subsets (1895–1948 and 1949–2003), using the subperiod with the stronger association with climate for the calibration (Stahle and Cleaveland 1992). Using ordinary least-squares regression analysis, I calculated calibration equations that predicted the selected climate variable using tree-ring indices as predictors. These equations are commonly known as transfer functions (Fritts 2001). More complex regression models using higher-order terms may be used to reconstruct precipitation, but studies have shown that other forms of regression do not reduce the mean-square-error beyond that obtained using straight line forms (Blasing *et al.* 1988). Outliers that exceed tolerances according to Studentized residual and Cook's *d* tests were evaluated for possible removal from the model (Grissino-Mayer 1995). I withheld outlier observations from the final model according to the applicable tolerance criteria (Grissino-Mayer 1995). I attempted to determine the cause for the outliers by examining known historical disturbance events (e.g. hurricanes, fire, etc.) or other factors that may have produced noise in the climate response.

To determine how well the tree-ring reconstructions replicate the instrumental record of climate, I verified the calibration equations using the subset withheld from the calibration computations (Fritts 2001). To test the statistical fidelity of the reconstructions, I used the Pearson correlation over the verification period and the t-test (Stahle and Cleaveland 1992; Grissino-Mayer 1996; Cook *et al.* 1996). These tests compare the predicted values of climate to the actual values of the instrumental record. If the statistical tests proved statistically significant, I used the entire period of the instrumental record to compute a new transfer function for the final reconstructions. The final transfer function is more statistically rigorous than in the test sequence because the number of observations used in the model is doubled (Grissino-Mayer 1996).

4.2.2.7 Trend Analysis

Long tree-ring climate reconstructions can be used to observe changes in the trends and persistence of climate patterns (LaMarche and Fritts 1971). I examined annual, decadal, and multidecadal trends to determine the coherence of climate conditions in the Southeastern Coastal Plain over time. I first examined extreme individual years of drought and wetness and compared the three chronologies to determine if a regional pattern of extreme conditions existed during those years. I also identified periods of above- and below-average moisture conditions by smoothing the climate reconstructions with a centrally-weighted moving average. I analyzed decadal trends using a 10-year moving average and multidecadal trends using a 50-year moving average. To better quantify the magnitude of past climatic fluctuations, I converted the reconstructed values to standard deviation units (z-scores) by subtracting the series mean and dividing by the standard deviation of the series (Johnston 1980; Grissino-Mayer 1995). I arbitrarily defined the beginning of an extreme period when the standard deviation unit first fell below a value of – 1.0 sd or above + 1.0 sd. The period was considered complete when the yearly value exceeded – 1.0 sd or dropped below the + 1.0 sd. level. However, these standards were more a guideline than an absolute rule in my analysis. I compared the persistence of dry or moist conditions at the various sites at the interannual, decadal, and multidecadal level to determine the variability of climate through time.

4.2.2.8 Spectral Analysis

To determine the presence of significant cycles over the period of reconstruction, I used spectral analysis. I used Fourier transforms in SAS statistical software to compute the spectral density and squared coherence function for the climate reconstruction (SAS 2004). To test whether or not the reconstruction represented a white noise sequence, I used the Fisher's Kappa test and the Bartlett's Kolmogorov-Smirnov statistic (Fuller 1976). A white noise sequence is one that cannot be broken down into sums of sine and cosine wavelengths, so a white noise sequence has no statistically significant spectral peaks (Brocklebank and Dickey 1986). If the series showed the presence of red noise, I examined the periodogram values for important frequencies. The analyses looked for both short-term cycles such as the 11-year sunspot cycle, the quasi-biennial pulse, the 22-year Hale solar cycle, or the 18.6-year tidal cycle as well as longer-term cycles (Berry and Perry 1973; Currie 1981). The spectral analysis also aided in identifying the possible effects of atmospheric teleconnections that will be examined in detail in Chapter 5.

4.3 Results

4.3.1 Tree-ring Chronologies

The three master chronologies of TRW totaled over 100 measured series in each chronology (Table 4.1) (Appendices A and B). A number of series were not used because of weak or nonexistent crossdating. Including series that crossdated poorly would have

Table 4.1 Summary of tree-ring data for master chronologies. TX = Texas, EAFB = Eglin Air Force Base, SC = South Carolina.

	Period of record	Number of samples	Interseries correlation	Mean sensitivity
TX (TRW)	1632–2003	125	0.52	0.35
TX (LWW)	1662–2003	32	0.56	0.57
TX (EWW)	1661–2003	25	0.50	0.34
EAFB	1507–2003	144	0.51	0.31
SC (TRW)	1458–2003	105	0.50	0.27
SC (LWW)	1470–2003	48	0.49	0.43
SC (EWW)	1469–2003	32	0.47	0.27

added nonclimatic noise in the chronologies and weakened the climate signal. The number of series that could not be included from the Texas, EAFB, and South Carolina chronologies were 41, 36, and 63 series, respectively. The number of South Carolina series that were not crossdated was unusually high in large measure because of the extremely narrow rings in many of the stunted longleaf pines. Like Meldahl *et al.* (1999), I had particular difficulty in crossdating the EWW and LWW chronologies. I attribute these problems to the lack of variability in the earlywood or latewood during suppressions and the difficulty of measuring extremely narrow rings. During periods of extreme suppression and slow growth, the tree rings are exceptionally difficult to measure, even at high levels of magnification.

Two descriptive statistics, interseries correlation and mean sensitivity, were used to characterize the statistical quality of the three chronologies. Interseries correlation, the Pearson correlation coefficient among the individual series at each site, is considered an index of the signal-to-noise ratio in the chronology (Foster and Brooks 2001). All trees do not display the same tree-ring pattern because of stand dynamics and injuries, but measurement errors can also be a noise-producing factor. During periods of extreme suppression and slow growth, the tree-ring increments seem to be less sensitive to climate, and the tree rings are difficult to measure accurately even at high magnification. All TRW chronologies exhibited an interseries correlation greater than or equal to 0.47.

Mean sensitivity is a measure of the relative difference in width from one ring to the next and is calculated by averaging the percent change from ring to adjacent ring (Fritts 2001). Mean sensitivity is also a sufficient indicator of climate responsiveness (LaMarche 1980). The mean sensitivity of the Texas chronology (0.35) is the highest of any published longleaf pine chronology for TRW. Compared to other longleaf pine chronologies where mean sensitivity was computed, the values are much higher than in the Meldahl *et al.* (1999) study, where mean sensitivity values ranged from 0.18 to 0.24 in southern Alabama. The values are comparable to the Foster and Brooks (2001) study where the mean sensitivity ranged from 0.31 to 0.33 in peninsular Florida. The LWW chronologies display a significantly higher mean sensitivity than the other chronologies. The LWW chronology from Texas has a higher mean sensitivity (0.57) than any pine chronology from the southeastern U.S. Not surprisingly, the relatively small sample of trees from the George Russell property at the western limit of longleaf pine exhibited an exceptionally high mean sensitivity (0.65) for LWW. This area stands at the ecotone between pine forest and prairie/grasslands to the west.

A marked characteristic of all chronologies is the weaker interseries correlation for the segments where the living trees overlap the remnant, unanchored samples. The reasons for the weaker correlation are twofold. First, the first-formed rings (up to about 40-years-old) contain the least information about climate, so the agreement between climate response and ring width is less (Fritts 2001). Most living trees sampled in each chronology are approximately the same age, so the correlations during the period when these trees began early growth should be lower. Where the series started at the pith, removing the first 10 to 30 years normally improved the interseries correlation because reaction wood, common in the early stages of tree growth, was removed from the analysis. Second, in the periods where the remnant wood overlaps with the living trees, that portion of the remnant wood generally contains the rings produced when the tree has aged significantly. Older trees are less vigorous than young trees, so the climate response between tree groups of different age is not the same (Douglass 1919; Fritts 2001).

The age of the EAFB and South Carolina chronologies are only exceeded in the Southeastern Coastal Plain by a network of baldcypress chronologies (Stahle *et al.* 1988; Stahle and Cleaveland 1992; Stahle and Cleaveland 1994), and in the interior southeastern U.S., only by Guyette's (1981) 850-year eastern red cedar (*J. virginiana* L.) chronology from the Missouri Ozarks. The number of samples and length of the chronologies from EAFB and South Carolina are unprecedented for any southern pine chronology in the Southeast. The Texas chronology is the fourth oldest anchored longleaf pine chronology in the Southeast according to the International Tree Ring Data Bank (ITRDB), exceeded only by the Jeffries Smokehouse, North Carolina archeological chronology (dated to 1608) and the other two chronologies in this study. The sample depths of the EAFB and South Carolina TRW chronologies are excellent prior to 1650. EAFB has 12 series that date to at least 1617, and the South Carolina chronology has 12 series that date prior to 1600. One extraordinary sample from Sandy Island, SI083B, had an inner ring date of 1455 and over 360 annual rings, making this sample one of the oldest known samples of dated southern pine wood in the entire Southeast. The age of several individual samples was over 300 years, but the exact ages cannot be determined because the trees do not produce annual rings in the grass stage, and the relict samples were generally devoid of sapwood. The most long-lived tree in all the chronologies came from Eglin AFB and contained 437 rings (sample DN003).

I used the RESIDUAL rather than the STANDARD chronologies produced by ARSTAN because I found a better correlation between the RESIDUAL chronologies and climatic variables than with the standard chronology (Appendix B). The RESIDUAL chronology is a white noise series with all low-frequency variation removed and is developed by autoregressive modeling (Cook 1985). Using the residual chronology lowers the bias in indices and provides a robust signal of climate (Cook 1985).

Comparing these chronologies with other tree-ring chronologies from the region shows the strength of the association and the commonality of the climate signal. I chose the two or three (geographically) closest chronologies from the ITRDB for comparison with each TRW chronology (Table 4.2). Only in the case of EAFB were there longleaf pine chronologies close enough for a reasonable comparison. I computed Pearson correlation coefficients between the TRW chronologies from my three sites and the adjacent sites from the ITRDB. In some cases, the correlation coefficients were significant at the $p < 0.001$ level. Because of the strength of the relationships, the sites appear to reflect a common climate signal.

4.3.2 Climate Response

4.3.2.1 Total Ring Width

Correlation analysis between the three TRW chronologies and precipitation showed a fairly consistent response (Figures 4.3, 4.4A1, 4.4B1, and 4.4C1). July precipitation has the most significant positive relationship with annual increment in two of the three chronologies and is the most important month for summer precipitation in South Carolina (Figure 4.4C1). Spring precipitation, particularly in March and April, is also significant in all three regions. Interestingly, February precipitation has a significant positive relationship with pine growth in South Carolina (Figure 4.4C1), but this

Table 4.2 Correlation coefficients between my sites and adjacent sites (in ITRDB except as noted).

Site	Species	Correlation Coefficient
TX		
Peachtree Bottoms (PTB)	baldcypress	0.20***
Yegua Creek (YEG)	post oak (*Quercus stellata* Wang)	0.03
San Augustine NF (not in ITRDB – J. Glitzenstein)	post oak	0.16**
EAFB		
Choctawhatchee R. (CHK)	baldcypress	0.11*
Flomaton Natural Area (FNA)	longleaf pine	0.45***
J.W. Jones ERC (ICH)	longleaf pine	0.23***
SC		
Black River, NC (BLK)	baldcypress	0.04
Francis Beidler Swamp (FBS)	overcup oak (*Quercus lyrata* Walt.)	0.23***

* $p < 0.05$
** $p < 0.01$
*** $p < 0.001$ level

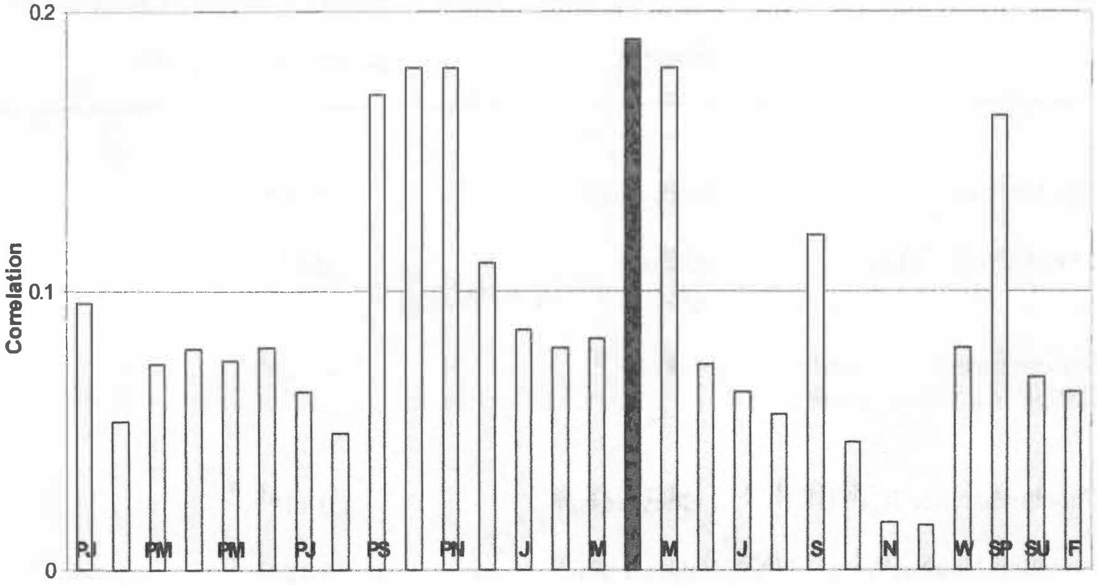


Figure 4.3 Exaggerated scale of climate correlation graphs in Figures 4.4–4.7. The bars are labeled by the month or season that the variable represents. The 24 monthly variables represent the 12 months in the previous year and 12 months in the current year. The months variables are abbreviated by the first letter of the month, and in the case of a month in the previous year, a "P" precedes the abbreviation. The seasonal variables are abbreviated as follows: W = winter, SP = spring, SU = summer, and F = fall.

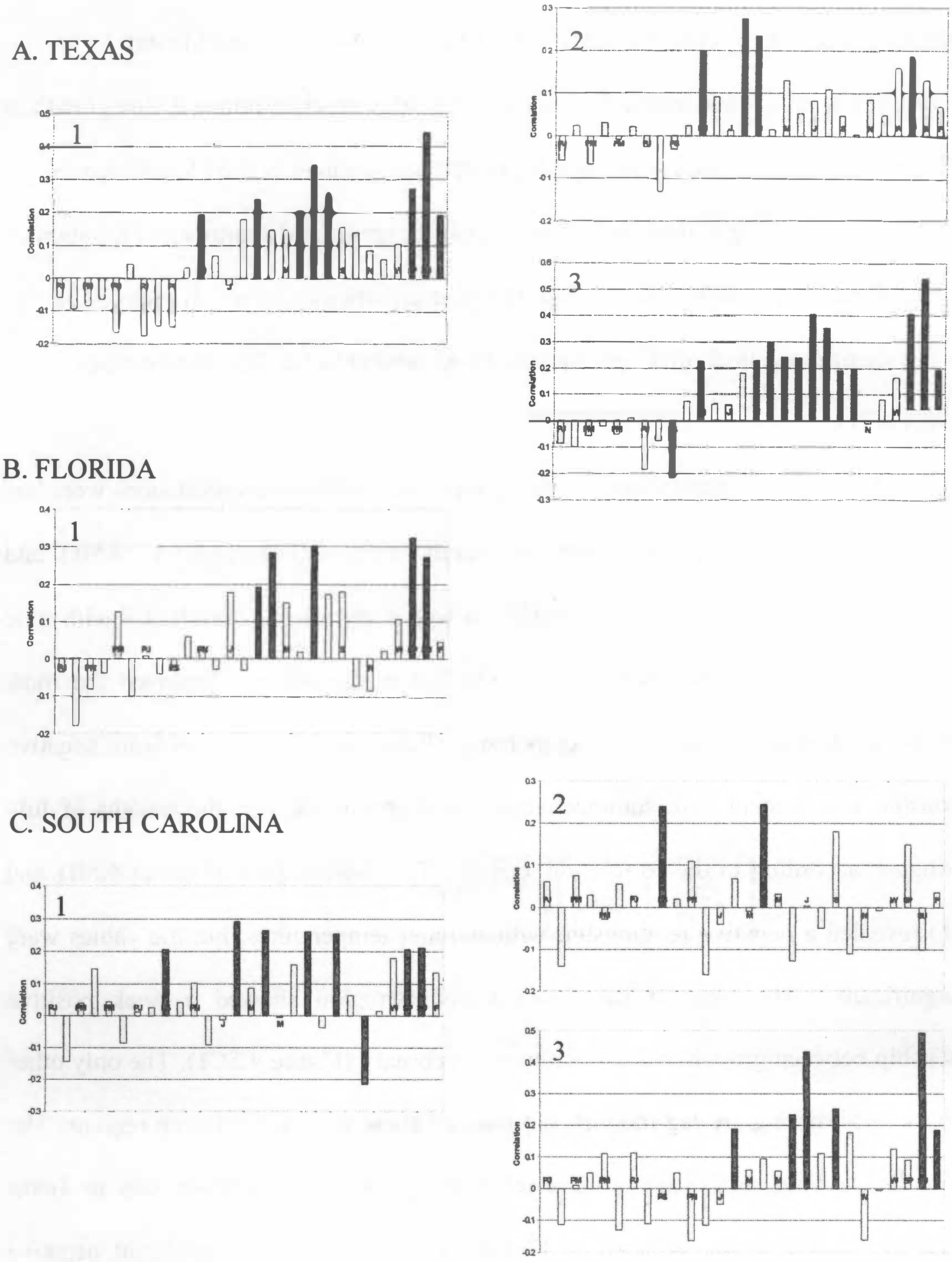
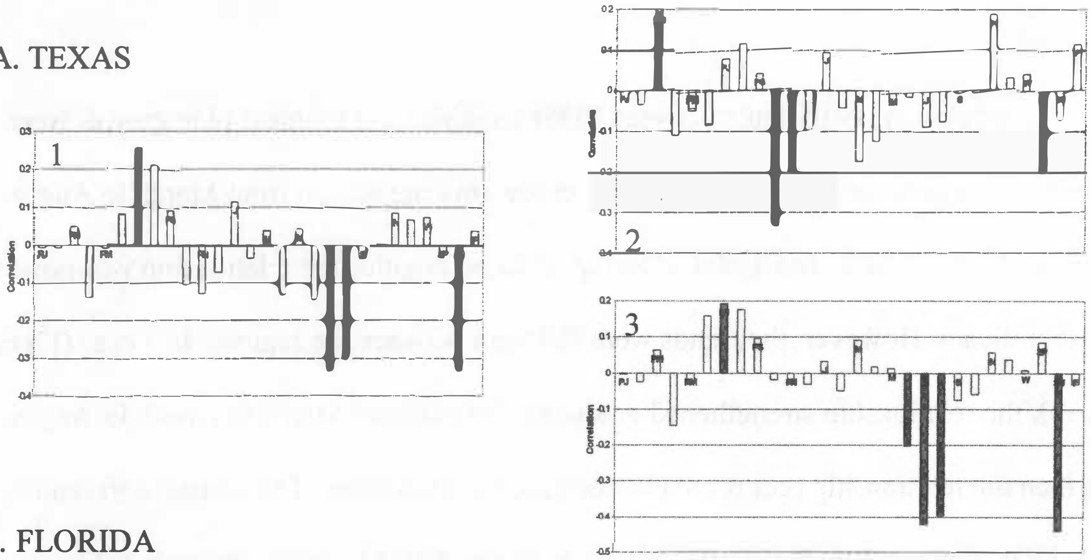


Figure 4.4 Correlation analysis between tree-ring indices and precipitation for previous January (PJ) to current December, seasons (W = winter, SP = spring, SU = summer, F = fall). Black bars indicate significant ($p < 0.05$) values. 1 = TRW, 2 = EWW, 3 = LWW.

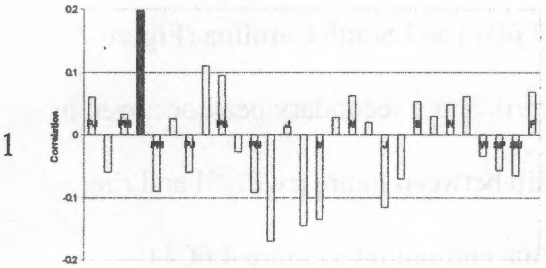
relationship is not evident in the other regions. The effect of previous November precipitation in Texas is weak but significant (Figure 4.4A1), and a significant relationship was also found between previous September precipitation and pine growth in South Carolina (Figure 4.4C1). No such lag effects are apparent in the Florida region (Figure 4.4B1). Looking at the seasonal relationships, spring and summer precipitation showed a significant positive relationship with pine growth indices for all regions. A weak but significant effect of fall precipitation was present in the Texas chronology (Figure 4.4A1).

Compared to the precipitation relationships, the temperature correlations were less consistent between regions, and correlations overall were low (Figures 4.5A1, 4.5B1, and 4.5C1). In fact, only one monthly variable showed a significant correlation with pine growth in two of the three chronologies. The Texas chronology displayed the most definitive response of tree growth to temperature (Figure 4.5A1). A significant negative relationship was evident with summer temperatures, particularly in the months of July and August, according to the correlation analysis. The other regions (Figures 4.5B1 and 4.4C1) revealed a negative relationship with summer temperatures, but the values were non-significant. The trees in the South Carolina region showed a weak positive relationship between growth and temperature in February (Figure 4.5C1). The only other variables worth noting are lag months, but none of these matched between regions. The lag months showing significant positive relationships were the previous July in Texas (Figure 4.5A1) and previous April in Florida (Figure 4.5B1). A significant negative relationship existed between previous October temperature and growth indices in South Carolina (Figure 4.5C1); non-significant but negative relationships with October

A. TEXAS



B. FLORIDA



C. SOUTH CAROLINA

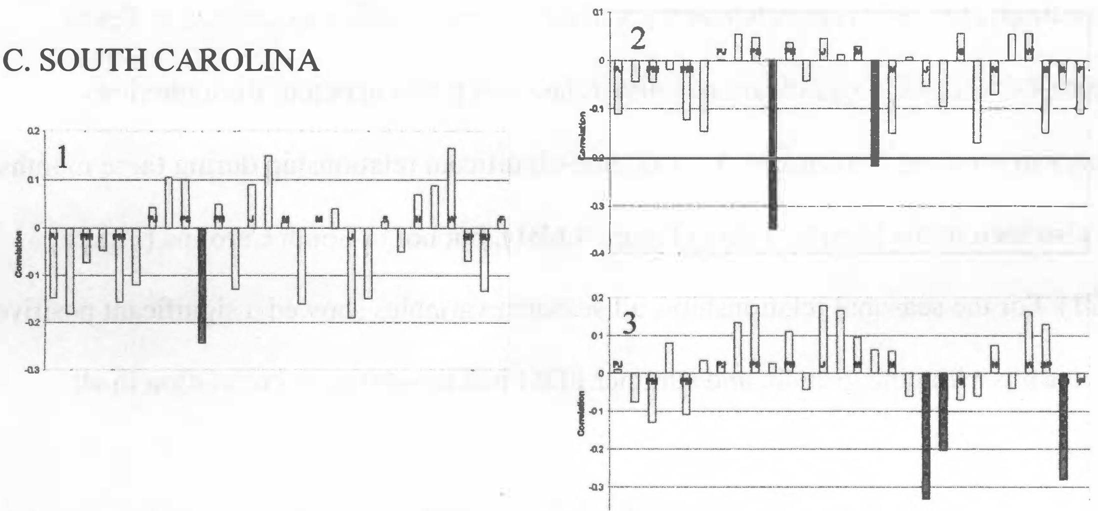


Figure 4.5 Correlation analysis between tree-ring indices and temperature for previous January (PJ) to current December, seasons (W, SP, SU, F). Black bars indicate significant ($p < 0.05$) values. 1 = TRW, 2 = EWW, 3 = LWW.

temperatures of the previous year are also present in the other two regions (Figures 4.5A1 and 4.4B1).

Correlation coefficients between PDSI variables and longleaf pine growth were significant throughout most of the months in the growing season from March to August (Figures 4.6A1, 4.6B1, and 4.6C1). During all these months, the relationship was positive and significant. However, the trends were different between the regions. In Texas (Figure 4.6A1), the relationship strengthened gradually from current March to a peak in August, and then the relationship progressively decreased to December. The highest correlation with TRW for any climate variable was with August PDSI in the Texas region (Figure 4.6A1) ($r = 0.46$, $p < 0.001$). For Florida (Figure 4.6B1) and South Carolina (Figure 4.6C1) chronologies, the relationship peaked in April, and a secondary peak occurred in the summer and early fall. A significant relationship between February PDSI and ring width indices was only evident in the South Carolina chronology (Figure 4.6C1). Interestingly, the only region where lag variables were significant occurred in Texas (Figure 4.6A1), and a significant negative relationship was apparent from previous January to previous September. A weak, non-significant relationship during these months was also seen in the Florida region (Figure 4.6B1), but not in South Carolina (Figure 4.6C1). For the seasonal relationships, all seasonal variables showed a significant positive relationship with pine growth, and summer PDSI had the strongest correlation in all regions.

The relationship between PHDI and TRW was similar to the relationship between PDSI and TRW (Figures 4.7A1, 4.7B1, and 4.7C1). As with the PDSI variable, a significant correlation existed in current-year March, and this relationship increased

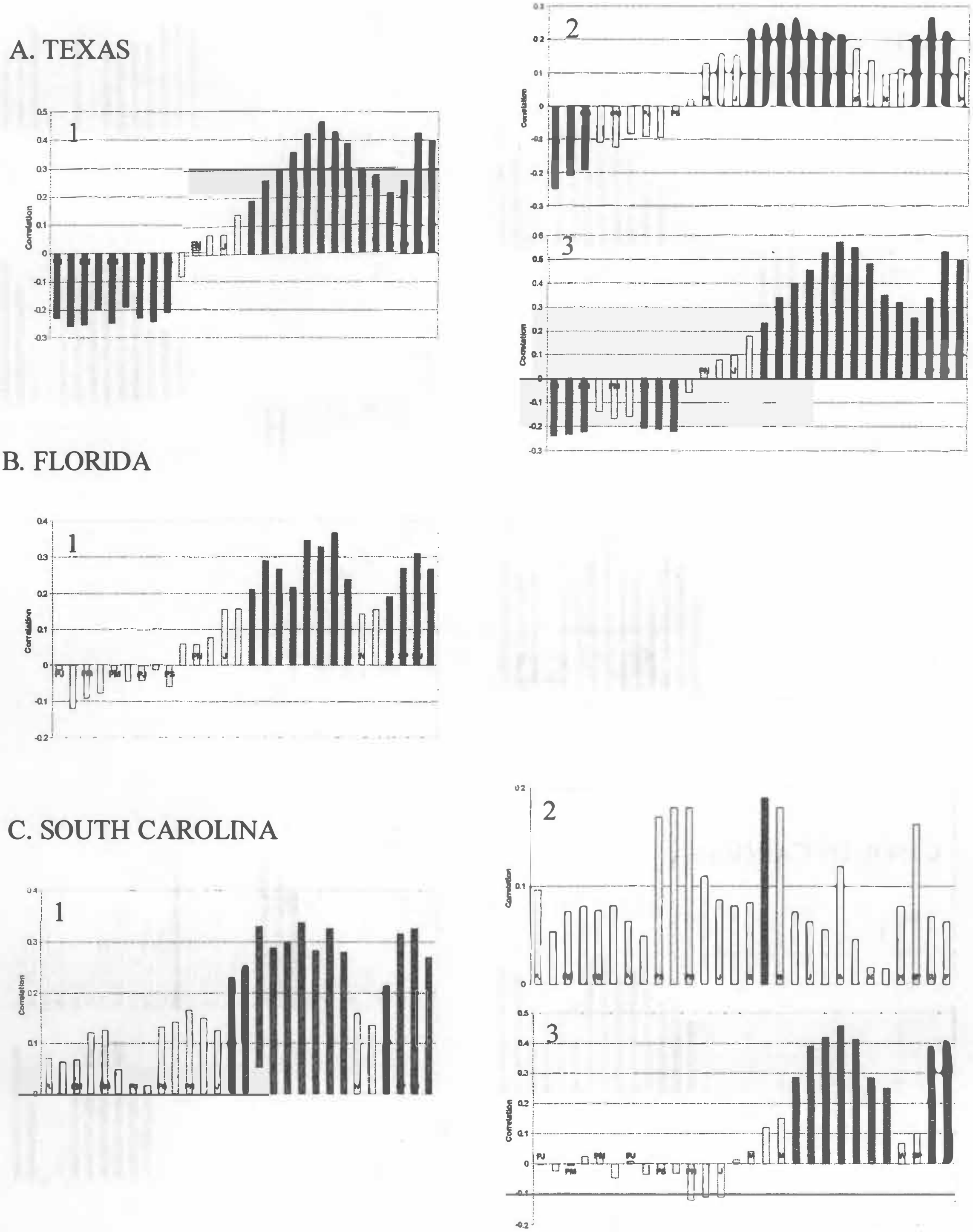
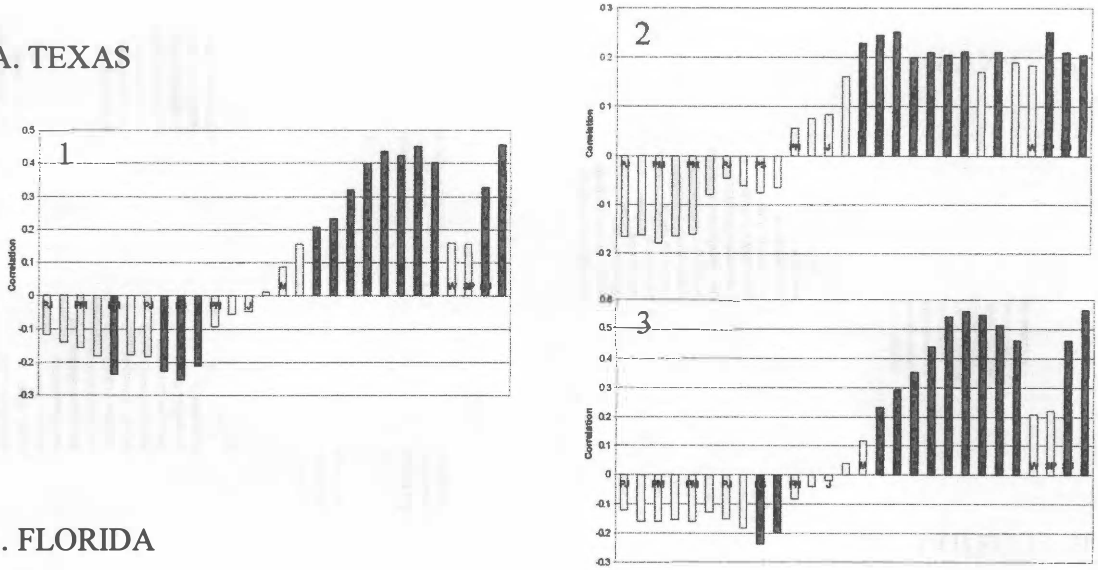
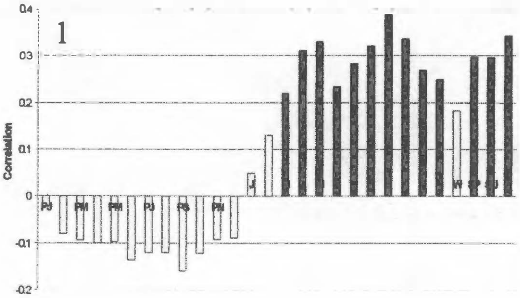


Figure 4.6 Correlation analysis between tree-ring indices and PDSI for previous January (PJ) to current December, seasons (W, SP, SU, F). Black bars indicate significant ($p < 0.05$) values. 1 = TRW, 2 = EWW, 3 = LWW.

A. TEXAS



B. FLORIDA



C. SOUTH CAROLINA

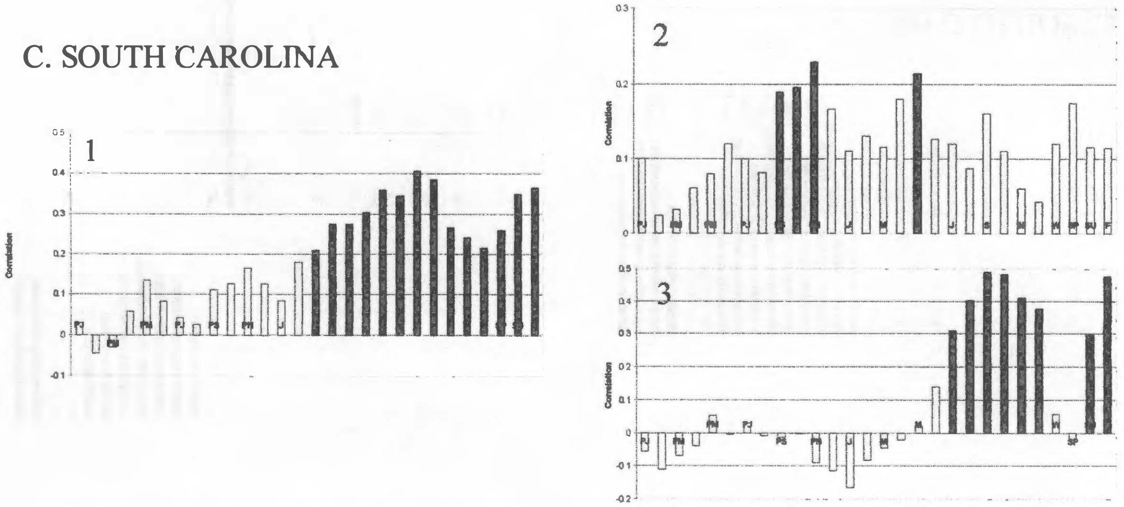


Figure 4.7 Correlation analysis between tree-ring indices and PHDI for previous January (PJ) to current December, seasons (W, SP, SU, F). Black bars indicate significant ($p <$ 0.05) values. 1 = TRW, 2 = EWW, 3 = LWW.

progressively to a peak late in the growing season and decreased thereafter. However, the peak was shifted one or two months later in the year, and significant correlations continued through current December in all regions. September PHDI generally had the highest correlation with TRW among all the monthly variables. A significant negative relationship was evident between late summer and early fall PHDI and TRW in the Texas region (Figure 4.7A1), and a similar but non-significant pattern was apparent in the Florida chronology (Figure 4.7B1). For the seasonal variables, the highest correlation for all three areas occurred in fall, and spring and summer PHDI variables were likewise significant.

4.3.2.2 Earlywood Width

The response of earlywood formation to all climatic variables was generally weaker in South Carolina than in Texas, but a few general relationships are clear, particularly for the current spring months and previous fall. Precipitation and PDSI values showed a significant positive correlation with earlywood growth for the month of April in South Carolina (Figures 4.4C2 and 4.6C2), and a significant negative correlation existed between temperature and earlywood formation in the same month. In Texas, precipitation earlier in the current year (February and March) was more significant, and monthly PDSI variables from February to August were statistically significant as well (Figure 4.6A2). Interestingly, the response of earlywood to PHDI was statistically significant earlier in the growing season (March) in South Carolina (Figure 4.6C2), and every month from March to September showed a statistically significant relationship with PHDI in Texas (Figure 4.7A2). Earlywood formation appeared to be affected by conditions in late summer and fall of the previous year. Significant positive relationships existed between EW growth and both precipitation and PHDI in the prior year September and September–November, respectively, in South Carolina (Figure 4.7C2), and previous November precipitation in Texas (Figure 4.7A2). A weak but similar relationship was evident in the PDSI variable in South Carolina (Figure 4.6C2), but no such relationship was evident in Texas (Figure 4.6A2). Rather, PDSI was negatively related to PDSI and PHDI in the previous January to previous March. Previous year temperature in October showed a significant negative relationship with EW growth in South Carolina (Figure 4.5C2), and the temperatures in Texas had a similar effect in the prior October and November (Figure 4.5A2). None of the seasonal variables showed significant relationships to EW formation in South Carolina, but spring rainfall and temperature were particularly significant in Texas (Figures 4.4A2 and 4.5A2). The effects of spring soil moisture conditions were also indicated by high correlations for spring PDSI and PHDI in Texas (Figures 4.6A2 and 4.7A2).

4.3.2.3 Latewood Width

In contrast to earlywood, latewood formation was more significantly influenced by all climatic variables, and the Texas LWW generally showed higher correlations than in South Carolina. The highest correlations between latewood formation and both precipitation and temperature was in the month of July for both regions, and the highest seasonal correlation was in the summer for both regions. Every month in the growing season (March through October) showed a statistically significant relationship between precipitation and LWW in Texas (Figure 4.4A3). In addition, February precipitation was weakly but significantly correlated with latewood formation in South Carolina (Figure 4.4C3), but the relationship was the weakest among the statistically significant monthly variables for rainfall. As in the TRW chronologies, the PDSI and PHDI variables showed increasingly significant correlations throughout the growing season beginning in June or July (March or April in Texas) and peaking in September or August (Figures 4.6A3, 4.6C3, 4.7A3, and 4.7C3). After the peak, significant but progressively weaker correlations were evident through December for both variables. The highest correlation between LWW and any other climate variable was with August PDSI in Texas (Figure 4.6A3) ($r = 0.57, p < 0.001$). Both PDSI and PHDI in the summer and fall were significantly correlated with latewood growth. Interestingly, none of the lag variables for South Carolina was significantly related to latewood formation (Figures 4.6C3 and 4.7C3). In contrast, the PDSI and PHDI values for Texas showed a consistent (but not always significant) negative relationship with LWW from previous January through previous October (Figures 4.6A3 and 4.7A3). Another notable trend was a weak positive relationship between summer temperatures of the previous season and LWW in Texas (Figure 4.5A3).

4.3.3 Climate Reconstructions

4.3.3.1 Model Results

I reconstructed September PHDI because of the superior amount of variance explained in the regression model developed for all sites. Although September PHDI did not have the highest correlation for all sites, I chose a single climate variable for commonality. Because of the persistence built into the Palmer indices, September PHDI provided a good representation of the average moisture conditions during the spring and summer growing season.

The results of the calibration and verification procedure showed that the percent variance explained by the regression model ranged from 31% to 45% (Table 4.3). For the Texas and Florida chronologies, the instrumental data from the earlier subperiod (1895–1948) correlated better than in the later subperiod (1949–2003). For this reason, the earlier subperiod was used for calibration, while the later subperiod was reserved for verification. The opposite was true for the South Carolina chronology, so the calibration and verification periods were reversed. Outlier observations noted by high values of the Studentized residual were identified and withheld from the calibration model. All models verified with a statistically significant Pearson correlation coefficient ($p < 0.001$) (Table 4.4), and a relatively close fit between actual and estimated PHDI values is apparent for all models (Figures 4.8–4.10). I used the regression equation developed from the calibration period to reconstruct September PHDI for the entire period of each chronology (Figures 4.11A–4.13A).

4.3.3.2 Trend Analysis

Interannual, decadal, and multidecadal variability were evident in the full reconstructions of PHDI, 10-year moving average, and 50-year moving average (Figures 4.11–4.13) graphs. For this analysis, the early portions of each chronology, in which the sample depth dropped considerably (down to four series), were not considered in the rankings or comparisons, but the values in those periods were noted for qualitative purposes. Reconstructed PHDI (or sd) values that exceeded + 1 or – 1 were considered to

Table 4.3 Calibration model results for estimating September PHDI.

Site	Period	Parameter Estimate	Constant	F- value*	r^2
Texas	1895–1948	6.75	– 6.99	28.6	0.36
Florida	1895–1948	8.26	– 8.82	22.6	0.31
SC	1949–2002	6.38	– 5.81	39.5	0.45

* $p < 0.001$ level

Table 4.4 Verification test results for actual versus predicted September PHDI values over the verification period.

Site	Period	Correlation*	t-test (means)
Texas	1949–2003	0.56	1.07***
Florida	1949–2003	0.38	2.57**
SC	1895–1948	0.64	– 5.99**

* $p < 0.001$

** $p < 0.01$

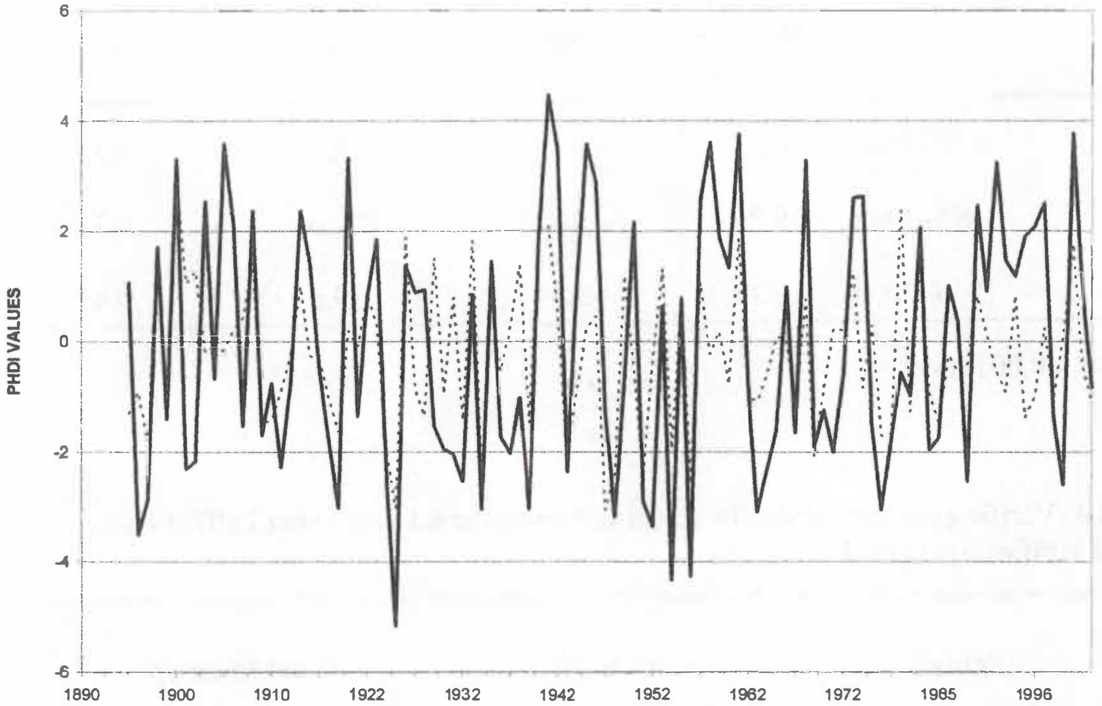


Figure 4.8 Observed (solid lines) and reconstructed (dashed lines) September PHDI for the period 1895–2003 for Texas.

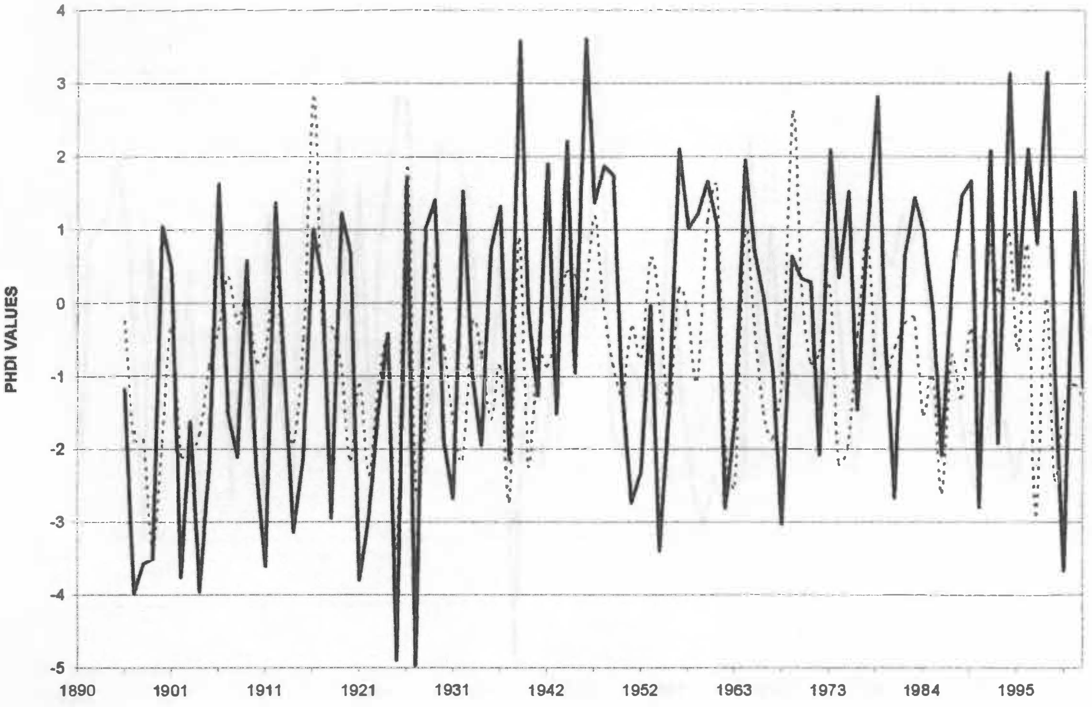


Figure 4.9 Observed (solid lines) and reconstructed (dashed lines) September PHDI for the period 1895–2003 for Florida.

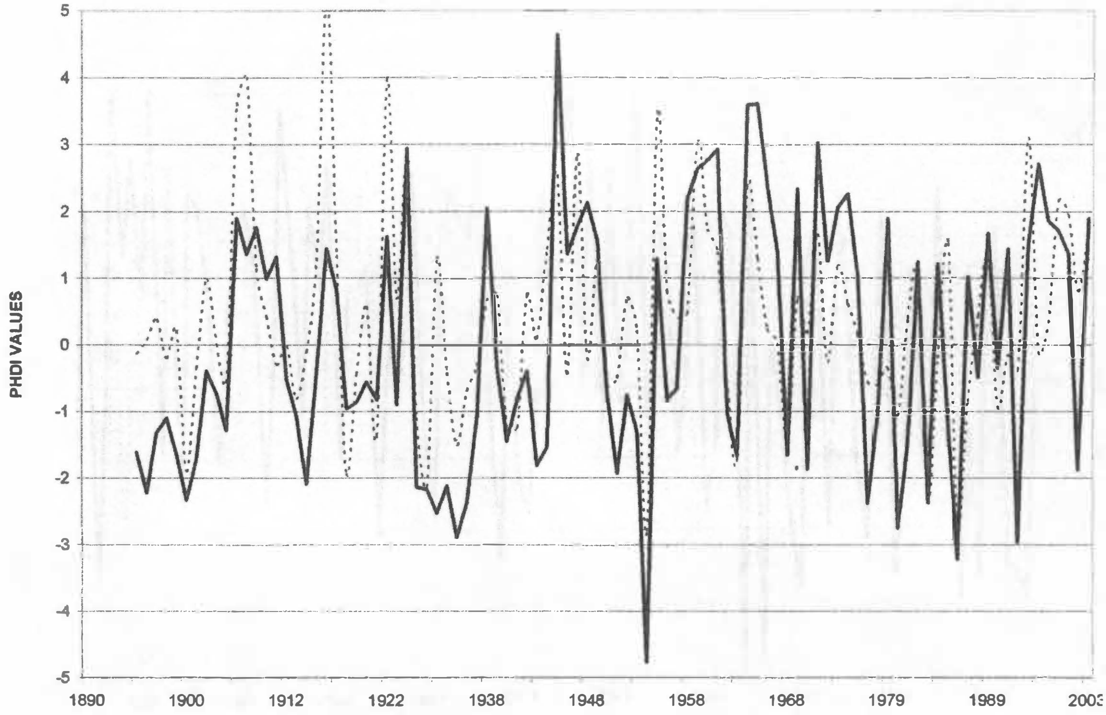


Figure 4.10 Observed (solid lines) and reconstructed (dashed lines) September PHDI for the period 1895–2003 for South Carolina.

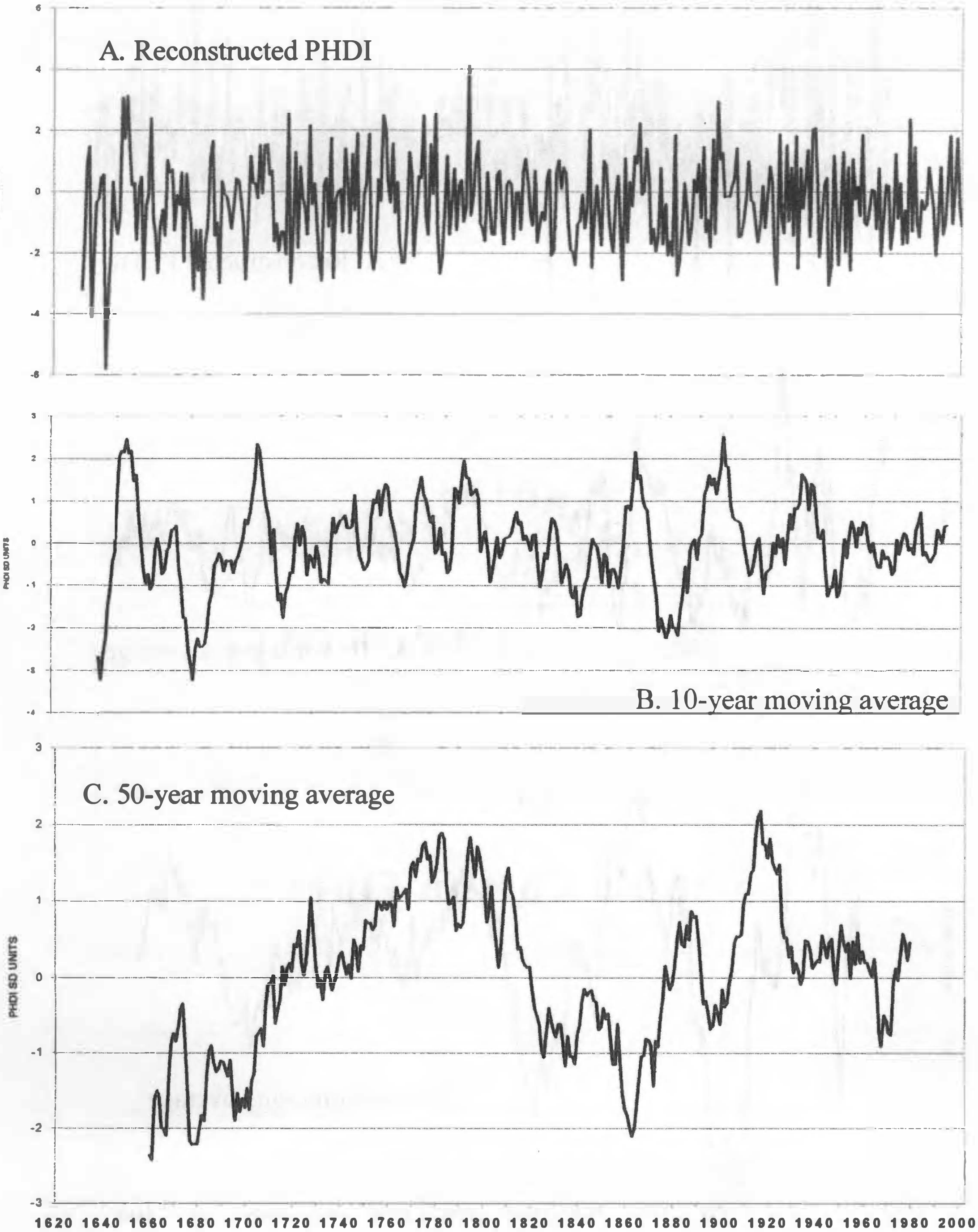


Figure 4.11 Reconstructed September PHDI and moving average values converted to z-scores for Texas. A = reconstructed PHDI from 1632–2003; B = 10-year moving average of reconstructed PHDI converted to z-scores; C = 50-year moving average of reconstructed PHDI converted to z-scores.

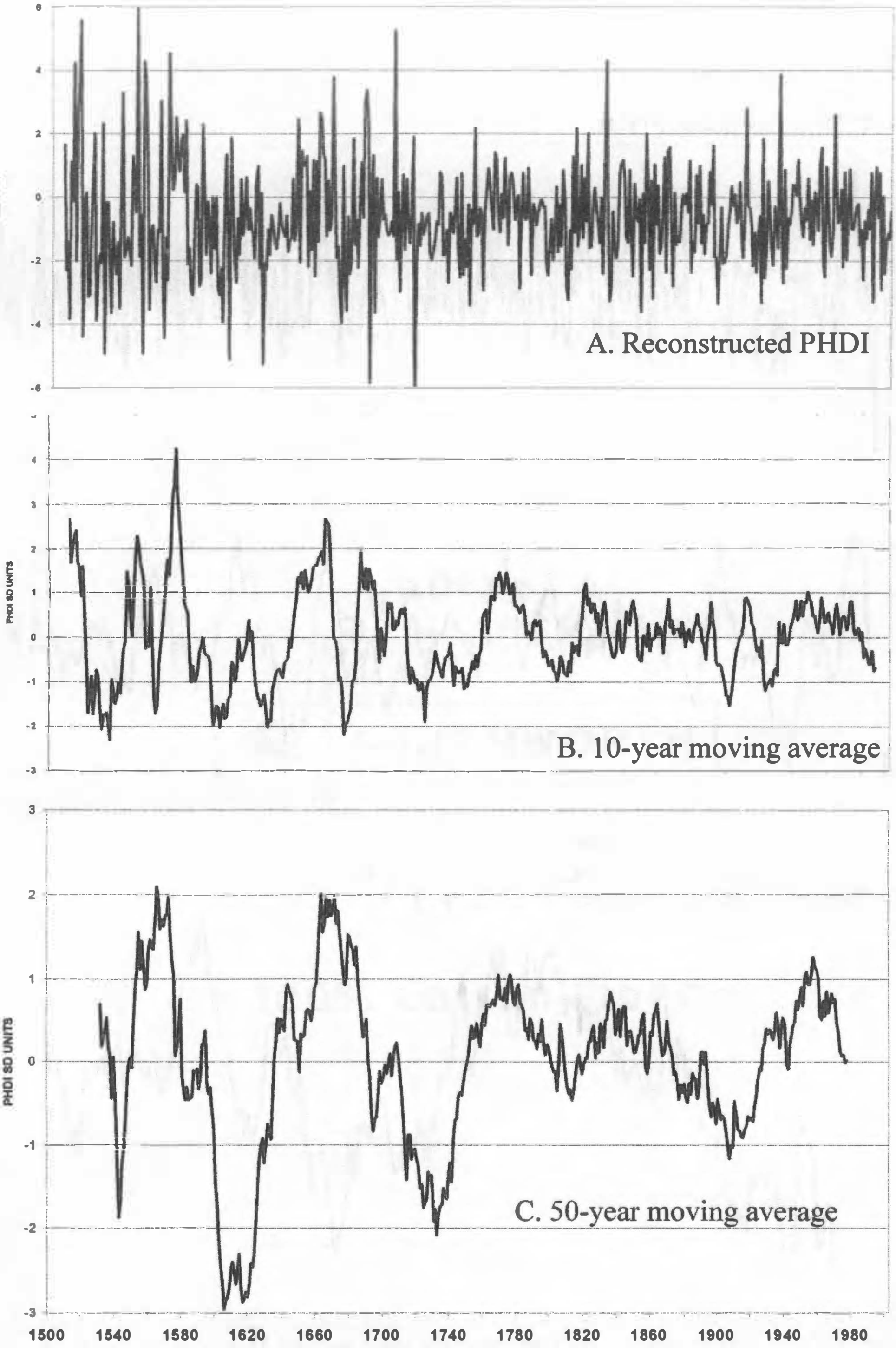


Figure 4.12 Reconstructed September PHDI and moving average values converted to z-scores for Florida. A = reconstructed PHDI from 1507–2003; B = 10-year moving average of reconstructed PHDI converted to z-scores; C = 50-year moving average of reconstructed PHDI converted to z-scores.

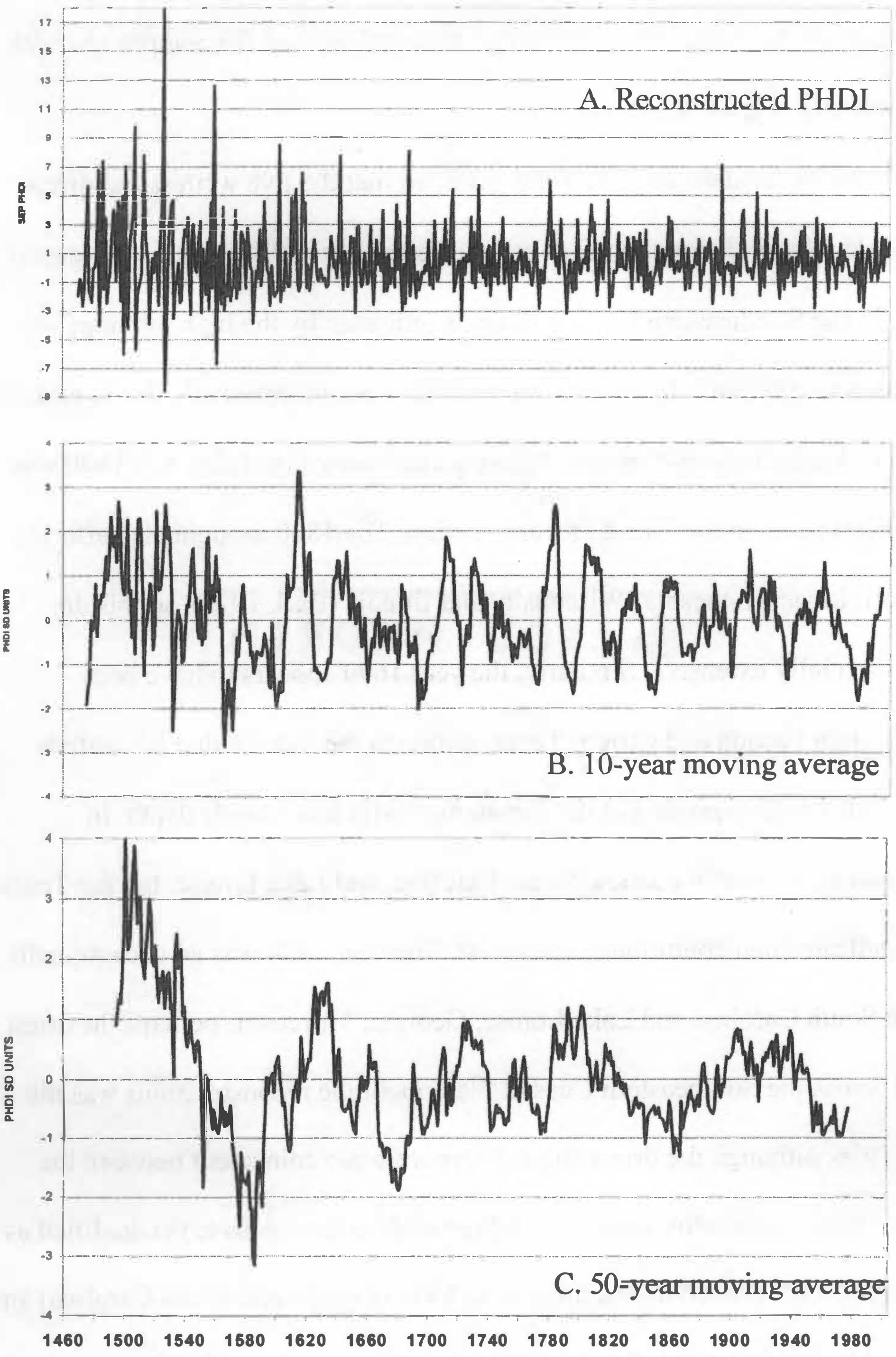


Figure 4.13 Reconstructed September PHDI and moving average values converted to z-scores for South Carolina. A = reconstructed PHDI from 1470–2003; B = 10-year moving average of reconstructed PHDI converted to z-scores; C = 50-year moving average of reconstructed PHDI converted to z-scores.

be indicative of wet or dry periods. Ring-width indices for Lake Louise, Georgia were used as a surrogate for growing season rainfall in this analysis and for comparison with the other chronologies (Figure 4.14).

Inspection of individual extreme years revealed that the five wettest and driest years showed little relation among the sites except for the year 1925 (Table 4.5), one of the driest years in the Southeastern Coastal Plain as indicated by the high rankings in both eastern Texas and Florida. The year 1860 was likewise exceptionally dry in eastern Texas, Florida, and Lake Louise, Georgia. Although not shown on Table 4.5, 1860 was one of the ten driest years in the Florida reconstruction. The 1860 drought also affected Kansas, Missouri, Iowa, Minnesota, Wisconsin, and Illinois (Bark 1978), so this dry period was also spatially extensive. Similarly, the year 1690 appears to have been extremely dry in both Florida and eastern Texas, although the index value for eastern Texas was calculated from a portion of the chronology with low sample depth. In contrast, 1853 was a dry year in Florida, South Carolina, and Lake Louise, but the Texas reconstruction indicates that conditions were moist. The year 1954 was an exceptionally dry year in both South Carolina and Lake Louise, Georgia. Moreover, perhaps the driest six-year period across the Southeastern Coastal Plain in all the reconstructions was the period 1951 to 1956, although the driest single years were not coincident between the reconstructions. Other noteworthy years that did not rank in the top five, yet qualified as drought years in two or more reconstructions were 1963 (Florida and South Carolina) and 1986 (Florida and South Carolina). Examining the wet years, the late 1680s are noteworthy for the high amount of rainfall, as all three reconstructions indicate abundant rainfall in 1687 and 1688. The year 1832 was also a very wet year in all the

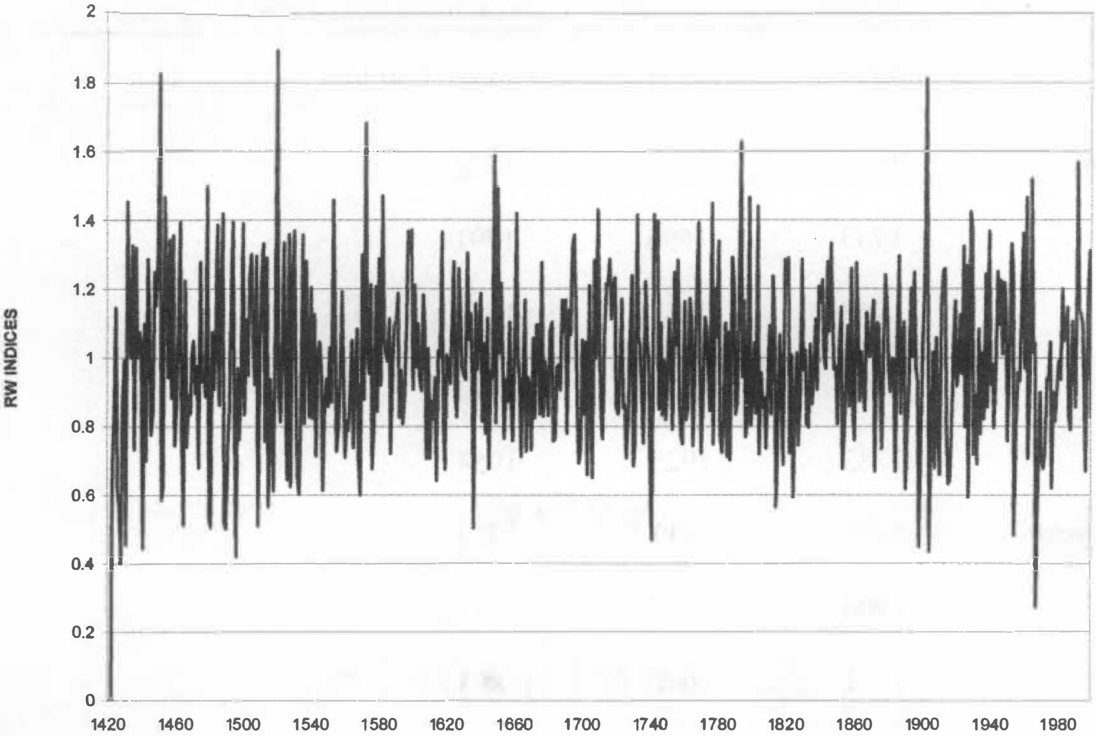


Figure 4.14 Ring-width indices from Lake Louise, Georgia longleaf pine chronology (Grissino-Mayer, unpublished data).

Table 4.5 The five driest and wettest years in the reconstructions in order of precedence.

Site	Texas	Florida	South Carolina
Driest years	1925	1717	1722
	1733	1690	1791
	1948	1853	1683
	1860	1750	1773
	1783	1925	1954
Wettest years	1795	1717	1687
	1900	1832	1642
	1781	1668	1893
	1776	1688	1780
	1941	1753	1733

reconstructions, and 1833 was also moist. The year 1776 was an extremely wet year in both eastern Texas and Lake Louise and above average in Florida.

In terms of annual trends, some of the wettest years are sometimes followed swiftly by an exceptionally dry year. Such was the case in eastern Texas, where the high rainfall in 1781 was soon followed by extreme drought in 1783. Another interesting finding is that some of the most extreme events have occurred within the past century, although comparisons with values prior to *ca.* 1600 are difficult because of low sample depth.

Examining the 10-year averaged values for decadal trends, the three driest and wettest decades in each region show few obvious cross-regional similarities (Table 4.6). Because the Texas chronology is substantially shorter than the other two chronologies, comparisons are more limited. Surprisingly, in two cases, one of the driest decades in one section of the Southeastern Coastal Plain was also one of the wettest in another region. The 1897 to 1907 dry period in Florida approximately corresponds to the 1900 to 1909 wet decade in eastern Texas. Similarly, the 1768 to 1777 dry decade in South Carolina was coincident with a very moist decade (1770–1779) in Florida. Interestingly, one of the driest decades in the South Carolina chronology (1768–1777) was immediately followed by one of the wettest ten consecutive years in the reconstruction (1778–1787). Likewise, the extremely dry 1876–1885 decade in eastern Texas was preceded by one of the wettest decades in the reconstruction (1863–1872).

Another difference between the chronologies is the persistence of wet and dry conditions. In the Texas reconstruction, high (low) values of PHDI were sustained for longer periods without interruption by low (high) values of PHDI compared to the other

Table 4.6 The three driest and wettest decades in the reconstructions in order of precedence.

	Texas	Florida	South Carolina
Driest Decades	1876–1885	1671–1680	1599–1609
	1838–1847	1626–1635	1844–1853
	1947–1956	1897–1906	1768–1777
Wettest decades	1900–1909	1660–1669	1778–1787
	1757–1766	1683–1692	1610–1619
	1863–1872	1770–1779	1708–1717

two regions (Figure 4.11B). The Florida reconstruction displayed the lowest tendency for sustained extreme values of any region. Moreover, the South Carolina and Texas reconstructions (Figures 4.11B and 4.13B) exhibit a greater degree of variability and a greater tendency to swing into extreme conditions than in the Florida chronology.

A few similarities in decadal trends were evident, however. The wet period in the early 1700s in South Carolina (1708–1717) approximately coincided with very moist conditions in eastern Texas, although the values in the eastern Texas chronology are tentative because of the low sample size before 1720. The driest decade in Florida in the reconstruction (1671–1680) corresponded to the driest period in the reconstruction for eastern Texas, but again, the sample depth in the late 1600s is low for the eastern Texas chronology. Also, the third wettest decade (1770–1779) in Florida coincided with a period of above-average precipitation in Texas, although this decade did not rank among the top three for that site.

Inspection of the 50-year averaged PHDI representations revealed that substantial changes in moisture regimes were evident at multidecadal scales (Tables 4.7–4.9). In this analysis, when the average conditions were above zero, the period was considered moist, and dry conditions were assumed when the trend line was below zero. One of the most striking trends is the difference in the frequency of shifts in moisture regimes between the regions. South Carolina clearly exhibited more frequent shifts in moisture regimes than the other regions at multidecadal scales (Figure 4.13C), and Texas and Florida were fairly similar in this regard (Figures 4.11C and 4.12C). The average length of a single climate period in Texas, Florida, and South Carolina was 67, 61, and 47 years, respectively. Both Texas and Florida experienced a long period of wet conditions in the reconstruction

Table 4.7 Multidecadal dry and wet periods for East Texas.

WET		1716–1820		1881–1935	
AVERAGE					1935–1985
DRY	1660–1715		1821–1880		

Table 4.8 Multidecadal dry and wet periods for Florida.

WET	1550–1595		1641–1705		1751–1875		1931–1985
DRY		1596–1640		1706–1750		1876–1930	

Table 4.9 Multidecadal dry and wet periods for South Carolina.

WET	1495–1550		1606–1650		1701–1740		1781–1830		1885–1950	
AVERAGE						1741–1780				
DRY		1550–1605		1656–1700				1831–1884		1951–1985

(1716–1820 in Texas, 1750–1875 in Florida) (Figures 4.11C and 4.12C). I considered the brief interval of dry conditions in the early 1800s in Florida insufficient to break the 1750 to 1875 period of wetter-than-average conditions.

Another noteworthy characteristic of the multidecadal representation was the synchronized shifts in moisture regimes across the Southeastern Coastal Plain. Regime shifts occurred simultaneously in Florida and South Carolina around 1550, 1600, and 1650, the early 1700s, mid-1700s, and 1880 (Figures 4.12C and 4.13C). Similarly, shifts in moisture regimes occurred in the early 1700s, 1820, and 1880 in eastern Texas (Figure 4.11C), and both Florida and eastern Texas saw a nearly coincident shift around 1930 (Figures 4.11C and 4.12C). Interestingly, the shifts were in opposing directions in different regions in many cases. For example, every coincident shift in Florida was negatively related to the shift in South Carolina, so that one region entered a period of above-average precipitation when the other region started a period of below-average precipitation. Moreover, the coincident shifts in Florida also showed opposing trends with conditions in Texas until the 1930s, which indicates that changes on multidecadal scales in Texas more closely matched conditions in South Carolina, even though these regions were the farthest distance apart.

4.3.3.3 Spectral Analysis

Results of the Fisher's Kappa test and the Bartlett's Kolmogorov-Smirnov statistic were non-significant for all series, so I accepted the null hypothesis that the reconstructions were white noise. The test statistics for Florida and South Carolina were far from significant, but the Bartlett's Kolmogorov-Smirnov statistic for the Texas chronology was 0.08 ($p = 0.19$), which indicated a weak but non-significant spectral signature. The largest peak in the spectral density function for Texas corresponded to a period of 18 years, with a lesser peak at 6 years (Figure 4.15). The spectral density functions for Florida and South Carolina displayed peaks at 20 and 27 years (Figures 4.16 and 4.17), but the output was considered unreliable because of the low level of statistical significance for both analyses.

4.4 Discussion

4.4.1 Climate and Tree-Growth Response

4.4.1.1 General

As in previous dendroclimatic research with longleaf pine, the results were sometimes inconsistent between regions and disagreed with the results of previous studies. Evidently, the growth response of longleaf pine is highly site dependent and varies with soil conditions, depth to groundwater, latitude/longitude, and seasonal climatic conditions. However, certain broad generalizations can be inferred that are common to many longleaf pine studies, such as the important influence of growing-season precipitation on longleaf pine growth. Another general observation is the greater sensitivity of latewood than earlywood to climate variables. In the Florida panhandle, latewood production begins in late May or June and ends in November, but the exact time is variable (Lodewick 1930). Information for latewood production periods at the other sites is not available, but I assume that the other sites have a comparable period. Evidently, conditions later in the growing season, when the trees are stressed by high evapotranspiration rates, are more moisture-limiting than those early in the growing

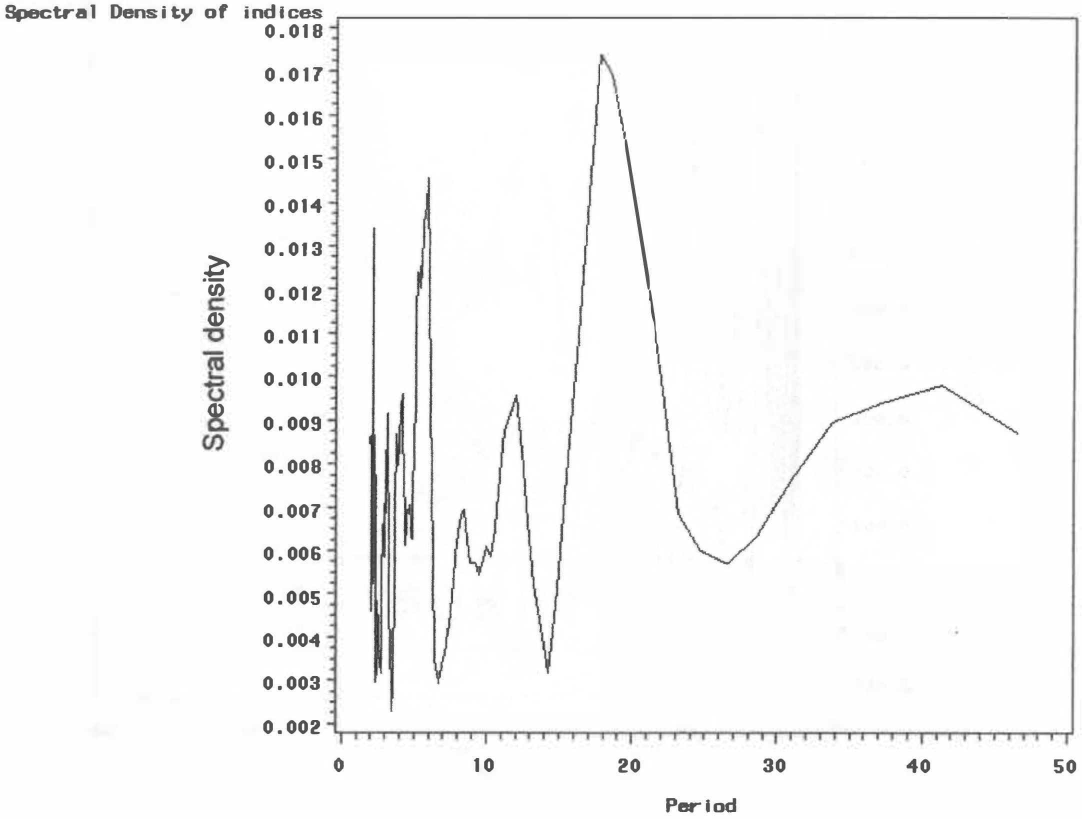


Figure 4.15 Spectral density function for Texas site.

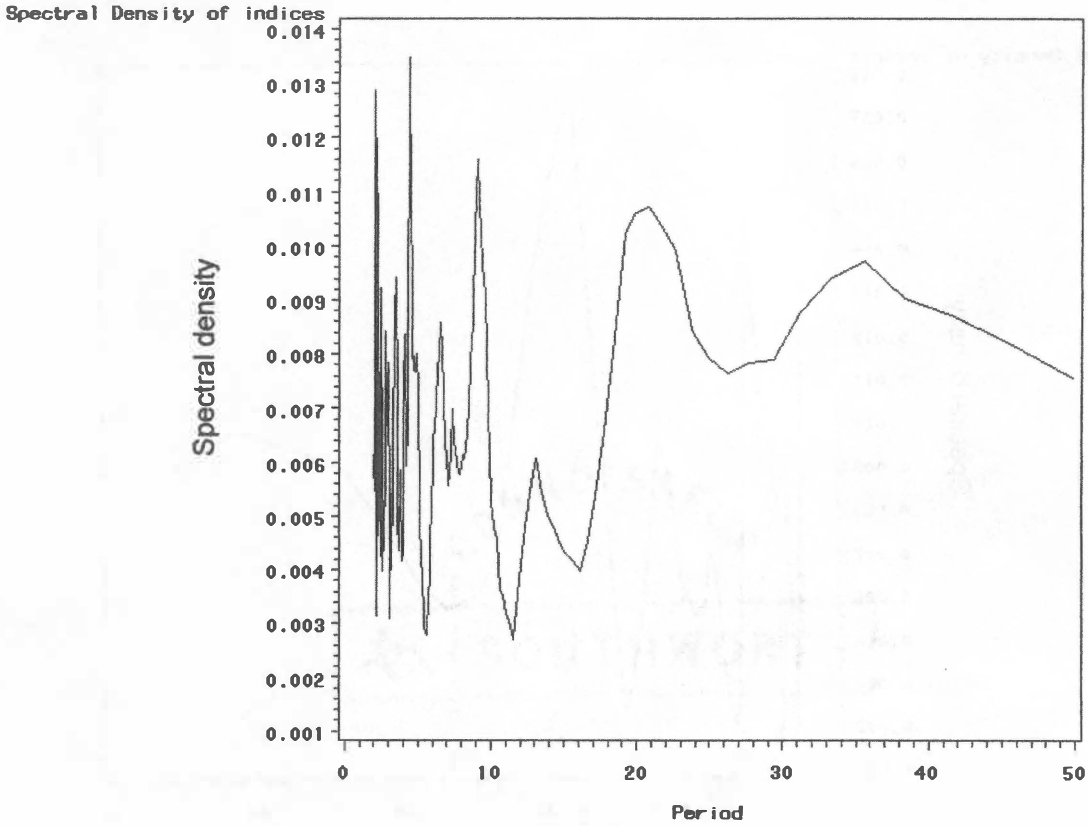


Figure 4.16 Spectral density function for Florida site.

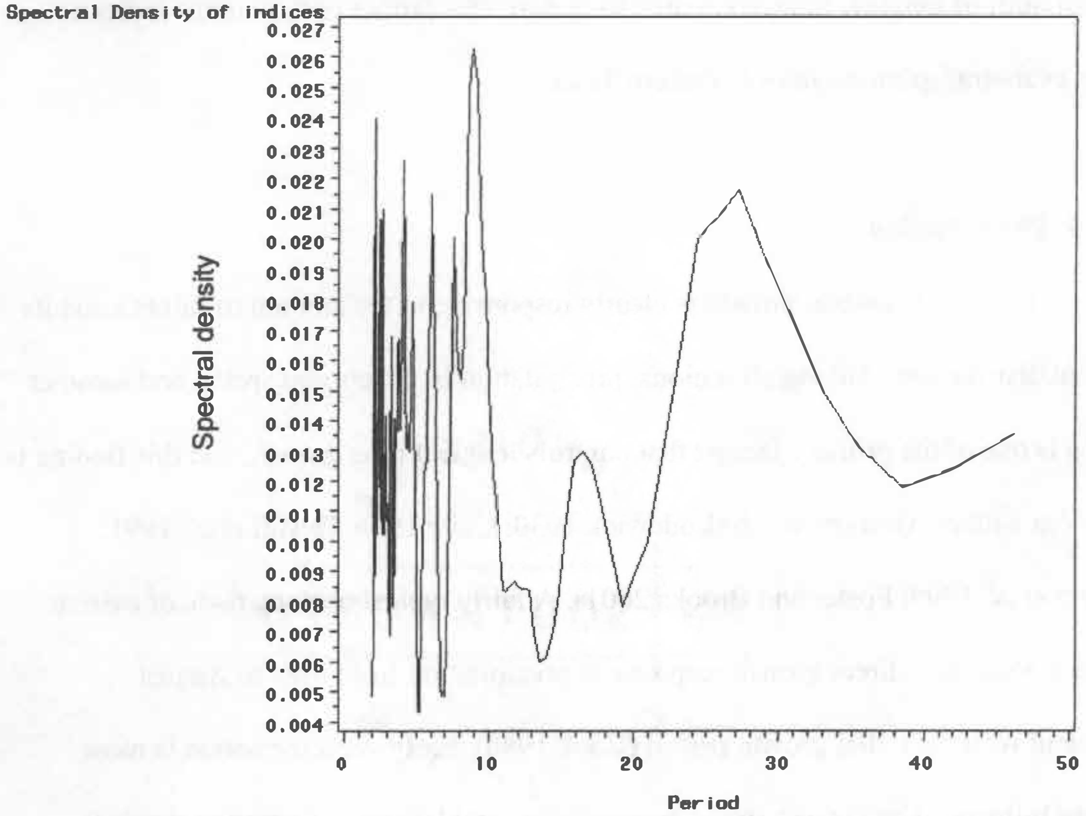


Figure 4.17 Spectral density function for South Carolina site.

season. Moreover, the generally higher mean sensitivity and ring-width variability at the western limit of longleaf pine, compared to that of sites farther east, perhaps indicates higher evapotranspiration rates in eastern Texas.

4.4.1.2 Precipitation

The rate of cambial growth is clearly responsive to the amount of rainfall and its seasonal distribution. Among all regions, precipitation in the current spring and summer months is one of the primary factors that controls longleaf pine growth, and this finding is consistent with previous research (Lodewick 1930; Coile 1936; Devall *et al.* 1991; Meldahl *et al.* 1999; Foster and Brooks 2001). A fairly typical characteristic of eastern trees is a dominant, direct growth response to precipitation from May to August coincident with the radial growth period (Cook 1980). Earlywood formation is most strongly influenced by current spring precipitation, and latewood formation depends heavily on current summer rainfall. Latewood growth is highly sensitive to summer precipitation amounts, as low water availability prompts the early formation of latewood, and the amount of latewood production is shortened by continued dry conditions (Kozlowski 1971). Drought conditions slow cambial growth considerably, and summer moisture deficits when evapotranspiration demands are high have a large impact on internal water relations (Cook *et al.* 1988). Other studies have shown that the latewood production is highly responsive to summer rainfall (Lodewick 1930; Meldahl *et al.* 1999).

The effects of preconditioning from rainfall in the previous year were slight and not particularly consistent, but fall precipitation of the preceding year appears to aid growth in the following year. In this study, the highest correlations between tree growth and precipitation in the prior year occurred with previous September (for South Carolina) or November (for Texas) precipitation and EWW/LWW. The effects may be later in the fall for Texas because of the longer growing season in that area. Earlywood growth responds positively to rainfall in fall of the prior year, presumably because longleaf pine builds carbohydrate reserves during the fall that are used in the growth flush in the following spring. These findings contrast with the study by Foster and Brooks (2001), who found a significant positive relationship between previous June and July precipitation and TRW. Moreover, Meldahl *et al.* (1999) observed a significant negative relationship between both TRW and latewood growth and precipitation from August to December of the previous year, and no such relationship is apparent in this study. Meldahl *et al.* (1999) conducted their study in Escambia County, Alabama, only 90 km from the Eglin AFB study site. Even though the climate conditions are rather similar, the results are different. The negative relationship in the South Carolina region between current November precipitation and TRW is the only trend that seems to be related to the Meldahl *et al.* (1999) finding. No plausible explanation is known for this relationship, but abundant rain and the accompanying cloud cover could reduce the rate of photosynthesis and cambial growth in the late fall.

An interesting trend in the correlation analysis shows that the relationship between precipitation and tree growth is not constant throughout the spring and summer growing season. March, April, and July precipitation appear to be consistently influential for tree growth, while rainfall in the months of May and June is generally less important. These patterns may reflect the seasonal growth flushes that occur in longleaf pine. Like many of the southern pines of the temperate zone in the United States, longleaf pine exhibits recurrent flushing (Kozlowski 1971). McGregor and Kramer (1963) noted three peaks in photosynthesis for loblolly pine in the North Carolina Piedmont that corresponded to three flushes of new needles.

The presence of false rings in many of the longleaf pine samples may be attributed to flushes of growth, among other factors (Kozlowski 1971). In the first seasonal growth flush of March and April, longleaf pine probably utilizes both carbohydrate reserves and current photosynthesis, as is the case with shortleaf pine (McGregor and Kramer 1963). The generally low correlation between earlywood formation and all precipitation variables in this study and others (Lodewick 1930; Meldahl *et al.* 1999) tends to validate this conclusion. Apparently, longleaf pine trees use stored food reserves extensively in the formation of earlywood cells, and current year precipitation has less effect. However, sufficient rainfall is likely needed in the early spring to allow the release of stored carbohydrates. In the late spring, woody plant root reserves tend to be low (Grelen 1983). In the latter part of the growing season, a second flush of growth would likely use more current photosynthate, as carbohydrate reserves would have been largely exhausted. Thus, the noticeable peaks in monthly correlation may correspond to periods when the trees typically begin to undergo a growth flush.

Precipitation in the month of February was significant in South Carolina and Texas and affected TRW, EWW, and LWW. The influence of precipitation in the dormant season may be indicative of preconditioning or, possibly, winter photosynthesis. Studies on when longleaf pine breaks dormancy in coastal South Carolina are not available, but research in the Florida panhandle indicates that cambial activity (earlywood formation) for longleaf pine normally begins in March (Paul and Marts 1931). Research has shown that winter photosynthesis can occur in southern pines in the Southeast, and carbohydrate reserves can build appreciably in the winter (Hepting 1945). Studies of loblolly pine in the Piedmont of North Carolina indicate that photosynthesis can begin as early as February (McGregor and Kramer 1963). Why February precipitation is not effective in Florida is not clear, but data on earlywood and latewood may reveal relationships not apparent in the TRW data. Also, no reasonable explanation exists for the much stronger influence of February precipitation on EWW (but not TRW) in Texas compared to South Carolina.

Comparing the response of pine growth to precipitation among the three sites, the longleaf pines in the Texas region appear to be more responsive to precipitation variables than the sites to the east. Also, the mean sensitivity of the Texas chronology is much higher than the mean sensitivity of the other chronologies. Where climate is more limiting to tree growth, mean sensitivity tends to be higher (Fritts 2001). The difference in the effect of precipitation may be the result of two factors. First, because the eastern Texas area is slightly warmer and drier, particularly in the summer, than the sites farther east, evapotranspiration rates are higher. Eastern Texas is approximately 1° C hotter than the Florida panhandle in the summer, and rainfall is critical at the far western edge of the range of longleaf pine (Schmidtling and Hipkins 1998). Consequently, longleaf pines in the Texas region are more susceptible to rainfall deficiencies and the related costs of high respiration and tissue maintenance. This finding illustrates the importance of the concept of ecological amplitude, which states that climate becomes highly limiting to tree growth near the margins of a species' natural range (Fritts 2001).

Secondly, the difference in climate sensitivity between the Texas sites and sites farther east could be attributed to edaphic conditions. Edaphic conditions relate to a number of site variables that include soil texture, moisture regimes, depth of soil layers, infiltration rates, and litter types (Walker 1999). In a comparison of growth responses of longleaf pine on xeric sandhills versus transitional moisture zones, Foster and Brooks (2001) found statistically significant differences in response to climate variables between the two zones. Sand pines in coastal areas have shown a stronger climate/growth relationship than in inland sites, possibly because of the physiological stress created by shallow freshwater lenses and permeable sands (Parker *et al.* 2001). I observed a similar pattern at the sites at EAFB, where trees at White Point, a coastal site, exhibited a stronger climate/growth response than trees in the two inland sites.

Comparing the three sites as a whole, the soils in most of the South Carolina and Florida sites are extremely sandy and consequently have low moisture retention, while the soils in Texas are finer and have a greater ability to retain water. On sandy, dry soils like Quartzipsamments, even with abundant rainfall, the soil can become extremely dry within a week (Outcalt 1993). The longleaf pine sandhills have been described as deserts in the rain because of the soil characteristics (Brendemuehl 1981). Therefore, the effectiveness of a particular precipitation event would be less on the sandy sites because the water would tend to drain more quickly through the soil profile to the groundwater table. In sandy soils, the amount of water that a longleaf pine tree would be able to take up in its root system would be less than in a more loamy soil. Lodewick (1930), who found no relationship between ring width and precipitation in the dormant season in western Florida, attributed the lack of climate response to the deep, sandy soils that do not store water.

The idea that trees would be less responsive to climate where the soil moisture condition is xeric than at sites where soils are moister seems to be at odds with the generally accepted heuristics of dendrochronology (Fritts 2001). For example, the principle of site selection implies that trees that grow in the driest sites should be selected for studies of tree rings and drought (Fritts 2001). However, "dry" (in the sense of this dendroclimatological principle), refers to a climate with low precipitation and not a characteristically dry soil condition.

4.4.1.3 Temperature

The relationship between temperature and pine growth is much weaker than that with precipitation. Moreover, the results were generally different between regions. Other studies have demonstrated the weak response of longleaf pine growth to temperature fluctuations (Lodewick 1930; Meldahl *et al.* 1999). The most consistent trend in this study was the negative influence of warm summer temperatures on cambial growth, particularly for the Texas region. An inverse response to temperatures during the growing season is typical for eastern trees (Cook 1980). Other studies have also shown a significant negative association between warm summer temperatures and longleaf pine growth (Meldahl *et al.* 1999; Foster and Brooks 2001). The warmer and drier summer conditions in Texas are likely responsible for the stronger negative correlation with summer temperatures.

Temperature affects photosynthesis in trees by regulating respiration, transpiration, and gas exchange and high temperatures tend to favor respiration over net carbon assimilation (Kozlowski 1971; Foster and Brooks 2001). Temperatures in the

Coastal Plain can reach high extremes, with temperatures in the shade that approach 38° C for weeks at a time (Sutton and Sutton 1985). High temperatures in the summer seem to check photosynthesis because of increased respiration. Internal water deficits may occur because of accelerated transpiration, which causes stomatal closure and reduced gas exchange (Kozlowski 1971).

In most cases, the effects of temperatures in the previous year showed an almost complete lack of similarity between sites. With reference to the positive relationship between previous July temperatures and growth in the current year in the Texas region, Meldahl *et al.* (1999) found a similar relationship between late summer temperatures and current growth. Hot summer temperatures in Texas may cause longleaf pine trees to shut down growth and use the stored food in the following year. In Florida, the same explanation would not seem to apply for previous April temperatures because stored carbohydrates would probably be used later in the growing season. Like Florida, Texas EWW was significantly related to temperature in the prior spring (May), but no logical explanation is apparent for this relationship except for persistence in the tree-ring series or the temporal climate pattern (e.g., ENSO).

One of the most statistically significant relationships between tree-ring growth and temperature variables is that previous October temperatures are negatively related to earlywood formation in South Carolina and Texas. Similarly, Foster and Brooks (2001) found a negative relationship between December temperatures and longleaf pine growth near Tampa, Florida. Possibly, cool October temperatures could reflect an early winter and dormant season, and if the trees ceased their annual growth prematurely, additional photosynthate could be stored for immediate growth at the start of the next growing season.

The significant correlation between temperature and ring width may not actually be a direct causative relationship because temperatures are often related to precipitation and cloud cover. The exceptionally hot years are also normally extremely dry years (1925, 1986), so the slower growth during warm years may in fact reflect the lack of moisture. Suppression of convection by subsidence favors warm surface temperatures (Dole 2000). When there is a lack of cloud cover under conditions of high pressure, temperatures will increase because of the greater incoming solar radiation. As both temperature and precipitation affect soil moisture and the water available for plant uptake, both factors are evidently involved. However, variations in temperature may have an even smaller effect than is reflected in the correlation analysis.

Early cambial activity would be expected in years where winters are unseasonably warm and spring temperatures are mild (Snyder *et al.* 1977), as growth that extends into the late fall would be expected in a late-arriving winter. However, temperatures in the late winter and early spring do not appear to affect diameter growth, except marginally in the case of South Carolina. The positive but non-significant relationship between winter temperatures and pine growth in the South Carolina region may represent the effect of the more varied length in the growing season in that region, located considerably farther north than the other sites.

In contrast to the longleaf pines in this study, other southern pine species seem to benefit from an extended growing season. Orwig and Abrams (1997) concluded that Virginia pine (*Pinus virginiana* Mill.) in northern Virginia experienced extended periods of radial growth because of warm early spring and/or autumn temperatures. Perhaps the proximity of the longleaf pine sites to the coast results in a more consistent length of the growing season than sites farther north. Alternatively, if cambial growth is indeed delayed because of a colder winter, cambial activity may occur later but more rapidly so that the length of the growing season has little effect on the amount of xylem added each year. Longleaf pines in the more northerly states, such as Virginia, may show a more consistent growth response to warm winter temperatures than those sampled in this study.

4.4.1.4 Composite Variables

The growth response to both PDSI and PHDI was much more pronounced than with precipitation and temperature. Foster and Brooks (2001) also observed a higher correlation between tree growth and PDSI than with temperature or precipitation. A large degree of autocorrelation exists in both Palmer indices, so the high correlations with pine growth over several consecutive months of the year can be attributed, in part, to this persistence (Grissino-Mayer and Butler 1993). Because the contribution of each successive month is given an increasing weight, up to the month for which the drought index is computed, the individual contribution of each month in the growing season may not be accurately reflected (Blasing *et al.* 1988). However, the autocorrelation does not explain the more statistically significant relationship in general. Because Palmer indices integrate the available water content of the soil, temperature, and precipitation, the composite nature of the variables more closely reflects the conditions required for tree growth than precipitation or temperature alone. Moreover, both indices are formulated to indicate drought conditions. Drought is not merely low rainfall, but is a relative term based on the expected rainfall for an area at a given time of year (Burroughs *et al.* 1996). Trees are presumably acclimated to general prevailing conditions and show variations in growth response more strongly when environmental conditions are outside the normal range.

The strongest relationships between pine growth and the Palmer indices in this study occurred in July to November. Other research has obtained similar results. Foster and Brooks (2001) noted that in Florida, PDSI showed the highest correlation with total ring growth in the summer months, and in southern Georgia, West *et al.* (1993) observed the strongest relationships with September and October PDSI. Moreover, Meldahl *et al.* (1999) found high correlations between longleaf pine growth and PHDI in the months of August and September in southern Alabama. In this study, latewood formation was highly correlated with July to November PDSI and PHDI. As expected, earlywood formation was most highly correlated with moisture conditions in the spring (March and April). However, earlywood widths in Texas were significantly correlated with moisture in almost all months of the growing season (March through August). The extended significant relationship is probably not wholly attributable to persistence in the composite variables, as the same trend is not evident in the South Carolina EWW. Conceivably, earlywood formation continues later into the growing season in Texas in some years, and then rapid latewood formation occurs in late summer and fall. Following the same trend as the precipitation variable, the Palmer indices were not as strongly correlated with longleaf pine growth in the spring as in the summer and late fall, which indicates that moisture conditions are much more critical late in the growing season. Late summer and early fall droughts can affect the rate of carbohydrate conversion to new tissues, and even with substantial carbohydrate reserves, cambial growth can be checked (Kozlowski 1971).

Another noticeable trend is that the peak in correlation is later in the growing season for PHDI than PDSI, and the relationship remains significant into December for PHDI. The difference can be attributed to the slower response of PHDI to changes in weather regimes, and the values for December represent the persistence carried over from the fall months. That active photosynthesis significantly would affect cambial growth in December of the current year is highly unlikely. Therefore, the apparent growth response to November and December drought indices is probably spurious.

The effects of PDSI and PHDI in the previous year showed considerable disagreement between the three regions. No plausible explanation is available for the significant negative relationship between the Palmer indices and TRW (and LWW to a lesser degree) in the previous year in Texas but not in the other areas. Florida shows a similar pattern, but the values are not statistically significant. Foster and Brooks (2001) found no such relationship in peninsular Florida, and in fact, longleaf pines growing in transitional settings displayed a positive relationship between PDSI values in the summer months of the previous year and total ring growth. One explanation for the trend found in this study could be an autocorrelation with climate, meaning that extremely dry years could normally be followed by a wetter year. Another possibility is that when climate conditions are unfavorable during the growing season, longleaf pine trees in the Texas region shift their emphasis to root storage in order to survive until the next growing season. This survival mechanism may be a unique phenotypic characteristic of eastern Texas longleaf pines with a genetic basis.

Wells and Wakeley (1970) demonstrated that longleaf pine from several geographic sources show substantial variation in growth rates and disease resistance. Seed sources from warmer climates tend to grow more rapidly than those from colder climates (Schmidtling and Hipkins 1998). Other species of southern pine have exhibited differences in response to climatic stress among genotypes. Loblolly pines growing at the western edge of the species' natural range are more drought resistant than those from other geographic locations (Zobel and Goddard 1955). The genetic characteristics of growth and survival may be important at the far western edge of the range of longleaf pine (Schmidtling and Sluder 1995). Therefore, because the Big Thicket chronology is near the western edge of its natural distribution, and Sandy Island is considerably farther north than the other sites, the difference in adaptive traits between the three locations may be substantial enough to create a disparate climate response.

The other significant growth response with lag variables is a positive relationship between fall PHDI (and to a lesser degree PDSI) and South Carolina earlywood formation. This trend coincides with the effect of fall temperature and precipitation in the preceding year on South Carolina earlywood growth. Favorable moisture conditions in the fall may allow longleaf pines to store carbohydrates late in the growing season that will be utilized in the flush of earlywood in the next spring. Latewood formation is unaffected by the moisture conditions in the preceding year, probably because cambial growth of latewood cells is exclusively produced from current year photosynthate.

4.4.1.5 Factors that Affect Correlation Results

The models of tree growth account for less than 40% of the variance in PHDI, so several other factors are clearly involved. Non-climatic disturbances were not considered in the analysis, and these will be reviewed in the next section. The allocation of photosynthate in trees is complex and the addition of xylem (diameter growth) is generally a low priority compared to maintenance respiration, production of fine roots and leaves, flower and seed production, branch growth, and root extension (Kozlowski 1971; Oliver and Larson 1990). While these priorities are acknowledged, these complex interactions of tree physiology are beyond the scope of this research. Several other variables could account for the lack of explained variance, and these include the type of precipitation, phenotypic characteristics, tree age, and other climate factors. One possible explanation for the lack of correlation between precipitation and pine growth may be the type of precipitation that occurs in the Southeastern Coastal Plain. Much of the summer precipitation is in the form of isolated thundershowers. High intensity, short duration precipitation, while supplying frequent rainfall, tends to produce more runoff or throughflow and less effective moisture for tree growth. In contrast, winter precipitation is usually of much lower intensity and longer duration in the Coastal Plain. However, precipitation in the months of December through February has a less significant effect on cambial growth than summer rainfall. Moreover, about one fourth of the annual rainfall in the southeastern U.S. is produced by dissipating hurricanes, and these storms typically bring between 15 and 31 cm of short-duration rainfall to affected areas over a one or two day period (Bair 1992). The growth response from these high rainfall amounts may be less than expected because rainfall intensity is high. Also, hurricane rainfall typically comes in the fall when precipitation is less influential on current year growth.

Cambial growth is also influenced by needle and cone development (Kozlowski 1971). Because longleaf pines retain their needles for an average of two years and as long as three years, needles can affect cambial activity for several years (Wahlenberg 1946; Meldahl *et al.* 1999). Longleaf pines reproduce by masting when they reach 30 or 40 years, and the amount of cones produced each year varies considerably both temporally and spatially (Boyer 1986). During active seed years, height and diameter growth as well as foliage production are often slowed (Kozlowski 1971). In years when there is a heavy seed crop and abundant cone production, more carbohydrates may be allocated to cone production than in years of weak masting, and the effects of reproduction could mask the climate signal.

Lodewick (1930) found a total disagreement between precipitation and xylem production during a year when the seed crop was heavy. The radial increment of longleaf pine during the heavy mast year decreased in proportion to the seed-producing capacity of longleaf pines in western Florida. Lodewick (1930) hypothesized that the food reserves during the seed year may be utilized at the expense of xylem production, or the photosynthate produced in the current year could be diverted to seed production. Determining the influence of masting on cambial growth was beyond the scope of this study, but should be considered for further research.

Another element that affects the correlations is the variation in diameter growth within trees, particularly for TRW and LWW. Although some studies have indicated that ring width in longleaf pines does not vary considerably among different radii (Lodewick

1930), this study found that TRW and LWW, in particular, can be considerably different on one side of the tree compared to the other. Longleaf pines do not add xylem uniformly in the stem each year, so differences in sensitivity to climate fluctuations are evident within a single tree. These differences in growth rates can be attributed to the formation of reaction wood in many cases, but the exact causes for the variations in ring width around the circumference of the tree are unknown. Thus, the correlation between two radii from one tree normally did not exceed 0.70 in most cases. These differences add additional noise that can reduce the climate signal.

Another reason that may account for the unexplained variance is the ability of longleaf pine to endure extremely dry conditions. Longleaf pine trees are able to extract water at 3% volumetric water content, considerably below the assumed wilting point of 6% (Harrington *et al.* 2003). Because of their resistance to drought, longleaf pine trees may be less sensitive to periods of decreased moisture than other species growing in the Southeastern Coastal Plain. For example, the response of shortleaf pine in northern Georgia to monthly precipitation values (Grissino-Mayer and Butler 1993) was higher than that of longleaf pine in this study.

A fifth factor that may have affected the correlation is the difference in climate response as the trees age. Older trees are less vigorous than young trees, and the climate response between tree groups of different age is not the same (Douglass 1919). As tree biomass changes, the relationship between climate and tree growth may change as well (Grissino-Mayer and Butler 1993). As trees age, the relations between food, water, and hormones change as the proportion of crown to stem decreases and translocation becomes more difficult (Kozlowski 1971). Foliar stomatal conductance is lower in taller trees because of the longer path lengths in stems and branches which slows the flow of water from soil to leaves to a greater extent (Ryan and Yoder 1997). Moreover, the ratio of younger, physiologically active tissue versus older, less active tissue decreases as trees grow (Kramer and Kozlowski 1979). The annual growth increment of trees narrows as they age, and the response to rainfall and other climatic conditions is less than in younger, more vigorous trees (Lodewick 1930). Several missing or partial rings occurred in the older samples and not in the younger trees, a trend that is not uncommon as older trees may cease cambial growth near the stem base (Kozlowski 1971). West *et al.* (1993) found that longleaf pine trees in southern Georgia exhibited different growth responses to precipitation, temperature, and PDSI depending on the age of the trees. Trees that averaged 125 years of age were generally more responsive to all climate variables than trees that averaged 250 years of age (West *et al.* 1993). This study found similar results, as two of the three chronologies showed stronger climate relationships in the early part of the instrumental record when the trees were younger, despite the fact that the most recent period of the instrumental record is of higher quality than the earlier record (Cook *et al.* 1988).

Finally, this study did not consider certain other possible climatic factors such as cloud cover and humidity, and these variables can be important to longleaf pine growth. For example, the rate of depletion of soil moisture may be more important for growth than the soil moisture content itself (Moehring and Ralston 1967). Humidity affects the rates of absorption of water through the roots and the loss of water through transpiration, so when humidity is low, transpiration is high. Consequently, trees can experience low internal water deficits when the soil is partially dry but the humidity is high (Kozlowski 1971).

4.4.2 Climate Reconstruction

4.4.2.1 General

The large deviations from the mean in the early portions of each reconstruction are indicative of low sample depth. Clearly, the greater variance in the early part of the chronologies does not imply that the climate shifted from high variability and extreme events to a more moderate climate regime over time. The beginning of the chronology is also composed of rings formed when the trees were young, and these rings (e.g., juvenile growth) are often unreliable measures of climate (Fritts 2001). Therefore, any conclusions drawn from the data where the sample depth is low are made with the recognition of limitations of the information and the reliability of the reconstruction.

4.4.2.2 Analysis of Model Outliers and Stand Disturbance

In the period of the instrumental record, the outliers that were removed from the reconstruction models seemed to be related to extreme (high or low) moisture levels and various disturbances. I removed seven, five, and nine outliers in the Texas, Florida, and South Carolina chronologies, respectively. More than half of all outliers were associated with PHDI values exceeding +/– 3.0, which indicates exceptionally moist or dry years. One possible explanation for the weak relationship between tree growth and PHDI in very wet years is that moisture is not limiting to growth when rainfall is excessive, and the rainfall may be providing more water than the tree can use. In some cases, heavy rainfall of short duration occurred in a certain growing season, but the rainfall amounts had little effect on the annual increment. For example, in 1975, a tropical depression produced over 29 cm of rain at EAFB on 28–29 July, and Hurricane Eloise dumped an additional 34 cm of rain over a two-day period in September. The annual ring width for 1975 was slightly above average, but the enormous rainfall total made the predicted value appear as an outlier. Apparently, much of the rainfall ended up as runoff and was not taken up by the trees. As far as an explanation for outliers during extremely dry years, the ability of longleaf pine to withstand extreme drought may reduce the degree of climate response during severe droughts. In other words, the relationship between annual increment and levels of drought may be nonlinear.

In other cases, stand or even regional scale disturbances may have played a role. Whether or not there is a direct relationship between the known disturbances and the anomalous growth patterns is not completely known, but I identified disturbances from the historical records that were coincident with many outlier years. In some cases, the reason for the unusual growth pattern could not be attributed to any known cause, but pine beetles, hurricanes, logging, masting, ice storms, wildfires, and prescribed burning seemed to have contributed noise to the climate signal in these chronologies.

First, in the eastern Texas model, outliers appear to have been related to a major beetle outbreak in the Big Thicket from 1973 to 1975 (Cozine 1976). In the years 1973 and 1974, the longleaf pines experienced below-average growth when the precipitation was exceptionally high. Not only was the PHDI exceptionally high (> 4.5) for September in all three years, the PHDI was above 2.0 for virtually every month in the growing season of those three years. The eastern Texas climate model tends to underestimate extremely wet years (Figure 4.8), and this tendency may be attributed to excessive runoff when antecedent conditions are moist. However, the possibility that pine beetles infested and slowed the growth of live longleaf pine trees as they fought off the pests cannot be discounted.

Second, hurricanes may have been the cause of outliers in all three regions. In eastern Texas, the eye of a Category 3 hurricane passed just east of the Big Thicket in 1918, an outlier year. The longleaf pine growth was much greater than predicted for that year as the September PHDI was – 4.86. The anomalously high growth may be attributed to a release from competition if many of the larger trees were downed by the storm. The 1936 outlier in the Florida model may be been related to a Category 3 hurricane that passed over EAFB on July 1936, generating winds over 160 kph at Niceville, near the center of EAFB. The hurricane may have released trees from competition and caused unusually high growth rates in a dry growing season. When trees experience a release, they are less affected by the prevailing climate conditions because of the wealth of nutrients and water available when competing trees are killed. Likewise, in South Carolina, Hurricane Hugo in 1989 appeared to influence an outlier year in 1990 by creating anomalously fast cambial growth in a dry growing season. With the frequency of hurricanes in places such as EAFB, the fact that there were not a large numbers of outliers attributable to hurricanes is surprising, if, in fact, hurricanes are a major disturbance that affects longleaf pine growth. Because hurricanes are slightly more common at EAFB than the other sites, the poorer quality of the climate model at EAFB could be related to the frequency of hurricane disturbance at this location compared to the other two.

In addition to hurricanes, logging likely produced noise in the Texas and South Carolina chronologies. The Turkey Creek stand in the Big Thicket was first logged in about 1929, and this outlier year was marked by much greater growth than the moisture conditions would have predicted. As in the case of the hurricanes, the death of many overstory trees could have allowed a release because of the reduction of competition. In like manner, logging seems to have greatly affected the stands on Sandy Island, South Carolina in the mid-1920s. Every year from 1925 to 1927 was an outlier year that showed above average growth despite very low PHDI values in each year. Although the exact year of logging at Sandy Island is not known, this prominent release and the dates of the outer rings on stumps points to the mid-1920s as a likely period of logging.

Fourth, ice storms may have influenced longleaf pine growth rates and created outlier values in my models. In February 1969, a severe ice storm struck the Sandhill region of South Carolina near Cheraw and killed many longleaf pines and broke branches on the surviving trees (Van Lear and Saucier 1973). While the Sandy Island area was not significantly affected, the site chronology from Poinsett Electronic Combat Range (PECR), near Cheraw, has a narrow ring in 1969, when moisture conditions were above normal. Possibly, damage in the canopy of trees sampled at PECR reduced their photosynthetic capacity. The effect on the PECR trees was not enough to create an outlier in the overall South Carolina chronology, but the noise reduced the overall interseries correlation for the South Carolina chronology and helped mask the effects of climate.

Fifth, prescribed burning apparently caused anomalously slow growth in some instances. Studies in sandy, upland soils of the Coastal Plain have shown that prescribed burning can reduce the growth rate of longleaf pine trees (Boyer 1987). The reason that burning can seriously reduce the growth of longleaf pine is not known (Boyer 1987). In this study, for example, the first year of prescribed fire by the Nature Conservancy at Sandy Island may have slowed growth in 1999 as shown by the anomalously narrow ring. Fires had not occurred on the Island for several decades, so the burn in the early spring of 1999 appears to have slowed cambial activity and diminished growth in that year.

Heavy masting is also worthy of mention with regard to possible explanations for outliers and areas for future research. Although the exact conditions of masting in individual stands or regions of the Coastal Plain are not known, particularly heavy mast years have been noted in a few studies (Wahlenberg 1946; Boyer 1986; McKay 2000). The years 1919 and 1920 were heavy mast years in certain sections of the Coastal Plain (Wahlenberg 1946), and longleaf pine growth in 1920 in eastern Texas was well below average for the precipitation conditions. Similarly, the 1974 seed crop was noticeably heavy (Boyer 1986), and the 1974 ring in South Carolina was much narrower than predicted. Clearly, more extensive research into the nature of relationships between masting and cambial activity is needed, because the coincidence of outlier years when masting is heavy points to a possible cause-and-effect relationship.

This cursory investigation of outliers and the possible disturbances related to them points out one of the major weaknesses of dendroclimatic reconstructions in the Southeastern Coastal Plain. While events in the historical record can be linked to anomalous growth rates in trees, disturbances that happened several hundred years in the past are difficult to identify and tease out from the climate signal because of the absence of instrumental climate data. As such, the values reflected in a reconstruction are assumed to represent the climate conditions. Even when spline curve-fitting techniques are used to remove noise associated with non-climatic disturbances at a site, any disturbance common to the entire site will remain to some degree in the final site chronology (Cook 1980). Increased sample depth at the site is unlikely to resolve the dilemma, which is the most vexing problem for closed-canopy forest dendrochronology (Cook 1980). Sampling for different species in the region or the same species in non-contiguous sites is a necessity in order to factor out non-climatic variance (Cook 1980). In my analysis of the reconstructions, I was able to identify, in limited instances, disturbances that seemed to affect the climate signal by comparing reconstructions between sites.

4.4.2.3 Disturbances that Affect the Reconstruction

As the study of outliers indicates, disturbances in Southeastern Coastal Plain forests have the potential to alter the climate response of longleaf pine. Because disturbance effects may be confused with climate forcing, dendroclimatic studies should ideally be conducted in undisturbed old-growth forests (Stahle and Cleaveland 1992). Unfortunately, the Southeastern Coastal Plain experiences some of the highest rates of disturbance in the United States because of hurricanes, abundant thunderstorms, and lightning-ignited fires. Therefore, dendroclimatic studies in the Southeastern Coastal Plain must recognize the limitations of the data because finding a stand that has been free of disturbance for several hundred years or even several decades is difficult, if not impossible. Because a particular disturbance event can create opposite yet profound growth responses from the same event, determining the effects of past disturbances can be problematic (Van Arsdale *et al.* 1998). Additionally, adverse climate conditions may occur simultaneously with a non-climatic disturbance. Despite these limitations, I have identified several known destructive events that may have influenced the growth of longleaf pine and obscured the climate signal, and I present a few examples as evidence, including earthquake, ice and snow storms, and hurricanes.

First, the great Charleston earthquake on August 31, 1886 appears to have affected the South Carolina chronology. One of the earthquake epicenters was 34 km northwest of Charleston, South Carolina (Wallace 1961). This earthquake measured between 6 and 7 on the Modified Mercalli Intensity scale in the vicinity of Sandy Island and was the largest earthquake on historical record for the southeastern United States (Wallace 1961; Coffman *et al.* 1982). One of the most narrow rings in the entire South Carolina chronology is in 1887, even though historical records indicate that rainfall was near normal in the Carolinas in 1887 (Battle *et al.* 1892; NCDC 2005). The 1888 ring is also quite narrow despite historical records that indicate average rainfall for that year (Battle *et al.* 1892). Possibly, the liquefaction of coarse sands disrupted or damaged the root systems, and the swaying of the trees could have damaged the crowns. Cross-sections of some of the larger trees from Sandy Island appear to have large transverse cracks that split the pith as if the tree had been subjected to intense stress. Because the heartwood of the tree is the most dense and least flexible, it is likely that the interior portion of the trunk would crack under great stress before the more pliant sapwood.

A second disturbance that seems to have affected the chronologies is ice storms. In February 1835, near the end of the Little Ice Age, an Arctic outbreak pushed into the Southeast, and the temperature reached – 14° C in northern Florida (Gannon 1993). The

St. John's River near St. Augustine, Florida, was partly frozen, and a northwest wind blew strongly for 10 days (Harper 1958). While Bartram does not mention an ice storm associated with this outbreak, Lyell noted that "the ice of this storm" killed orange trees on the Atlantic Coast (Lyell 1849). Occasional severe ice storms are known to have occurred near the Gulf of Mexico (Wesley 2000), so a severe ice storm in the Florida panhandle is certainly possible. If an ice storm preceded the catastrophic freeze in northern Florida, the accompanying winds would have caused much pruning of longleaf pine branches. The ten days of strong winds and cold temperatures would have enhanced the stress and fatigue on longleaf pine branches.

One of the most pronounced growth suppressions in the entire EAFB reconstruction occurred from 1835 to 1839. While this period of narrow rings may have been related to extended dry conditions, the presence of this anomalous growth after a period of exceptionally cold temperatures, and probably ice accumulation, indicates that this extreme storm event likely affected the trees' growth for several years at EAFB. Moreover, if the period 1835 to 1839 was, in fact, a drought in the Florida panhandle, it is unlikely that such an extended period of below-average precipitation would not be apparent at my other two sites in the Southeastern Coastal Plain. The longleaf pine chronology from nearby Flomaton, Alabama, does not show a pronounced suppression in this period, but the trees from this chronology were only 10 to 20 years old when the event occurred. Smaller trees would not have been affected in the same manner as large trees with expansive canopies. Although the cold air outbreak in 1935 affected the Atlantic Coast, and to some degree eastern Texas, the late 1930s were a period of above-average growth in both the South Carolina and eastern Texas regions. Why this storm appeared to have affected only the trees in the Florida panhandle and not trees in coastal Carolina is not known, particularly when Lyell stated that the 1835 event killed trees in the Carolinas (Lyell 1849). In any case, severe ice storms on the outer Coastal Plain are a very rare event, and the 1835 storm that affected Florida is probably unequalled in the instrumental record.

In addition to possible ice storm effects, large snowstorms may have also influenced the tree-ring record. A heavy snowfall event that could have affected the South Carolina chronology occurred on February 28, 1792. The amount of snowfall that occurred is not known, but the weight of the snow caused the Ashely River Bridge near Charleston to collapse. One of the narrowest rings in the chronology is 1792, and it is possible that the weight of the snow from this event could have resulted in damage to longleaf pine branches in the vicinity. Another year when both snowfall and climate (drought conditions) may have worked in concert to slow longleaf pine growth was 1899, the year of one of the narrowest rings in the EAFB chronology. Snow fell from central Florida to Maine in the blizzard of February 1899, and the temperature reached – 14° C in Pensacola and – 19° C in Tallahassee. The exact amount of snowfall received at EAFB is not known, but New Orleans received 20 cm of snow and the port of New Orleans iced over. The year 1899 was also exceptionally dry as well, so quantifying the relative effects of climate and disturbance is problematic.

Another historical winter-weather event worthy of note occurred in 1690. This event may be important in terms of the ability to obtain longleaf samples in the Big Thicket area that date earlier than the 1600s. A particularly severe ice storm that was described by Spanish explorers struck near the Sabine River in Louisiana near the border with Texas (Truett and Lay 1984). In the late fall of 1690, snow and sleet fell for hours, and ice formed so thickly and heavily that many branches were broken and trees uprooted (Truett and Lay 1984). In 24 hours, the explorers counted over 200 fallen trees in their camp with over a thousand downed trees in the surrounding countryside (Truett and Lay 1984). Many of these trees must have been rather large, as many mules and horses were killed by the falling trees (Truett and Lay 1984). Assuming that a number of these trees were old-growth, this disturbance is significant and illustrates the power of ice storms in Southeastern Coastal Plain history. A tree-ring signature in the Texas chronology would be expected from such a powerful ice storm, but the chronology reveals only a mild increase in growth rates. The few trees that date to 1690 were, for the most part, young (< 30 years) at the time of the ice storm. Disturbance creates releases, but not all trees respond in the same manner to a release. Small-crowned intermediate trees do not respond as promptly as longleaf pines of other sizes and shapes (Boyer 1990). Nonetheless, the lack of older remnants that date earlier than the mid-1600s in the Big Thicket may be explained by this catastrophic ice event. If many of the larger pines were felled, the remnants may have decayed over the past 300 years, as longleaf pine stumps and logs cannot resist complete decay indefinitely. Alternatively, the massive amounts of woody debris would have made the area susceptible to a catastrophic fire, and the fire could have replaced entire stands of trees.

A final disturbance that may have influenced the chronologies is hurricanes. For example, an August 1779 severe hurricane that destroyed the fleet of Don Bernardo de Galvez of Spain prior to the Battle of Pensacola may have affected longleaf pine growth at EAFB (Rush 1996). Rings from the years 1780 and 1781 were exceptionally narrow in the EAFB chronology, but growth in Texas and South Carolina was above average. Similarly, growth at nearby Lake Louise, Georgia was exceptionally great in 1780. A baldcypress chronology from the Choctawhatchee River site near EAFB shows no anomalous growth in 1780 and 1781, but baldcypress seems to be very resistant to hurricane winds (Sheffield and Thompson 1992). In any case, climate or wind disturbance does not appear to affect baldcypress in that vicinity.

The trees at EAFB that exhibited the narrow rings were those of considerable age, while the trees that were young in 1780 tended to display a near-average ring width. Possibly, the large trees at EAFB were more damaged by the hurricane and lost needles or branches, while the small trees were less affected. Because the exact track of the storm and the wind speed is unknown, the link between this hurricane and the unusual growth pattern at EAFB is questionable, but is certainly a possibility.

An example of how the effects of an historical disturbance event can be discounted can be found in the August 1881 storm that was especially severe in Charleston, South Carolina. The years 1882 to 1886 at Sandy Island show above-average growth, which can be indicative of a release from competition. The effects of climate cannot be ruled out using the historical precipitation record at Charleston, which began in 1887. However, the overcup oak chronology from the Francis Beidler Swamp (southwest of Sandy Island) shows the same above-average growth pattern for the five-year period as the longleaf pines at Sandy Island. Therefore, I attributed the period 1882 to 1886 of above-average growth to favorable climate conditions in South Carolina and not to a release from competition caused by localized disturbance.

Another class of disturbance that will be examined in greater detail in the next chapter is fire. Forest fires or the absence of forest fires can affect the growth of trees considerably. Fires can reduce the diameter and height growth of young longleaf pines by regular burning (Boyer 1994). In some cases, though, fires can create significant releases. After a fire, very little year-to-year variability may be evident for several years, especially in trees that undergo a growth release because of mineral nutrients infused into the soil and the reduction of competition for nutrients (Fritts 2001). These conditions persist until climatic factors once again become limiting to tree growth. When fires are suppressed or infrequent, overcrowding from fire suppression slows the growth of longleaf pines (Bruce 1947). If fires were frequent in the history of longleaf pine forests, fires may add noise that reduces the climate signal in tree rings.

4.4.2.4 Comparison of Climate Reconstructions in the Southeast

Generalizing and aggregating spatial and temporal climatic phenomena over a large region such as the Southeastern Coastal Plain is challenging, particularly when comparing climate reconstructions based on a variety of tree species. Different species in the same general area may grow under different physiographic conditions, and their growth may be correlated differently with climatic variables (Kozlowski 1971). Moreover, the Southeastern Coastal Plain does not display an entirely homogeneous moisture regime throughout the year (Henderson and Vega 1996). In fact, the three sites are located in three different precipitation "subregions," depending on the season (Henderson and Vega 1996). Despite these limitations, my analysis will attempt to identify historical trends within the Southeast Coastal Plain and note periods of synchronicity and spatial coherence. I used other published reconstructions, both for a comparison of results, and to determine spatial and temporal relationships within the region. Because of the weak sample depth in the 1500s and early 1600s, in particular, comparisons are made with the recognition that the values obtained from only a few trees may not be indicative of the site or regional conditions.

4.4.2.5 Annual and Multi-annual Extremes

The focus of several dendroclimatic reconstructions in the eastern U.S. has been on extreme climate conditions, and drought has been emphasized in particular because of its adverse economic effects (Cook *et al.* 1988). Droughts that last two to six weeks occur quite frequently in the southern states (Moyle and Zahner 1954), but droughts that last several months to years are less common. Long-term droughts are caused by a persistent aberration of the atmospheric circulation, and in most cases, large-scale vertical motion is lacking because of prevailing high pressure conditions (Felch 1978; Dole 2000).

In terms of annual extreme droughts, the extent of the 1925 dry spell in the Southeastern Coastal Plain is noteworthy as one of the driest years in my Florida reconstruction was in 1925. Furthermore, the driest year in my Texas reconstruction was 1925, and the driest year in a 282-year post oak reconstruction from central Texas was also 1925 (Stahle and Cleaveland 1988). The South Carolina chronology does not reflect a dry year in 1925. This may be the result of stand disturbance (logging), because the instrumental record indicates that 1925 was an exceptionally dry year (SEP PHDI = – 4.68) in coastal South Carolina. The year 1925 was also the narrowest ring among loblolly and shortleaf pine chronologies in north-central Georgia (Grissino-Mayer 1988).

Based on this evidence, I conclude that the driest single year since 1700 across the Southeastern Coastal Plain was 1925.

These findings seem to contradict the research of Cook *et al.* (1988), who determined that the driest year in the southeastern U.S. since 1700 was in 1986, using a reconstruction of June PDSI. In the Cook *et al.* (1988) study, chronologies were developed from trees in the southern Appalachian Mountains in Kentucky, eastern Tennessee, Virginia, and the Carolinas. None of these sites was within the Southeastern Coastal Plain, where the climatic conditions appear to have been different. Moreover, Cook *et al.* (1988) compared an instrumental PDSI value from 1986 with reconstructed PDSI values, as their drought reconstruction only extended to 1977. While the year 1986 shows clearly as a drought year in my Florida and South Carolina chronologies, the drought did not affect eastern Texas, as the instrumental and tree-ring record indicate. Therefore, I conclude that the 1925 drought was more widespread and severe across the Southeastern Coastal Plain than the 1986 drought.

Another extremely dry year that affected a large portion of the U.S. occurred in 1860. A study of annual precipitation in the south-central United States from 1750 to 1980 found that the severe drought of 1860 may have been the worst drought in the south-central United States during the entire 231-year period (Blasing *et al.* 1988). The 1860 drought also affected areas of the north-central U.S. as far north as Minnesota (Bark 1978). This study shows that the 1860 drought also extended into portions of the Southeastern Coastal Plain as far east as Georgia, so this is one of the most widespread single years of drought, in terms of spatial extent, since 1750. The areal extent of this drought is similar to the drought of the mid-1950s, but the latter drought lasted longer and did not display the synchroneity in a single year of the 1860 event.

Concerning multi-annual extreme events, Stahle *et al.* (1998) reconstructed July PHDI with baldcypress trees and found that the driest 3-year episode in the entire 800-year reconstruction occurred from 1587 to 1589. This event also was coincident with the failed Lost Colony of Roanoke Island. According to Stahle *et al.* (1998), this event affected the entire Southeastern United States, as the network of chronologies used in the reconstruction ranged along the Coastal Plain from the Mississippi Valley to southern Virginia. The years 1588 and 1589 were exceptionally dry in my Florida chronology, which supports Stahle's findings. The years 1587 to 1589 were moderately dry in my South Carolina chronology. Stahle *et al.* (1998) also stated that the driest 7-year period in 770 years was from 1606 to 1612, coincident with the near-abandonment of the Jamestown Colony. However, Stahle *et al.* (1998) found that the drought did not encompass the entire Southeast, as the Mississippi Valley experienced above-average rainfall. The years 1606 to 1609 were dry in my South Carolina chronology as well, but not in the Texas or Florida chronologies.

Dissimilar climatic conditions across the breadth of the Southeast Coastal Plain are not unexpected (Henderson and Vega 1996). In a study of historical moisture extremes in eastern North America, Cook *et al.* (1995) found that not much commonality exists in the occurrence of multi-year periods of drought and wetness among different regions. Stahle and Cleaveland (1992) postulated that spatial heterogeneity of rainfall over the Southeast can be attributed to the shifts in the average zonal position of the Bermuda High. As an example, position of the Bermuda High from 1606 to 1612 could have affected the Atlantic seaboard and not the western portions of the Southeastern Coastal Plain, because the western portion could have received advected moisture from the Gulf of Mexico. A comparison of my results to a study of five-year droughts in the Southeast (Cook *et al.* 1995) provides another illustration.

Although the driest five-year periods were not analyzed in my study, Cook *et al.* (1995) list the five driest five-year periods in the Southeast since 1700, respectively, as 1816–1820, 1746–1750, 1877–1881, 1951–1955, and 1894–1898. These findings generally disagree with the results of this study, but the tree-ring data for the Southeast used in the Cook *et al.* (1995) study were taken from Georgia and the Carolinas only. The period 1816–1820 was unremarkable in all three of my sites. The period 1746–1750 was dry only in Florida and generally above average in the other regions. The period 1877–1881 was fairly dry in Texas, wet in Florida, and unremarkable in South Carolina.

Despite these differences, the latter two five-year periods (1951–1955 and 1894–1898) showed considerable agreement with this study. The 1894 to 1898 drought was apparent in below-average conditions in the reconstruction South Carolina and eastern Texas, but rainfall was above average in Florida. The period 1951 to 1955 was the driest five-year period among all my reconstructions, and the 1950s drought was certainly extensive in other areas of the U.S. as well. The drought west of the Mississippi during the period from 1950 to 1956 was one of the worst on record, particularly across the Great Plains (Wells and Wakeley 1970; Borchert 1971). In their 283-year reconstruction of June PDSI in central Texas, Stahle and Cleaveland (1988) found that the most severe period of consecutive June droughts occurred from 1951 to 1956. Furthermore, the most severe drought of the 20th century in the south-central U.S., according to instrumental records, occurred in the 1950s (Blasing *et al.* 1988). Therefore, I conclude that the most severe and extensive five-year drought period in the Southeastern Coastal Plain in my reconstructions occurred in the 1950s.

The five wettest periods in the Cook *et al.* (1995) reconstruction were, in order of precedence, 1821–1825, 1859–1863, 1832–1836, 1957–1961, 1721–1725. Again, substantial disagreements exist with my study and these findings. For example, the 1821–1825 period was one of the driest five-year periods in my South Carolina reconstruction and was similarly drier than average in Texas. Furthermore, the 1721 to 1725 period was dry in my South Carolina reconstruction, but wet in Florida and average in eastern Texas. The five-year period with the most agreement with the Cook *et al.* (1995) study was 1957 to 1961, which appears wet in all regions. The 1859 to 1863 period was generally wet in all reconstructions, except the dry year in 1860 interrupted the wet spell. The 1832 to 1836 five-year period relates favorably to wet periods in all my chronologies save Florida, but I believe the 1835 ice and freeze event adversely affected that Florida climate signal. This case represents a clear example of how comparison between other chronologies can highlight anomalies in dendroclimatic reconstructions that are attributable to non-climatic factors.

4.4.2.6 Decadal and Multidecadal Trends

Extreme climatic events that persist for a decade or more are much less frequent than multi-annual droughts. However, prolonged drought on decadal and longer time scales is an important feature of U.S. climate (Dole 2000). Long-term droughts may be enhanced by the initial dry conditions, as decreases in evapotranspiration may reduce local moisture sources in the dry region (Dole 2000). In the Southeastern Coastal Plain, few studies have rank-ordered dry and wet periods on decadal scales. Moreover, comparisons between studies of multidecadal moisture conditions are difficult because of varying criteria for what constitutes a regime shift between dry and wet conditions. I compared my results with several published studies from the Southeastern Coastal Plain and the southwestern U.S.

In a study by Anderson *et al.* (1995) of the Savannah River chiefdoms, extreme moisture conditions for the spring season were reconstructed for an area along the South Carolina-Georgia border from A.D. 1005 to 1600. The area sampled is separated from my South Carolina sites by around 230 km straight line distance and 100 km longitudinally. The years 1559 to 1569, when the Santa Elena Spanish colony was present at Parris Island, South Carolina, were extremely dry years (Anderson *et al.* 1995). Similarly, my Florida reconstruction also shows that this particular decade was extremely dry, although the sample depth is low for this portion of the reconstruction. In fact, the year 1569 is one of the driest in the Florida and Lake Louise reconstructions, which matches the results of Anderson *et al.* (1995). Apparently, this drought severely affected the Coastal Plain from southern South Carolina through the Florida panhandle. According to my South Carolina reconstruction, the northern part of the state was less affected by the long-term drought during the early 1560s, but an exceptionally dry period occurred from 1564 to 1572, with the latter years of that period being the driest. Perhaps the center of the drought shifted northward in the 1570s as the average position of the Bermuda high shifted. When a drought occurs for an extended period, the center of the drought may shift considerably over time. For example, the center of drought in the Southwest shifted from 1952 to 1956 within seven southwestern states (Thomas 1962).

The nearest published reconstruction to my Big Thicket chronology was developed by Stahle and Cleaveland (1988) in central Texas using post oak. The driest decades during this reconstruction were, in order of precedence, 1855–1864, 1950–1959, and 1772–1781 (Stahle and Cleaveland 1988). As in my reconstruction, these decades were interrupted by a year or two of average to above average conditions. Similarly, a study of drought conditions in the south-central U.S. since 1750 found that the 1855 to 1864 period was the most severe drought in the reconstruction (Blasing *et al.* 1988). The only similar 10-year dry period in my eastern Texas reconstruction was 1947 to 1956, which corresponds approximately to the 1950 to 1959 period of Stahle and Cleavland (1988). Also, the period 1772 to 1781 roughly corresponds to the third driest period in my South Carolina chronology (1768–1777). Interestingly, the decade from 1772 to 1781 exhibited predominantly wet conditions in eastern Texas in my reconstruction, even though central Texas experienced an extreme drought. Because eastern Texas is within an ecotone between the humid climate of the Southeast and the more arid climate of the Southwest, such differences are not surprising, despite some similarities in annual extremes. Eastern Texas is situated astride the boundary between the East drought region of the U.S. and the Midcontinent drought region as defined by Warrick *et al.* (1975). Apparently, widespread high pressure systems in certain years may affect large areas of the Coastal Plain into central Texas, but the general condition at the decadal scale is that the flow of moisture from the Gulf of Mexico will assert more influence on eastern Texas than on the region farther to the west. The rather abrupt transition from forest to scrub vegetation that separates eastern and central Texas tends to validate that assertion.

Another finding worthy of note is that some of the most extreme wet periods in the eastern U.S. correspond to the most extreme dry periods in the southwestern U.S. The decade 1778 to 1787 was one of the five intervals of greatest drought in northwestern New Mexico since AD 985 (D'Arrigo and Jacoby 1991), but this period was the wettest decade in the entire South Carolina reconstruction. The fact that this decade was highlighted in separate studies from two sites separated by thousands of kilometers is remarkable in itself, given the length of the two reconstructions. Similarly, the period 1835 to 1849 was the wettest period in the D'Arrigo and Jacoby (1991) reconstruction, but the period 1838 to 1847 was one of the driest decades in the eastern Texas reconstruction. One of the four wettest years in the D'Arrigo and Jacoby (1991) reconstruction was 1941, which ranked among the five wettest years in the Texas reconstruction. Also, the 1895 to 1904 period was the second driest interval in northwestern New Mexico, and the 1897 to 1906 decade was among the three driest decades in the Florida reconstruction (D'Arrigo and Jacoby 1991). These observations demonstrate that extreme moisture anomalies at decadal scales in the desert Southwest can be temporally coherent with anomalies in the Southeastern Coastal Plain.

Concerning multidecadal trends, a reconstruction of June PDSI for North Carolina (Stahle *et al.* 1988) found that the later stages of the Little Ice Age (1650 to 1750) were marked by dry conditions, and this dry century was followed by generally wetter conditions that persisted until 1984. My reconstruction of PHDI in South Carolina generally agrees with Stahle *et al.* (1988) in terms of a generally dry period from 1650 to

1750, although a mild period of enhanced moisture is apparent from 1700 to 1750. In terms of wet periods, Stahle *et al.* (1988) found that one of the wettest 29-year periods in the past 1614 years occurred from 1956 to 1984. My reconstructions do not agree with this finding. In fact, the period from 1951 to 1985 was a predominantly dry period in the South Carolina chronology. While Stahle *et al.* (1988) observed that wet and dry regimes lasted for about 30 years each, my reconstruction showed a periodicity of close to 50 years. In the southern Appalachians, the two driest 40-year periods since 1700 were 1735–1775 and 1910–1954 (Cook *et al.* 1988). The 1735–1775 period spans approximately the same period of average precipitation conditions in South Carolina from 1741 to 1780. My other site chronologies show no temporal correspondence.

I found that on the multidecadal level, growing season moisture conditions shifted on average every 67, 61, and 49 years in Texas, Florida, and South Carolina respectively. Stahle *et al.* (1988) determined that on the multidecadal level, spring climate in North Carolina shifted between wet and dry climate regimes on average every 34 years. The relatively shorter length of moisture regimes in the Stahle *et al.* (1988) study is probably an artifact of the smoothing method, as Stahle *et al.* used a 25-year smoothing spline, while I utilized a 50-year moving average.

These shifting trends in growing season precipitation may be attributed to the position and strength of the Bermuda High in the subtropical North Atlantic (Stahle and Cleaveland 1992). The Bermuda High, a subtropical Atlantic circulation feature, has the strongest contemporaneous correlation with total winter rainfall and mean temperature in the Southeast (Katz *et al.* 2003). In winter, higher temperatures and more precipitation occur when the average position of the Bermuda High shifts eastward (Katz *et al.* 2003).

Dry conditions tend to prevail in the spring when the Bermuda High expands westward, which diverts moisture advection farther west around the high (Stahle and Cleaveland 1992). If the high shifts to the northeastern Atlantic, anticyclonic circulation around the high draws moisture from the Gulf of Mexico at the western and southern periphery of the high pressure system. During rainfall extremes in the spring and summer, the longitudinal displacement of anticyclonic circulation tends to create these opposing moisture conditions (Stahle and Cleaveland 1992).

Not only does the strength and position of the Bermuda High affect conditions in the Southeastern Coastal Plain, but it can also affect the mid-continent (Central Plains). The Gulf of Mexico is the primary source for precipitation for the central and eastern U.S. in the spring and summer (Dole 2000). When the jet stream and Bermuda High are situated north and northeast of their average position, less moisture is drawn from the Gulf of Mexico and the Caribbean onto the Gulf Coast and into the Central Plains (Liu and Fearn 2000). This situation may have created the conditions of the 1860 drought that affected the Southeastern Coastal Plain and the Central U.S. Although the mechanisms for initiating drought in the U.S. are varied and complex, a common synoptic feature is a persistent anomalous anticyclone just upstream of the drought region (Dole 2000), so this explanation for the 1860 drought is plausible. Anomalous anticylonic circulation west of the Great Lakes could have also created anomalous moisture fluxes in 1860, so to attribute a particular mechanism to a historical (prior to instrumental record) drought event is speculative, at best.

The shifting position of the Bermuda High may explain the phenomenon of extreme drought (wet) episodes followed by extreme wet (drought) episodes.

The oscillatory nature of this moisture pattern is evident in all reconstructions. This pattern of extreme dry intervals followed immediately by extremely wet intervals has also been noted in the southwestern U.S. (D'Arrigo and Jacoby 1991). In North Carolina, the wet years of 1985 and 1986 were followed by two years of intense drought in the past 125 years (Stahle *et al.* 1988). Possibly, a major shift in the Atlantic anticyclone over a short period could restore favorable conditions for moisture flux into the Coastal Plain following years of persistent drought.

A final comment on the trend analysis concerns the persistence of wet and dry conditions among my three sites. In the Texas reconstruction, moisture regimes at multi-decadal scales were sustained for longer periods (67-year average) than at the other two sites. The Florida reconstruction showed intermediate length, and the South Carolina reconstruction showed the shortest average periods for moisture regimes. Moisture regimes may be more persistent in eastern Texas because the Teexas climate is related to the Midcontinent region, where droughts are more frequent and climate patterns are more persistent (Bark 1978). The greater variability of climate patterns in South Carolina compared to the other sites may be because the area is affected by a greater variety of weather systems that originate in the Atlantic Ocean and the Gulf of Mexico. Also, the Bermuda High may exert a greater influence on coastal South Carolina than on areas farther westward in the Southeast Coastal Plain. Finally, at decadal scales, the South Carolina and Texas reconstructions exhibit a greater degree of variability and a greater tendency to swing into extreme conditions than in the Florida chronology. Perhaps the more consistent supply of growing season thunderstorms in the Florida panhandle reduces the variability in moisture conditions because of proximity to the Gulf of Mexico (and more southerly latitude).

4.4.2.7 Spectral Analysis

The largest peak in the spectral density function for Texas corresponded to a period of 18 years, with lesser peaks at 5.9 and 2.2 years. A 2- to 7-year period is also indicative of ENSO events (Cane and Zebiak 1985), and the spectral peak at 5.9 years may relate to ENSO, as the correlation analysis indicates a significant relationship between SOI and the climate reconstruction. A similar and significant peak at 6.25 years was found in a reconstruction of winter SOI from trees in subtropical North America and Indonesia (Stahle *et al.* 1998). A more in-depth analysis of the effects of ENSO on my reconstructions will be in the next chapter.

Multi-year fluctuations of climate in the U.S. are driven primarily by internal stochastic processes of the atmosphere-ocean-cryosphere system that may not require any external mechanisms such as solar and lunar forcing (Cook *et al.* 1995). However, the 18-year spectral peak in Texas may correspond to the 18.6 period in the lunar nodal tide (Currie 1981). An analysis of central Texas drought history revealed marginally significant spectral peaks at frequencies near the lunar nodal tide and the quasi-biennial pulse (Stahle and Cleaveland 1988). A weak tendency for an 18- to 19-year periodicity was also noted in a reconstruction of drought in the south-central U.S. (Blasing *et al.* 1988). The quasi-periodicity at 18 years revealed in this study appears to agree with those findings. Thus, the orographic modulation of an 18.6-year quasi-standing wave by the Rocky Mountains may affect portions of Texas (Currie 1981; Stahle and Cleaveland

1988). Studies of drought in the Great Plains have revealed similar periodicities near this frequency peak (Meko *et al.* 1985). Moreover, the Texas drought history study showed a concentration of low-frequency variance near 2.3 years, which corresponds to the quasi-biennial pulse (Stahle and Cleaveland 1988; Barry and Perry 1973). Again, the 2.3-year spectral peak observed in this study closely agrees with that of Stahle and Cleaveland (1988), which indicates that similar processes may affect eastern and central Texas.

Why the other sites did not exhibit significant periodicities is unclear. The spectral density function for South Carolina displayed a peak at 27 years, but the signal was weak. A 26-year peak noted in spectral analysis of a July drought reconstruction for the Hudson Valley, New York may have been related to the soli-lunar tidal influence (Cook and Jacoby 1979). Perhaps this harmonic also affects the southern portion of the Atlantic seaboard, but to a lesser extent. In any event, the rhythms of moisture regimes and tree growth seem to be more affected by internal stochastic mechanisms than by external forcings such as sunspot activity.

Chapter 5

Atmospheric Teleconnections in the Southeastern U.S.

"...in making meteorological applications of statistical methods, it is important to have as definite ideas as possible regarding the reliability of the conclusions reached and of the causal relationships which the analysis may indicate."

- Sir Gilbert Walker (Nash 2002)

5.1 Introduction

The proper interpretation of instrumental and proxy climate records relies on understanding how regional climate is related to large-scale ocean-atmospheric interactions such as El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), the North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO) (Sutton and Hodson 2005). The southeastern U.S. is affected by all of these teleconnections to varying degrees over space and time. This chapter provides the first analysis of the effects of these teleconnections on longleaf pine growth in the Southeastern Coastal Plain. Both temperature and precipitation conditions are affected by these oscillations, so the exact relationship between the teleconnection and tree growth in terms of physiological response was difficult to discern in this study. However, the influence of each oscillation was apparent in longleaf pine growth at all sites. As the characteristics of ENSO were previously described in Chapter 1, I will only introduce PDO, NAO, and AMO before I present my analysis.

5.1.1 Pacific Decadal Oscillation

The PDO is the dominant decadal mode of North Pacific sea surface temperature (Mantua *et al.* 1997). The PDO varies between warm (positive) and cool (negative) phases every 20 to 30 years (Mantua *et al.* 1997). Warm phases prevailed from 1925 to 1946 and from 1977 through the mid-1990s, while cool phases were dominant from 1890 to 1924 and from 1947 to 1976 (Mantua and Hare 2002). In the southeastern U.S., warm phases typically bring wet conditions and cool phases are drier (Mantua and Hare 2002). Tree-ring reconstructions have estimated the PDO index as far back as 1700, and both interannual and decadal variability is evident in these reconstructions (D'Arrigo *et al.* 2001).

A number of scientists believe PDO modulates ENSO in the U.S. (Kerr 1999; Biondi *et al.* 2001; Cleaveland *et al.* 2003). Moreover, climate anomalies associated with PDO are similar but less extreme than those linked to ENSO variations, as the warm-phase PDO produces anomaly patterns similar to El Niño (Mantua and Hare 2002). The warm-phase ENSO events are typically stronger when they are in phase with PDO events, so ENSO-related rainfall anomalies are often associated with PDO phases (Enfield *et al.* 2001). For example, in the PDO warm phase, El Niño events exhibit a generally stronger pattern of wet winters in the southern tier of the U.S. (Gershunov and Barnett 1998).

5.1.2 North Atlantic Oscillation

The NAO is an oscillation of atmospheric mass between the subtropics and the high latitudes that affects the zonal wind strength across the Atlantic Ocean (Rogers

1984; Seagar *et al.* 2000). The periodicity of this phenomenon is around two years but can range up to decades (Seagar *et al.* 2000). In the positive phase, the pressure difference between the Azores high and the Icelandic low is accentuated, especially in winter when the pressure differential becomes particularly strong (D'aleo and Grube 2002). As a consequence, the jet stream flows faster across the Atlantic into Western Europe and drains cold air off the North American continent, and the result is warmer temperatures on the east coast of the U.S. in winter and spring (Rogers 1984; D'aleo and Grube 2002). During a negative NAO, higher pressure develops or extends into the far northern Atlantic, and relatively low pressure typifies the Azores high. The decreased pressure gradient in the northern Atlantic retards the movement of cold air off the North American continent, and cold air masses as well as storm tracks shift southward in the U.S. (D'aleo and Grube 2002). Consequently, cooler temperatures and heavy snows often predominate in the Southeast in the negative phase. The NAO index was generally positive from around 1900 to 1930 and from 1980 to 2000, and the index was mostly negative from the early 1940s to the early 1970s (Hurrell 1995; Seagar *et al.* 2000).

In the Southeast, the NAO affects both temperature and precipitation. Although the NAO index is strongest in the winter, the signal is also robust in the spring and summer (Enfield *et al.* 2000; Rogers 1990). Warmer than average temperatures occur in winter during the positive phase of the NAO (Rogers 1984; Katz *et al.* 2003). The NAO also can affect the passage of hurricanes during the summer and fall seasons (Caviedes 2001). During the negative phase of the NAO, hurricane activity tends to increase, and hurricane storm tracks are shifted southward toward the Gulf of Mexico and the Caribbean (Elsner *et al.* 2000; Molinari and Mestas-Nuñez 2003). When the July NAO index is higher, more hurricanes tend to strike the East coast than the Gulf Coast (Elsner *et al.* 2000). The reason for these changes is that the midlatitude jet stream is shifted northward in a strong NAO, and the Bermuda/Azores High is shifted eastward, relative to a weaker NAO condition (Elsner *et al.* 2000).

5.1.3 Atlantic Multidecadal Oscillation

The AMO is a multi-decadal pattern of surface temperature variability centered on the North Atlantic Ocean (0–70° N) (Kerr 2000; Knight *et al.* 2005). The AMO index is a 10-yr running mean of detrended sea surface temperature (SST) anomalies averaged over the North Atlantic with amplitude of 0.4° C (Enfield *et al.* 2001). Not only is the AMO linked to North American climate, but via teleconnections also affects Sahel droughts and rainfall in Brazil (Knight *et al.* 2005). The AMO operates on much lower frequencies than the NAO. The oscillatory nature of the phenomenon, which occurs on approximately 50 to 70-year cycles, is related to the variability in oceanic thermohaline circulation and the associated meridional heat transport (McCabe *et al.* 2004; Knight *et al.* 2005). The NAO is linked to the AMO because the speed of the winds across the Labrador Sea affects thermohaline circulation (Kerr 2000).

In the 20th century, the AMO had an important role in modulating boreal summer (June, July, and August) climate in the U.S. on multidecadal time scales (Sutton and Hodson 2005). In the warm (positive) phase of the AMO, summer precipitation in many regions of the U.S. is lower and temperatures are warmer than in the cool phase (McCabe *et al.* 2004; Sutton and Hodson 2005). Warm phases of the AMO occurred in the late 19th century and from 1931 to 1960; Midwest droughts in the 1930s and 1950s have been linked to AMO (Enfield *et al.* 2001). Cool phases of the AMO occurred from 1905 to 1925 and from 1965 to 1990 (Sutton and Hodson 2005). The effects of AMO on the southeastern U.S. have not been studied extensively, but river discharges in southern Florida vary by as much as 40% between warm and cool phases, because of differences in summer rainfall (Enfield *et al.* 2001). In southern Florida, summer rainfall is reduced during the negative phase of the AMO, but is above average in the positive phase (Enfield *et al.* 2001). During the winter, however, the warm phase is characterized by lower geopotential heights and increased cyclonic activity in the Southeast (Enfield *et al.* 2001).

5.2 Methods

5.2.1 Data Collection

5.2.1.1 ENSO

No single index of ENSO events has been accepted as the universal standard in the scientific community (Smith *et al.* 1999; Hanley *et al.* 2003). I used the Japan Meteorological Agency index (JMA) that is based on the observed and reconstructed sea-surface temperature (SST) anomalies from the tropical Pacific from 1868 to the present (Parker *et al.* 2001; COAPS 2005). The JMA uses an objective procedure to define El Niño that is quite consistent with the understanding within the ENSO research community (Trenberth 1997). The index is a 5-month running mean of spatially averaged SST anomalies over the tropical Pacific Ocean from 4° N to 4° S and from 150° to 90° W (Sittel 1994; Smith *et al.* 1999). The JMA index is based on observed data from 1949 to present, but from 1868 to 1948 the index is based on reconstructed monthly mean SST fields (Sittel 1994). Strong similarities exist between JMA indices and other common indices of ENSO such as the Niño 3 and Niño 3.4 (Hanley *et al.* 2003). The JMA indices are more sensitive to La Niña events than the other indices but are less sensitive to warm events (Hanley *et al.* 2003).

5.2.1.2 PDO

I utilized the Joint Institute for the Study of Atmosphere and Ocean (JISAO) PDO index from the University of Washington from 1900 to 2000 (JISAO 2005). These indices are derived from the leading principal component (PC) of monthly SST anomalies in the North Pacific Ocean poleward of 20^{o} N. To separate the pattern of variability from any "global warming" signal that may be present in the data, the monthly mean global average SST anomalies have been removed (JISAO 2005). The indices that predate 1925 are considered less reliable (Drake *et al.* 2002), but I used the full dataset in the analysis to incorporate the cool phase of the PDO in the early 1900s.

5.2.1.3 NAO

NAO indices used in this study were compiled by the Climate Analysis Section of the National Center for Atmospheric Research (NCAR) (NCAR 2005). The index is based on the normalized sea level pressures between Ponta Delgada, Azores and Stykkisholmur/Reykavik, Iceland from 1865 to 2002. Positive values of the index indicate stronger-than-average westerlies in the mid-latitudes (NCAR 2005).

5.2.1.4 AMO

I obtained AMO indices from the National Oceanic and Atmospheric Administration – Cooperative Institute for Research in Environmental Sciences (NOAA-CIRES) Climate Diagnostics Center website (NOAA 2005). The data spanned the years from 1871 to the present, and the indices represent the area-averaged SST in the Atlantic north of the equator.

5.22 Statistical Analysis

I used the tree-ring reconstructions for each site in statistical analyses with the various teleconnection indices over the entire period of the teleconnection data. I analyzed Pearson correlation coefficients between monthly climate indices and reconstructed tree-ring indices for a 24-month period from January of the previous year to December of the current year. Because El Niño and La Niña events could be examined for the effects that surround a particular annual event, I utilized additional statistical analyses for ENSO events. Using Superposed Epoch Analysis (SEA) (Swetnam 1993; Grissino-Mayer 1995), I examined the effects of El Niño and La Niña events on the reconstructed tree-ring indices. In this study, SEA provides graphical and statistical techniques for evaluating the conditions leading up to, during, and immediately after ENSO events and entails the stacking (*i.e.*, superposing) of ENSO event years and calculating the average growth conditions leading up to and after individual ENSO event years (Swetnam 1993). No generally-accepted classification scheme exists for categorizing ENSO events (Schmidt *et al.* 2001), so I applied the scheme applicable to the JMA SST dataset. I categorized El Niño/La Niña events using the criteria devised by

Sittel (1994). Namely, if the JMA SST index values equaled or exceeded 0.5° C for six consecutive months (including October, November and December) the ENSO year was classified as El Niño. If the index values equaled or exceeded – 0.5° C, they were La Niña years (Sittel *et al.* 1994). Defining El Niño and La Niña events as single-year phenomena is not always an accurate depiction of the ENSO condition, because warm events may span up to two years (Michaelsen and Thompson 1992). Nevertheless, I used a lead of three years prior to the ENSO event, the year of the event, and a lag of three years after the event as my window of examination.

To determine the average relationship over the entire period of the teleconnection datasets, I also examined changes in the relationship over time. For each dataset, I subjectively divided each instrumental dataset into equal periods to detect changes in the effects of teleconnections over time for each composite chronology. In all cases except ENSO, I attempted to divide the instrumental data into periods that roughly paralleled the phases of the particular teleconnection of interest. The purpose for making this type of arbitrary division was to determine whether any consistent trends were present in the effects of tree growth according to the phase of the teleconnection. I used total ring width for all analyses and earlywood and latewood widths where available.

For the ENSO analysis, I divided the dataset from 1868–2003 into three equal periods: 1868–1913 (ENSO A), 1914–1958 (ENSO B), and 1959–2003 (ENSO C). For the PDO, I divided the dataset from 1900–2000 into four equal periods that approximately correspond to warm and cool phases of the PDO: 1900–1925 (cool phase, PDO A), 1926–1950 (warm phase, PDO B), 1951–1975 (cool phase, PDO C), and 1976–2000 (warm phase, PDO D) (Mantua and Hare 2002). I divided the NAO dataset into four equal periods that roughly follow the trends of positive and negative phases of the NAO: 1865–1900 (neutral, NAO A), 1900–1935 (positive phase, NAO B), 1936–1970 (negative phase, NAO C), and 1971–2002 (positive phase, NAO D) (Hurrell 1995). Finally, I separated the AMO dataset into four equal periods that roughly correspond to AMO warm and cool phases: 1871–1900 (warm phase, AMO A), 1901–1930 (cold phase, AMO B), 1931–1960 (warm phase, AMO C), and 1961–1990 (cold phase, AMO D) (Sutton and Hodson 2005).

5.3 Results

5.3.1 ENSO

5.3.1.1 Average over Entire Record (1868–2003)

In the correlation analyses, I found statistically significant relationships between monthly SST indices and longleaf pine tree growth in both Texas (Figure 5.1, Figure 5.2A) and South Carolina (Figure 5.2C), but not in Florida (Figure 5.2B). A positive relationship was evident between SST indices from the previous growing season (previous May to previous October) and tree growth in the Texas region (Figure 5.2A). This signal was primarily present in the earlywood (Figure 5.2A2), with statistically significant, positive relationships evident for some months between the previous July and the current January. The latewood signal (Figure 5.2A3) roughly corresponded to this trend, but the correlation coefficients were non-significant. In all cases, the relationship between SST indices and growth in the current year was weak and predominantly negative. For the Florida chronology (Figure 5.2B), a similar but non-significant

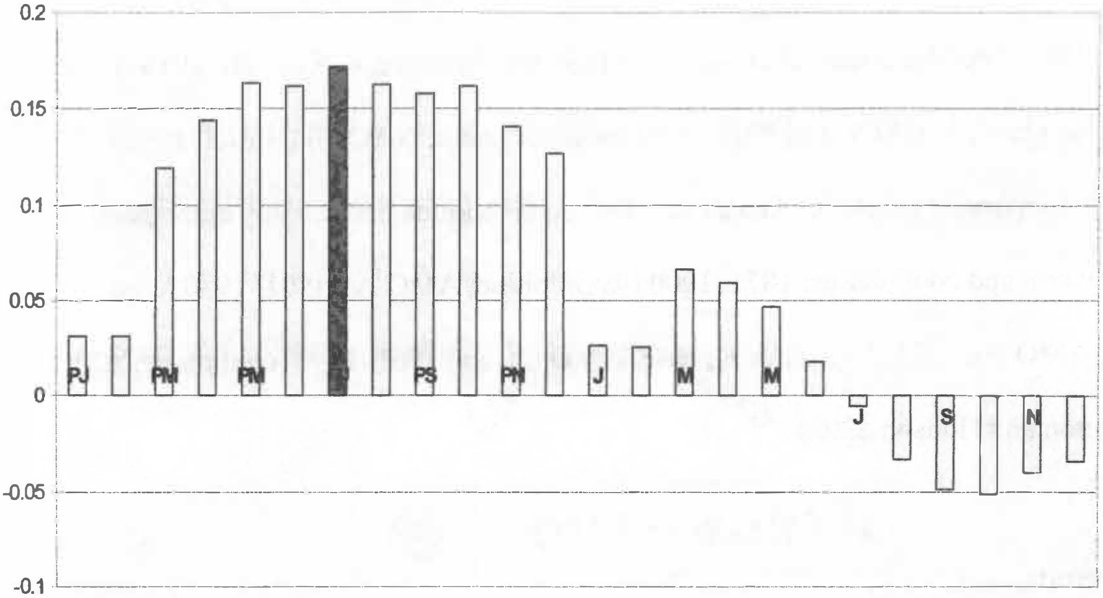
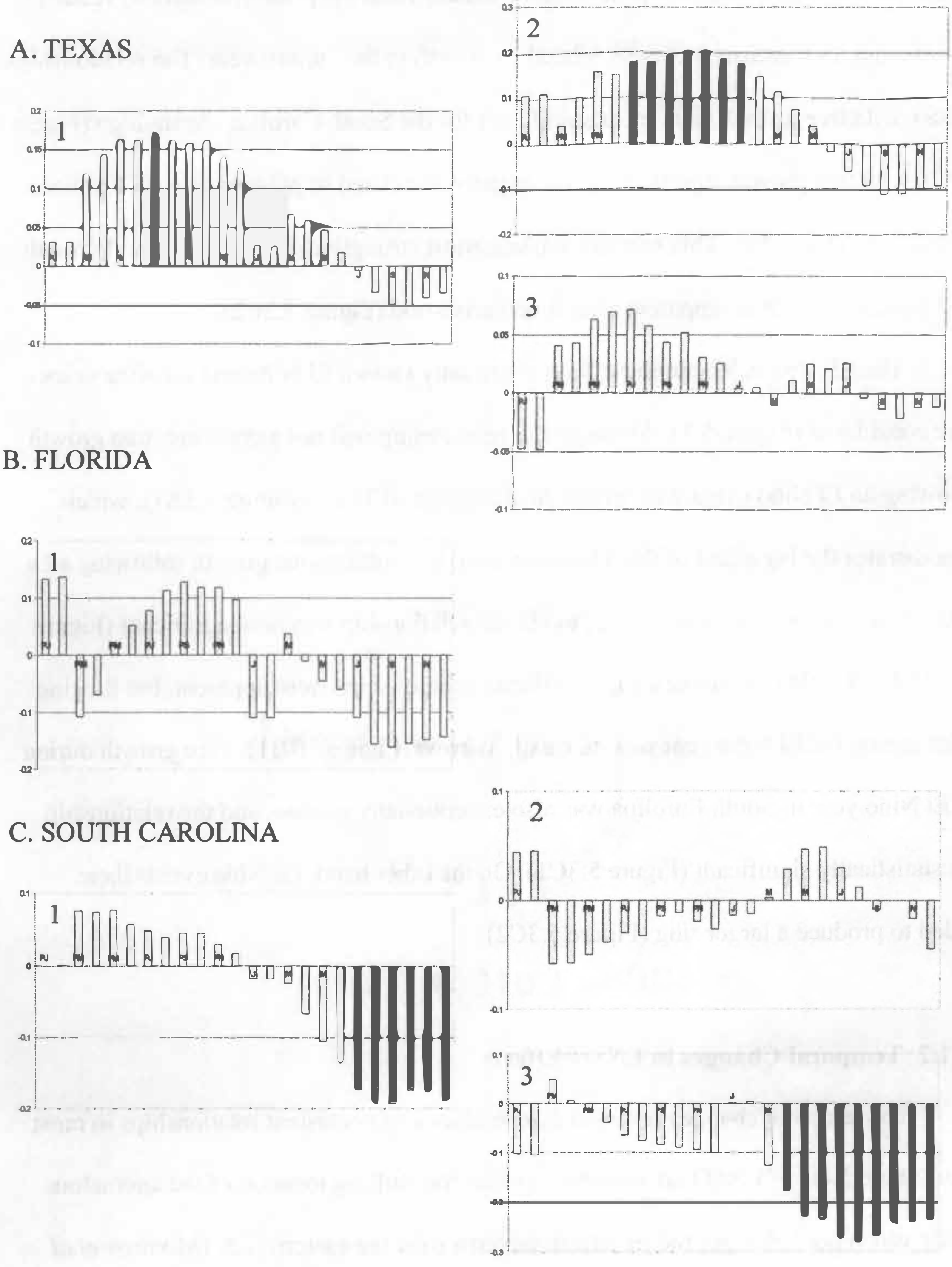


Figure 5.1 Exaggerated scale of climate correlation graphs in Figures 5.2–5.23. The bars are labeled by the month or season that the variable represents. The 24 monthly variables represent the 12 months in the previous year and 12 months in the current year. The months variables are abbreviated by the first letter of the month, and in the case of a month in the previous year, a "P" precedes the abbreviation.



A. TEXAS

B. FLORIDA

C. SOUTH CAROLINA

Figure 5.2 Correlation coefficients between JMA SST monthly index values and tree-ring indices for 1868–2003. Black bars indicate significance at 0.05 level. 1 = TRW, 2 = EWW, 3 = LWW.

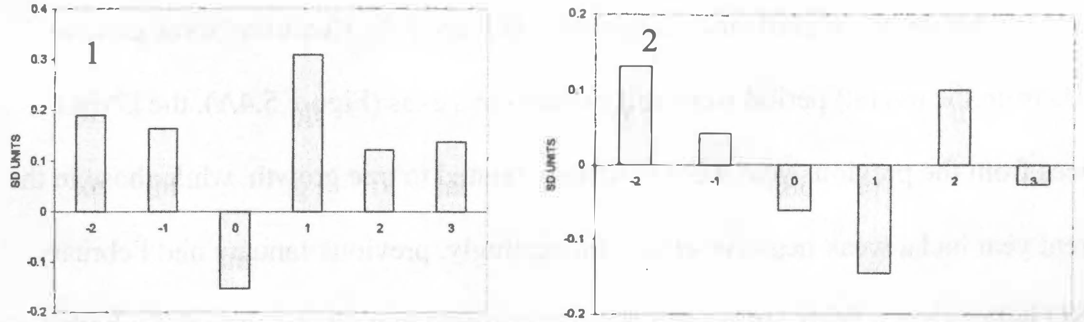
relationship was evident, with positive SST indices from the prior year directly related to growth, and SST indices inversely related to growth in the current year. The relationships of SST with tree growth were most significant for the South Carolina chronology (Figure 5.2C), with tree growth significantly and negatively related to present-year SST indices from July to December. This relationship was most strongly evident in latewood growth (Figure 5.2C3), with no apparent effects on earlywood (Figure 5.2C2).

The SEA revealed similar effects when only known El Niño and La Niña years were considered (Figure 5.3). Although the relationship was not significant, tree growth following an El Niño event was greater than average in Texas (Figure 5.3A1), which demonstrates the lag effect of the teleconnection. In contrast, tree growth following a La Niña event was lower than average, though the relationship was non-significant (Figure 5.3A2). For Florida, no statistically significant relationships were apparent, but the ring width during the El Niño year was unusually narrow (Figure 5.3B1). Tree growth during the El Niño year in South Carolina was also exceptionally narrow, and the relationship was statistically significant (Figure 5.3C1). On the other hand, La Niña events there tended to produce a larger ring (Figure 5.3C2).

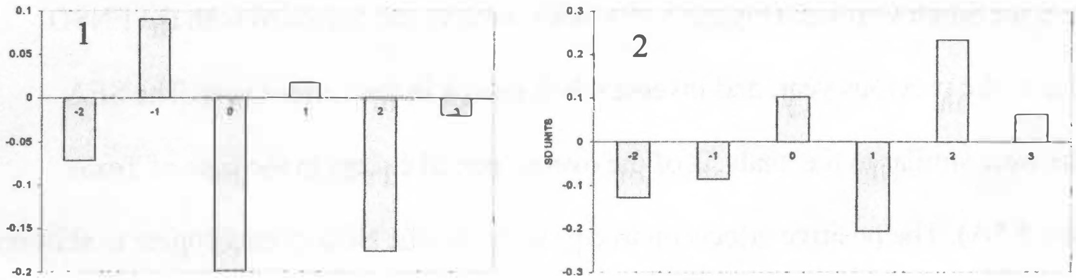
5.3.1.2 Temporal Changes in ENSO Effects

The temporal changes revealed a general lack of consistent relationships in most cases. The effects of ENSO are variable because the shifting location of the anomalous Pacific warm pool changes the jet stream patterns over the eastern U.S. (Montroy *et al.* 1998). The regional effects of each ENSO event will vary depending on how the characteristics of the event interact with the normal circulation pattern in the area (Simard

A. TEXAS



B. FLORIDA



C. SOUTH CAROLINA

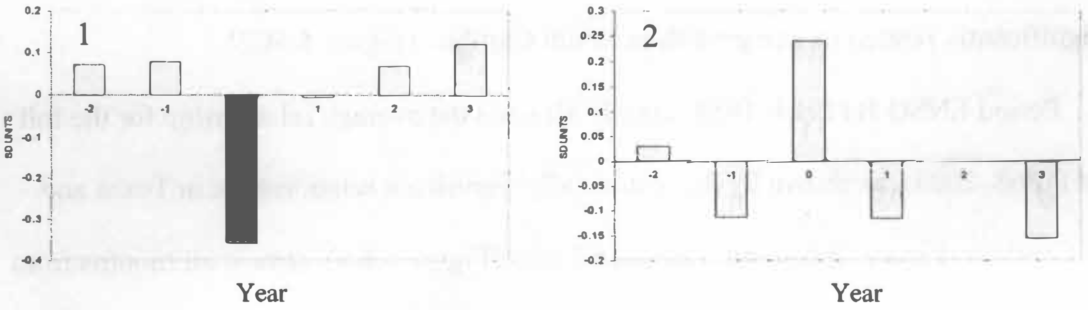


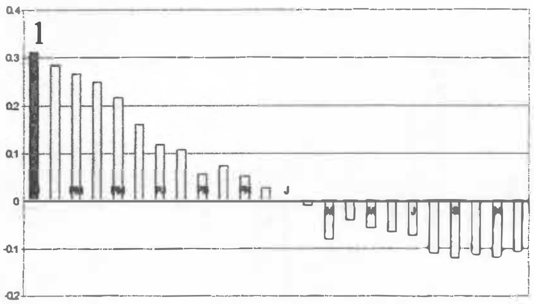
Figure 5.3 Superposed epoch analysis of ENSO effects on tree-ring indices for the period 1868–2003. Black bars indicate significance at 0.05 level. 1 = El Niño, 2 = La Niña.

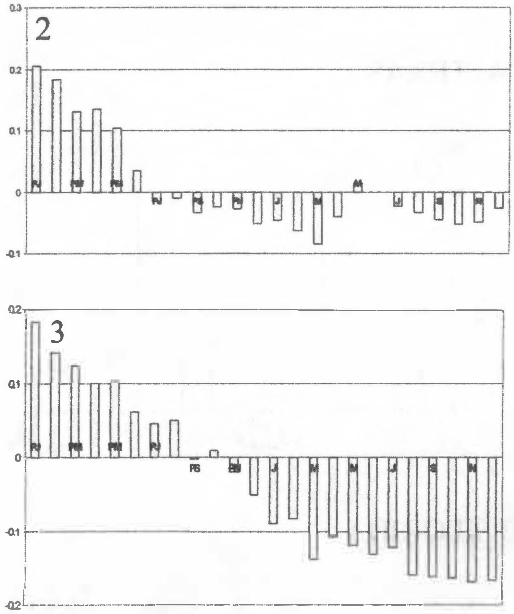
et al. 1985). Therefore, individual El Niño and La Niña winters are rarely similar with regard to atmospheric flow in the Gulf of Mexico region (Vega *et al.* 1998).

The relationships in ENSO A (1868–1913) were generally weak in all areas, with almost no statistically significant relationships (Figure 5.4). However, some general trends from the overall period were still present. In Texas (Figure 5.4A), the ENSO indices from the previous year were positively related to tree growth, while those in the current year had a weak negative effect. Interestingly, previous January and February ENSO indices had a fairly strong and positive correlation with tree growth for both Texas and Florida (Figures 5.4A and 5.4B). The same general pattern for the overall period was evident for South Carolina (Figure 5.4C), with positive relationships with the ENSO indices of the previous year, and inverse relationships in the current year. The SEA results were similar to the analysis of the overall period except in the case of Texas (Figure 5.5A). The positive effects on tree growth after El Niño events appear to shift one year to year t+2 (Figure 5.5A1). El Niño years tend to be characterized by slow growth in Florida and South Carolina (Figures 5.5B1 and 5.5C1), and La Niña years were positively and significantly related to tree growth in South Carolina (Figure 5.5C2).

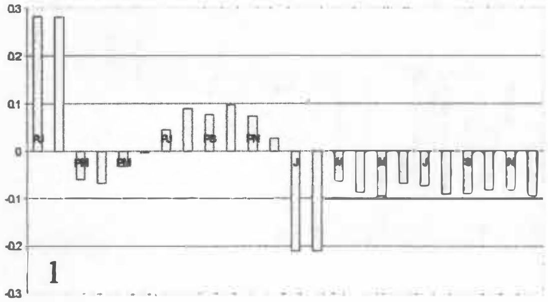
Period ENSO B (1914–1958) clearly affected the average relationship for the full period (1868–2003), as shown by the statistically significant relationships in Texas and South Carolina (Figures 5.6A and 5.6C). In Texas (Figure 5.6A), almost all months from the previous July to the current January were significantly and positively related to total ring width and earlywood width. Results of the SEA support this relationship, as the tree growth in year t+1 is abnormally large at a statistically significant level for El Niño events (Figure 5.7A1), whereas growth is unusually slow in year t+1 for La Niña events

A. TEXAS

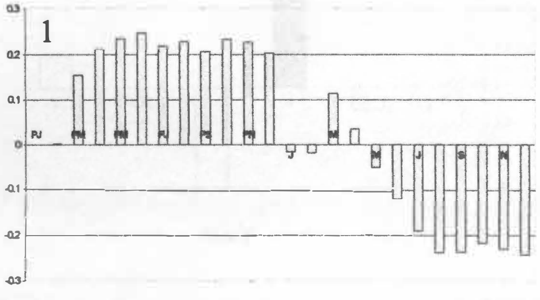




B. FLORIDA



C. SOUTH CAROLINA



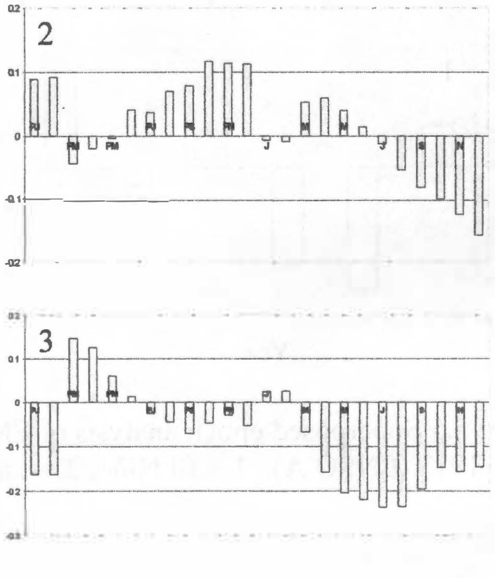


Figure 5.4 Correlation coefficients between JMA SST monthly index values and tree-ring indices for 1868–1913 (ENSO A).

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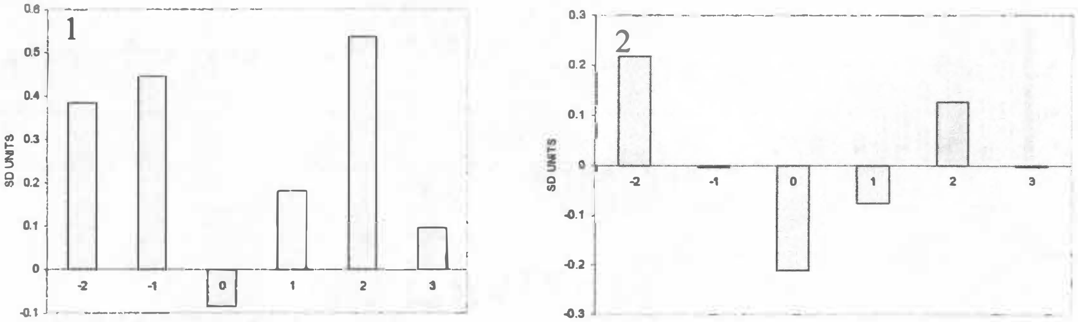
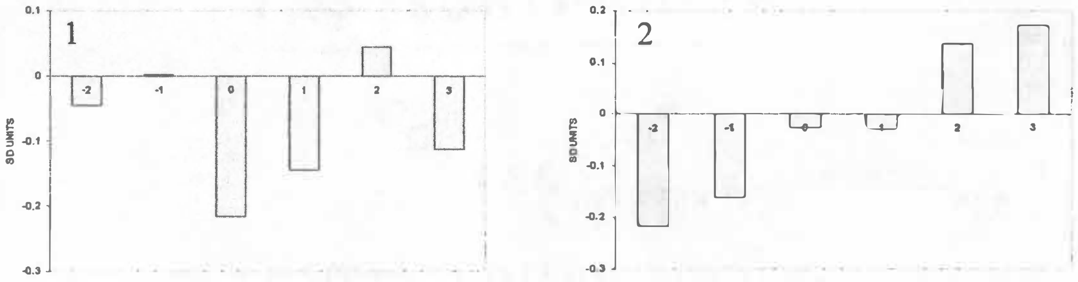


B. FLORIDA



C. SOUTH CAROLINA

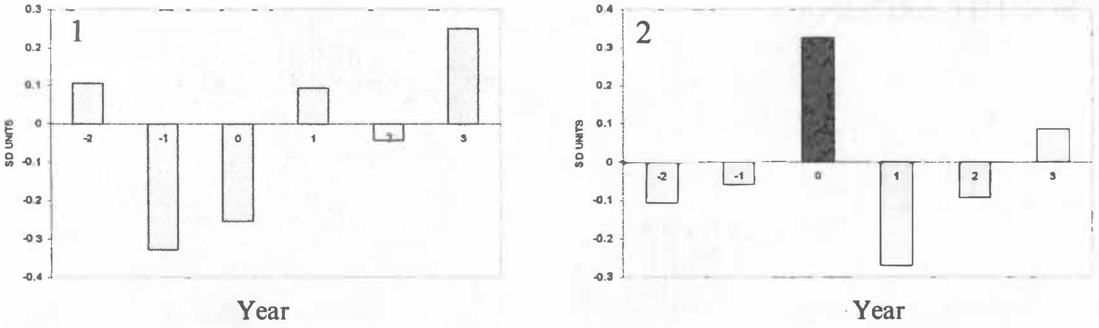
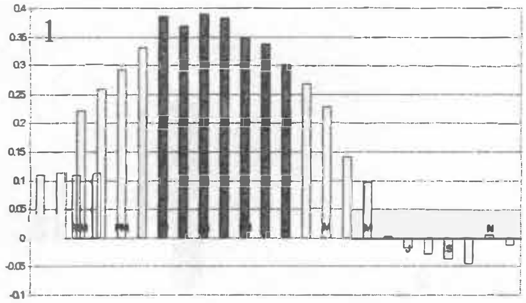
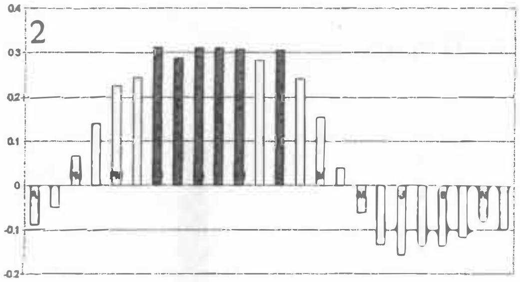
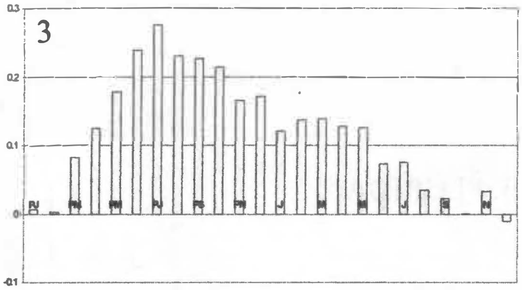


Figure 5.5 Superposed epoch analysis of ENSO effects on tree-ring indices for the period 1868–1913 (ENSO A). 1 = El Niño, 2 = La Niña.

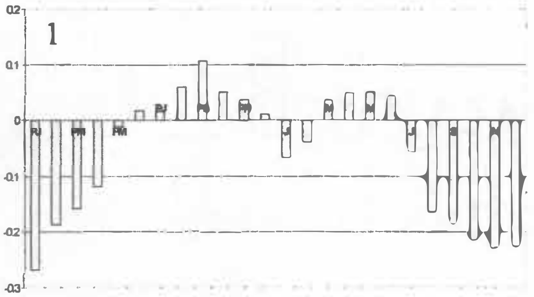
A. TEXAS



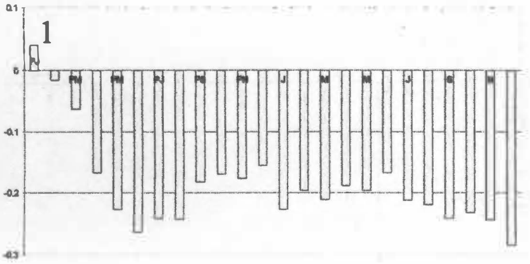


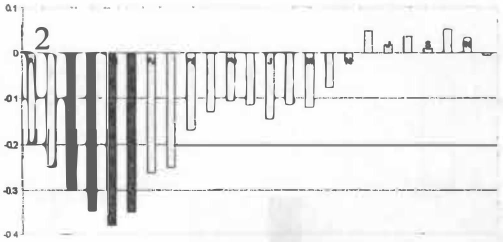


B. FLORIDA



C. SOUTH CAROLINA





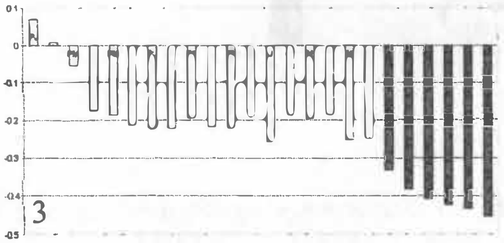
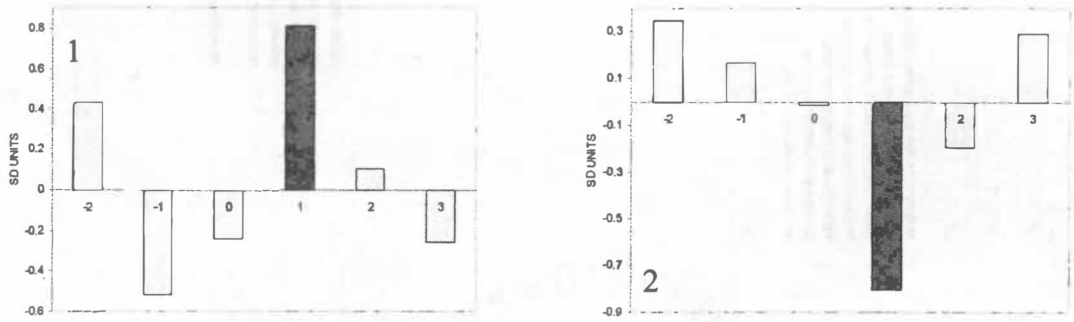
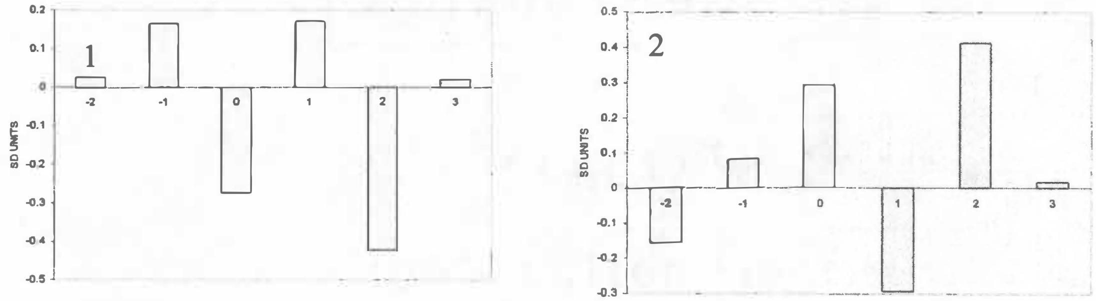


Figure 5.6 Correlation coefficients between JMA SST monthly index values and tree-ring indices for 1914–1958 (ENSO B).

A. TEXAS



B. FLORIDA



C. SOUTH CAROLINA

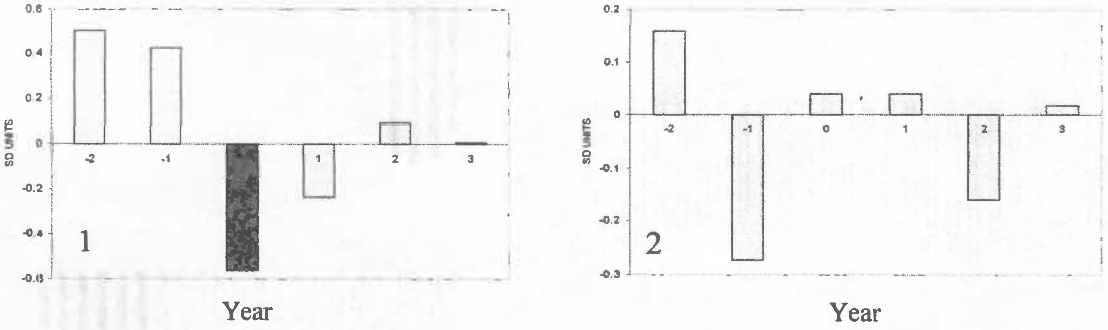
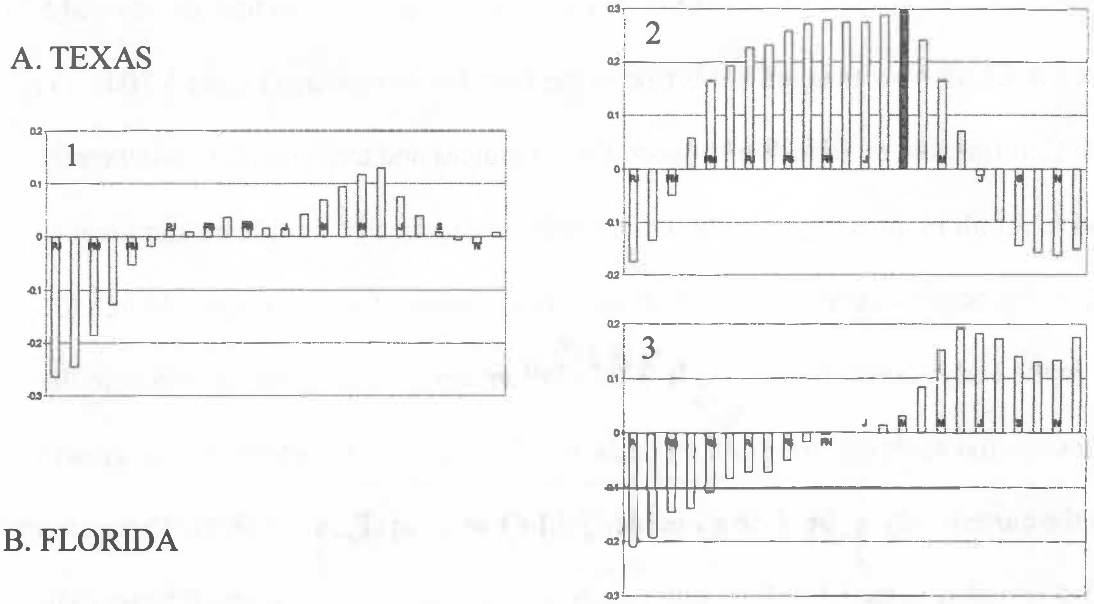


Figure 5.7 Superposed epoch analysis of ENSO effects on tree-ring indices for the period 1914–1958 (ENSO B). 1 = El Niño, 2 = La Niña.

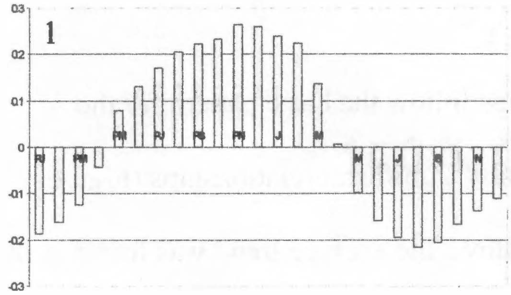
(Figure 5.7A2). The general trend of negative relationships between tree growth and SST indices in El Niño years again holds true in the Florida chronology (Figure 5.7B1). For South Carolina, the relationship between ENSO indices and tree growth was generally negative for all months (Figure 5.6C). Curiously, a statistically significant and inverse relationship occurs between tree growth and ENSO indices for the previous March to June in the earlywood (Figure 5.6C2). This relationship is not evident elsewhere in the South Carolina analysis. The strongly negative effects of ENSO indices on tree growth from the current July to December are seen in the latewood (Figure 5.6C3). These effects are also revealed in the SEA for South Carolina, where tree growth is much lower than average in El Niño years (Figure 5.7C1).

For ENSO C (1959–2003), the relationships follow the basic pattern for the overall period (1868–2003) but with few statistically significant relationships (Figure 5.8). For Texas, however, the only pattern that follows the average trend was found in the earlywood widths (Figure 5.8A2), where tree growth is positively related to ENSO indices in the previous year, but the relationship is shifted by a few months into the current year. The pattern in Florida (Figure 5.8B1) is the strongest for any of the subperiods, and positive relationships in the prior year are followed by negative relationships in the current year. The basic relationships that are apparent for the full period of record are present in South Carolina as well (Figure 5.8C). SEA revealed no significant relationships except in the case of South Carolina, where a statistically significant and negative relationship exists for La Niña events at year t+3 (Figure 5.9C2).

A. TEXAS



B. FLORIDA



C. SOUTH CAROLINA

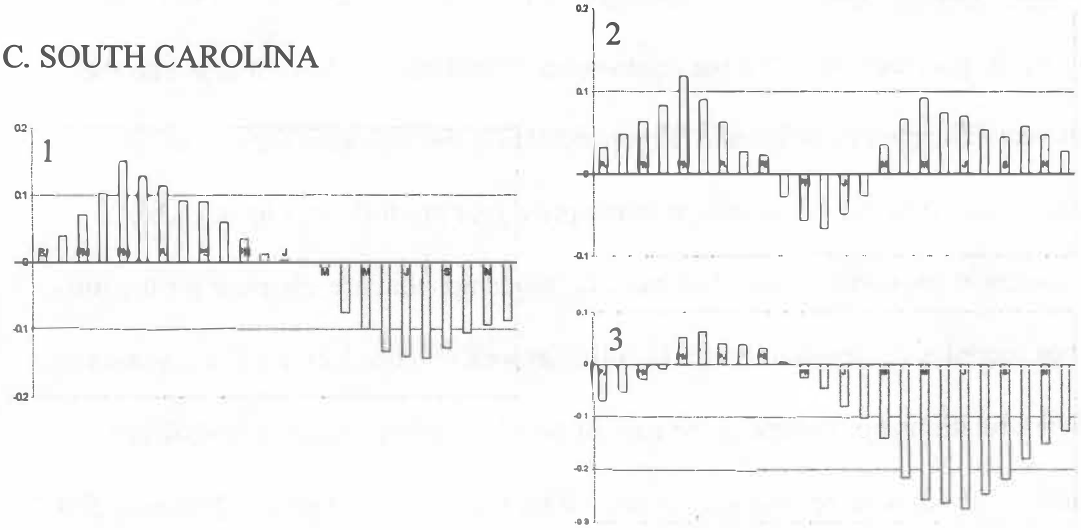
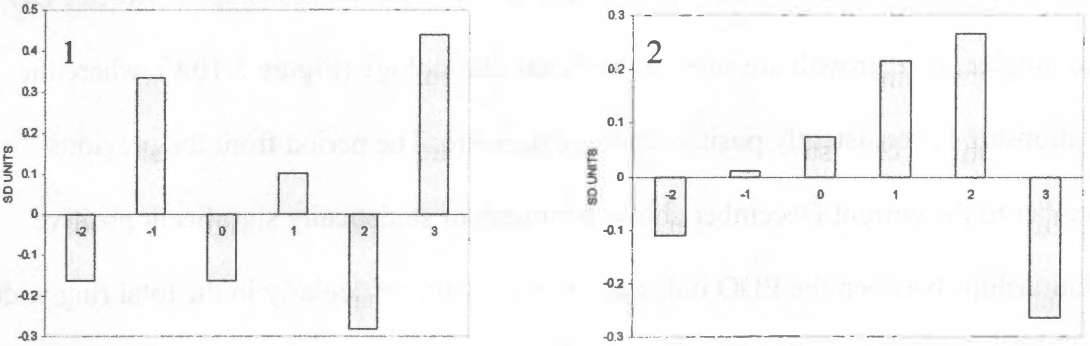
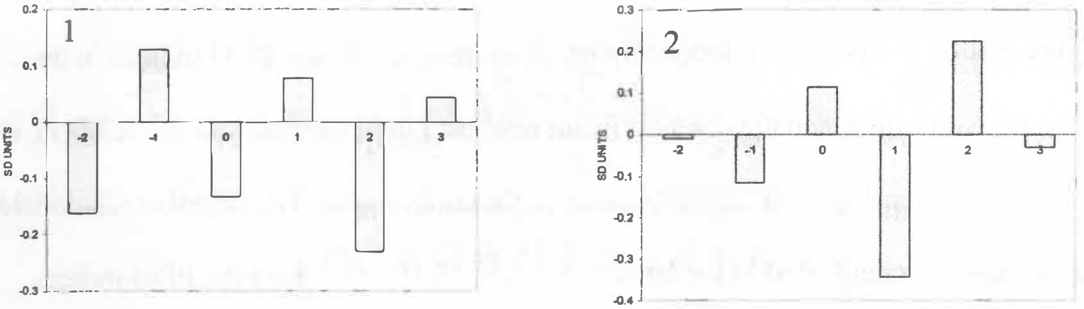


Figure 5.8 Correlation coefficients between JMA SST monthly index values and tree-ring indices for 1959–2003 (ENSO C).

A. TEXAS



B. FLORIDA



C. SOUTH CAROLINA

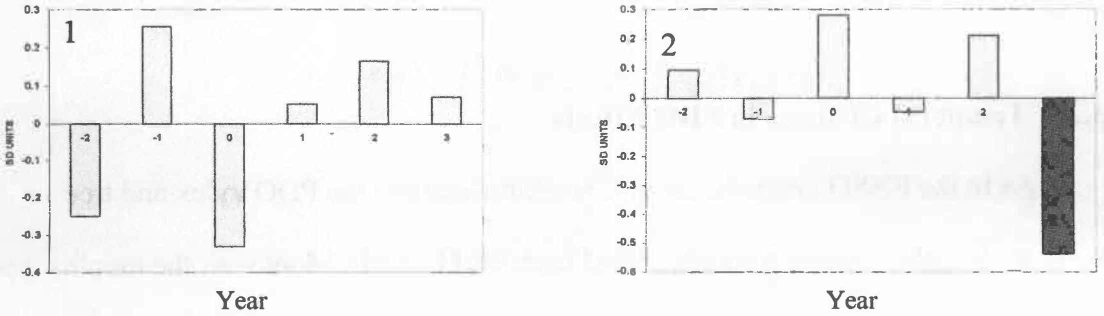


Figure 5.9 Superposed epoch analysis of ENSO effects on tree-ring indices for the period 1959–2003 (ENSO C). 1 = El Niño, 2 = La Niña.

5.3.2 PDO

5.3.2.1 Average over Entire Record (1900–2000)

For the 100 years of the PDO record, the strongest relationships between PDO and longleaf pine growth are seen in the Texas chronology (Figure 5.10A), where the relationship is consistently positive in large measure. The period from the previous October to the current December shows a number of statistically significant positive relationships between the PDO index and tree growth, particularly in the total ring width and earlywood widths (Figures 5.10A1 and 5.10A2). No clear relationships are evident, however, in the case of Florida (Figure 5.10B1). The general pattern for South Carolina (Figure 5.10C) is a positive relationship between tree growth and PDO indices in the previous year (with a statistically significant relationship in the previous November), and a negative relationship with the PDO index in the current year. The negative relationship is most strongly manifested in the latewood (Figure 5.10C3), where the PDO indices from the current year for July through December are significantly correlated with tree growth.

5.3.2.2 Temporal Changes in PDO Effects

As in the ENSO analysis, the relationships between the PDO index and tree growth are largely variable through time (Figures 5.11–5.14). Moreover, the months that display statistically significant relationships between PDO indices and tree growth are scattered and varied. For Texas, the relationship is generally positive during all periods except for PDO D (Figure 5.14A). Statistically significant and positive relationships are evident between PDO indices and tree growth in the previous October and current June

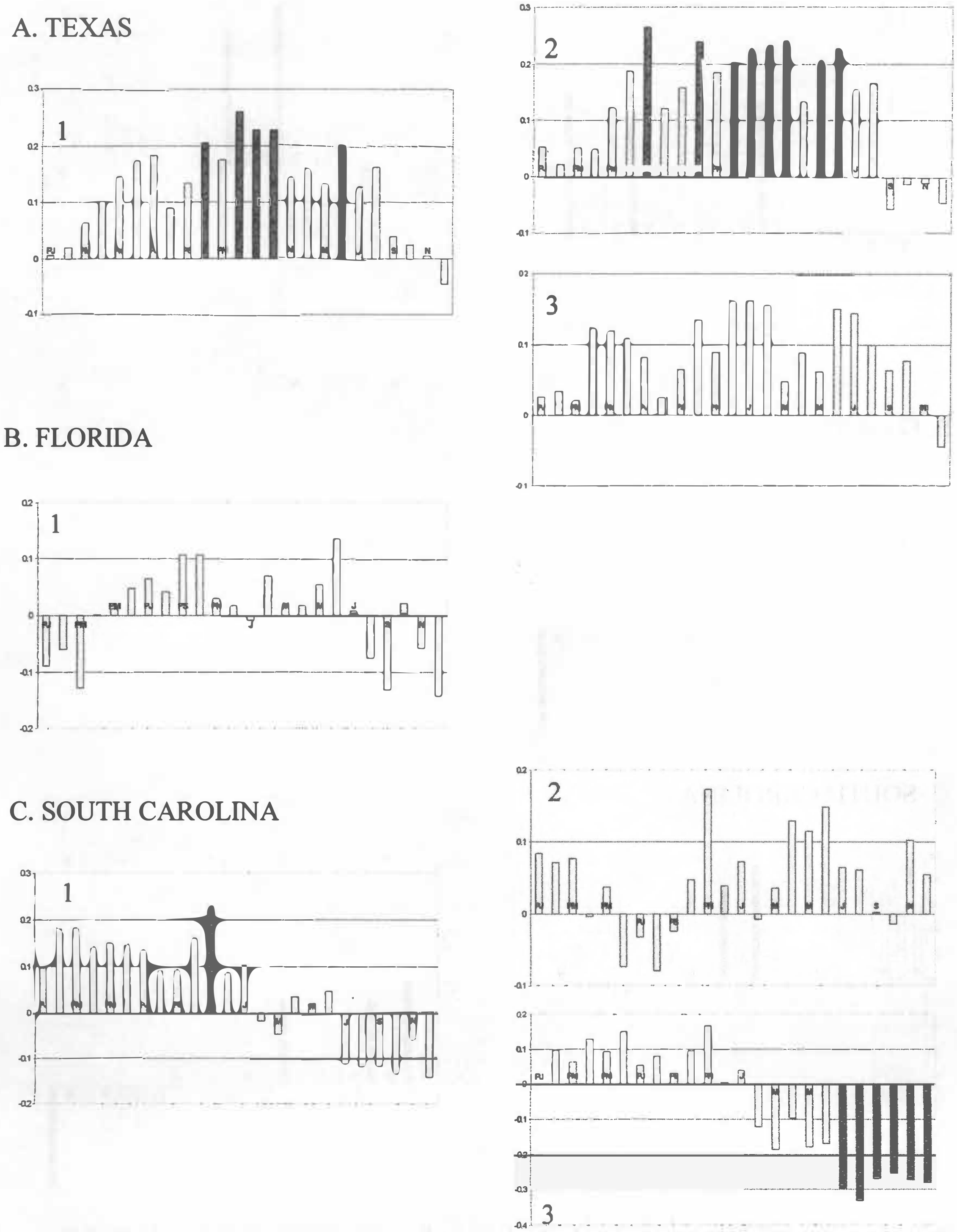


Figure 5.10 Correlation coefficients between PDO monthly index values and tree-ring indices for 1900–2000. Black bars indicate significance at 0.05 level. 1 = TRW, 2 = EWW, 3 = LWW. .

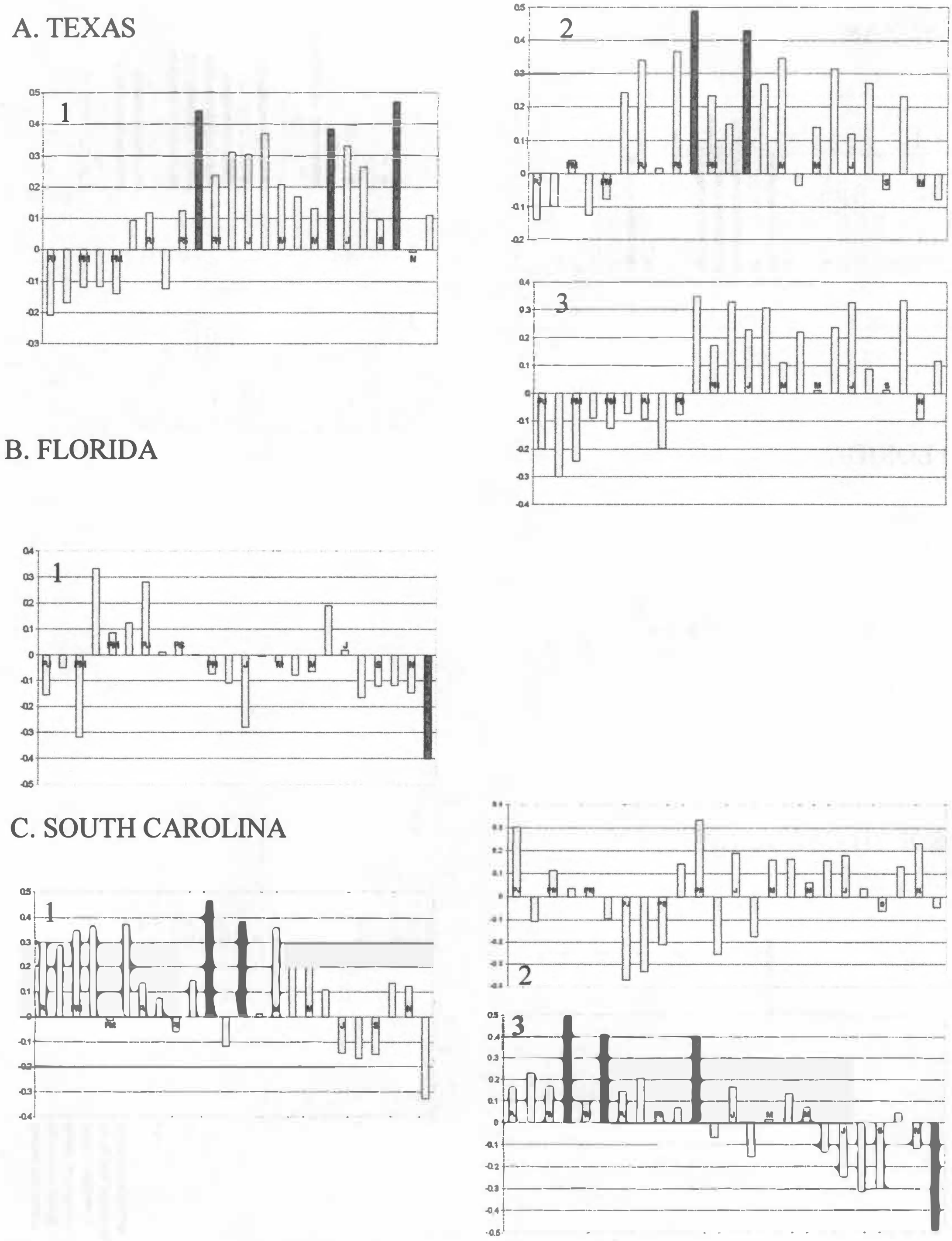
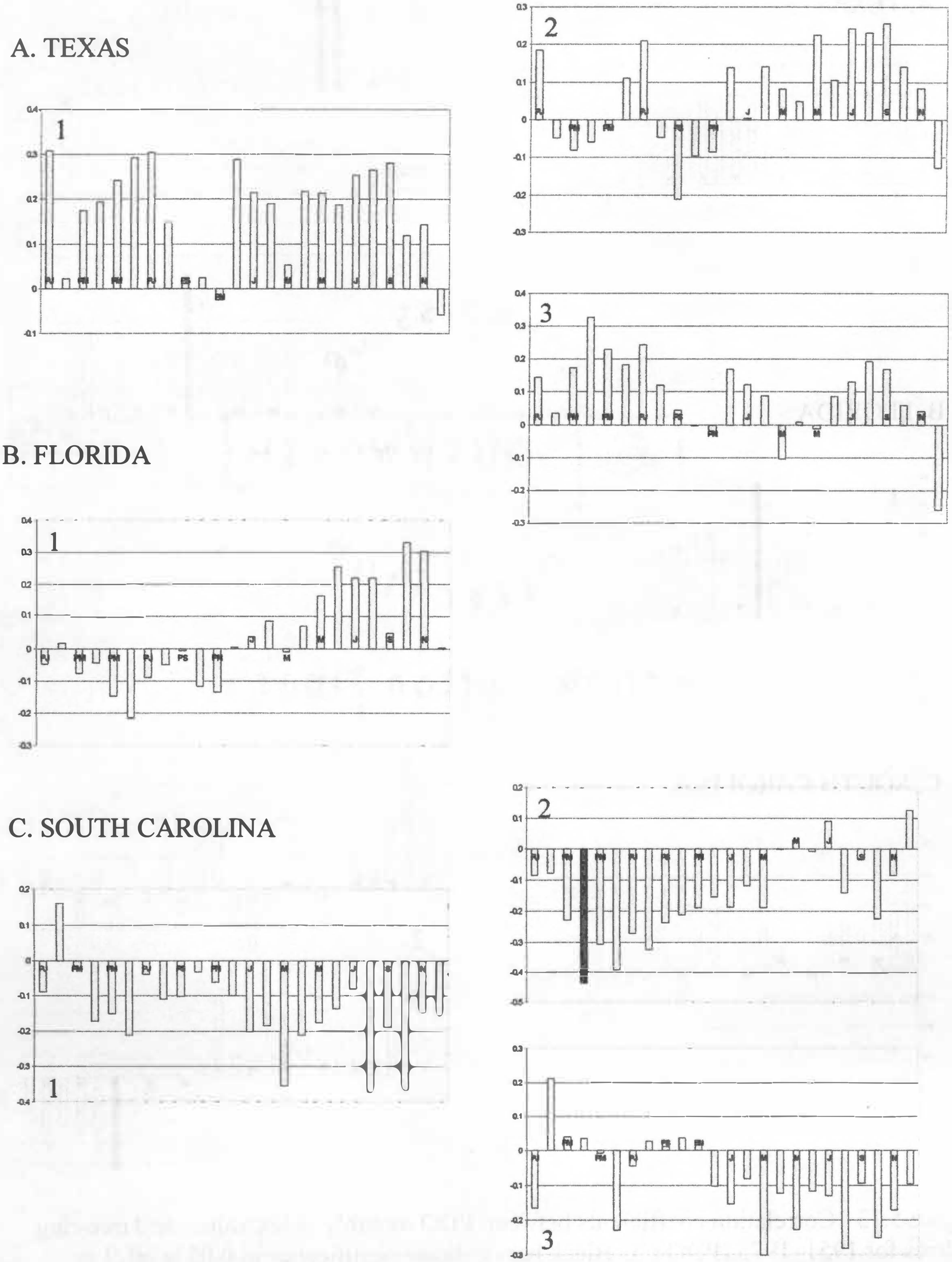


Figure 5.11 Correlation coefficients between PDO monthly index values and tree-ring indices for 1900–1925 (PDO A). Black bars indicate significance at 0.05 level. 1 = TRW, 2 = EWW, 3 = LWW.



A. TEXAS

B. FLORIDA

C. SOUTH CAROLINA

Figure 5.12 Correlation coefficients between PDO monthly index values and tree-ring indices for 1926–1950 (PDO B). Black bars indicate significance at 0.05 level. 1 = TRW, 2 = EWW, 3 = LWW.

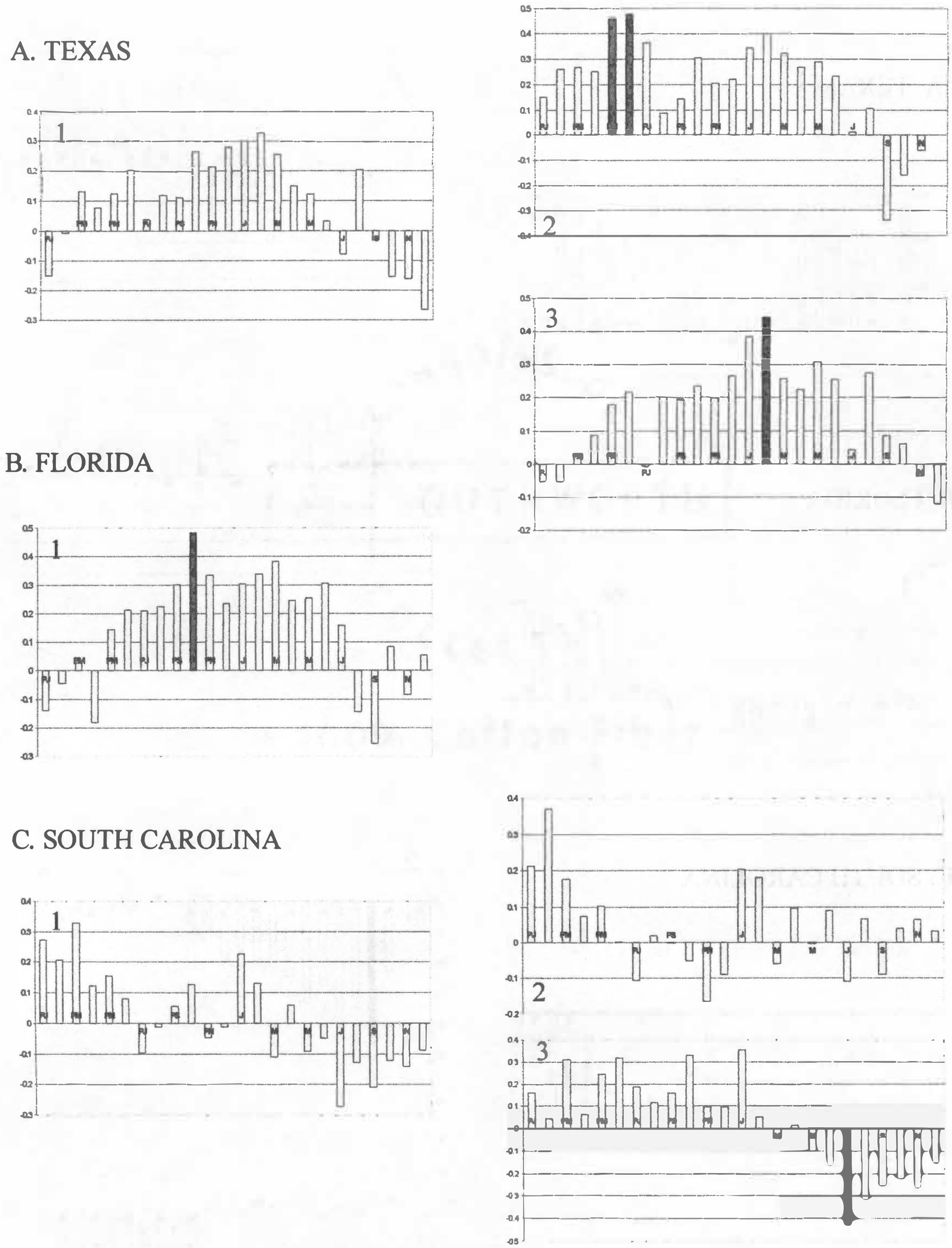
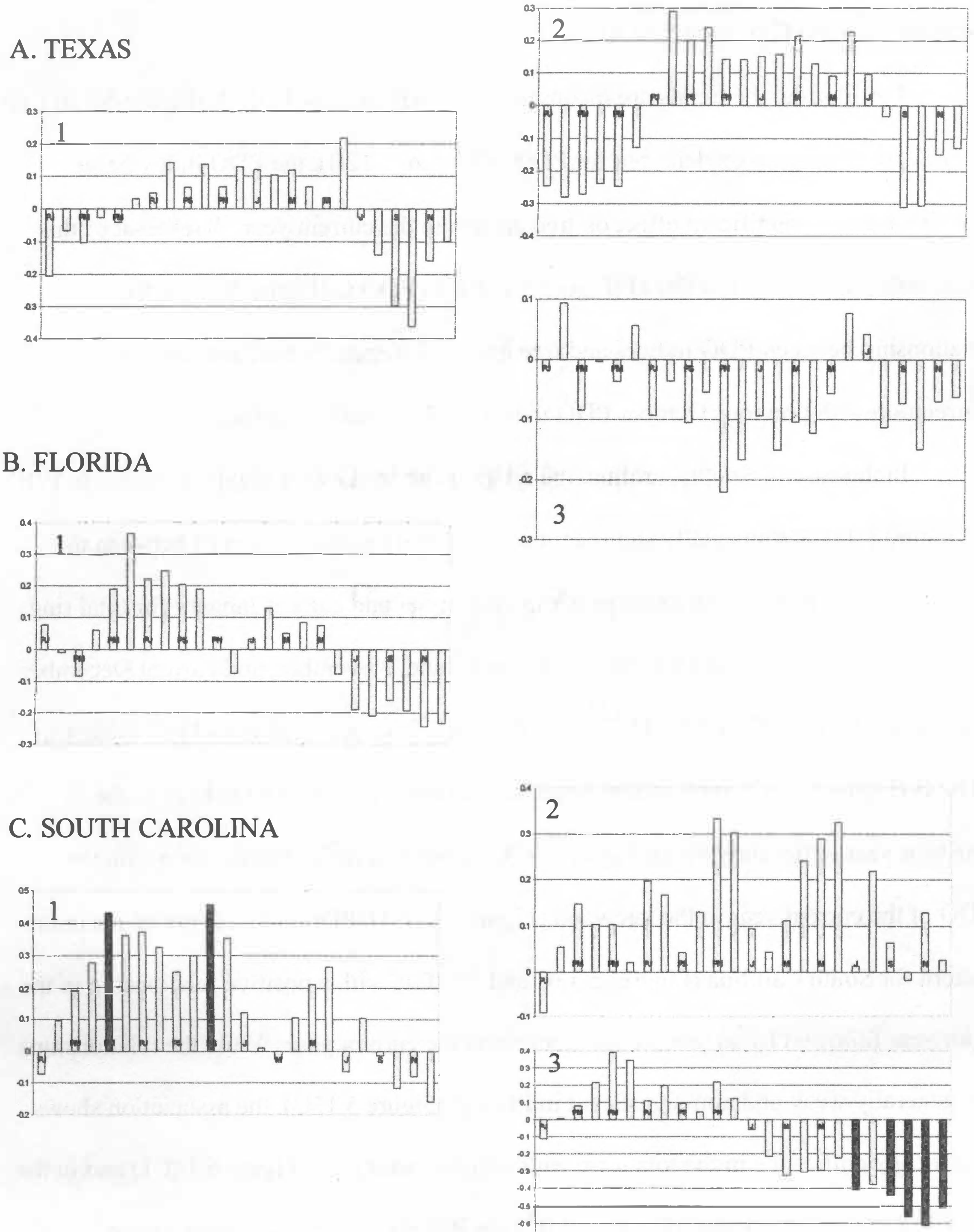


Figure 5.13. Correlation coefficients between PDO monthly index values and tree-ring indices for 1951–1975 (PDO C). Black bars indicate significance at 0.05 level. 1 = TRW, 2 = EWW, 3 = LWW.



A. TEXAS

B. FLORIDA

C. SOUTH CAROLINA

Figure 5.14 Correlation coefficients between PDO monthly index values and tree-ring indices for 1976–2000 (PDO D). Black bars indicate significance at 0.05 level. 1 = TRW, 2 = EWW, 3 = LWW.

and October in PDO A (Figure 5.11A) and in the previous May and June and current February in PDO C (Figure 5.13A).

For Florida, the trends are inconsistent throughout. For PDO A (Figure 5.11B), no significant effects are evident, but for PDO B (Figure 5.12B), the PDO index has a positive but non-significant effect on tree growth in the current year. A reversal of this relationship is evident in PDO D (Figure 5.14B). In PDO C (Figure 5.13B), the relationship between PDO indices and tree growth is generally positive, and the correlation with previous October PDO indices is statistically significant.

In the case of South Carolina, the relationship is likewise highly sporadic. In PDO A (Figure 5.11C), statistically significant and positive relationships exist between the PDO index and tree growth in the previous November and current January for total ring width (Figure 5.11C1), and with previous April, June, November, and current December for latewood width (Figure 5.11C3). Tree growth is inversely related to PDO indices in PDO B (Figure 5.12C), with a clear negative relationship with PDO indices in the previous year in the earlywood (Figure 5.12C2), and a negative relationship with the PDO of the current year in the latewood (Figure 5.12C3). PDO C and D reveal a similar pattern for South Carolina (Figures 5.13C and 5.14C) , with a positive relationship in the prior year followed by an inverse relationship in the current year. While the relationships are generally weak and non-significant in PDO C (Figure 5.13C), the association shows statistical significance in the total ring width for the prior year (Figure 5.14C1) and in the latewood in the current year (Figure 5.14C3) in PDO D. In fact, the months from September through December show highly significant correlations between tree growth and PDO indices in the latewood (Figure 5.14C3). PDO D (Figure 5.14C) obviously influences the overall pattern of the relationship from 1900–2000 in South Carolina.

5.3.3 NAO

5.3.3.1 Average over Entire Record (1865–2002)

The effects of NAO on tree growth at all sites were generally weak and unpredictable except for a few select months in which the NAO index was related to tree growth at statistically significant levels (Figure 5.15). In almost all cases, the association between NAO indices and tree growth was negative. In the Texas chronology (Figure 5.15A), the NAO index for January of the previous year was significantly and inversely associated with total ring width (Figure 5.15A1) and latewood width (Figure 5.15A3). For earlywood widths (Figure 5.15A2), previous March and December NAO indices were positively related to tree growth, while for latewood widths (Figure 5.15A3), NAO indices for the previous January and August were negatively related to tree growth. Similarly, the NAO index from the previous August also showed an inverse correlation with tree growth in Florida (Figure 5.15B1) and South Carolina (Figure 5.15C), but these effects were apparent in the total ring width (Figures 5.15B1 and 5.15C1) and earlywood widths (Figure 5.15C2) as opposed to latewood widths as in Texas. Another consistent trend between Florida and South Carolina was the inverse relationship between the NAO index in May and tree growth for total ring width (Figure 5.15B1 and 5.15C1) and both earlywood and latewood widths (Figures 5.15C2 and 5.15C3). Although the effects were not statistically significant, the NAO index for May also had a negative effect on tree growth for Texas (Figure 5.15A1).

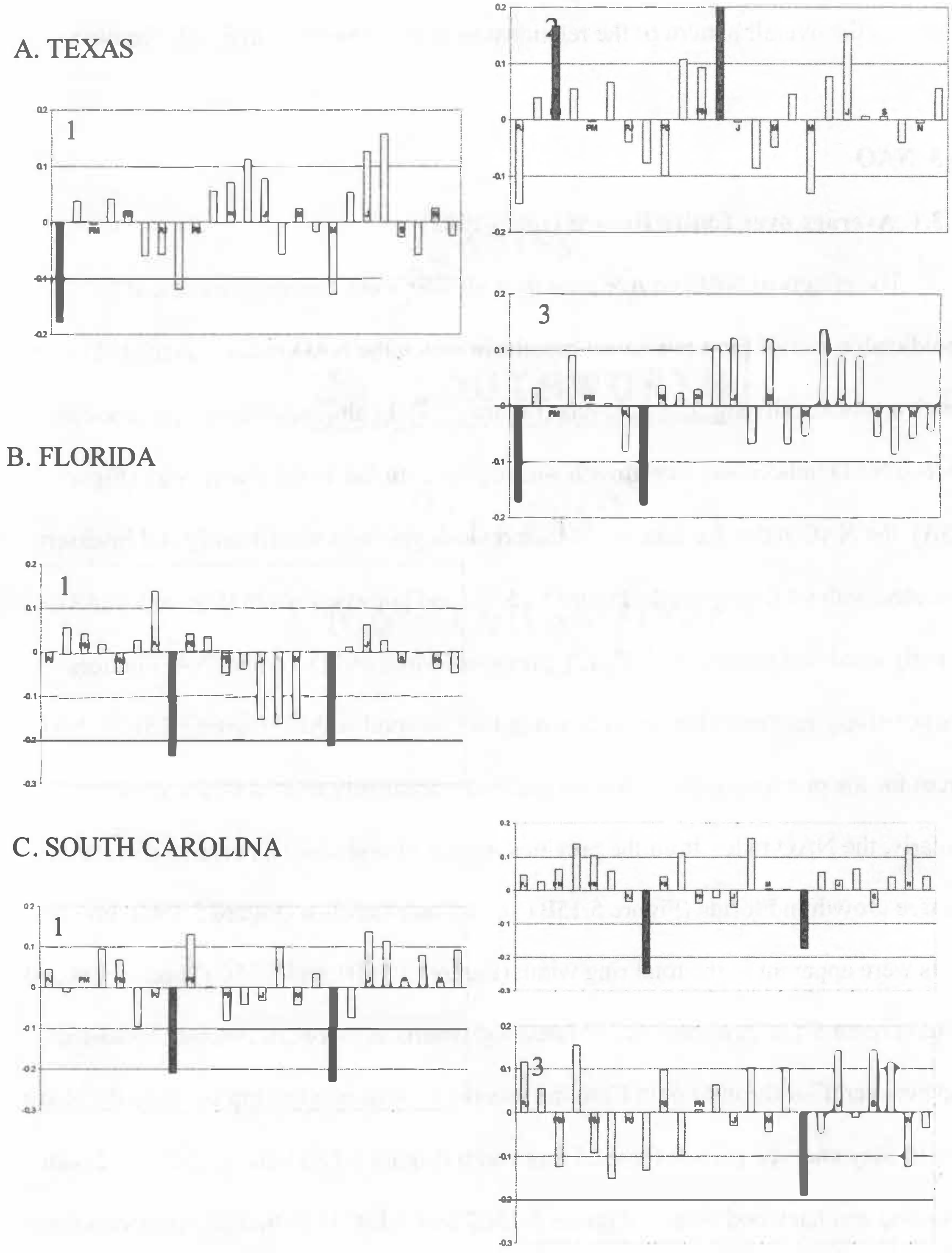


Figure 5.15 Correlation coefficients between NAO monthly index values and tree-ring indices for 1865–2002. Black bars indicate significance at 0.05 level. 1 = TRW, 2 = EWW, 3 = LWW.

5.3.3.2 Temporal Changes in NAO Effects

An examination of the changes through time of NAO effects reveals a continually erratic signal of NAO over the 24 month period of analysis, but the months that showed statistically significant relationships between NAO indices and tree growth remain generally consistent throughout (Figures 5.16–5.19). For example, in Texas, the NAO index for the previous January is almost always inversely related to total ring width except in NAO B (Figure 5.17A1). Although the level of statistical significance varies through time, the NAO indices from the previous July through September tend to show a negative relationship with tree growth in the latewood in all periods except NAO D (Figure 5.19A3). Curiously, the NAO index in the current November and December was positively and significantly correlated to earlywood growth in NAO A (Figure 5.16A2) and B (Figure 5.17A2). Another unusual finding was the positive relationship between the NAO index and earlywood growth in June for NAO C (Figure 5.18A2).

For the Florida chronology, the negative relationship between NAO indices from the August of the year prior and May of the current year was consistent in all periods except NAO D (Figure 5.19B). In fact, the relationship with respect to the NAO index of the previous August and tree growth was statistically significant in both NAO A (Figure 5.161) and B (Figure 5.17B1). The only other month with statistically significant correlation coefficients was December of the prior year in NAO B (Figure 5.17B1), but this relationship was not consistent with the other periods.

As in the Florida case, the NAO indices from the previous August and current May for South Carolina were inversely related to total ring width in most periods, but the relationship was strongest in NAO A (Figure 5.16C1) and B (Figure 5.17C1). The only

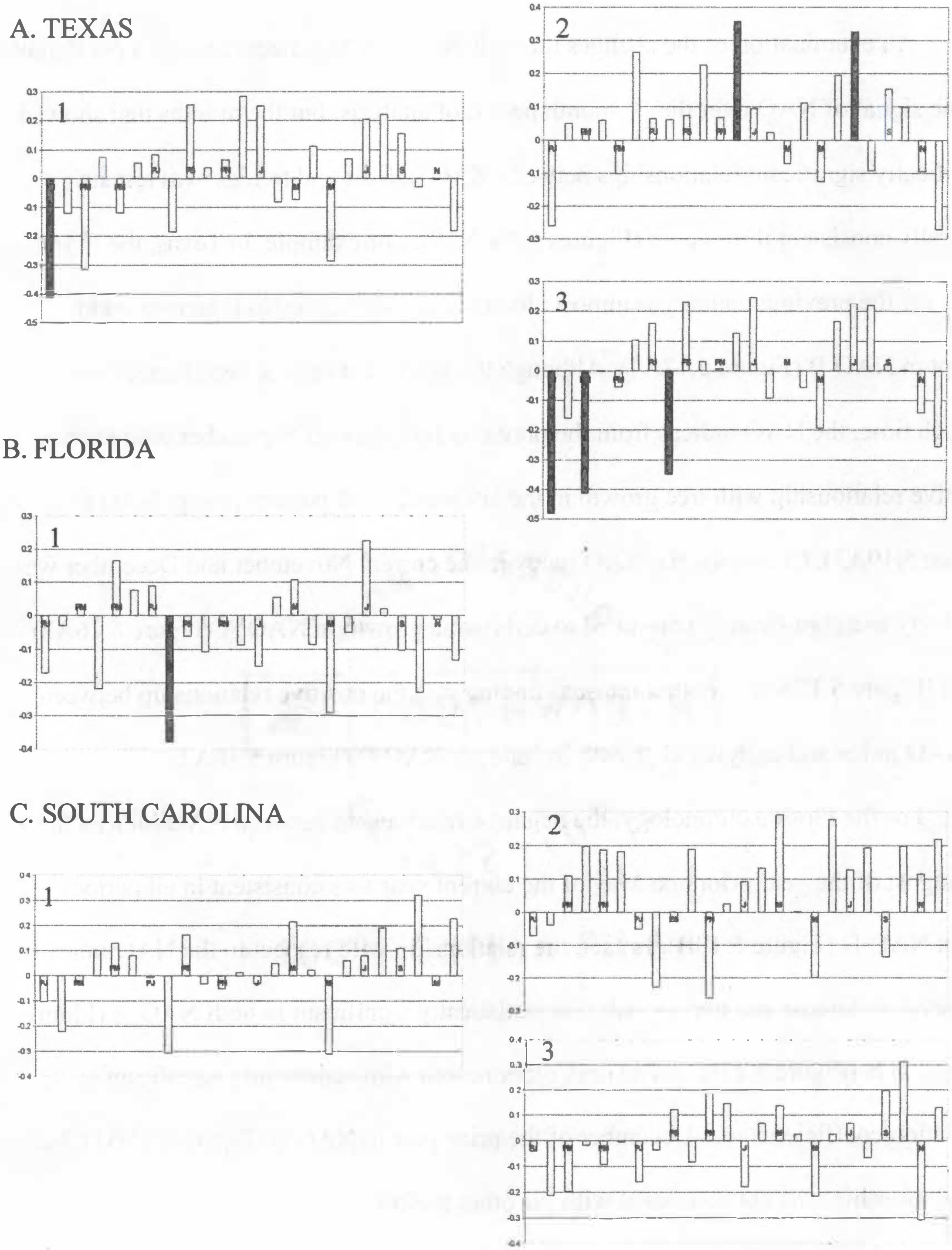
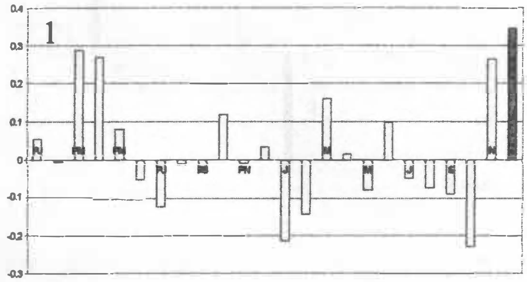
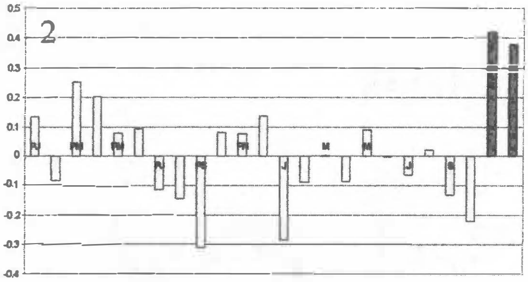
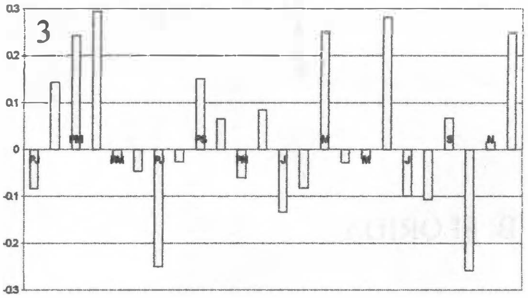


Figure 5.16 Correlation coefficients between NAO monthly index values and tree-ring indices for 1865–1900 (NAO A). Black bars indicate significance at 0.05 level. 1 = TRW, 2 = EWW, 3 = LWW.

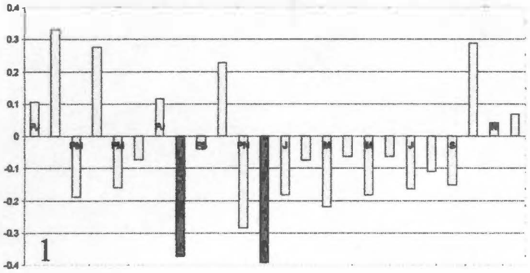
A. TEXAS



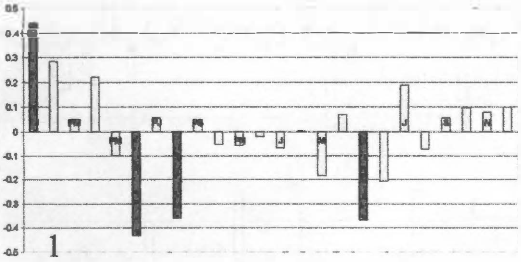


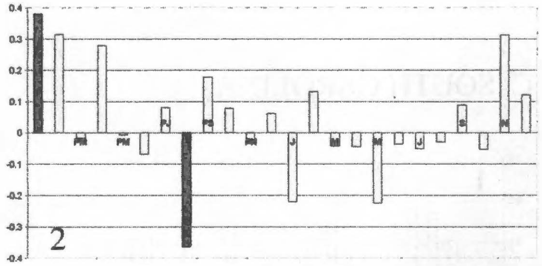


B. FLORIDA



C. SOUTH CAROLINA





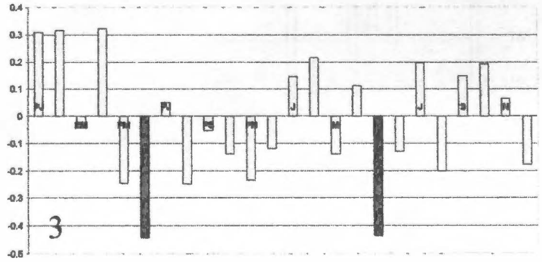
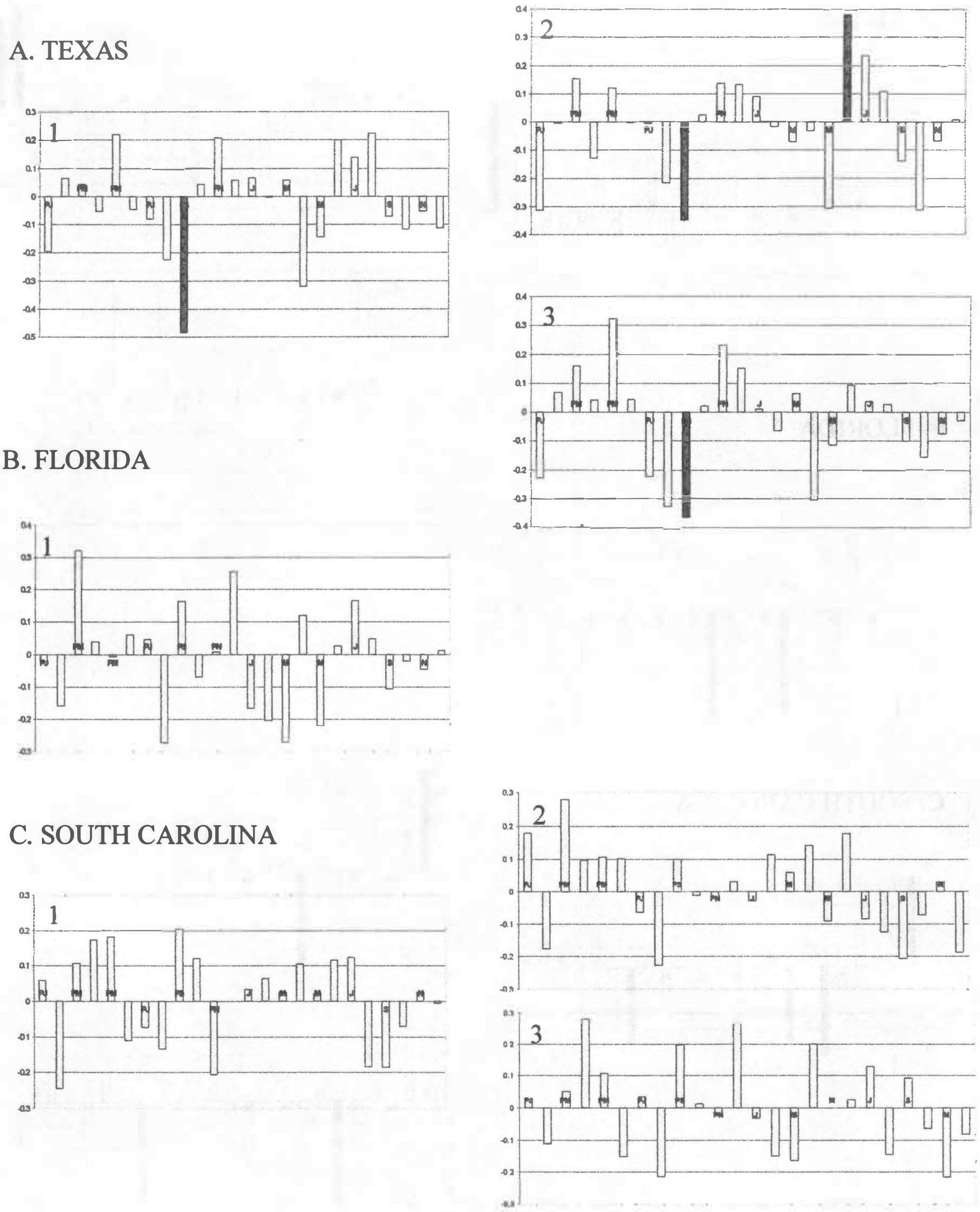


Figure 5.17 Correlation coefficients between NAO monthly index values and tree-ring indices for 1901–1935 (NAO B). Black bars indicate significance at 0.05 level. 1 = TRW, 2 = EWW, 3 = LWW.

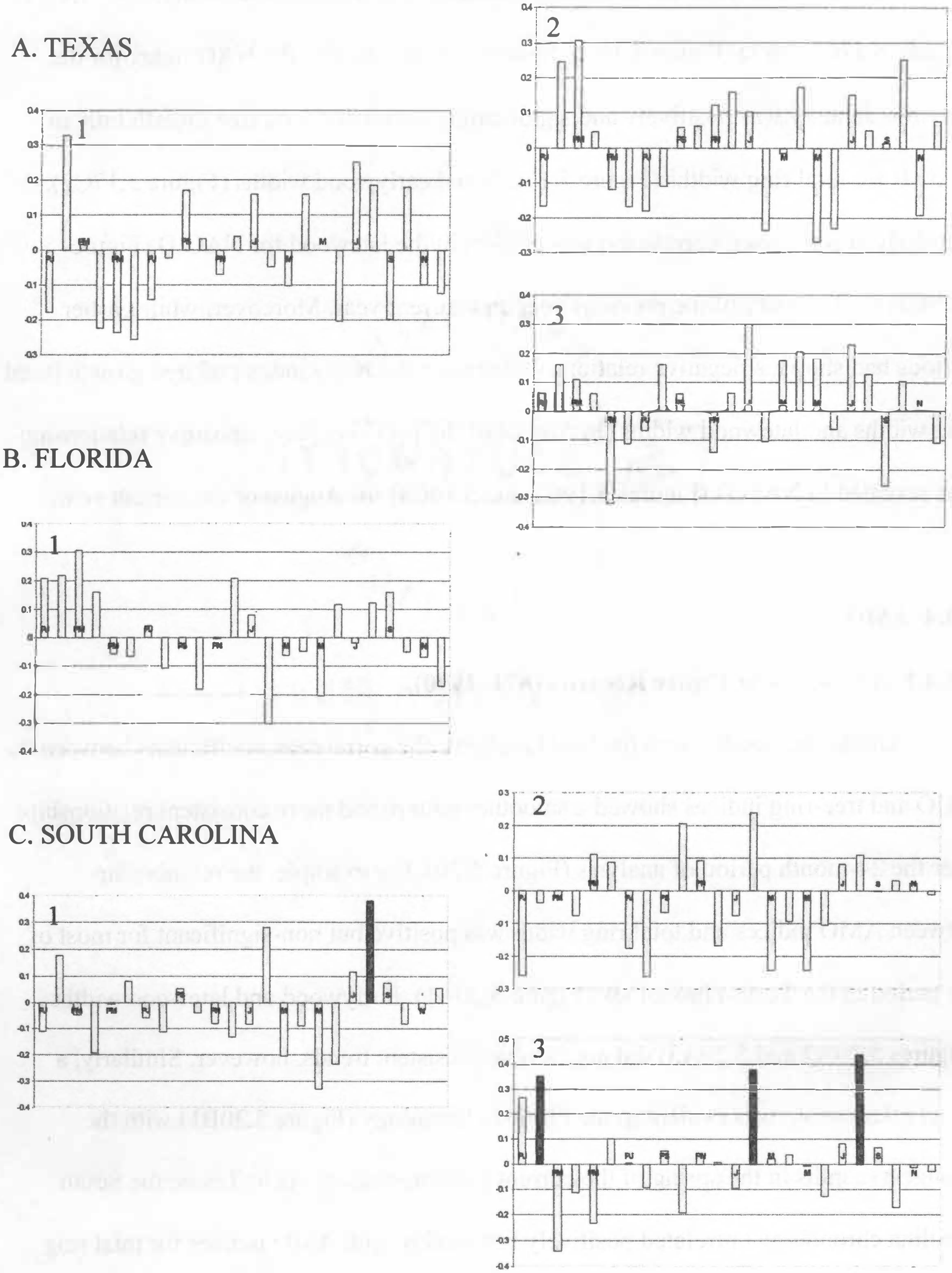


A. TEXAS

B. FLORIDA

C. SOUTH CAROLINA

Figure 5.18 Correlation coefficients between NAO monthly index values and tree-ring indices for 1936–1970 (NAO C). Black bars indicate significance at 0.05 level. 1 = TRW, 2 = EWW, 3 = LWW.


A. TEXAS

B. FLORIDA

C. SOUTH CAROLINA

Figure 5.19 Correlation coefficients between NAO monthly index values and tree-ring indices for 1971–2002 (NAO D). Black bars indicate significance at 0.05 level. 1 = TRW, 2 = EWW, 3 = LWW.

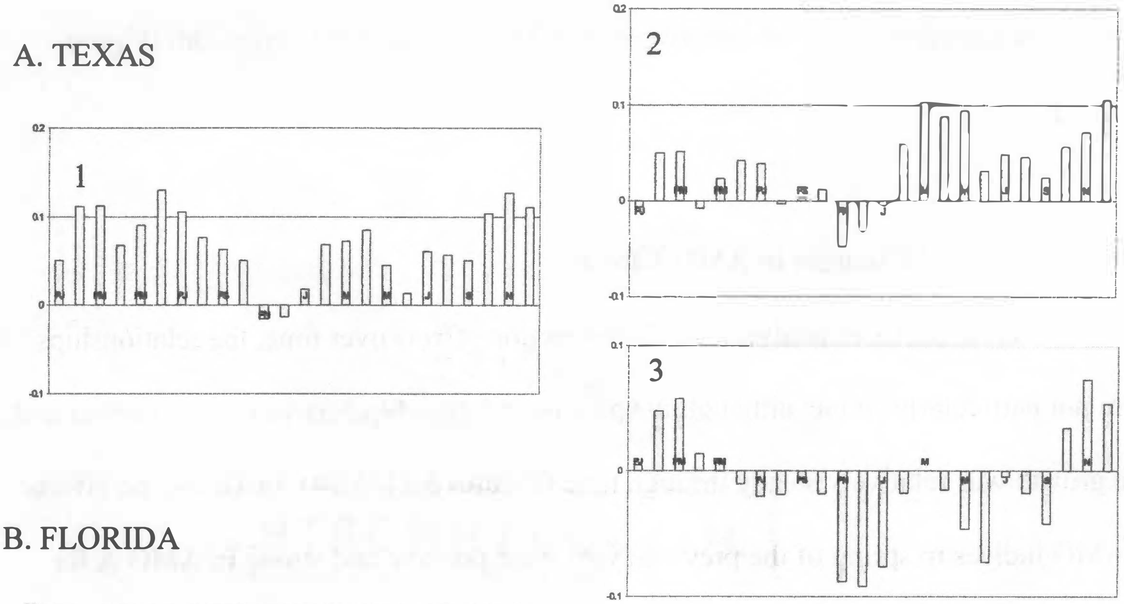
periods in South Carolina that showed statistically significant correlations were NAO B (Figure 5.17C) and D (Figure 5.19C), however. Interestingly, the NAO index for the previous January was positively and significantly correlated with tree growth only in NAO B for total ring widths (Figure 5.17C1) and earlywood widths (Figure 5.17C2). Similarly, a significant correlation was evident in the latewood for NAO D (Figure 5.19C3) for February of the previous year and current year. Moreover, while earlier periods had shown a negative relationship between the NAO index and tree growth (total ring widths and latewood widths) in August of the previous year, a positive relationship was revealed in NAO D (Figures 5.19C1 and 5.19C3) for August of the current year.

5.3.4 AMO

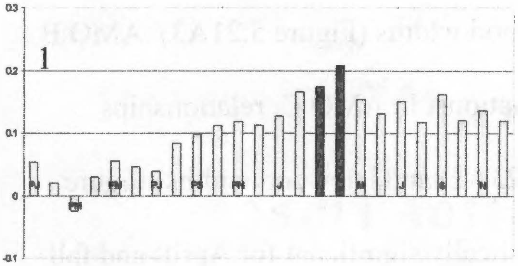
5.3.4.1 Average over Entire Record (1871–1990)

Unlike the results from the NAO analysis, the correlation coefficients between the AMO and tree-ring indices showed a smoother pattern and more consistent relationships over the 24-month period of analysis (Figure 5.20). For example, the relationship between AMO indices and total ring width was positive but non-significant for most of the period in the Texas chronology (Figure 5.20A1). Earlywood and latewood widths (Figures 5.20A2 and 5.20A3) did not exhibit consistent trends, however. Similarly, a direct relationship was evident in the Florida chronology (Figure 5.20B1) with the strongest months in the spring of the current growing season. As in Texas, the South Carolina chronology correlated positively but weakly with AMO indices for total ring widths (Figure 5.20C1) and earlywood widths (Figure 5.20C2), but relationships with latewood widths were nonexistent (Figure 5.20C3). Although the values were not

A. TEXAS



B. FLORIDA



C. SOUTH CAROLINA

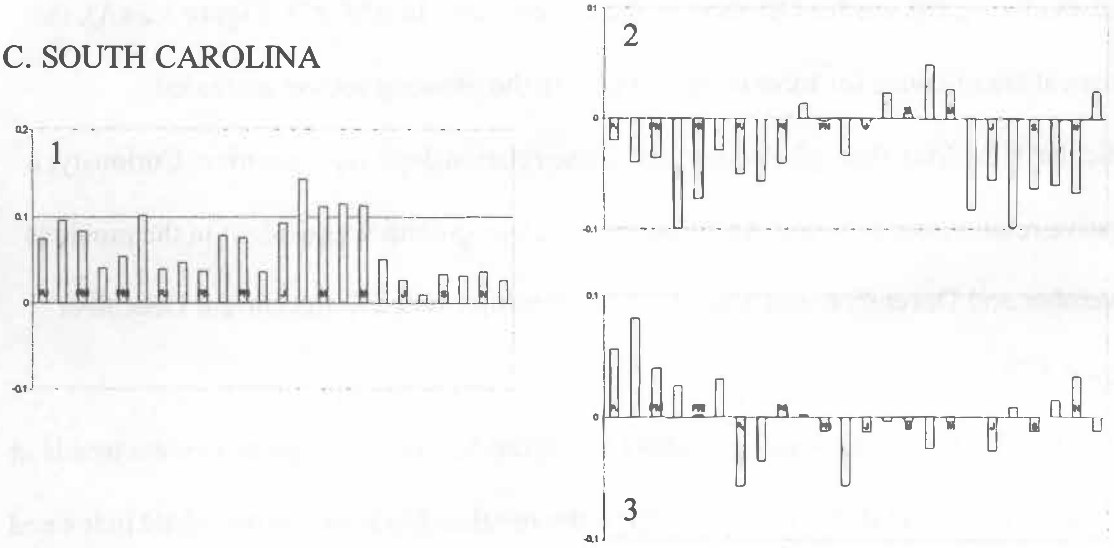


Figure 5.20 Correlation coefficients between AMO monthly index values and tree-ring indices for 1871–1990. Black bars indicate significance at 0.05 level. 1 = TRW, 2 = EWW, 3 = LWW.

statistically significant, as in the Florida case, the late winter to early spring months showed the strongest relationship between AMO indices and total ring width (Figure 5.20C1).

5.3.4.2 Temporal Changes in AMO Effects

As in all previous analyses of teleconnection effects over time, the relationships were not particularly stable, although the positive relationship between AMO indices and tree growth was relatively steady through time (Figures 5.21–5.24). In Texas, the effects of AMO indices in spring of the previous year were positive and strong in AMO A for both total ring widths (Figure 5.21A1) and latewood widths (Figure 5.21A3). AMO B (Figure 5.22A), however, showed no clear associations. In AMO C, relationships between AMO indices and earlywood (Figure 5.23A2) and latewood widths (Figure 5.23A3) were positive and strong in spring (statistically significant for April) and fall (statistically significant for October) of the current year. In AMO D (Figure 5.24A), the statistical significance for most of the months in the growing season increased, particularly for May through August, and these relationships were positive. Curiously, a negative relationship between AMO indices and tree growth was evident in the previous November and December, and a positive relationship existed in the current December (Figure 5.24A1).

For the Florida chronology, AMO A (Figure 5.21B1) showed no evident trends in AMO effects. For AMO B (Figure 5.22B1), the relationship between the AMO index and tree growth is generally positive with a peak in September of the previous year and current April. The pattern in AMO C (Figure 5.23B1) and D (Figure 5.24B1) is

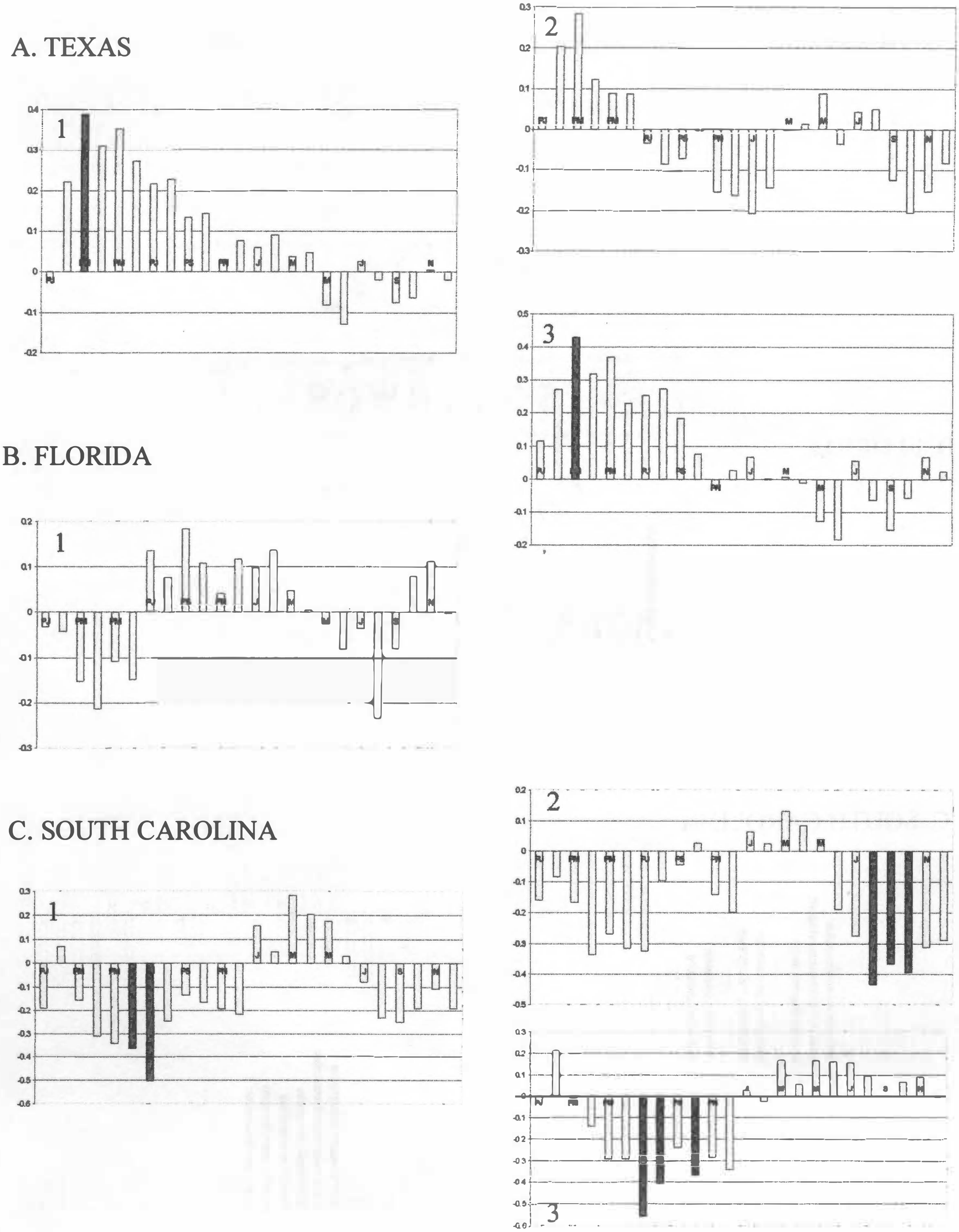
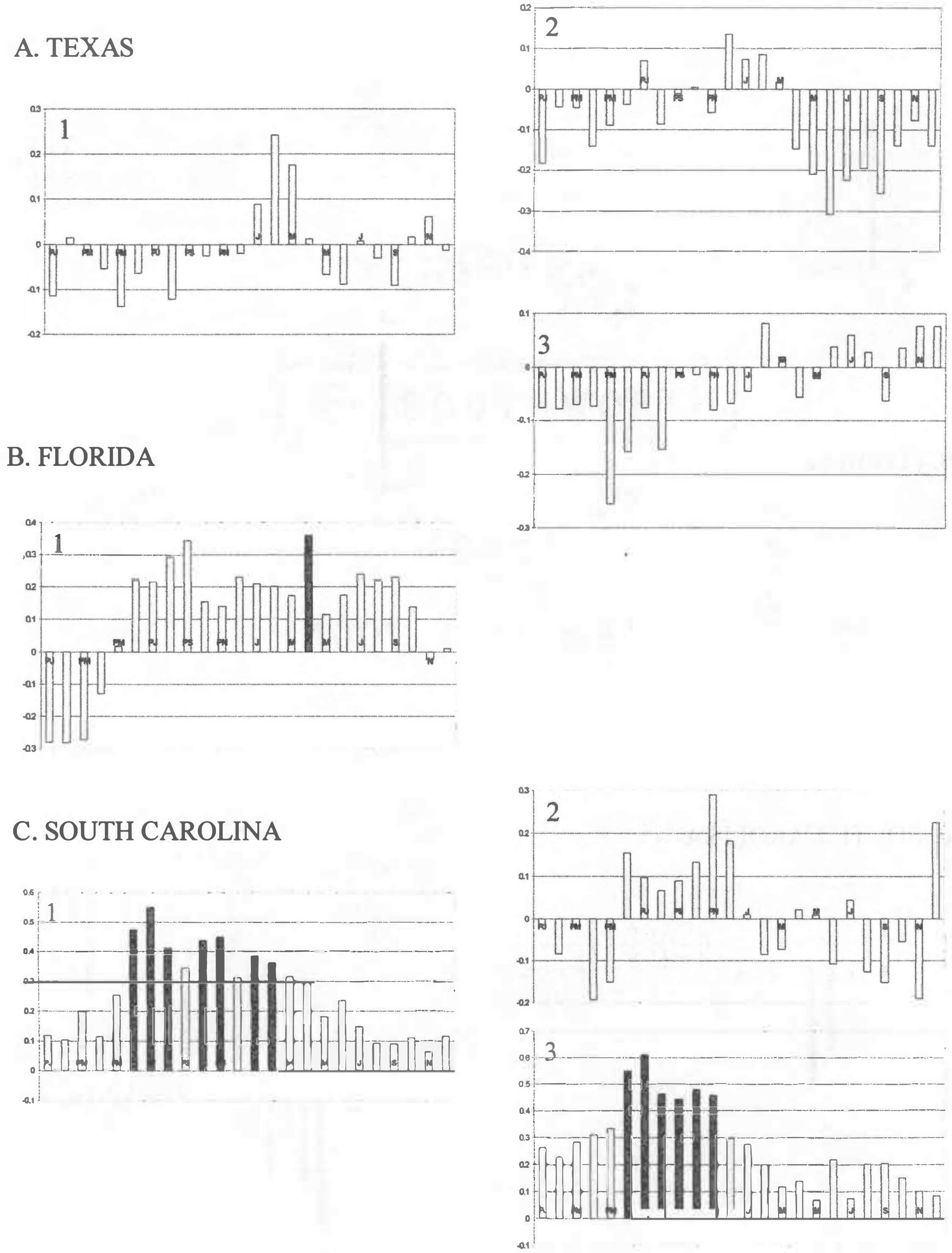


Figure 5.21 Correlation coefficients between AMO monthly index values and tree-ring indices for 1871–1900 (AMO A). Black bars indicate significance at 0.05 level. 1 = TRW, 2 = EWW, 3 = LWW.


A. TEXAS

B. FLORIDA

C. SOUTH CAROLINA

Figure 5.22 Correlation coefficients between AMO monthly index values and tree-ring indices for 1901–1930 (AMO B). Black bars indicate significance at 0.05 level. 1 = TRW, 2 = EWW, 3 = LWW.

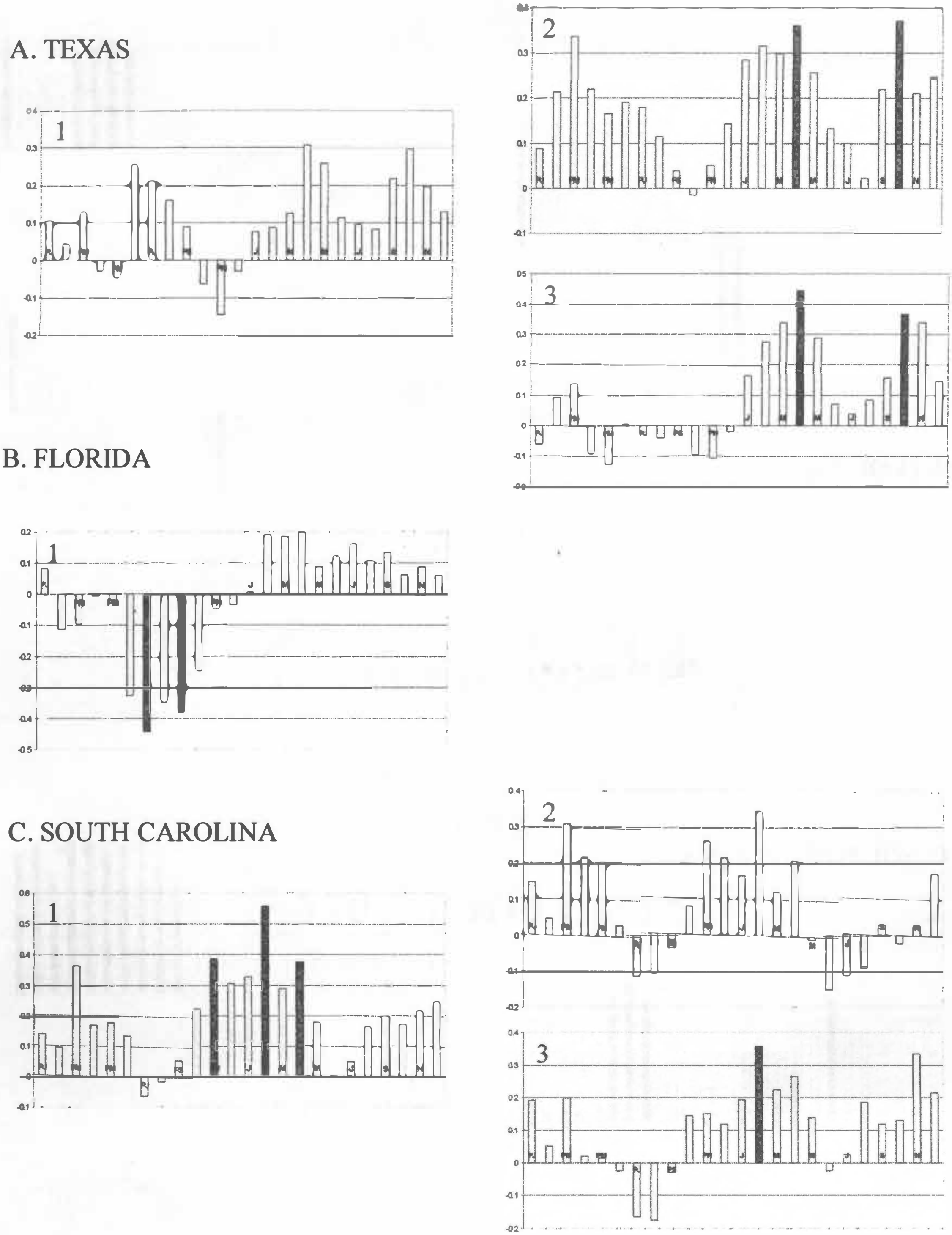


Figure 5.23 Correlation coefficients between AMO monthly index values and tree-ring indices for 1931–1960 (AMO C). Black bars indicate significance at 0.05 level. 1 = TRW, 2 = EWW, 3 = LWW.

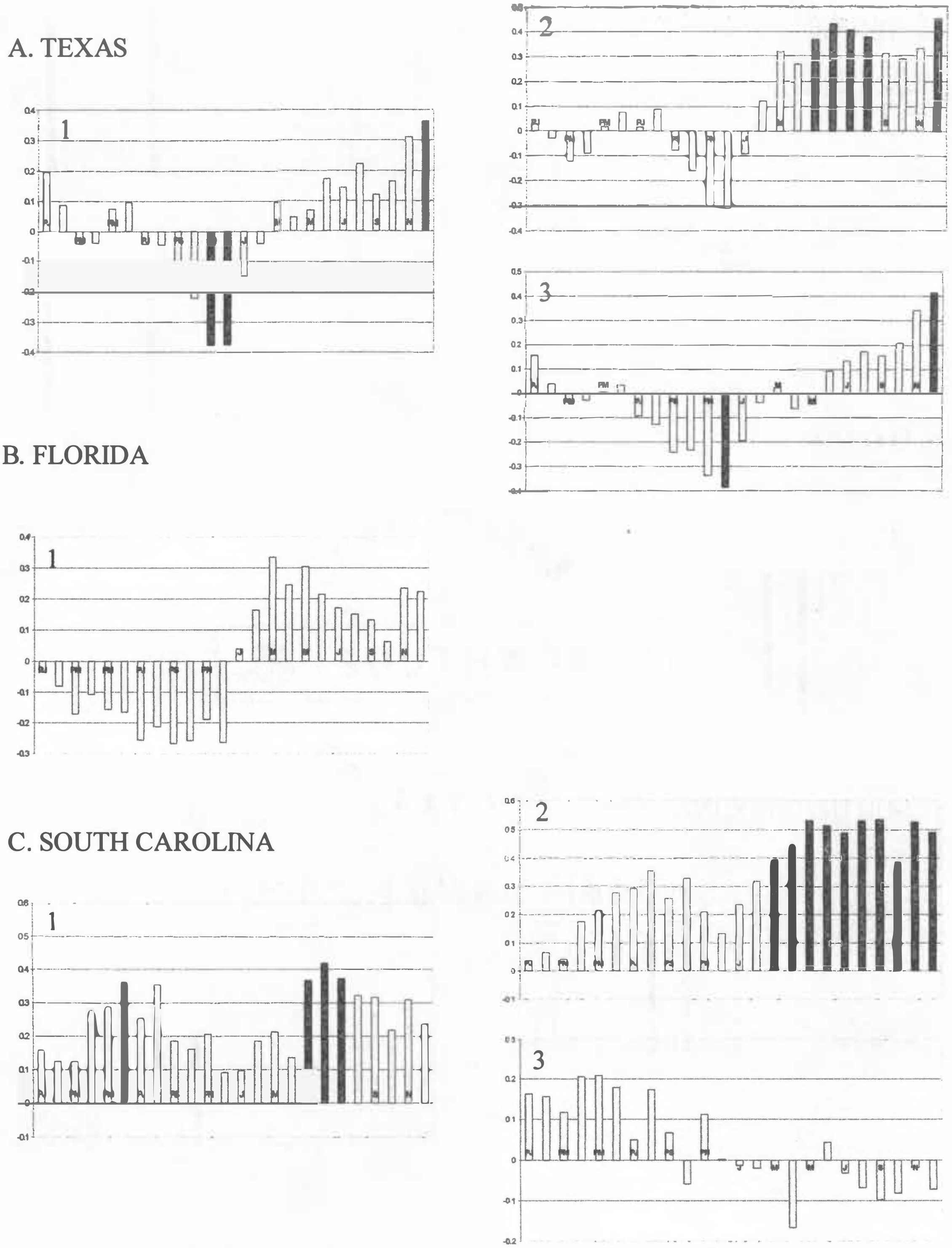


Figure 5.24 Correlation coefficients between AMO monthly index values and tree-ring indices for 1961–1990 (AMO D). Black bars indicate significance at 0.05 level. 1 = TRW, 2 = EWW, 3 = LWW.

remarkably similar, with a negative relationship in the previous year followed by a direct relationship in the current year. The association between tree growth and AMO indices is strongest from the previous June through the previous September in AMO C (Figure 5.23B1).

The correlations in the South Carolina results between AMO indices and tree growth are mostly positive for all periods except in AMO A (Figure 5.21C). For AMO A, AMO indices in June and July of the previous year are negatively correlated with tree growth for total ring widths (Figure 5.21C1) and latewood widths (Figure 5.21C3). Moreover, earlywood widths (Figure 5.21C2) are negatively and significantly correlated with AMO indices in August through October of the current year. In AMO B (Figure 5.22C), the strongest relationships are from June of the prior year through February of the current year, and these positive associations are found in both the total ring width (Figure 5.22C1) and latewood width (Figure 5.22C3). The correlations between AMO indices and tree growth in AMO C (Figure 5.23C) are highest in the previous November through current February, with a strong statistically significant positive relationship in February in both total ring widths (Figure 5.23C1) and latewood widths (Figure 5.23C3). In AMO D, the effects of AMO are particularly significant from February through December in earlywood widths (Figure 5.24C2) but not in the latewood (Figure 5.24C3). The correlations coefficients for these months are some of the highest in any of the teleconnection analyses.

5.4 Discussion

The effects of these four teleconnections on tree growth in the three locations of the Southeastern Coastal Plain were not stable over time, but the statistical significance of the relationships indicates that all of these oscillations affect the region to some degree. The weakness of using tree rings to examine the effects of teleconnections in the Southeast is that the timing of the strongest teleconnections may occur in the winter when the trees are least sensitive to moisture anomalies. For example, the NAO and ENSO are most strongly teleconnected with the southeastern U.S. during the winter (Stahle and Cleaveland 1992). Individually, these teleconnections represent only a small portion of the variance in climate in the Southeastern Coastal Plain. Moreover, the strength of these teleconnections varies through time, and one particular phase of one teleconnection can significantly affect other "competing" teleconnnections. In fact, the most important influence on rainfall in the Southeast is not teleconnections such as ENSO, but the Bermuda High pressure system (Katz *et al.* 2003). Thus, climate anomalies in the extratropics are often unrelated to remote signals from maritime sources.

The analysis of temporal variations in the teleconnections displays the complexity of the effects through time and illustrates the difficulty in determining the appropriate temporal scales for this type of analysis. Only using average values obscures the inherent variability in the strength and consistency of the teleconnections. Moreover, the relationship between the phase of teleconnections and their effects is not straightforward.

The results also underscore the importance of analyzing earlywood, latewood, and total ring widths separately, because the strength of the teleconnection signal is usually most pronounced in one of these measurements of the annual increment. As these results demonstrate, the potential for increasing the skill of tree-ring reconstruction models of teleconnections is much greater if earlywood, latewood, and total ring widths are incorporated into tree-ring chronologies.

5.4.1 ENSO

The presence of a significant effect of ENSO on longleaf pine trees in the Southeastern Coastal Plain was not unexpected, but the statistically significant results are noteworthy. The signal from ENSO in the U.S. is small compared to the natural variability of the local climate, so a considerable amount of climate variability from one ENSO event to the next must be unrelated to SSTs in the tropical Pacific (Dole 2000). For this reason, several studies in the Southeastern U.S. have found little to no influence of ENSO on tree growth. A strong ENSO influence on summer drought reconstructions for the southeastern U.S. was not detected by Cleaveland *et al.* (1992), but the region was poorly represented by climate sensitive tree-ring chronologies. Previous studies with region-wide data from baldcypress trees showed no statistically significant, and generally weak, effects of ENSO in the Southeast (Stahle and Cleaveland 1992; Stahle and Cleaveland 1996).

No statistically significant telecommunication relationships were evident for the Florida chronology, but several robust associations were apparent in Texas and South Carolina. Despite the fact that ENSO events in the southeastern U.S. primarily affect winter precipitation and temperature (Smith *et al.* 1999), I attribute the primary effects of ENSO on tree growth to ENSO conditions during the previous/current summer and early fall months. A fair amount of persistence is evident in the ENSO data, and this persistence is manifested in significant correlations that continue into December of the current year. However, the highest correlation coefficients are those relating tree ring width to ENSO normally from July to September, so I believe ENSO conditions in these months have the most important effect on tree growth.

For all the chronologies, a generally positive relationship exists between ENSO and tree growth in the prior year, while a negative relationship exists between ENSO and tree growth in the current year. The relationship with the ENSO indices of the prior year and tree growth was strongest at the Texas site, while the relationship in the current year was the most salient at the South Carolina site. For the Florida chronology, the most consistent relationship was the inverse relationship between ENSO and tree growth in the current year. Sittel (1994) found that summer precipitation levels were below average during El Niño summers in northern Florida, so my findings are in agreement with his.

The results of the SEA for Texas show that the effects of ENSO events are most significant in year t+1. These findings are not unexpected, based on the typical lag in ENSO teleconnection effects in the Northern Hemisphere. El Niño events typically develop in March through May and last at least one year, but the effects are most evident in the extratropics in the northern winter at the end of year that the event develops and into year t+1 (Diaz and Kiladis 1992). Cleaveland *et al.* (1992) also found that warm ENSO events in Texas produced above-average tree growth in year t+1, and La Niña events had the opposite effect. Similarly, Woodhouse (1993) found a one year lag in tree-response to ENSO events in the Colorado Front Range.

For Florida and South Carolina, no lag effect is apparent in the SEA analysis however, and El Niño events have tended to produce below-average tree growth.

Conversely, La Niña events produce above-average tree growth. I attribute these differences in growth to variations in dry moisture conditions in summer and early fall that are primarily manifested in poor latewood growth. These findings support previous research on ENSO in the Southeast. El Niño summers are generally drier than normal in North Carolina, while La Niña summers show an opposite effect (Roswintiarti *et al.* 1998; Boyles 2000). Katz *et al.* (2003) also found a negative relationship between the Southern Oscillation (SO) index and winter precipitation in Tallahassee, Florida. However, for most other sites in the Southeast, no association was evident between the SO and winter precipitation (Katze *et al.* 2003). Corn yields in Florida and South Carolina are generally higher in La Niña years, presumably because of higher June rainfall during cool ENSO events (Hansen *et al.* 1998; Mennis 2001). That the longleaf pine growth in South Carolina seemed to be significantly affected by ENSO is not surprising because Sir Gilbert Walker used pressure data from Charleston, South Carolina in his initial investigations of the Southern Oscillation (Stahle *et al.* 1998).

The relatively weak response of longleaf pine trees in the Florida panhandle to ENSO events is similar to the findings of Parker *et al.* (2001). No relationship was found between growth and ENSO phase for inland stands of sand pine in the Florida panhandle (Parker *et al.* 2001). However, sand pine stands in coastal areas of the panhandle within 200 km of EAFB showed a positive growth response to warm-phase ENSO events (Parker *et al.* 2001), in contrast to these conclusions. The differences in tree growth response between coastal and inland sites of the panhandle are distinct, and the reasons are undoubtedly complex.

With respect to the temporal changes in ENSO effects, ENSO B (1914–1958) showed the strongest effects of the ENSO teleconnection of any period in this study. Although her study only encompassed a small portion of ENSO B, Miller (2005) found a significant ($p < 0.05$) relationship between Niño 3.4 SST indices and tree-ring oxygen isotopes from longleaf and slash pines in southern Georgia in the 1950s. Interestingly, Cole and Cook (1998) found that ENSO variance was weak from 1925–1955 and that the teleconnection weakly affected the continental U.S. Cole and Cook (1998) also found that from 1875 to 1910, the ENSO influence on moisture anomalies was more extensive than in later periods. My data do not support these findings, at least with regard to the Southeastern Coastal Plain. However, Cole and Cook (1998) used reconstructed and instrumental PDSI, and not tree-ring indices, in their assessment, and they used Niño 3.4 indices instead of the JMA SST index.

ENSO B was dominated by the warm phase of the PDO (1926–1950), and ENSO effects are typically stronger when they are in phase with the PDO (Enfield *et al.* 2001). The SEA revealed statistically significant relationships between El Niño and tree growth for Texas and South Carolina in ENSO B. The striking negative correlations in the latewood in ENSO B for South Carolina in the previous year are anomalous and may indicate a possible lag effect, similar to the Texas case. The latter part of ENSO C (1959–2003) was also dominated by the warm phase of the PDO, but the correlations were generally weak. Miller (2005) found few significant correlations with ENSO indices and tree-ring oxygen isotopes during this same period. The relatively weak growth response to ENSO in ENSO C is surprising because some of the strongest El Niño events on record occurred in the 1980s and 1990s (Trenberth and Hoar 1996; Rajagopalan *et al.* 1997; Fagan 1999; Changnon 2000).

Why there is a general lag in the ENSO teleconnection in Texas and not in South Carolina and Florida is not clear. The climatic conditions in east Texas are generally more consistent with conditions in the Southern Plains than the rest of the Southeastern Coastal Plain (Cleaveland *et al.* 1992; Vega *et al.* 1996). The panhandle of Florida and coastal South Carolina are in the same winter precipitation region (East Coast) in the scheme of Henderson and Vega (1996). Moreover, a bipolar relationship has been shown between ENSO-drought signatures in the Southwest and the mid-Atlantic region (Cole and Cook 1998). A similar bipolar correlation structure may exist between east Texas and the southern Plains and the eastern portions of the Coastal Plain.

5.4.2 PDO

As expected, the primary effects of the PDO on longleaf pine growth are positive relationships that normally occur in the fall through early winter of the previous year. Warm phases of the PDO from October through March typically bring cool and wet conditions to the Southeast in the winter and spring (Mantua *et al.* 1997), so positive PDO conditions should be conducive to tree growth. These relationships are not consistent over all periods, however. Very little response to summer PDO indices is evident because the PDO expression typically does not persist through the summer (Newman *et al.* 2003).

The pattern of PDO effects on longleaf pine growth is roughly analogous to the effects of ENSO. A generally positive relationship with the PDO from the previous year is followed by a predominantly negative but weaker relationship in the current year. This pattern is most visible in the Florida and South Carolina results. The generally positive relationship in Texas between PDO indices and tree growth is probably related to the more westward location. As in the ENSO analysis, the strongest effect on tree growth in Texas is the positive relationship in the previous year. Curiously, the influence of the PDO is most strongly manifested in the earlywood in Texas and in the latewood in South Carolina. Miller (2005) also found the strongest PDO signals in the latewood in pine trees from southern Georgia.

That the response to ENSO bears some resemblance to the PDO response is not unexpected. Not only does the average pattern over the period of record have similarities, but the patterns of tree-growth response for ENSO C (1959–2003) are rather like the patterns in PDO C (1951–1975) and D (1976–2000). Also, both ENSO B (1914–1958) and PDO B (1926–1950) have a similar pattern for South Carolina, as both show a predominantly negative relationship between the teleconnection indices and tree growth. Many researchers believe that the PDO modulates the effects of ENSO or vice versa (Kerr 1999; Biondi *et al.* 2001; Cleaveland *et al.* 2003; Newman *et al.* 2003), and the PDO is difficult to distinguish from ENSO because of the significant correlation between winter SOI and the PDO (Cole and Cook 1998). Possibly, some of the effects of PDO that are shown in these results may be more related to ENSO. Tree-ring data can integrate ENSO forcing in a manner similar to, but not necessarily forced by, the North Pacific (Newman *et al.* 2003). Nonetheless, a few marked differences point toward a separate effect of the PDO.

Compared to the ENSO results, the months that show statistically significant relationships are more temporally sporadic in the PDO analysis. The reason for this difference is that the PDO index values show less persistence than the ENSO indices. The fact that the same months often project as statistically significant during different periods at all sites is intriguing. Apparently, even though the PDO affects the Southeast during narrow windows of time, the results are significant enough to affect tree growth. The PDO index in the previous November and the previous October was significant during at least one of the PDO sub-periods at all sites. Boyles (2000) found that the PDO correlates well with precipitation but not temperature in North Carolina. Therefore, I attribute the primary PDO signal in longleaf pines to enhanced precipitation in the fall and winter that preconditions the tree for growth in the coming year.

With respect to temporal changes in the PDO, no consistent trends were evident in the tree-growth response by PDO phase. In fact, the tree growth response to PDO indices was opposite in large measure between the warm phases in PDO B and PDO D. The response in the earlywood for South Carolina is a prime example, when the predominantly negative relationship in the previous year for PDO B is juxtaposed with the predominantly positive relationship in the prior year for PDO D. In contrast, the tree-growth response for the cool phase in PDO C is similar to the growth response in PDO D, a predominantly warm phase.

An interesting finding in PDO D is the exceptionally high correlations between PDO indices and tree growth in South Carolina. This period strongly influenced the overall pattern of tree-growth response seen over the entire period of record (1900–2000). Miller (2005) also found a robust influence of PDO in the latewood during PDO D, but the effects during the current year were positive. As in this study, relationships in the month of November showed statistical significance during PDO D in the Miller (2005) study. The pattern of tree-growth response in PDO D is quite similar to ENSO C. Whether the strong El Niño events of the late 20th century influenced the PDO signal in South Carolina is not clear, but the possibility exists that the effects of these teleconnections are related in some way. The warm phase of the PDO may have strengthened the effects of ENSO in South Carolina so that summers were generally drier in El Niño conditions. Gershunov and Barnett (1998) define the conditions when both oscillations are in the same phase as constructive phases, and this scenario represents a constructive situation.

5.4.3 NAO

Although the NAO significantly correlated with tree growth in all three areas, few monthly variables were correlated at a statistically significant level. Stahle and Cleaveland (1992) found no correlation between the NAO and spring precipitation in the Southeast, but Katz *et al.* (2003) found a statistically significant relationship between the NAO and winter mean maximum temperature at many sites in the Southeast. The NAO is more variable than the first two teleconnections, so the persistence evident in the relationships between ENSO and PDO indices and tree growth are not apparent in these results. The monthly NAO indices that affect tree growth are remarkably consistent between sites, however.

NAO indices in August of the previous year have a negative relationship with tree growth at all sites, and the relationships are statistically significant in Florida and South

Carolina. Katz et al. (2003) also found a negative relationship of borderline significance with winter total precipitation and the NAO in Tallahassee, Florida. NAO indices in September of the previous year were significantly related to tree growth in Texas in NAO D. During the negative phase of the NAO, hurricane activity is known to increase in the Atlantic and Gulf of Mexico (Elsner *et al.* 2000). The strong association between tree growth and NAO indices in August or September may be related to hurricane activity and associated precipitation, as these months are typically associated with tropical cyclone formation. Elsner *et al.* (2000) found a connection between hurricane activity and the July NAO index in the Southeast, and the tree growth response in this study roughly corresponds to this seasonal timeframe.

The fairly consistent negative correlation between longleaf pine growth and NAO indices in May could be related to the higher temperatures in the spring during positive phases of the NAO. Higher temperatures in winter and spring are common on the east coast during the positive phase of the NAO (Rogers 1984; Boyles 2000). The climate analysis for South Carolina in Chapter 4 demonstrated that temperature has an inverse relationship with earlywood growth in the month of April, so this explanation is plausible.

Some of the other statistically significant relationships are difficult to explain. In particular, the statistically significant relationship between the NAO index in November and December in NAO B for Texas appears spurious. Conditions in the last months of the year that are typically outside of the growing season appear to affect earlywood formation. A causal relationship in this case is impossible but would be probable if the signal was in the latewood. The positive and statistically significant association with the

NAO index and tree growth in the current June, July, and August during certain periods in Texas and South Carolina is unusual given the negative correlations that prevail in the previous year for these months. Finally, the effects of the NAO index in January and February of the previous and/or current year were statistically significant in both South Carolina and Texas during certain periods, but the sign of the relationship was inconsistent. The strongest season of NAO influence is in the winter months, but how the NAO index in January affects tree growth is not clear, as longleaf pines are normally dormant during this month. Preconditioning is certainly plausible, but precipitation and temperature conditions in January do not appear to affect longleaf pine growth. In Chapter 4, however, precipitation in February was shown to influence total ring width in South Carolina, so an increase in rainfall during the positive phase of the NAO may explain the positive association with February NAO indices in South Carolina in NAO D.

That an NAO signal is evident in tree growth at these sites is not unexpected given that some NAO reconstructions have been developed using trees from sites in coastal South Carolina (Cook *et al.* 1998) and central Texas (Cook *et al.* 2002). However, other studies in the Southeast would indicate that the NAO signature is weak or nonexistent. Miller (2005) found no significant correlations with NAO and the long-term oxygen isotope variations in the tree-ring record in southern Georgia. The NAO is only significantly correlated with temperature in North Carolina and not precipitation in the latter half of the 20th century (Boyles 2000). The effects of temperature on tree growth are generally minor, however, compared to precipitation in the Southeastern Coastal Plain.

With respect to temporal changes in the effects of the teleconnection, the predominant phase of the NAO seemed to have a common effect on tree-growth response through time in South Carolina only. Statistically significant relationships were evident only during the predominantly positive phases of the NAO (NAO B and D) in South Carolina. Curiously, however, the effects were generally not the same. In both periods, however, the NAO indices from the previous year's winter (January and February) significantly affected tree growth. The period with the weakest NAO influence on tree growth was NAO D, as no statistically significant effects were evident in Texas or Florida during this period. Interestingly, the influence of the PDO during this same period was likewise subdued in these two areas.

5.4.4 AMO

Over the entire period of record, the average signal of the AMO is not particularly robust, but during certain periods, the relationship between the AMO and tree growth is highly significant in some areas. The inherent persistence of this index increases the apparent relationship with monthly indices so that the effects are exaggerated, but the statistical significance of the effects is worth noting.

Generally, the relationship between the AMO and tree growth is positive, except in the case of AMO A (1871–1900) in South Carolina. Miller (2005) also found that the AMO was negatively related to earlywood oxygen isotope values in tree rings in southern Georgia before 1950, but positively related after that period. The AMO primarily influences summer precipitation, but this study suggests that rainfall in all seasons may be affected. In fact, the strongest overall signature in both Florida and South Carolina is between February and April. Although the effects of AMO during the positive phase have been found to bring less rainfall in the summer over the U.S. (Sutton and Hodson 2005), this study suggests that the positive phase is conducive to tree growth, especially in the spring and summer. These results agree with the findings of Enfield *et al.* (2001), who found that summer rainfall was greater in southern Florida during the positive phase of the AMO.

The effects of the AMO were particularly pronounced in AMO D. Interestingly, the influence of both PDO and NAO was generally weak during the period, although AMO D represents a slightly longer period of analysis. Perhaps the influence of the AMO has assumed dominance in recent decades in the Southeast. The fact that the AMO signature was most pronounced in the earlywood in both Texas and South Carolina in AMO D is noteworthy. Miller (2005) also found that the strongest AMO signature was in the earlywood of longleaf and slash pines. The graphs of the correlations for both Texas and South Carolina earlywood reveal that the persistence of the teleconnection indices (the AMO index is a 10-year running mean) presents some spurious relationships. Clearly, AMO indices in the summer and fall could not be related to earlywood growth in the current year.

The predominant AMO phase did not produce a unique signature at any of the sites, but the strongest influence of the AMO was in the cold phase in both AMO B and D for South Carolina. These results approximately mirror the effects of the NAO in South Carolina, where NAO B and D showed the highest correlations between NAO indices and tree growth. Possibly, the NAO may reinforce the AMO when the NAO is in the positive phase and the AMO is in the cold or negative phase. In any case, the stronger influence of these Atlantic teleconnections in trees in coastal South Carolina compared to the other sites is not unexpected.

Another intriguing feature in the Florida results was the generally negative relationship with the AMO in the previous year and positive relationship in the current year in AMO C and D. The consistency of the pattern between two separate periods of analysis shows that different phases of the AMO do not change the tree growth response in the Florida panhandle. This pattern in AMO C and D in Florida approximately corresponds in an inverse manner to the tree-growth response for Florida in ENSO C and PDO D. The inverse relationship points to a possible competitive influence on climate between Atlantic and Pacific teleconnections in the Florida panhandle.

5.5 Conclusions

5.5.1 General

The effects of atmospheric teleconnections on longleaf pine growth in the Southeastern Coastal Plain are complex and unstable through time. The competing influences of these teleconnections and the prevailing local climate controls cause these relationships to be temporally and spatially inconsistent. Often, the effects of the prevailing phase of the teleconnection were opposite in sign, as in PDO B and D (both warm phases) and NAO B and D (both positive) in South Carolina. The length of the temporal slice used in the temporal analysis obviously affects the amount of variability found in the results, as the variability will inevitably increase as the time period in question is shortened. Nevertheless, the subperiods selected encompassed several decades, and marked differences at these temporal scales are noteworthy. Also, the differences in the sensitivity of earlywood, latewood, and total ring widths to the effects of teleconnections illustrate the importance of gleaning all available information from the samples.

5.5.2 ENSO

The most consistent relationship between ENSO and longleaf pine growth was a direct association during the prior year and an inverse relationship during the current year. The most salient effect in Texas is a lag or preconditioning relationship with ENSO in the year prior to growth, and this influence is most prominent in the earlywood. In contrast, ENSO conditions concurrent with the growth year have the most effect in Florida and South Carolina, and this relationship is most strongly manifested in the latewood in South Carolina. No statistically significant relationships were evident between ENSO and tree growth in Florida, but the pattern of monthly influence was generally consistent through time. The most statistically significant correlations between ENSO and tree growth in both Texas and South Carolina were normally from July through September. This finding indicates that although the effects of the ENSO teleconnection are most prominent in winter and early spring, summer and late fall conditions are also influenced by ENSO in the Southeastern Coastal Plain. Finally, the most robust climate signal in the tree-ring record was evident in ENSO B (1914–1958).

5.5.3 PDO

The effects of PDO on longleaf pine growth over the two-year period of analysis are similar to the effects of ENSO in three ways. First, positive relationships with PDO in the year prior to growth are followed by negative relationships in the current year in South Carolina and Florida. Second, the association between PDO and tree growth in Florida was generally weak and not statistically significant, and the PDO signal was more pronounced in longleaf pine growth in Texas and South Carolina. Third, the effects of PDO were most pronounced in the earlywood in Texas and the latewood in South Carolina. Whether or not the effects of PDO and ENSO on the Southeastern Coastal Plain are related is not clear, but the pattern of tree-growth response in PDO D (1976–2000) is remarkably similar to the pattern in ENSO C for South Carolina. I suspect that their effects are intertwined in some fashion so that one may counteract or reinforce the other, depending on the predominant phase.

5.5.4 NAO

If only the average condition over the instrumental record for each teleconnection is considered, the most widespread and consistently significant relationships between tree growth and any teleconnection for single months of the year occurred with the NAO. NAO indices for August of the previous year showed a negative and statistically significant relationship with longleaf pine growth in all major sites. Negative phases of the NAO, which bring more hurricane activity in the Atlantic and Gulf of Mexico, favorably affect longleaf pine growth during the hurricane season. NAO in May of the current year was also inversely related to tree growth at statistically significant levels in Florida and South Carolina, and this relationship was also weak, but evident, in Texas. The warm temperatures generally associated with the positive phase of the AMO during spring may explain this relationship.

5.5.5 AMO

The average relationship between AMO and tree growth (TRW) for all months over the full period of record (1871–1990) was the most consistent among all regions for any teleconnection. The association in most months was positive, which indicates that moisture conditions are favorable during the warm phase of the AMO. Curiously, the highest correlations between the AMO and tree growth in South Carolina were found in the predominantly cold phases of the AMO (AMO B and D). As with the NAO, both earlywood and latewood widths were significantly correlated with AMO during different time periods, and the effects were often remarkably similar.

5.5.6 Future Research

This study was limited in temporal extent and did not incorporate any of the available proxy reconstructions of ocean-atmospheric teleconnections. Reconstructions of ENSO, NAO and other teleconnections using proxy and historical data have extended our record of some of these phenomena more than 1000 years into the past (Lough and Fritts 1985; Quinn *et al.* 1987; Quinn 1990; Whetton *et al.* 1996; Cook et al. 2002). Comparing my climate reconstruction with these historical records of ENSO would provide a better understanding of how atmospheric teleconnections have affected the Southeast in previous centuries and would increase our knowledge of trends in general climatic patterns of the past.

To obtain the most complete picture of the effects of teleconnections on tree growth, all available information must be extracted from the tree rings. This study would have greatly benefited from earlywood and latewood measurements from the Florida samples. As the techniques for extracting isotope information from wood become more refined and streamlined, the addition of tree-ring oxygen isotope information should improve the ability to detect the influences of these teleconnections. The combination of data from tree rings and other high-resolution proxies will improve our knowledge of teleconnection effects and our ability to reconstruct these phenomena.

Finally, although this study answers many of the questions concerning the effects of teleconnections on longleaf pine growth in the Southeast, the results unfortunately leave many questions unanswered in terms of the precise cause and effect relationships between tree growth and teleconnections. Our knowledge of how these teleconnections affect certain regions of the U.S. is limited. Understanding how these connections work, both individually and in concert, will aid in our efforts to understand why and how trees respond to teleconnections.

Chapter 6

Historical Fire Regimes in Longleaf Pine Forests

6.1 Introduction

"...man proposes and nature disposes, and that only conforming with natural laws can he turn them to this benefit."

- H.H. Chapman, forester, 1947

Fire was a significant factor in the development of all but the wettest, most arid, or most fire-sheltered plant communities in the U.S. (Frost 2000). Of these plant communities, the longleaf pine forest is one of the most fire-dependent. Not only does longleaf pine thrive in a regime of frequent fire, but grasses and forbs common to many longleaf pine communities multiply with increasing fire frequency (Waldrop *et al.* 1992). The fuels provided by the groundcover and litter in the Southeastern Coastal Plain are very flammable. The fuels will ignite quickly a few hours after a rain, particularly in the summer months when evapotranspiration rates are high (Wahlenberg 1946). Many plants are sclerophyllous and contain large amounts of cellulose and lignin (Wells 1942). Consequently, the litter produced by these plants decomposes slowly, and litter accumulates rapidly (Christensen 1981). In pine-wiregrass savannas, living and dead surface fuels approach a steady-state mass of about 1,000 kg/ha, and the likelihood of fire increases each year thereafter because the living component dimishes (Christensen 1981). Comparable fuel conditions exist in other Coastal Plain ecosystems, such as pine flatwoods (Hough and Albini 1978; Christensen 1981). Herbaceous vegetation such as wiregrass is particularly flammable and conducive to the spread of fires. In the winter, most herbaceous vegetation dies back, and if not burned, contributes to the litter accumulation for the following year (Robertson and Ostertag 2003).

From the earliest written accounts, high fire frequency has been a constant theme in the forests of the Southeastern Coastal Plain, and in most cases, the fires were attributed to Native Americans (Bartram 1791; Lawson 1714; Christensen 1981). From 1500–1830, numerous credible observers saw frequent burning in the eastern U.S. by Native Americans that created open woodland and "savannah-like" areas (Lorimer 2001). Harper (1914) noted that fire was frequent in the open longleaf pine forests, and the original longleaf pine flatwoods were "so open that wagons can be driven through them almost anywhere." Clearly, the fire regime was such that the woody understory was very scant, and the pine forests appeared to have been burned nearly every year (Harper 1914). Even in the late 20th century, wildland fires have been more prevalent in the Southeast than in most other regions of the U.S. Between 1960 and 1970, 58% of all wildfires occurred in the southeastern states, even though this region comprises less than 20% of the country (Christensen 1981).

6.2 Rise of Longleaf Pine Forests and the Role of Fire

"In nature, fire is a great regenerative force, one might even say rejuvenative force, without which plant and animal succession, in the absence of climatic upheaval or physiographic cataclysm (or at least of great climatic or physiographic change), would be retarded so that old, senescent, and decadent communities would cover the earth."

- E.V. Komarek, Sr., 1962

Because the majority of species endemic to the longleaf pine forest are adapted to fire, this assemblage must have been evolved with frequent fire over a long period of time (Means 1996). In the early- to mid-Holocene, southern pine forests that included longleaf pines replaced oak and hickory-dominated forests throughout much of the Southeastern Coastal Plain (Watts *et al.* 1996). A significant climatic event during the early- to mid-Holocene was the Hypsithermal interval from 8500 to 4000 BP (Delcourt and Delcourt 1980). This predominantly warm and wet period in the Southeast was coincident with the spreading of pine habitats out of the Florida/Georgia region (Conner *et al.* 2001). The more pronounced influence of the maritime tropical airmass from the Gulf of Mexico around 6000 BP promoted the expansion of southern pines in the Coastal Plain (Delcourt 1980). Moreover, the radiation regime had changed to conditions similar to the present by 6000 BP (Watts *et al.* 1992). Perhaps the change in radiation levels and increased moisture levels brought more thunderstorms accompanied by frequent lightning strikes (Watts *et al.* 1996). Frequent lightning would have caused more natural fire ignitions in the region. Oak and hickory forests were replaced by southern Diploxylon pine forests in the sandy uplands by 5000 BP (Delcourt 1980), and longleaf pine may have been the predominant plant association in the Coastal Plain from 5000 BP until the late 19th century (Watts 1971).

The climate at 5000 BP was similar to the present climate, with abundant precipitation throughout the growing season, and sea levels were approximately the same as today (Delcourt 1980). Modern levels of insolation and a reduced summer-winter contrast characterized the climate, and summer thunderstorms were doubtless prevalent, particularly in close proximity to the coast (Watts and Hansen 1994; Watts *et al.* 1996).

The warm-temperate plant communities in the Gulf Coastal Plain may have changed their areal prominence in the late Quaternary in direct response to the recurrence interval of disturbances such as fire, and fire likely played a vital role in the expansion of longleaf pine forests (Delcourt and Delcourt 1983). The shifting dominance of oak and pine in the early- to mid-Holocene in some areas of the Southeastern Coastal Plain suggests the influence of fire, as these species were the most likely to persist in a disturbance regime with frequent fire. The reduction of oak at the expense of (primarily) longleaf pine may have resulted gradually from increased fire frequency by a combination of increased thunderstorms in the growing season and anthropogenic fires. While the early- to mid-Holocene was marked by climatic changes in the Southeast more conducive to natural fire ignitions (*i.e.*, lightning), perhaps the most significant factor in shaping the Gulf Coastal Plain forest composition was the appearance of humans on the landscape.

Although the climate has become somewhat cooler and more mesic since 5000 BP, the forest composition has not changed significantly, perhaps due to the influence of humans (Watts 1971; Conner *et al.* 2001). As water became more available and wetlands expanded, new food-gathering and hunting economies were increasingly possible (Watts *et al.* 1996), and anthropogenic fires may have been more widespread. The role of Native Americans may have been particularly important in the expansion and continuation of longleaf pine ecosystems which are highly reliant on fire for their perpetuation.

Humans have occupied eastern North America for the entire post-glacial period (Delcourt *et al.* 1993). Native American populations fluctuated during the Holocene (Anderson 1991), but at the time of first European contact, as many as 1.5 to 2 million Indians lived in the forests of the Southeast, although these numbers declined by almost

95% by 1700 (Earley 2004). Most of these indigenous groups were from the Mississippian culture which centered on maize agriculture in fertile river valleys (Earley 2004). The forest species most likely to have survived the Native American fire regime are pine and oak, and these species thrived during this period. Was frequent burning by Native Americans the catalyst that created the longleaf pine ecosystem, largely dominated by a single major woody species? The relative importance of natural and anthropogenic fires can be inferred only from circumstantial, indirect evidence (Lorimer 2001). Therefore, scientists have not reached a consensus on the relative effects of Indian fires versus lightning fires (Frost 2000).

Several authors have argued that natural disturbance was sufficient to maintain the longleaf pine forest, because pyrophytic vegetation developed long before the arrival of the Native Americans (Harper 1943; Komarek 1974). Any fire-dependent species must be lightning-ignition dependent because Native Americans have only been in North America since the Holocene (Frost 2000). The longleaf pine forests may have evolved with lightning-ignited fires that burned predominantly during the growing season (Komarek 1968; Frost 2000; Earley 2004).The characteristics of longleaf pine and associated bunch grasses facilitate the ignition and spread of fire during the humid growing season (Landers 1991). The increase in thunderstorms during the Holocene lends credence to this argument, as more lightning-ignited fires would have occurred in the Southeastern Coastal Plain (Myers 1990).

Longleaf pines transmute a localized disturbance—lightning—into a widespread disturbance—surface fires (Platt *et al.* 1988). The primary generator of lightning is thunderstorms, and the average thunderstorm produces one or two strokes of lightning in a 2.6 km^2 area (Lightning Protection Institute 1962; Komarek 1964). The Southeast has the highest frequency of thunderstorms of any region in North America (Komarek 1968; Earley 2004). Florida has 70 to 90 thunderstorm days per year, more than any other state in the nation (Maier 1977). However, most lightning fires in the U.S. occur in the western states because rainfall sometimes does not accompany thunderstorms in that region (Oliver and Larson 1990). The actual number of lightning fires is 3 to 5 times higher in the Rocky Mountains and Pacific states than in the Southeast (Taylor 1974; Christensen 1981). The structure and moisture content of fuels in the Coastal Plain may result in fewer fires per strike than in more xeric habitats (Pyne 1982).

Even though heavy rains during thunderstorms tend to reduce the possibility of the spread of fire (Early 2004), thunderstorms with very light rain in longleaf pine forests can produce lightning-ignited fires that spread rapidly (Chapman 1950). Convective thunderstorms around the Gulf of Mexico can produce “dry lightning” in which there is little or no precipitation (Komarek 1965). Lightning can produce fires in heavy rainstorms as well (Komarek 1966), and resin-soaked stumps and snags of dead longleaf pine may smolder for several days or weeks. These smoldering fires provide a re-ignition source for fires extinguished by thunderstorm rains when fuels have dried out (Platt *et al.* 1988).

Natural lightning-caused fires occur primarily in the growing season when thunderstorms are prevalent (Glitzenstein *et al.* 2003). Lightning-initiated fires are most frequent in the early summer from May to July, and in Florida, nearly all lightning-ignited fires occur in the summer (Komarek 1964). Frequent summer fires tended to exclude some species of trees from Coastal Plain forests, while some endemic species such as wiregrass thrived in a summer fire regime (Christensen 1981). Annual summer burns are adequate to eliminate hardwood regeneration in some longleaf forests (Waldrop *et al.* 1992). Wiregrass flowers and produces abundant viable seed only following growing-season fires (Conner *et al.* 2001).

Notwithstanding the role of lightning-generated fires in the Southeastern Coastal Plain, many authors point toward the influence of human populations on the creation of the forest ecosystems in the eastern U.S. (Coker 1969; Pyne 1982; Williams 1989; Lorimer 2001). Although lightning ignitions caused many fires, Native Americans augmented these natural wildfires with intentional fires (Pyne 1982). Pyne (1996) postulated that the fire regime that was in place when Europeans arrived in the Southeast was anthropogenic. Comparing historic fire frequency with modern data of fires caused by lightning suggests that humans caused most of the fires in presettlement times, at least on mesic or dry-mesic sites (Lorimer 2001). However, lightning may have been more important in the extreme southeastern U.S. where lightning is very frequent (Lorimer 2001). The history of anthropogenic fire effects is complex and not well documented, but the theory that certain forest ecosystems came about as a result of anthropogenic disturbance is well regarded by some members of the scientific community.

Delcourt and Delcourt (1987) found that prehistoric human populations maintained forests in early stages of succession by creating a new disturbance regime of frequent fires. In their study at Horse Bog, North Carolina, Delcourt and Delcourt (1997) postulated that the Native Americans encouraged the growth of certain types of trees through the selective use of fire. Native American burning patterns were an overriding influence on vegetation patterns in the early 19th century in the Missouri Ozarks (Batek *et* *al.* 1999). When Europeans arrived in North America, early travelers reported the Native American custom of burning the woodlands each year (Earley 2004). Rostlund (1957) concluded from a comprehensive review of historical accounts from the 16th through the 19th century that Native Americans had created extensive areas of open woodland in the Southeast by frequent burning prior to European contact. Lyell (1849) commented that the Indian practice of burning the grass in Alabama helped eliminate hardwoods to the benefit of pines. Indians were not particularly concerned with putting fires out, so their fires could burn extensively (Earley 2004).

Native Americans used fires for numerous purposes in addition to cooking and warmth. They cleared the surrounding woods of underbrush to avoid being surprised by hostile forces (Williams 1989). In agricultural communities, fire eliminated diseases in fields and fertilized the soils (Pyne 1982). They burned patches of land where they gathered berries or to promote the growth of tubers (Pyne 1996). The most widespread use of fire, however, was for hunting bear, raccoons, and deer. In Florida, the Seminoles also used fire to hunt alligators (Pyne 1996). Economies based on hunting large game may have been favored in the mid-Holocene Southeast in oak scrub/forest with prairie openings (Watts *et al.* 1996), and Pyne (1982) argues that nomadic hunters may have been enlarging the range of their prey with frequent fires. The open woodlands and extensive grassland ecotone promoted deer and turkey populations by stimulating grass growth and making acorns easier to find (Hudson 1976; Pyne 1982). Large herds of deer, and flocks of turkey numbering in the hundreds, were seen by early Europeans in the southeastern uplands (Hudson 1976). Bartram noted that Indians set fires to corral game in a small area so that the animals would be easier to kill (Heyward 1939; Edgar 1998). Indians surrounded deer with fire and drove them toward the hunters (Hudson 1976).

The season of the year that Native Americans used fire for hunting is the subject of speculation. Komarek (1965) believed that Indians used summer fires because they were dependent on "natural livestock" (i.e., deer and turkeys). Pyne (1996) speculated that Native Americans burned the woods in late fall, winter, and early spring, thereby protecting themselves from wildfire in the summer. Others contend that fall and winter burns were favored by Native Americans (Hudson 1976; Glitzenstein *et al.* 2003; Earley 2004). Thomas Morton, living in New England in the early 1600s, remarked that the "Salvages" burned the woodlands twice a year in spring and fall (Morton 1642). If Native Americans ignited most fires outside of the growing season, they would have likely increased the annual percentage of fires occurring in the dormant season of tree growth.

One aspect of Native American history revealed by archaeology seems to refute the idea that humans were integral to the early to mid-Holocene expansion of pine in the Southeastern Coastal Plain. Archaeological evidence indicates that human populations decreased as oak-dominated forests in the Coastal Plain shifted to pine dominance (Anderson 1991). Anderson (1991) states that at the end of the Early Archaic Period (ca. 7500 BP), a major regional population shift out of the Coastal Plain may have occurred, as evidenced by the low numbers of Bifurcate projectile points in Florida, Georgia, and South Carolina. Anderson (1996) found that major Mid-Archaic (5500–7500 BP) concentrations of Indians were uncommon in northern Florida except in the Panhandle. Similarly, Mid-Archaic sites in Alabama are uncommon except along major rivers (Anderson 1996). However, the dense concentrations of Early Archaic (7500–9000 BP) populations in northeastern South Carolina roughly coincide with the rise of pine dominance in this region. Their subsequent general relocation out of the Coastal Plain in the Mid-Archaic is approximately coeval with the spread of pine forests in the region (Anderson 1996).

Anderson (1991) posits that the reason for this shift was the increase in dominance of the southern pines at the expense of hardwoods because of climatic change in the Hypsithermal climatic interval. During this transition, the pine forests of the Coastal Plain had a lower carrying capacity for game animals and less mast-producing trees (Anderson 1991). If these statements are correct, the Native American population had only minor influence on the fire regime of the Southeast during the Mid-Archaic period. Yet, the Early Archaic populations may have had an influence on the rise of pine in certain states such as the Carolinas.

The statements by other researchers that large herds of game thrived in the longleaf pine forests, subsisting on the herbaceous plants, scrub oak, and longleaf pine seeds, tend to refute the idea the pine forests had a low carrying capacity (Hudson 1976; Pyne 1982). Anderson (1991) conceded that these areas may have actually been inhabited in the Mid-Archaic, and the Bifurcate projectile points may not have been used as widely as in the Piedmont and Coastal Plain. The Kirk Corner Notched-type projectile may have seen a continuation through this period (to perhaps *ca.* 6000 B.C.) in some areas of the Coastal Plain (Anderson 1991). Small oaks in the understory may have provided a source of mast for Native Americans, and the pine-dominated woods could have supported large numbers of game animals such as white-tailed deer and turkey.

Perhaps Native American burning only slightly increased fire coverage in the Southeastern Coastal Plain by including peninsulas and patches of uplands that were otherwise naturally protected from fire (Frost 1993). Frost (2000) believed that the role of Indian burning in the Coastal Plain was probably insignificant because of the high frequency of naturally-occurring lightning fires. In the Gulf Coastal Plain, lightning fires would have likely preempted the fuel the Indians might have used in most years (Frost 2000). Where the terrain is more dissected in the upper Coastal Plain and into the Piedmont, Indian burning may have been more important (Frost 2000). In any event, the influence of Native American burning declined with the arrival of the Europeans. During the 1600s, Indian populations in the Southeast decreased dramatically because of diseases introduced from Europe, and by 1700, Indian populations had declined by almost 95% from the period when European explorers first arrived (Savage 1970; Earley 2004). Therefore, the forest encountered by settlers in the early 19th century may have been less affected by fire than forests in previous centuries (assuming Native Americans had an effect) (Lorimer 2001). This theory implies that high population densities are necessary to substantially influence fire regimes, but this supposition may be questionable. Native American hunters traveled great distances from village sites on hunting expeditions and used fire to drive game, so anthropogenic ignitions could have occurred far from river valleys where population concentrations were highest.

Native Americans undoubtedly set fires fairly frequently in the Southeastern Coastal Plain, and Euro-American settlers continued the practice of woodland burning. Not surprisingly, the pollen record and fire-scar research in the forests of eastern North America suggest that fire frequencies in presettlement times were roughly equal to fire frequencies in the 150 years after settlement (Lorimer 2001). Many of the fires ignited by settlers in the Southeastern Coastal Plain were caused by herdsmen, whose cattle and hogs roamed in the free-range conditions (Earley 2004). The herding of livestock started first in the South Atlantic portion of the Coastal Plain in the 16th century, and progressed westward in the Coastal Plain into Texas (Earley 2004). The "cowboys" of the southern forests were the prototype of the western range of later centuries (Williams 1989). Cattle herdsmen set fires in the winter or early spring to stimulate the growth of forage in the early spring (Heyward 1939; Komarek 1965). Fires increase the availability of forage and browse plants and increase their nutritive qualities in southeastern forests (Komarek 1974; Lewis *et al.* 1982). Adjacent areas were burned in succession so that cattle could move progressively from site to site (Komarek 1974).

If the practice of setting winter and early spring fires was different from the Native American's season for burning, the seasonality of fires would have shifted with the arrival of Euro-Americans. Pyne (1996) states that Euro-American settlers co-opted or imitated indigenous fire practices, implying that the settlers burned in essentially the same manner as the natives. In any case, because plants that flourish in a regime of summer fires have persisted through the period of Euro-American settlement, growing season fires must have continued, augmented by dormant season fires. Otherwise, certain pyrophytic plants that are dependent on periodic summer fires in longleaf pine ecosystems may have been selected against and would not have persisted (Gliztenstein *et al.* 2003).

6.3 Methods

6.3.1 Field Methods

I obtained fire-scarred samples from all three study areas: Sandy Island, South Carolina; EAFB (Donut and Brandt Pond sites); and the Big Thicket in Texas. An additional fire-scarred sample from Lake Louise, Georgia (LLC036) was also used in the analysis. Because living longleaf pine trees generally could not be cut with a chain saw on all of my sites, I obtained very few samples from live trees with visible "catfaces" or open fire wounds. Only a limited number of fire-scarred trees were noted on any of the sites, and land managers only allowed sampling on a few of those trees. Preservation of longleaf pine trees is a priority, so I took only small sections from a few living trees using the techniques described in Arno and Sneck (1977). Although I could have cored all of the living trees with visible fire scars, cores are not practical for dating multiple scars within a tree (Sheppard *et al.* 1988), so increment cores would have had little value in this study.

The cross-sections that I collected for the climate analysis study were also used in the fire history study when the sample contained a fire scar. Cross-sections were collected from logs, stumps, and standing snags. The partial cross-sections taken from living trees helped to verify the fire-scar dating techniques because the dates of prescribed burns were known and could be validated against the fire scars. Samples were wrapped tightly with plastic wrap to minimize damage to the wood in transit to the laboratory.

The methods used to obtain fire-scarred samples were not selected based on a random sampling technique. Random sampling methods are not suited to this study because of the scarcity of living, scarred trees. Moreover, virtually all available dead wood was sampled at each site because stumps, snags, and logs are not particularly abundant. I also targeted all living trees with catfaces or other evidence of possible fire injury. Because fire-scarred samples were obtained from a variety of environmental settings, they are reasonably representative of some of the forest types of the Southeastern Coastal Plain.

6.3.2 Laboratory Methods

First, all samples were frozen at – 40° C before analysis to kill any insects in the wood. Next, samples were mounted on plywood, as necessary, to keep them intact during the sanding and measuring process. Samples were sanded with a belt sander using sequentially finer grit sandpaper from ANSI 40-grit (500–595 μm) to ANSI 400-grit (20.6–23.6 μm) (Orvis and Grissino-Mayer 2002).

I crossdated each sample to the exact year of formation (Fritts 2001). I visually crossdated the samples and labeled the cores and cross sections appropriately. I used easily identifiable marker rings to assist in the crossdating process. Next, I measured the ring widths at 0.001 mm precision using a Velmex movable stage micrometer and the MeasureJ2X program. Measurements were taken as far from fire-scarred portions of the wood as possible to minimize the effects of the disturbance on the ring widths. I used the COFECHA program to ensure the accuracy of the crossdating (Holmes 1983; Grissino-Mayer 2001). COFECHA creates a master chronology from the raw ring widths and computes the level of correlation in successive time segments between each series and the master chronology to assess the quality of crossdating (Grissino-Mayer 2001). I used a 50-year segment length lagged 25 years, and if the COFECHA output showed that the rings were dated incorrectly, I visually verified and corrected the dating as necessary.

6.3.3 Identification of Fire Injury

Fire scars are injuries caused by fire that involve the disruption and death of some portion of the vascular cambium (Smith and Sutherland 2001). I dated all fire scars to the exact year of formation and when possible, to the season of occurrence. As differences in judgment about what constitutes a *bona fide* fire scar are possible (Madany *et al.* 1982), the fire scars were verified by a second observer. I identified fire scars by the presence of charcoal, scar tissue, excess resin ducts, and woundwood. Woundwood is caused by enhanced cell divisions of the vascular cambium around the margins of the fire scar (Smith and Sutherland 2001). Many of the fire scars were small, internal wounds that were not associated with the classic fire-scarred "catface" with multiple fire scars. Possibly, the cambium was damaged when the bark was charred, leaving a small wound that healed quickly within a few years. The cambium tissue of lodgepole pine, for example, may be killed if the heat from a fire is sufficient to char the bark (Gara *et al.* 1986). Conceivably, the same phenomenon may occur in longleaf pine.

"Trauma rings" were also used as indicators of a fire event. The term "trauma rings" was developed by Grissino-Mayer (1995) to describe distinct bands of resin normally associated with a fire scar. These features do not contain charcoal or scorched wood, so they are not related to the combustion of the vascular cambium. Trauma rings are similar to regular false rings as they can closely mimic latewood formation (Zackrisson 1980). Trauma rings are related to the "traumatic resin canals" described by

McBride (1983). Traumatic resin canals are tubular, intercellular spaces that are filled by resin secreted from surrounding epithelial cells in response to tree stress (McBride 1983). Traumatic resin canals may be caused by disease, insect attack, mechanical damage, and fire. Fire may damage xylem mother cells without damaging the cambium because undifferentiated tracheid cells may be more sensitive to extreme temperatures than cambial cells (Zackrisson 1980).

Traumatic resin canals may not be suitable evidence for fire events in all tree species. In sugar pine (*Pinus lambertiana* Dougl.) and ponderosa pine (*Pinus ponderosa* Dougl. ex. Lawson), resin canals are abundant in the wood, and most (if not all) may be unrelated to fire (McBride 1983). Furthermore, some research has shown that traumatic resin canals in white fir (*Abies concolor* Lindl. ex. Hildebr.) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) do not correspond well with known fire years, and resin canals do not synchronize with each other (McBride 1983). No studies have established the validity of using traumatic resin canals for fire history studies in longleaf pine, but traumatic resin canals have been used to successfully date fires in Scots pine (*Pinus sylvestris* L.) in Sweden (Zackrisson 1980) and Douglas-fir and ponderosa pine in New Mexico (Grissino-Mayer 1995). Other indicators of fire events included a dramatic increase or decrease in ring width that may or may not be accompanied by a fire scar (Zackrisson 1977; Brown and Swetnam 1994). Releases or suppressions that coincided with dated fire scars from other trees were used to indicate that the tree had been affected by the fire event.

I developed fire-scar data sheets for each sample, which included the fire-scar dates, inner- and outer-ring dates, descriptions of the injuries, site description, and recorder years. A tree is classified as a “recorder” when it is fire-scar susceptible (Grissino-Mayer 1995). A fire-scar susceptible tree has already been scarred by fire and has a relatively greater probability of being scarred by the next fire (Romme 1980). Fire-scar susceptible trees may return to non-recorder status if the tree heals over the wound or when the fire-scarred surface becomes obscured (Grissino-Mayer 1995). I entered the fire-scar data into the FHX2 software program for statistical analysis. FHX2 is a software program designed to analyze the fire history of forest ecosystems (Grissino-Mayer 1995). As such, FHX2 has the capability to enter, archive, store, edit, and statistically analyze fire history information from tree rings (Grissino-Mayer 2001b). To aid in the interpretation of fire regime changes, I used historical records and accounts of anthropogenic influences on fire such as Native American and Euro-American burning practices.

6.3.4 Fire Intervals

Fire frequency is defined as the average number of fires per year. Fire-scar information from a single tree represents “point” fire frequency, and this estimate is normally regarded as conservative because a single tree is unlikely to record all fires (Frost 2000). An “area” fire frequency or composite fire-scar chronology for an entire forest or stand can be developed that combines a number of point fire frequencies. Such an estimate may exaggerate the fire frequency because the area may include several compartments. The most reliable “area” fire frequency is the “site fire frequency” that provides a more accurate fire return interval for a particular fire compartment (Frost 2000). If trees over a wide area are scarred by the same fire, these trees would theoretically be in the same fire compartment (Frost 2000). I computed site fire frequencies for all sites from composite fire chronologies. I also computed a composite fire chronology for EAFB because of the similarity in fire occurrence between the two sites sampled.

I examined the fire intervals using numerous statistics including: (1) Mean Fire Interval (MFI), Weibull Median Interval (MEI), Weibull Modal Interval (MOI), standard deviation (SD), coefficient of variation (CV), minimum fire interval (Min), maximum fire interval (Max), lower exceedance interval (LEI), upper exceedance interval (UEI), and maximum hazard interval (MHI) (Grissino-Mayer 1995). The first three statistics are measures of central tendency. The MFI is the average of all fire intervals and assumes the data being modeled form a symmetric distribution (Grissino-Mayer 1995). Because fire interval data often display skewed distributions, the MFI may not be an adequate measure of central tendency (Baker 1992). The Weibull distribution is more flexible and does not assume normality, so the MEI and MOI are considered to be more robust measures of central tendency (Clark 1989; Grissino-Mayer 2001b). The MEI is the interval associated with the 50% exceedance level, and the MOI represents the greatest amount of area under the probability density function (Grissino-Mayer 1995; Grissino-Mayer 2001b).

The statistics measuring dispersion include the SD and the CV. The SD measures the variability about the MFI, and the CV is a standardized statistic that integrates both SD and MFI to facilitate comparisons of fire intervals between sites (Grissino-Mayer 1995). When large variability exists in the length of fire intervals, the CV values are also high (Lewis 2003).

The remaining statistics are measures of range. The minimum and maximum fire intervals are simply the shortest and longest intervals between fires. The LEI and UEI correspond to the 12.5 and 87.5 percentiles of the fire interval distribution and depict the thresholds for significantly short or long intervals (Grissino-Mayer 2001b). Finally, the MHI is the theoretical absolute maximum interval between fires that an ecosystem can sustain before burning is highly probable, and it is derived from the Weibull distribution (Grissino-Mayer 1995).

In the context of fire-regime statistics, period of reliability is an important concept. The period of reliability is the range of years considered suitable for statistical analysis in a fire history study and is based on the minimum number of fire-scarred samples in a given fire year (Grissino-Mayer 1995). This period starts with the year of first occurrence of fire and ends with the last occurrence of fire. The delineation of the minimum number of fire-scarred samples is rather arbitrary and depends on the total number and quality of samples and habitat type (Grissino-Mayer 1995). In this study, the number of samples was low compared to most fire history studies, so the period of reliability was set at a minimum of only one fire-scarred sample. As in almost all fire history studies, the “fading record” characterized by decreasing completeness and reliability is present in this study (Swetnam *et al.* 1999).

6.3.5 Fire Seasonality

To determine the season in which a fire occurred, I examined the intra-annual position of the ring. I used five categories (Baisan and Swetnam 1990; Grissino-Mayer

1995) to classify the season according to the position of the fire scar within the annual ring:

- Dormant season fire (D): Scar positioned between the latewood of the previous ring and the earlywood of the current year (*i.e.*, at the transition boundary). Because fires in the dormant season could occur in either the previous or current year, a subjective convention for assigning the year of the scar is necessary. I assigned scars in the dormant season to the current year because late winter-early spring fires are more common than late fall-early winter fires in the Southeastern Coastal Plain (Brenner 1991).
- Early season fire (E): Scar position in the first one-third of the earlywood.
- Middle season fire (M): Scar position in the middle one-third of the earlywood.
- Late season fire (L): Scar position in the latter one-third of the earlywood.
- Latter part the growing season fire (A): Scar position in the latewood.

The exact time of year when latewood production began each year is not known for each site, but I assumed that latewood production began in late May or June and ceased in November, based on a study in the Florida panhandle (Lodewick 1930). I verified the method of determining seasonality of fire at Sandy Island and the Donut by comparing the date of known fires to the intrannual position of the scar from a living tree. I determined the season of the year when fires were most prevalent from the FHX2 statistical output. To determine changes in fire seasonality through time, I looked for evidence of shifts in the dominant mode of seasonal occurrence over five sub-periods at each site (Grissino-Mayer 2000).

6.3.6 Fire/Climate Relationship

To test the relationship between climate and fire on interannual timescales, I used Superposed Epoch Analysis (Swetnam 1993). SEA provides graphical and statistical techniques for evaluating moisture conditions leading up to, during, and immediately after a fire event and has been used primarily in fire history studies in the American Southwest (Swetnam and Betancourt 1990; Swetnam 1993; Grissino-Mayer and Swetnam 2000; Veblen *et al.* 2000). SEA entails "stacking" (*i.e.*, superposing) fire event years and calculating the average climate conditions leading up to and after individual fire years (Grissino-Mayer 1995).

I used the FHX2 program's Epoch Analysis module to compute the SEA statistics (Grissino-Mayer 2001b). In my statistical runs, a pseudo-random number generator selected a different set of key years 1000 times, and then compared the actual events to the simulated events to determine any differences between the two datasets. I used datasets with both one minimum tree scarred and two minimum trees scarred to compare conditions at different scales of areal extent. When multiple trees are scarred by a fire, the fire likely covers a greater area than a fire where only one tree was scarred. SEA composites were computed using a seven-year window with three years preceding the fire year, the fire year, and three years after the fire event as the standard period of analysis. I used z-scores for the reconstructed PHDI values to determine the degree of departure from the mean climate in the seven-year window.

6.3.7 Fire Extent

The analysis of fire extent was only applicable for the EAFB sites because EAFB was the only major site with samples from widely-separated stands. At EAFB, Brandt Pond and the Donut were spatially distant, so the data from these sites was suited for providing a preliminary assessment of the spatial extent of fires at EAFB. Fires that occurred synchronously at both Brandt Pond and the Donut were considered spatially extensive. I also examined years when fires occurred at the Texas, Florida, and South Carolina sites to determine the degree to which climate may have affected fire activity over large areas of the Southeastern Coastal Plain.

6.4 Results

6.4.1 Fire Chronologies and Sample Information

The number of samples obtained at each site is low except in the case of Sandy Island, so the statistical reliability of these data should be considered preliminary (Table 6.1 and 6.2; Figures 6.1 – 6.4) (Appendix C). Similarly, although the periods of reliability represent several centuries in some cases, some portions of the fire record contain only one fire-scarred sample. However, this research represents an exploratory use of longleaf pine for fire-scar data and therefore is an initial assessment of the utility of these data for fire history analyses.

Most samples contained very few fire scars, except in two cases. In the first case, where the initial wounding of the tree by fire was not healed quickly, the tree continued to record fire for several decades (Figure 6.5). The second case included two samples,

Table 6.1 Sample information for each site.

Site	Number of Samples	Fire years	Scars per Tree		
			Min.	Max.	Avg.
Big Thicket	10	25	1	8	3.2
EAFB					
-Brandt Pond	6	40	1	26	7.3
-Donut	8	24	1	10	3.6
Sandy Island	19	22	1	3	1.6
Lake Louise	1	28	28	28	28
Total/Average	43	111	1	26	3.9

Table 6.2 Periods of reliability for the sample sites.

Site	Begin Year	End Year	Earliest Fire	Latest Fire	Period of Reliability (yrs)
Big Thicket	1668	1984	1714	1969	255
EAFB					
- Brandt Pond	1589	1963	1747	1918	171
- Donut	1517	2004	1626	2001	375
Sandy Island	1580	2004	1674	2002	328
Lake Louise	1463	1664	1466	1648	182

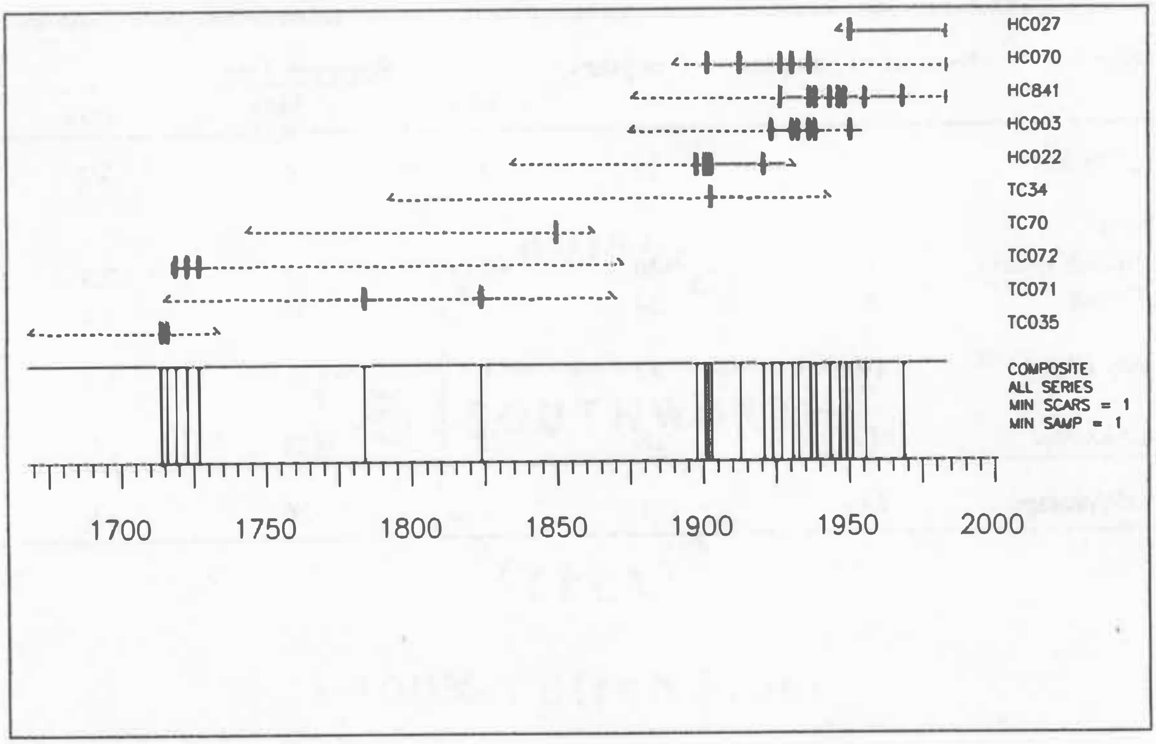


Figure 6.1 The master fire chart for the Big Thicket. The horizontal lines represent the samples, and the vertical tick marks indicate dated fire scars. Solid lines represent recorder years, while dashed lines represent non-recorder years.

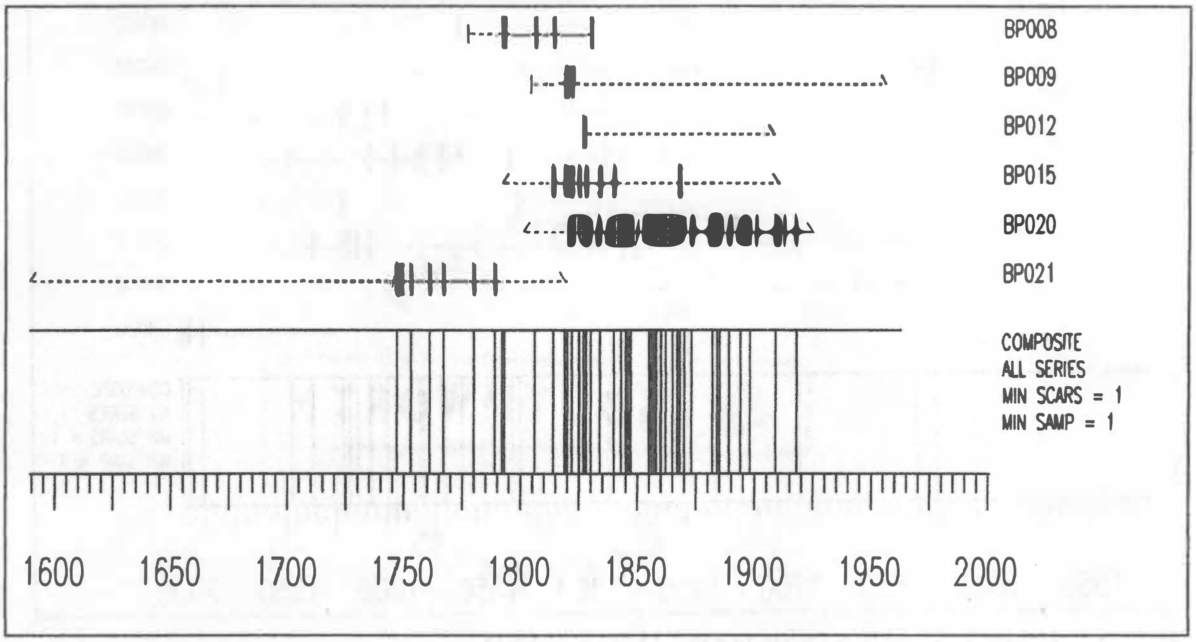


Figure 6.2 The master fire chart for Brandt Pond, EAFB.

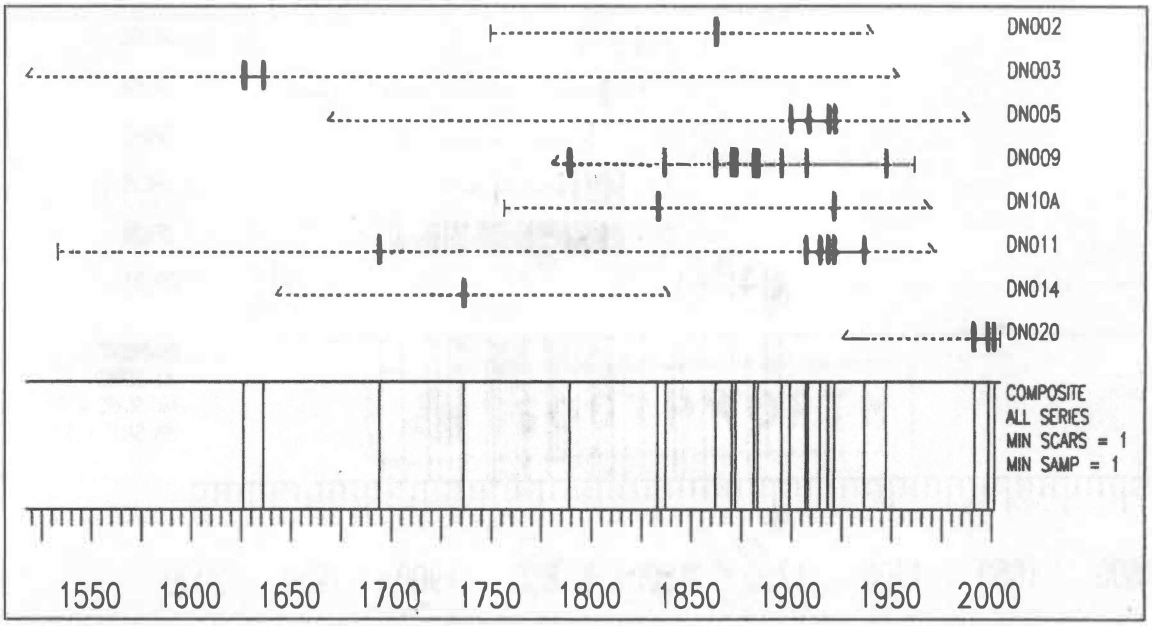


Figure 6.3 The master fire chart for the Donut, EAFB.

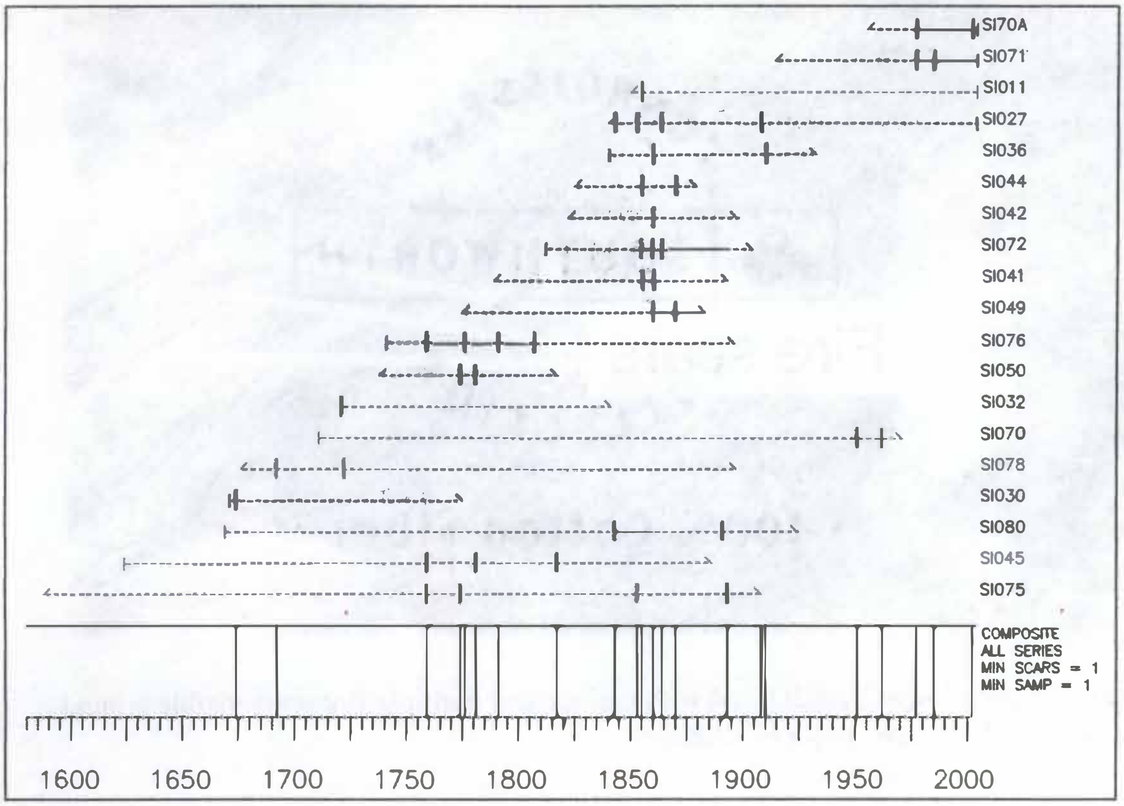


Figure 6.4 The master fire chart for Sandy Island.

Figure 6.5 Fallen log at Brandt Pond with catface and multiple fire scars visible around the open wound. Arrows point to scars.

one from Brandt Pond (BP 020) and the other from Lake Louise (LLC036), that were cut at the root-stem interface. These cross-sections contained abundant evidence of fire injury, but the trees did not form the classic fire-scarred "catface" as seen in the first case. The number of fire years at Brandt Pond is the highest of any site because of that single sample, even though Brandt Pond contained the fewest total samples. Sandy Island, with the largest number of samples, recorded the fewest fire years.

The majority of fire-scarred samples were found in the process of obtaining samples for the dendroclimatological portion of the study. In other words, the fire scars were discovered when sampling cross-sections for the climatic study and were embedded deep inside the tree. Very few stumps and other remnants had visible fire-scarred surfaces before the wood was cut and surfaced. The few living trees sampled came from trees with obvious basal injuries caused by fires at Sandy Island and the Donut (Figures 6.6 and 6.7).

6.4.2 Indicators of Fire Injury

I discovered the importance of sampling longleaf pine stumps as close to the ground as possible because of the value of the fire information that might be preserved at ground level (*i.e.*, "root-stem" interface), as shown by the sample from Brandt Pond. The low-intensity surface fires that dominated in the longleaf pine forests rarely left their marks on trees in the form of the classic fire-scarred "catface." Rather, the evidence in the wood was more subtle and is best seen near the "root-stem" interface near the base of the tree. This portion of the tree is most easily accessed when the tree has been uprooted by windthrow. Similarly, a study of ponderosa pine fire scars in Arizona revealed that

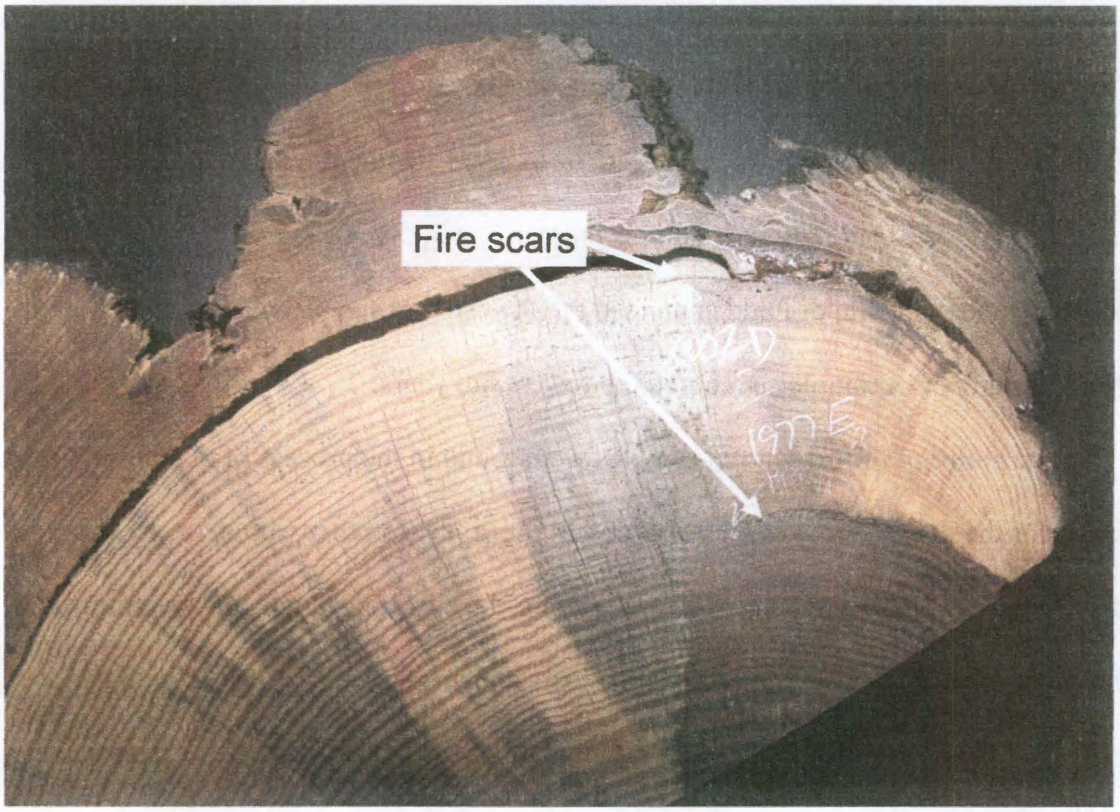


Figure 6.6 Fire scars on a partial cross-section carefully extracted from a living longleaf pine tree at Sandy Island.

Figure 6.7 Living, fire-scarred tree at the Donut site from which a partial cross-section was retrieved.

trees were scarred most frequently in the lowest cross sections of the tree bole (Dieterich and Swetnam 1984). Presumably, the close proximity to burning surface fuels makes the lower portion of the bole more sensitive to surface fires (Dieterich and Swetnam 1984). The surface fires left their mark in this portion of the tree by very small but obvious fire scars and "trauma rings" (Figures 6.8 and 6.9). Under magnification, these bands are distinctly cranberry-red to black in color and appear as dots of resin that have been seared in some cases. Although these bands do not traverse the entire annual ring, they normally appear at multiple locations within the ring. Evidently, fire injury only occurs where the vascular cambium or xylem is most vulnerable (*i.e.*, thinner portions of the bark) or where fuels have built up next to a particular side of the bole. The "trauma rings" were only visible in two samples of the over 100 cross-sections collected from three sites and the one cross-section from Lake Louise. BP020 was cut from a log at the Brandt Pond site (Figure 6.10). The cross-section was taken from the portion of the bole where the roots began to protrude.

One of the difficulties in working with wood at the root-stem interface is the unusual nature of the ring pattern and ring structure. False rings are much more prevalent, and missing or disappearing rings also occur more frequently than in the wood farther up the stem. However, close examination of the entire cross-section can produce successful crossdating of these pieces.

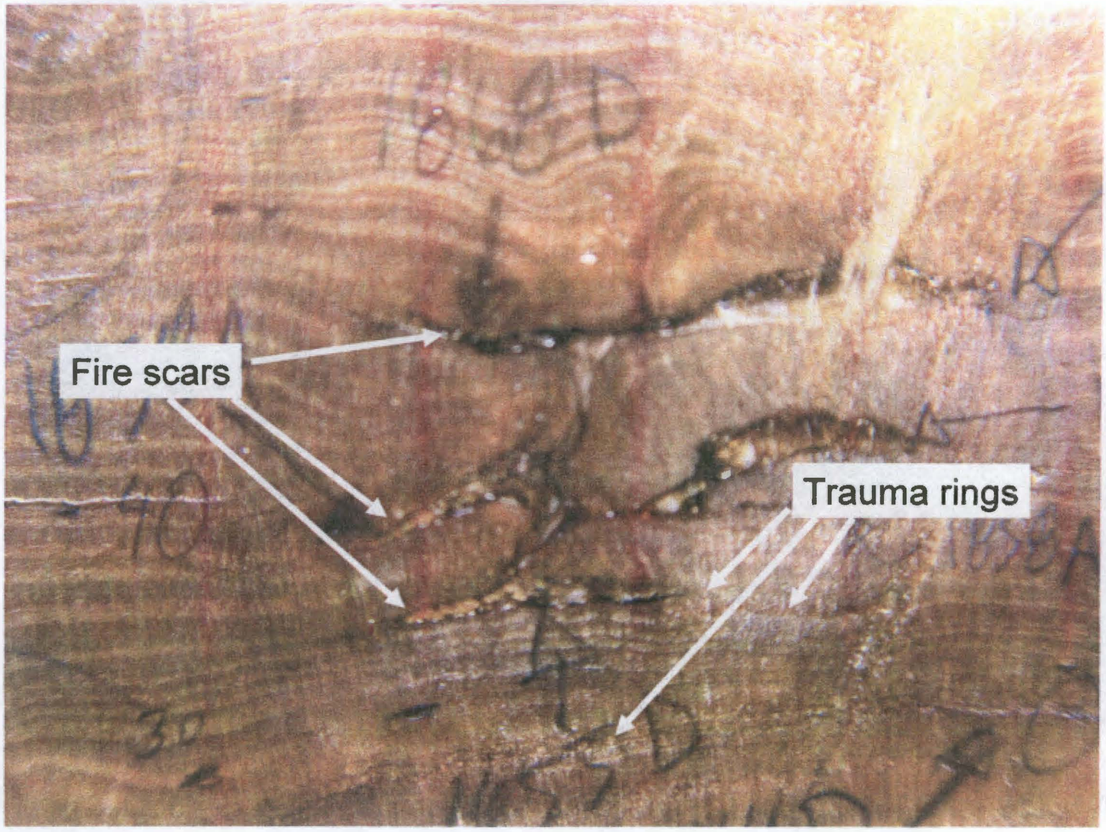


Figure 6.8 Fire scars and trauma rings in sample BP020 from Brandt Pond.

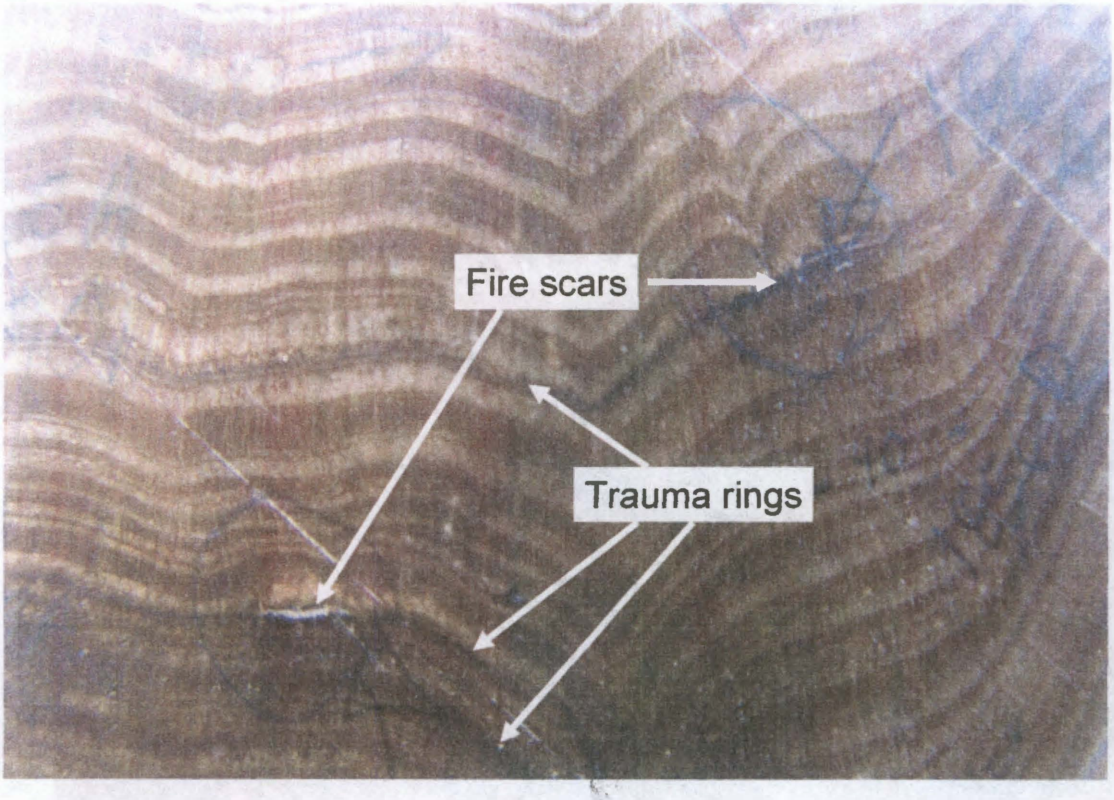


Figure 6.9 Fire scars and trauma rings in sample BP020 from Brandt Pond (Image 2).

Figure 6.10 Cutting the cross section for BP020 at the root-stem interface at Brandt Pond.

6.4.3 Fire Interval Analysis

"In the longleaf pine type of the south (and nowhere else in North America to the writer's knowledge) fire at frequent but not necessarily annual intervals is as dependable a factor of site as is climate or soil."

-H.H. Chapman, forester, 1932

The longest fire intervals (MFI, MEI, MOI) were found at Sandy Island, while fire was most frequent at EAFB (Table 6.3). The site with the highest fire frequency at EAFB was Brandt Pond. The minimum fire-free intervals were essentially the same values for all sites, but the maximum fire-free intervals varied considerably. The maximum fire-free interval at Brandt Pond was substantially less than at the other sites. The lowest variability was also at Brandt Pond, where the SD and CV were much lower than at the other sites. Brandt Pond also had the smallest difference between LEI and UEI, which is also indicative of low variability in fire intervals. The MHI at Sandy Island was much higher than at any other site.

The composite fire charts revealed a peak in fire frequency at the Big Thicket from 1900 to 1950 followed by a period of few fires. The peak in fire frequency at EAFB occurred between 1820 and 1920, after which fires dropped off considerably until the 1990s. At Sandy Island, fires were most frequent in the mid-1800s, and as at the other sites, fire frequency decreased dramatically in the 20th century.

6.4.4 Fire Seasonality

Although seasonality could not be determined for all fire scars, the percentage of fire-scarred samples for which seasonality could be determined for the Big Thicket,

Table 6.3 Descriptive statistics for all sites for all-scarred and 25% scarred (values are identical for both). BT- Big Thicket, BP- Brandt Pond, EG – EAFB all sites, DN – Donut, SI- Sandy Island, LL – Lake Louise. See section 6.3.4 for other abbreviations.

	MFI	MEI	MOI	SD	CV	Min	Max	LEI	UEI	MHI
BT	10.6	5.3	0.0	18.8	1.8	1.0	74.0	0.6	22.4	N/A
EG	6.36	3.67	0.0	10.5	1.65	1.0	58.0	0.52	13.5	N/A
BP	4.4	3.6	1.4	3.6	0.82	1.0	13.0	0.9	8.4	44.8
DN	16.3	10.7	0.0	18.2	1.1	1.0	58.0	1.8	34.5	N/A
SI	15.6	11.9	2.6	15.4	0.9	2.0	67.0	2.8	31.2	>1000
LL	6.7	5.5	2.4	5.4	0.8	1.0	21.0	1.6	12.9	230.8

EAFB, and Sandy Island was 56%, 76%, and 76%, respectively. The comparison of intra-annual position of fire scars with known prescribed fires from the Donut and Sandy Island showed good agreement between my seasonal classification and the fire events (Figure 6.11). For all fire scars over the period of record, at most sites, the majority of fires occurred during the dormant season (Figure 6.12). For Sandy Island and the Big Thicket, over 70% of fires occurred in the dormant season. For EAFB, however, most of the fires occurred in the late season, and the fires at EAFB were, in general, more evenly distributed throughout the year than at other locations. For sample LLC036, most fires (38%) occurred in the late season as well, with dormant, early and mid-season fires having approximately equal percentages. Early season fires were more common in the EAFB sites than elsewhere.

An analysis to determine temporal changes in seasonality showed that dormant-season fires dominated the Big Thicket site during all periods with little influence from early to mid-season fires (Figure 6.13). At EAFB, growing-season fires dominated in all periods, but dormant-season fires constituted from 20% to 49% of all fires beginning at 1702. Dormant-season fires also dominated at Sandy Island until the latter part of the 20th century. For LLC036, which spanned the period from 1463 to 1664, most fires occurred in the summer and fall prior to 1575. From 1575 to 1650, all fires were in the mid- to early season except one in the fall, and interestingly, no dormant-season fires occurred during this period.

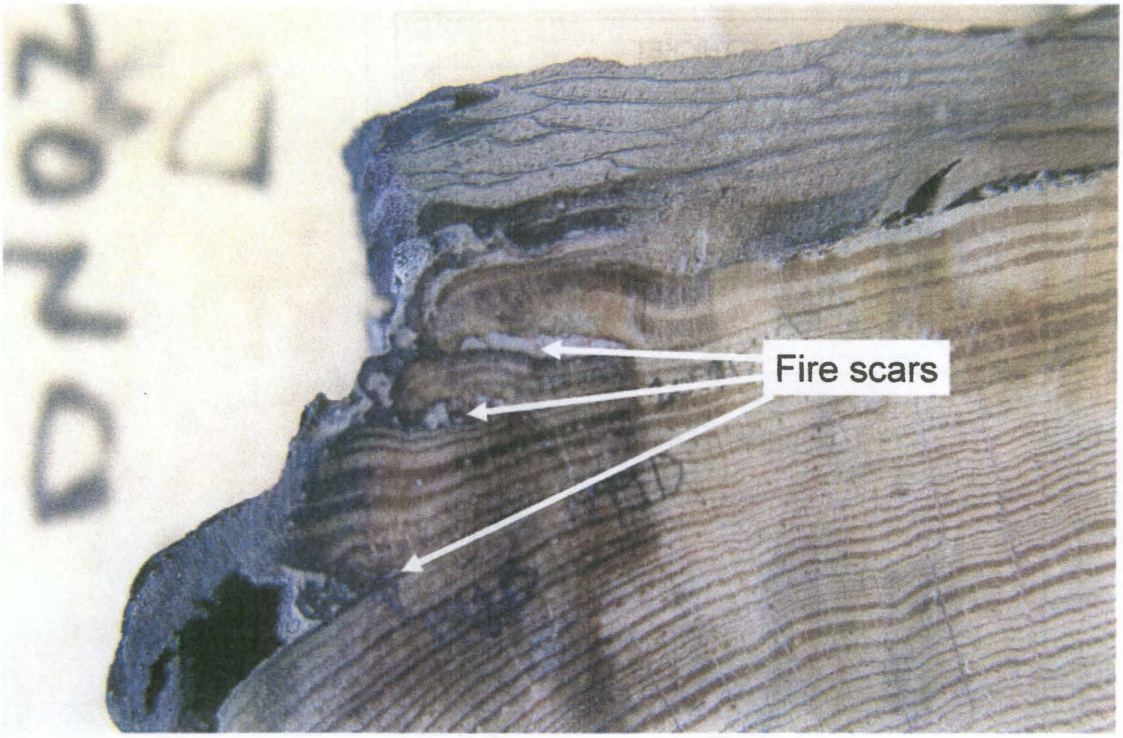


Figure 6.11 Partial cross section (DN020) cut from a living longleaf pine at the Donut site. The three fire scars labeled correspond to prescribed fires that occurred on February 1st 1992, February 17th 1999, and January 9th 2002. All fires were classified as dormant season fires. The annual ring for 1999 was exceptionally narrow and appeared to be related to mild drought coupled with fire suppression. The ring for 1992 was likewise a narrow ring even though the moisture conditions were normal for that year.

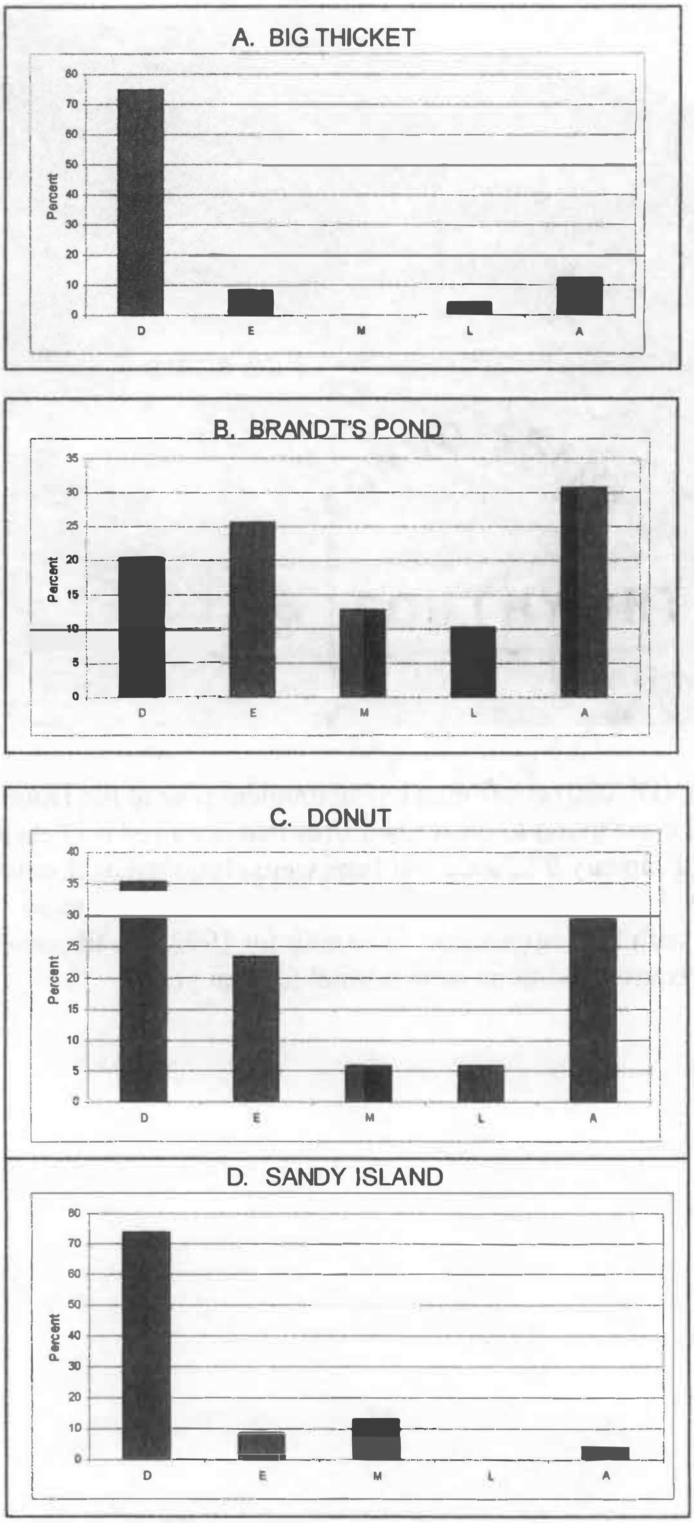


Figure 6.12 Seasonality of fires for all sites for the full period of reliability. A = Big Thicket, B = Brandt Pond, C = Donut, D = Sandy Island.

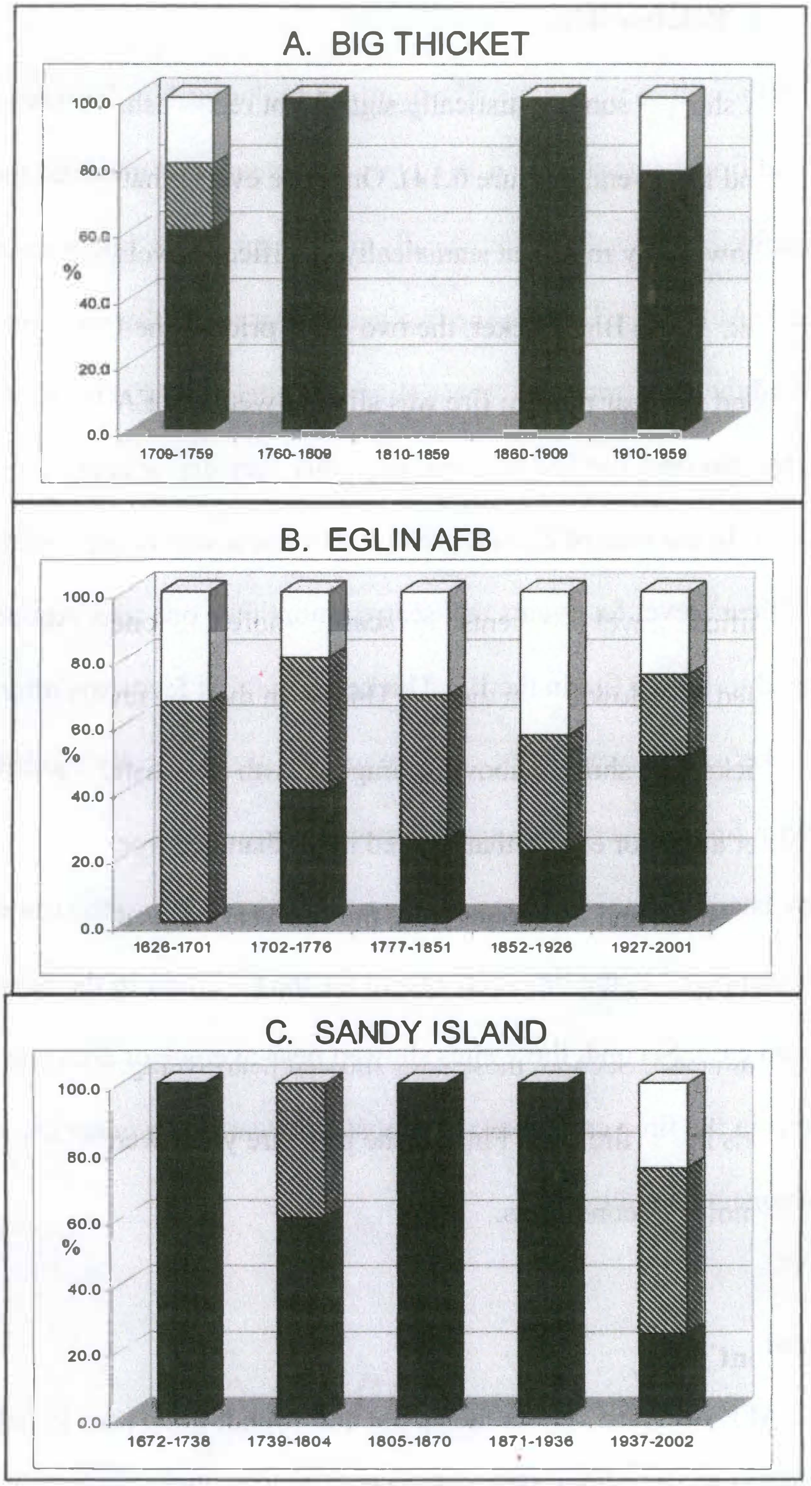


Figure 6.13 Changes in fire seasonality with periods of reliability subdivided into five periods of varying duration. The lower (dark) portion represents dormant-season (D) fires. The middle (hatched) portion represents early and mid-season (E and M) fires. The upper (white) portion represents late-season (L and A) fires. Blank periods are periods with no seasonality data. A = BT, B = EAFB, C = SI.

6.4.5 Fire/Climate Relationship

The SEA showed some statistically significant relationships between short-term climate trends and fire events (Figure 6.14). Only fire events that involved the scarring of multiple trees showed any results at statistically significant levels, but other general trends are evident. At the Big Thicket, the two years prior to the fire were wetter than the fire year itself, and the year prior to fire was slightly wetter at EAFB for fires that scarred more than one tree. Second, the fire year was normally very dry or near normal at the Big Thicket and EAFB. In the case of Brandt Pond, the fire year was exceptionally dry at a statistically significant level for events that scarred more than one tree. Above average tree growth tended to follow fire in the Big Thicket in the first few years after fire. In fact, the Big Thicket site showed above-average growth at statistically significant levels at two years after a fire for events that scarred more than one tree.

At Sandy Island and the Donut sites, the two years preceding the fire were not particularly wet compared to the fire year, except for the t – 2 year in the Sandy Island two-tree minimum case. Second, these sites showed near-average or above-average tree-growth conditions in the fire year. Finally, the post-fire years were generally years of below-average moisture conditions.

6.4.6 Fire Extent

Fires at EAFB occurred at both the Donut and Brandt Pond sites in only four years: 1789, 1862, 1870, and 1918. Widespread fires occurred in wet years that were typically preceded by one or two wet years. At the regional scale, very few fires occurred at all three major sites. EAFB shared fire years with Sandy Island in 1843, 1855, 1860,

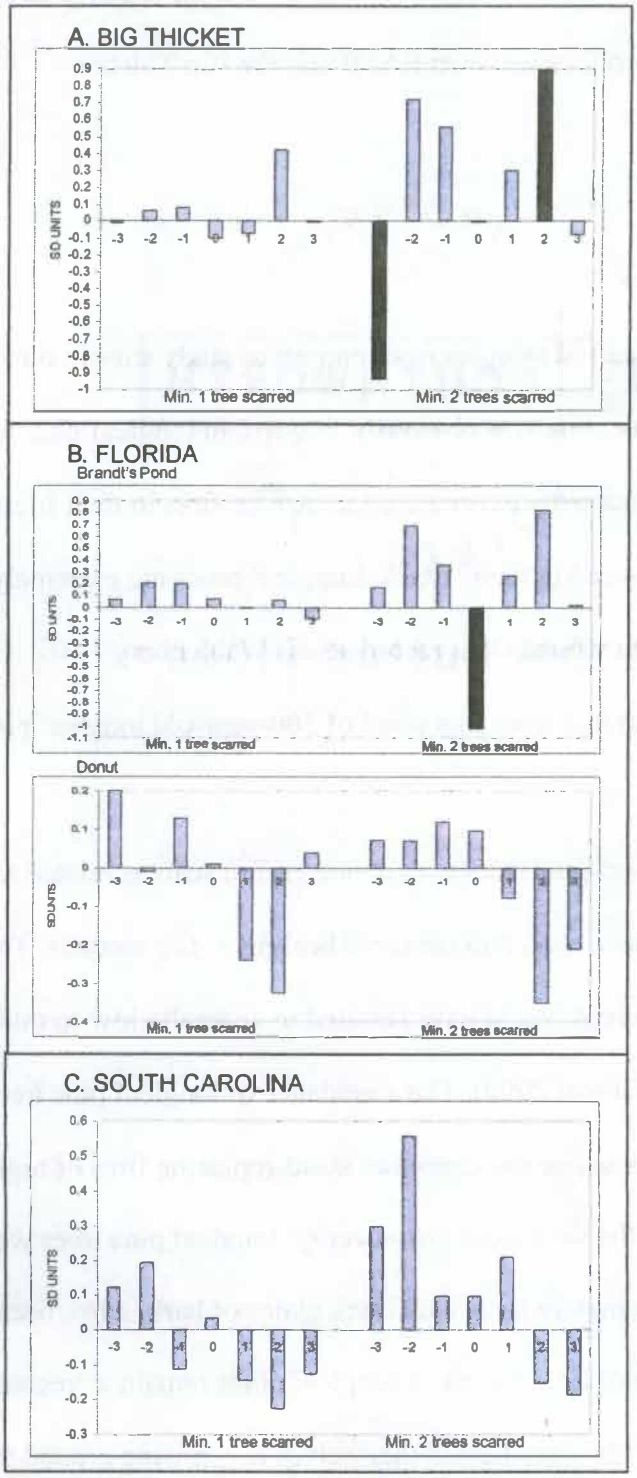


Figure 6.14 Results of the superposed epoch analysis based on one tree and two trees scarred for each site. Year 0 is the fire year. Solid black bars indicate statistically significant ($p < 0.05$) years. A = Big Thicket, B = Florida, C = South Carolina. The "SD units" represent the degree of departure from the mean reconstructed PHDI values.

1870, and 1908. The Big Thicket site and Sandy Island both experienced fire in 1951. Fire years were never synchronous between EAFB and the Big Thicket.

6.5 Discussion

6.5.1 Collection of Samples

The paucity of fire-scarred samples from numerous study sites in three states may seem surprising at first glance. Fire was obviously frequent in longleaf pine forests in the past, but trees that have undoubtedly experienced numerous fires in their lifetimes show little evidence of fire in the wood in many cases. Longleaf pines are extremely fire resistant and rarely have open wounds that record scars (Wahlenberg 1946). For example, Frost (2000) found no fire-scarred trees in a stand of 300-year-old longleaf pines in Gates County, North Carolina.

The scarcity of longleaf pine trees with abundant fire scars is related to the frequency of fire, the protective bark, and the rapid healing of fire wounds. The relatively high frequency of fire in all areas would have resulted in generally low-to mid-severity fires in longleaf pine forests (Frost 2000). The abundance of longleaf pine trees that exceed several hundred years in age indicates that stand-replacing fires of high severity were uncommon. If most of the fires were low-severity, longleaf pine trees were probably not scarred easily, especially mature trees with thick plates of bark. Also, because the trees heal quickly, the length of time that most longleaf pines remain a "recorder tree" is short. In this study, many of the trees healed themselves by growing around the wound within a decade or so after the scarring, and the remainder of the cross-section may have been free from scarring for centuries (Figure 6.15).

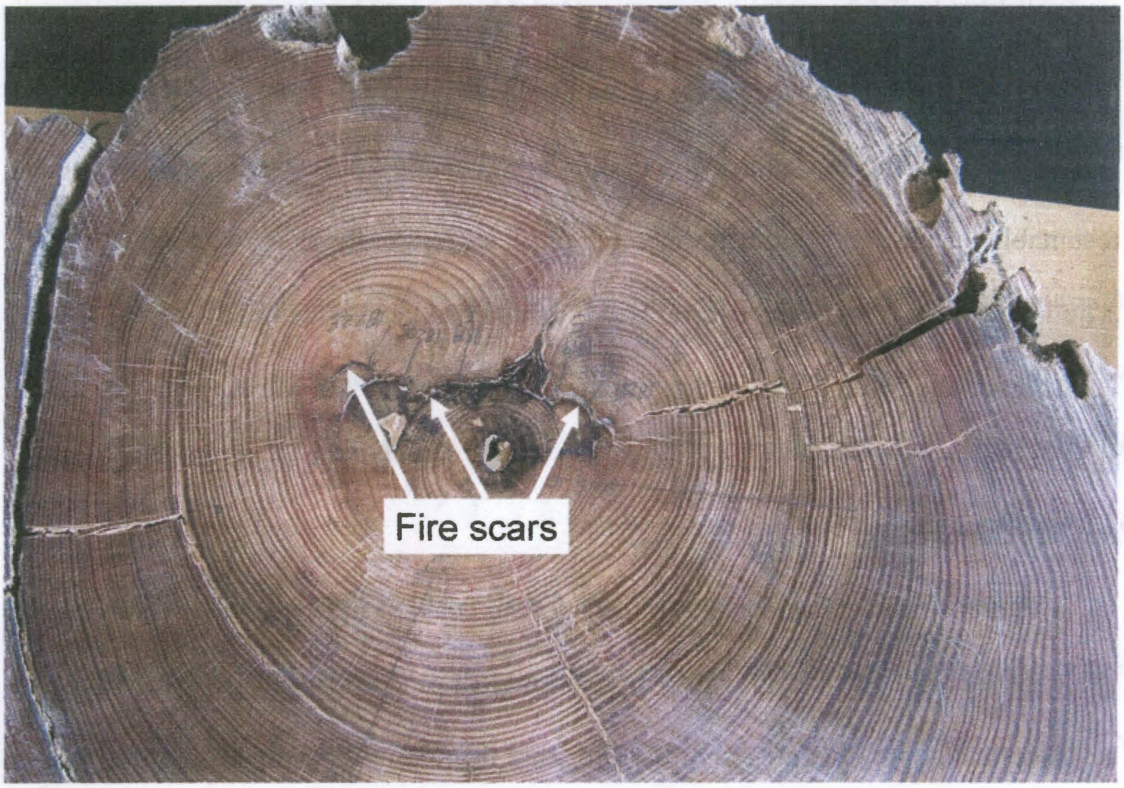


Figure 6.15 Fire scars on this sample from Brandt Pond occurred when the tree was young. No fire scars are evident once the initial wound was healed.

Normally, the trees must be wounded in some way first to provide an opening in the bark for fires to penetrate (Wahlenberg 1946). Once a tree has been fire-scarred, it can continue to record subsequent fires until the bark overgrows and seals the wound. The trees in this study were most susceptible to scarring by fire when they were young, presumably because the bark is thinner and provides less protection (Wahlenberg 1946). As an illustration, 63% of the trees at Sandy Island had been less than 50 years old when they received their first fire scar. Trees that were scarred later in life may have received a small fire injury from heat entering at a furrow or where the bark may have been stripped away for some reason.

Perhaps fire-scar studies have been slow to develop in Coastal Plain sites because visible evidence of fire scars is rather rare in longleaf pine forests. Many researchers have been skeptical about obtaining credible fire scars from longleaf pines (John McGuire, personal communication). Because longleaf pine remnants are normally the only wood that remains intact for several hundred years, in mixed stands, longleaf pine is still the only alternative for fire-scar dating of presettlement periods. In many cases, the evidence of fire scars has been hidden when the injury healed and the wood encased the scars. In such instances, the only way to reveal the scar is by cutting a cross-section that reveals the inner structure of the wood. Most live trees cannot be sampled in this manner because of conservation concerns, so the only alternative is to use stumps, logs, and snags. This dilemma makes the search for fire scars a “hit or miss” proposition in former longleaf pine stands.

Cross-sections taken at the root-stem interface appear to hold some promise for finding fire history information. Whether or not the “trauma rings” noted in this study are consistent indicators of fire injuries is not known with certainty. Komarek (1967) remarked that the greatest amount of heat from any fire is above the burning material. Unless soils are extremely dry, fuels are very concentrated, or fires burn in underground roots, the heat of fire remains primarily above the soil surface (Chandler *et al.* 1983). Because the soil is a good insulator, it does not heat appreciably in forest fires (Little 1979). Any increases in soil temperature, even under severe surface fires, are confined largely to the uppermost centimeter of mineral soil (Heyward 1938). Based on this statement, fire injury near the root-stem interface seems unlikely.

Other researchers have noted that fire can injure both above- and below-ground portions of living trees, and cambial tissue can be killed even when the bark remains intact (Smith and Sutherland 2001). Gara *et al.* (1986) found that the cambial tissue of lodgepole pine (*Pinus contorta* var. *murrayana* Doug. ex. Loud.) was killed if the heat was sufficient to char the bark. Also, root damage could occur at a depth of 5 cm in smoldering litter when soil temperatures exceed 50° C, and burned areas can produce root scars without bole scars (Gara *et al.* 1986).

Several factors in longleaf pine forests could contribute to heating of the cambium near the root-stem interface and the creation of trauma rings. First, the sandy soils in many areas of the Southeastern Coastal Plain are dry, particularly in the summer. Dry soils can heat up much more easily than moist soils (Chandler *et al.* 1983). Second, mature longleaf pines produce large amounts of litter from the shedding of needles. Forest floor litter and tree roots can burn in surface fires if litter is dry and burns hotly (Oliver and Larson 1990).

Intense heating of the soil would have been more likely, however, in ground fires. Ground fires continue to flame or smolder in the soil, burning the organic matter (Oliver and Larson 1990). Smoldering fires are common in duff, an inclusive term that refers to organic forest horizons (fermentation and humus layers) that accumulate above mineral soil (Pyne 1996). Duff has a greater probability of being ignited in backing surface fires than head surface fires because the fire burns slower and residence times are longer (C. Avery, pers. comm.) If duff is ignited, the smoldering organic matter in direct contact with the soil can raise the temperature above 300° C for several hours, with peak temperatures near 600° C (Pyne 1996). Smoldering fires of long duration may be more effective at raising soil temperatures than flaming combustion, even though the fire is hotter, because fires during flaming combustion are of shorter duration (Hugerford *et al.* 1995; Pyne 1996). Smoldering can produce enough heat to kill trees long after the fire has moved through the area (C. Avery, pers. comm.). Assuming that the heating of soil is related to the creation of trauma rings at the root-stem interface in longleaf pines, smoldering fires may be an important agent in creating the heat required to raise soil temperatures and injure cambial cells (Varner *et al.* 2005).

However, smoldering fires in duff were probably not likely if fires occurred every few years, as the organic material would have been consumed faster than it could accumulate. Humus in most pine soils is insufficient to support a ground fire because litter is typically slow to decompose in longleaf pine ecosystems where fires are frequent (Wahlenberg 1946; Christensen 1981; Christensen 1993a). Organic matter on the forest floor was probably scarce in presettlement times, but in the 20th century, substantial accumulations of surficial organic horizons have been observed around the base of large longleaf pines (Brockway and Lewis 1997; Varner *et al.* 2005). In fact, significant mortality of mature longleaf pines has occurred when fire was restored to forests where fires had been excluded, due to fire suppression for many decades.

Nonetheless, the trauma rings noted in this study may have been affected by ground fire to some degree when the interval between fires was greater than average. Litter could have built up around portions of the bole to a degree that the fire did not kill the tree but inflicted minor damage to the cambium. The trauma rings did not encompass the entire circumference of the tree, so the damage may reflect differential heating around the base of the tree caused by locally deep patches of litter.

6.5.2 Fire Intervals

6.5.2.1 Sample Size

The fire statistics reflected in this study are conservative estimates of fire intervals because trees do not scar with every passing fire, particularly in a low-to moderate-severity surface fire regime (Dieterich and Swetnam 1984; Swetnam *et al.* 1999). Moreover, the small sample size conditions the interpretations and lessens the probability of detecting all fires that occurred at a site. In the case of Brandt Pond, a single sample (BP020) contained many more fire injuries than any of the other samples. If my interpretation of the “trauma rings” is in error, the fire frequency was significantly less at the Brandt Pond site than is reported here. Finally, this analysis is essentially a stand-level study, and composite data from a larger area would be expected to yield a shorter fire return interval.

6.5.2.2 Factors that Affect Fire Frequency

Numerous estimates have been made of presettlement fire frequencies in longleaf pine forests (Heyward 1939; Christensen 1981; Frost 2000). These estimates often disagree by several years, but the common paradigm is that fire was frequent. As this study attests, the frequency of fires in presettlement forests was frequent but not entirely homogeneous throughout the Coastal Plain (Earley 2004). Christensen (1981) postulated that the "natural" fire frequency in Coastal Plain savannas was probably once every 2 to 8 years. Frost (2000) speculated that the presettlement fire frequency in the Lower Coastal Plain was 1 to 3 years, while upper Coastal Plain terraces with irregular surfaces and steeper slopes would have had a 4 to 6 year frequency. To the extent that these data represent "natural" conditions, this study confirms these assertions.

The MFI and MEI values were quite different for most of the sites, so I assumed that the MEI was more reliable because it accounts for skewness in the data. The lower values for MEI at EAFB, Big Thicket, and Lake Louise indicate that the fires have been roughly twice as frequent at these sites than at Sandy Island. The primary reason that Sandy Island has a lower fire frequency than the other sites is because the island is an isolated fire compartment that is also a small lightning target. Islands are normally exempt from natural fires except for those that originate on them, so that the smaller the island, the less the chances of fire (Harper 1911).

The fire compartments in most portions of the Southeastern Coastal Plain are exceptionally large. Fire frequency is directly proportional to the size of the natural fire compartment (Harcombe *et al.* 1993; Frost 2000). Fire compartments are "elements of the landscape with continuous fuel and no natural firebreaks, such that ignition in one part of the element would be likely to burn the whole" (Frost 2000). Before extensive settlement occurred in the Coastal Plain, artificial fire breaks such as roads and urban areas were less numerous, so fire compartments were larger. Vast, contiguous tracts of several hundred to over 1,000 km^2 existed without firebreaks in presettlement times (Ware *et al.* 1993; Frost 2000). Only waterways, wetland communities, or rain events could block the spread of fires in longleaf pine forests (Christensen 1981; Robbins and Myers 1992; Frost 1993). With the high frequency of cloud-to-ground lightning strikes occurring in the Southeast Coastal Plain, the fires that ignited from such strikes would have spread great distances. A fire igniting in Albany, Georgia might sweep through Tallahassee, Florida several weeks later (Earley 2004). Also, in the extremely rare instance of a high severity fire, fire may have jumped between fire compartments, ignoring the natural fire breaks (Frost 2000). In areas that are more dissected, such as the older Coastal Plain terraces, fire compartments are smaller, and fire frequencies would have been lower than in the newer surfaces of the Coastal Plain (Frost 2000).

The larger fire interval in the Big Thicket area, compared to the EAFB site, may be attributed to the greater degree of dissection by rivers and streams in the Big Thicket. The density of streams that could serve as fire breaks is higher in the Big Thicket than in the vicinity of Brandt Pond. Harcombe *et al.* (1993) also noted that many fire compartments in the Big Thicket are rather small, with relatively low predicted fire frequencies. Alternatively, lightning fires are more frequent in Florida than at the other sites, so the higher frequency of lightning combined with larger fire compartments would produce more fire activity. The rather high frequency of fire at Sandy Island, despite its separation from the rest of the Coastal Plain and the low probability of lightning striking such a small target, is surprising. In the 70 years of known history for Sandy Island, only two lightning fires have occurred on the island, in 1962 and 2004 (Mike Leslie, personal communication).

Few studies of lightning fires exist for islands in the Coastal Plain, and the results are mixed in terms of the frequency of lightning-ignited fires. On Cumberland Island, a barrier island off the southeastern coast of Georgia, three lightning fires occurred between 1972 and 1984 (Davison 1984). At Little St. George Island, a barrier island on the northern Gulf Coast of Florida, only two lightning-ignited fires are known to have occurred between 1963 and 2001 (Huffman *et al.* 2004). In these two cases, the frequency of thunderstorms is probably greater on barrier islands than in a more inland setting such as Sandy Island. Therefore, lightning was probably not the ignition source for many of the fires at Sandy Island. Presently, bear and deer are known to frequent Sandy Island (Furman Long, personal communication), so Native Americans and European settlers may have used the island as a winter hunting ground, as these animals could have been easily herded by fire with little possibility of escape. Pyne (1996) states that Native Americans in North Carolina often drove herd of deer into rivers or tidewaters, and the setting at Sandy Island would have been ideal for this purpose.

In addition, EAFB, Big Thicket, and Lake Louise are generally more mesic than the sandy, upland areas of Sandy Island. The moisture content at a particular site is affected by the prevailing climate and weather conditions as well as edaphic constraints (Christensen 1981). Factors that operate at smaller spatial scales exert "bottom-up" control on fire regimes that complement "top-down" controls such as climate at larger scales (Heyerdahl *et al.* 2001). "Bottom-up" controls on fire regimes may include slope, aspect, and elevation (Heyerdahl *et al.* 2001), but in this study, topographic position, depth to the local water table, and soil type may have been important factors in the Coastal Plain setting. Climatic factors are relatively similar among all the sites, except in the case of East Texas. Therefore, I assert that the edaphic conditions that create spatial variations in moisture conditions are another important influence on fire frequency in longleaf pine forests, with dry sites having less frequent fires than moist sites.

The moisture conditions in a particular edaphic and topographic setting influence the rate at which fuels can accumulate and become abundant enough to carry fire (Christensen 1981). Fire frequency in xeric sandhills and sand-pine scrub is closely related to the build-up of fuels (Christensen 1981). Even under prescribed fire, sandhill sites are not able to carry fire as often as more productive, wetter sites because of dry conditions and low rates of fuel production (Christensen 1981). The sparse groundcover of wiregrass at the highest elevations in the sandhills provides less fuel for fires, so the areas burn less frequently and less intensely (Earley 2004). On Sandy Island, for example, approximately four years of fuel accumulation are required to carry fire as a general rule (M. Leslie, pers. comm.). Fires can occur as frequently as biannually in many sites at EAFB, but the fire behavior is minimal and conditions must be exceptionally favorable (C. Avery, pers. comm.).

The shorter fire interval at Brandt Pond, compared to that of the Donut site, may indicate that fire was actually more frequent at EAFB than the composite statistics indicate. The samples at Brandt Pond included more wood with open fire scars and sample BP020, so these higher quality samples may have been more indicative of the fire regime at EAFB as a whole. Comparing the Brandt Pond fire intervals to Lake Louise, both composite chronologies contained samples from the root-stem interface, but the Lake Louise fire interval was slightly shorter. Because Lake Louise is situated near a riparian environment, the fuels may have been wetter, and fire would have occurred less frequently. Only when much drier conditions occurred could fire move into the site near Lake Louise. Similarly, fire frequency is controlled by fuel moisture in the lowland pine forests of the New Jersey Pine Barrens because poor drainage and high water table keeps fuels wetter (Little 1979).

While drier sandhills can only sustain a fire frequency of 3 to 5 years because of slow build-up of fine fuels, dry-mesic sandhills and flatwoods can sustain annual to biannual fires (Robbins and Myers 1992; Frost 1993). Dry-mesic conditions favor frequent fire because of rapid fuel accumulation accompanied by the occasional drying of fuels (Christensen 1993a). Wiregrass grows more densely with additional moisture and supports more frequent, intense fires (Earley 2004). Where wiregrass predominates, lightning fires will ignite very readily in a “three-year rough” (Komarek 1964). In longleaf pine savannas, the accumulation of dead leaves of wiregrass renders dry savanna areas highly flammable after 3 to 4 years (Christensen 1981). Studies of brown spot needle blight indicate that if a forest does not burn every 3 years, seedlings become subject to brown spot (Chapman 1932). Therefore, in the wetter sites, where brown spot would be more prevalent, the fires were more frequent and controlled brown spot. As a result, seedlings could establish and maintain longleaf pine as the dominant tree in the overstory. Additionally, areas with greater soil moisture than the sandhills could support a greater variety of hardwoods and other competitors, so more frequent fire would ensure that competing vegetation was suppressed. At the western limit of longleaf pine, frequent fire in pine savannas of the Big Thicket reduces tree density, and grasslands may develop if burning is particularly frequent or intense (Streng and Harcombe 1982; Williams 1989). Without frequent fire, hardwoods could become established and produce litter that is less flammable, creating the conditions for succession to pine-hardwood forests (Streng and Harcombe 1982).

An alternative explanation for the differences in fire frequencies between relatively dry and moist sites found in this study may relate to fire severity. In the dry sites, fire may have been just as frequent as in moist sites, but the fires were less severe because the fuels were less abundant. As a result, fires did not scar trees as often compared to the more moist sites because the fires were not as hot. Thus, the differences seen in this study reflect variations in fire severity and not fire frequency.

6.5.2.3 Fire Frequency and Longleaf Pine Ecosystems

Although the minimum fire interval at all sites was 1 to 2 years, the fire frequency was variable enough to allow for the recruitment of longleaf pine. Non-fire years tend to favor the survival of longleaf pine as it passes from the seedling to the sapling stage (Williams 1989). As early as the 1930s, Chapman (1932) noted that annual fire frequencies in north-central Louisiana do not appear to be natural or beneficial, because growth is slowed and seedlings may not survive. For successful recruitment in longleaf pine flatwoods where the soils are moist, fire-free periods are particularly important because competition from groundcover slows juvenile growth rates, which makes young longleaf pine trees more susceptible to mortality by fire than in the sandhills (Glitzenstein *et al.* 1995). Finally, fires could not have been more frequent than 1 or 2 years because fuels could not accumulate fast enough to accommodate a shorter return interval (Frost 2000).

Frequent fires would have resulted in stands that were mostly pure longleaf pine with few pines of other species or overstory hardwoods. Studies of frequently-burned plots show that frequent fires kill all loblolly and shortleaf seedlings and produce a fully-stocked longleaf stand (Bruce 1947). Even where the fire interval was as high as 10 to 12 years, a dominant woody understory would not have developed. Several decades without fire are required to substantially reduce herbaceous species and develop a dominant woody understory (Varner *et al.* 2000; Varner *et al.* 2005).

Moreover, the build-up of fuels over a decade or less would probably be insufficient to create moderate or even high-severity fires. Furthermore, the wide spacing between adult longleaf pines reduces the possibility of crown fires in old growth stands (Platt *et al.* 1988; Palik and Pederson 1996). The longevity of longleaf pines attests to the fact that crown fires or lethal ground fires in old-growth longleaf pine forests were extremely rare. The severity of a fire depends of the rate of spread and the weight of fuel consumed (Oliver and Larson 1990). With frequent fires, less fuel is available for consumption, so fires are less intense and severe. A typical fire in longleaf forests was probably a surface fire that burned a foot or two above the ground, and the chief fuel was the herbaceous cover and needle cast (Heyward 1939; Earley 2004).

However, after several decades of fire exclusion, fires can be severe and can damage even mature timber by duff consumption or crown scorch (Chapman 1932; Heyward 1939; C. Avery, pers.comm.). A prescribed burning experiment in Louisiana noted flames as high as 6 m where fire had been excluded for 17 years (Bruce 1947). The exact number of years required to build the duff layer to a sufficient depth to support a lethal ground fire is not known. Lateral root systems are particularly vulnerable in duff fires, as most of these roots are only 0.3 m from the surface (Wahlenberg 1946). After several decades, lateral roots that develop in the duff layer can be consumed in a ground fire, and this damage can be lethal to mature trees (Varner *et al*. 2005).

A final observation concerning the frequency of fire and longleaf pine ecology relates to germination. In areas where the herbaceous cover of wiregrass is thick, germination and establishment of seedlings is greatly reduced after 10 years of fire exclusion (Chapman 1932). The large seeds catch in the tall grass and have a lower probability of making contact with the mineral soil to effectively germinate than if the grass were burned over. On very dry sites, such as Sandy Island and the Donut, frequent fire would not have been as necessary as on wet sites because groundcover is sparse, which allows seeds to reach mineral soil and germinate in a condition free from competition (Landers *et al.* 1995). After a long period of needlefall, however, a substantial amount of duff accumulates, even in the driest sites. At the Sandy Island site, fires are less frequent than at the other sites, and duff may accumulate to considerable thickness between fires. A commonly held belief is that longleaf pine requires bare mineral soil for satisfactory germination and establishment (Boyer 1990). However, I observed at Sandy Island that longleaf pine can germinate readily in heavy duff or on fallen logs (Figures 6.16 and 6.17). Chapman (1947) also mentioned longleaf pines sprouting on rotten logs after a large seed crop. Furthermore, young longleaf saplings have been observed growing on rocks (John McGuire 2005, pers. comm.). Where soils are poor and competition for light and nutrients is minimal, such as in the sandy uplands

Figure 6.16 Longleaf pine that has germinated on fallen "nurse" log at Sandy Island.

Figure 6.17 Grass stage and sapling longleaf pine in heavy duff of turkey oak and pine straw, Sandy Island. No fires had occurred on this portion of the island for 20 years.

of Sandy Island, longleaf pine apparently germinates and establishes even without a fire event to expose the soil and kill competitors. If fires are not frequent and summer drought does not dry out the duff layer, the seedlings may be able to survive and reach the canopy before fire could cause mortality. Based on the establishment dates and known fires at Sandy Island, no clear relationship exists between fire events and the establishment of cohorts, so fire is evidently not required for regeneration at this site. This finding is complicated by the fact that longleaf pine does not produce annual rings in the grass stage. Therefore, this assertion is speculative and requires further investigation.

6.5.2.4 Temporal Changes in Fire Frequency

Regarding temporal changes in fire frequency, some periods of frequent fire were noticeable in each area, and these peaks seem to be related to anthropogenic ignitions. In the Big Thicket, fire was frequent from 1900 to 1950, a period when open-range livestock roamed the woods. Fire may have been more frequent before 1900, as the samples that recorded fire in the 20th century were the only ones with open "catfaces" that did not heal. Therefore, these samples were more likely to have recorded every fire than the samples from the earlier periods that contained only internal fire scars. A peak in fire frequency at EAFB from 1820 to 1920 coincides with the time when settlement began and livestock grazing was prevalent in northern Florida. While burning by herdsmen may have occurred every year, the rate of fuel accumulation in some areas may have been reduced because of grazing (Grelen 1983). Thus, the fire frequency could have possibly been higher, assuming that annual ignitions occurred, but livestock kept fuel levels low. At Sandy Island, fires were most frequent in the mid-1800s during the peak of rice production in Georgetown County. During that period, many slaves were engaged in rice farming around the island, and they may have caused the spike in fire frequency by igniting fires.

At all sites, fire frequency dramatically decreased in the 20th century. In the 1950s, open-range laws were enacted in East Texas, and these new laws, in concert with fire suppression, reduced the incidence of fire until prescribed burning commenced in the Big Thicket. At EAFB, fires were infrequent after 1920, and sand pine began to invade the area at this point (McCay 2000). Turpentining operations in the Choctawhatchee National Forest probably decreased the incidence of fire after 1920 because any fires in the vicinity of turpentine orchards were controlled to prevent their destruction. Also, the end of livestock grazing in the early 1930s and the advent of fire suppression further reduced the probability of fires. At Sandy Island, the frequency of fires drops off substantially, starting in the late 1800s. Based on the outer dates of stumps, logging probably occurred in the early 1900s. Although the sample depth drops off considerably in the 20th century, the decrease in fire frequency is accurate based on historical records. Fire suppression and the control of hunting fires is likely the primary cause of the reduced frequency of fire. Another factor contributing to lower fire activity may have been a decrease in fuels. The removal of pines from an area through logging results in decreased fire frequency because of the absence of pine needle fall (Christensen 1981). The removal of numerous old-growth longleaf pines from Sandy Island may have played a role in the lower fire frequencies in the early 1900s. If this hypothesis is true, it lends credence to the idea that the presence of longleaf pine creates conditions conducive to fire by the production of flammable fuels (Mutch 1970; Platt *et al.* 1988).

6.5.3 Fire Seasonality

6.5.3.1 Factors that Influenced Fire Seasonality

The longleaf pine forests are the "land of the 12-month fire season," and, given favorable fire conditions, the woods burn readily in any month of the year (Wahlenberg 1946; Hawley 1962). Favorable fire conditions include a continuous fuel supply, low humidity, and windy weather (Sutton and Sutton 1985). Dead wiregrass can accumulate into a mat of dry material that does not decay readily and may be at least 15 cm thick (Chapman 1932). On any dry day in all seasons, fire can spread in this dead wiregrass, even after a build-up of only a single year (Chapman 1932; Bruce 1947).

When the temperatures are low, the intensity of the burn is lower, so a hotter fire is required to raise temperatures to lethal levels compared to hot days (Little 1979). The study of fire seasonality in the Southeastern Coastal Plain is complicated by the large size of the compartments in the Coastal Plain. Because fires may have moved for several weeks or months across sections of the Coastal Plain, a single ignition in the spring may produce a fire in the early summer far from the ignition source. Thus, any discussion of seasonal effects should consider some variation in season length when discussing the timing of ignitions.

Although fires can occur in all seasons in the Southeastern Coastal Plain, seasonal climate patterns have a major influence on the season during which fires occur, and some seasons are more conducive to fire than others (Christensen 1993b). For example, in the longleaf pine savannas of the Coastal Plain, fires in the period of record are most frequent in the fall and spring because of the combination of droughts lasting several weeks and the accumulation of dead fuels during this period (Christensen 1993b; Pyne 1996). Also, temperatures, wind speed, and humidity are conducive to fires in the fall and spring. Although summer fires occur, the fuels tend to be green and not conducive to spread or high-intensity burning (Christensen 1993b).

Seasonality of fires is not only related to the characteristics of the fuels, but the source of ignitions is also important. In this study, I assume that ignitions that occurred in the summer (May through August) are primarily caused by lightning because the peak of lightning fires and thunderstorms in Florida is in July, and elsewhere in the Southeastern Coastal Plain, most thunderstorms occur in the summer (Brenner 1991). Also frontal storms in the spring and early summer can produce thunderstorms that ignite fires (Komarek 1966). This assumption discounts the effects of wintertime lightning in the Southeastern Coastal Plain. On the Southeast Gulf Coast from East Texas to the Florida Panhandle, a typical winter may experience 10 thunderstorm days (Goodman *et al.* 2000). In fact, the highest incidence of thunderstorm days in the winter months (December-February) in the United States occurs in this area of the Southeast Gulf Coast. However, the number of thunderstorms in the winter is substantially less than during the growing season. Fires occurring outside the summer months were assumed to be anthropogenic. In temperate and sub-tropical climates, human ignitions occur mainly in the late fall, winter, and early spring (Komarek 1964). Also, historical accounts indicate that Euro-American settlers set fires mainly in the winter and early spring, so this assumption seems valid.

Because most of the fires at all sites occurred during the dormant season, anthropogenic ignitions were probably more important at these sites than natural ignitions. The large number of fires in the dormant season may have affected the type of vegetation in certain longleaf ecosystems. Fires early in the growing season are more lethal to turkey and bluejack oak in longleaf pine savannahs than fires in other seasons of the year (Glitzenstein *et al.* 1995). Glitzenstein *et al.* (1995) postulated that a shift from predominantly growing season fires to dormant season fires over the last several centuries has transformed some longleaf pine savannas into more or less closed woodlands dominated largely by turkey and bluejack oak. The mix of oaks and pines that characterizes forests of the Big Thicket may be a result of the unusually high percentage of dormant season fires in the fire-scar record. This mixture of longleaf pine and upland oaks has persisted through the period of record covered by my fire history data for the Big Thicket as confirmed by age distribution data (Harcombe *et al.* 1993).

Komarek (1964) postulated that plant and animal communities have evolved largely as the effect of summer fires. The arrival of humans has changed the fire regime in the Southeastern Coastal Plain to a mix of dormant and growing season fires. What effect that change has made on vegetation assemblages is not known, but plant species such as wiregrass that thrive under the conditions of summer fire continued to thrive through the time of European settlement. Evidently, a mixed-season fire regime is adequate to maintain even longleaf pine savannas that seem to be particularly sensitive to the season of burn. Komarek (1965) believed that even when summer fires occur infrequently, grassy tracts such as in longleaf pine savannas could be maintained or enlarged. A study of prescribed burning in Coastal Plain flatwoods over four decades found that winter burns enhanced the growth of grasses and forbs while preventing the vigorous growth of an oak midstory (Brockway and Lewis 1997). Therefore, although summer burning produces more rapid and dramatic results in reducing midstory oaks, over a long period, winter burns can produce similar effects (Waldrop *et al.* 1992). Even if humans changed the season of burn, Brockway and Lewis (1997) indicate that no substantial changes in vegetative composition would have occurred in the long term. One element that these studies do not consider is the effects of deer browsing on oaks in presettlement forests. Large herds of deer were described by early explorers, and their browsing may have checked the growth of oak sprouts in longleaf pine forests, even if the season of burn would have allowed the proliferation of midstory oak trees (Waldrop *et al.* 1992).

The fire regime at EAFB is distinctly different from the other sites in terms of seasonality. A much higher percentage of fires occur in the growing season at EAFB than at the other sites. Perhaps the greater influence of thunderstorms in the growing season made this area more prone to lightning fires. EAFB is closer to the Gulf of Mexico and thunderstorms are more abundant here than at the other sites. Also, lightning fires peak in July and August in Florida, and these months are in the late season. However, the correlation between fire frequency and the abundance of thunderstorms is typically weak on a regional scale (Christensen 1993b). Although thunderstorms are much more frequent in the Southeastern U.S., forests in the southwestern U.S. lead the nation in the number of lightning fires and area burned each year (Barrows 1978). However, thunderstorms that occur in the fall may ignite fuels more readily during fall droughts when grasses begin to die back and needle litter is abundant. Needlefall is heaviest in the fall and winter (Wahlenberg 1946). Alternatively, the difference in the seasonality of fire may be related to varied anthropogenic effects. Big Thicket and Sandy Island may have had more man-made ignitions in the dormant season that preempted fires in the growing season because fuels were consumed in the winter.

6.5.3.2 Temporal Changes in Seasonality

Interpretations of temporal changes in fire seasonality are conditioned by the paucity of samples during certain periods. Very few samples are available for the Big Thicket from 1730 to 1900. The mix of dormant, late, and early season fires in the Big Thicket from 1709 to 1759 is indicative of the influence of anthropogenic ignitions, possibly set by the Caddoe hunting parties or other tribes, and natural ignitions. The preponderance of dormant-season fires in the Big Thicket in the period 1760 to 1809 may have been related to the arrival of the Alabama and Coushatta tribes from Louisiana in the latter decades of the 1700s. However, this conclusion would be dubious as this period contained only one fire scar for which seasonality could be determined. On the other hand, the period from 1860 to 1909 that was completely dominated by dormant-season fires may reflect burning by settlers in the winter. Settlers began arriving in the area in the 1830s, so the influence of human-caused ignitions is plausible. Dormant-season fires continued into the mid-1900s and ended around 1950, presumably when fire laws could be effectively enforced. East Texas was one of the last areas in the eastern U.S. to abide by stock laws, so the burning of open-range woodland likely continued well into the 20th century.

At EAFB, very few fires were recorded in the samples prior to 1700, but all fires occurred outside the dormant season. The early Indians who inhabited this portion of the Florida panhandle may have been more focused on coastal resources; they apparently did not affect the fire regime in inland areas. The arrival of the Lower Creeks by the mid-1700s brought more dormant season fires caused by hunting parties, and the percentage of dormant season fires increased in the period from 1702 to 1776. Interestingly, the percentage of dormant season fires decreased slightly through the early 1900s, even with the arrival of Euro-American settlers by the mid-1800s. If livestock grazing was intensive in the late 1800s and early 1900s, dormant- or early-season burns would have likely increased at the expense of late season fires based on the burning practices of cattlemen (Heyward 1939; Komarek 1965). Other than a slight increase in late-season fires, no changes are evident in fire seasonality from 1870 to the early 1920s. Therefore, the arrival of settlers apparently had little effect on the fire regime in this portion of the panhandle. The increase in dormant season fires in the latter portion of the 20th century may reflect the influence of wintertime ignitions from bombing ranges in close proximity to the Donut site and a preponderance of prescribed burns in the dormant season since 1972. All of the prescribed and unintentional burns at the Donut since 1991 have been in the months of January and February (C. Avery, pers. comm.)

At Sandy Island, the preponderance of fires in the dormant season tends to confirm the notion that Native Americans and Euro-American settlers set fires to drive game on the island. During the period of frequent fires in the mid-1800s when rice cultivation was being practiced, all the fires were during the dormant season. When fires in the dormant season did not preempt growing season fires by consuming available fuels, early- to mid-season thunderstorms were another source of ignitions. The reduced percentage of dormant season fires (and fires in general) from 1937 to 2002 is indicative of law enforcement against fires used for hunting which enabled fuels to build up and ignite during the growing season.

6.5.4 Fire/Climate Relationship

Because few significant relationships were evident in the SEA, short-term (a period of a few years) climate conditions are not particularly important to the fire regime of the Coastal Plain. The results were also different between sites. In some cases, short-term climate appears to affect fire activity in the years leading up to the fire and during the fire year. At other sites, no such relationship exists. However, the general trends evident in the results are worthy of examination.

In the dry climates of the Southwest, fire activity often peaks when several unusually wet years are followed by a drought year (Knapp 1995; Grissino-Mayer 1995; Grissino-Mayer *et al.* 2004). The wet years allow fine fuels to accumulate and ignite readily during drought conditions (Grissino-Mayer 1995). In the moist climate of the Central Appalachians, wet years prior to the fire year are not a necessary requirement for fires to occur (Lafon *et al.* 2005). The trend was somewhat apparent, however, at two locations in this study.

Although the relationships are not statistically significant, abundant precipitation may be effective in building up fine fuels at all sites for one or two years prior to fire events. Curiously, the Big Thicket site showed a statistically significant response in year t-3, indicating that three years prior to a fire, the conditions were exceptionally dry. No adequate explanation is available for this phenomenon. During the fire year, average to dry conditions seem to be associated with fire at all sites.

In humid climates, where heavy and continuous fuel loads may be present every year, drought in the fire year alone is often sufficient for fires to spread (Knapp 1995). When fuels are very dry, fires are much more likely to ignite and spread rapidly. In the southern and central Appalachians, for example, major fires tend to occur in years with a negative PDSI or below-average moisture conditions (Sutherland *et al.* 1995; Lafon *et al.* 2005). Drought conditions are particularly conducive to fires in Florida. After one particular Florida drought in 1962, 99 fires were documented after a single thunderstorm (Komarek 1965). The meteorological conditions that follow the drought are such that thunderstorms and lightning occur with little, if any, rain reaching the ground (Komarek 1965).

However, the general lack of a statistically significant relationship between moisture conditions in the year of fire and fire occurrence at all sites may be related to soil type. In other words, edaphic conditions temper the effects of short-term climate conditions. On dry soils like Quartzipsamments, even with abundant rainfall, the soil can become extremely dry within one week without substantial rainfall (Outcalt 1993). At Sandy Island, the high evapotranspiration rates in the summer cause the soil and duff to dry out within a week of significant rainfall, so the effects of a particularly heavy rain are short-lived (Mike Leslie, personal communication).

Moisture conditions during the fire year were slightly higher at Sandy Island and the Donut than at the other sites. In the case of Sandy Island, if the uplands dry more quickly in general than the other sites, prevailing moisture conditions may be less important during the fire year. Alternatively, the occurrence of fire on the island may have been more affected by the buildup of fuels and the timing of ignitions than climate conditions. No clear explanation is apparent for the differences at Brandt Pond and the Donut. The difference in sample size and quality of the samples are possible explanations.

Concerning the trends following fire events, I interpret these conditions to represent the response of trees to the fire event rather than of climate conditions succeeding the fire. I used tree-ring data as a climate proxy, but fire undoubtedly affects growth rates of longleaf pine trees. Although the trends are not completely consistent, tree growth at all sites except the Big Thicket tends to be suppressed after fire, while those in the more moist locations display above-average growth. In fact, the Big Thicket site showed above-average growth at statistically significant levels two years after a fire. Apparently, trees in sites where moisture is more available recover more quickly than those in extremely sandy sites. The Big Thicket soils are loamier, and the water table is closer to the surface. Also, the trees in moist sites may have more competition because of more dense growth in the understory or in the ground cover. The release of competition would cause an increase in wood production for surviving trees (Kozlowski 1971). Trees injured by fire in upland sites must allocate considerable photosynthate toward the repair of the injured site at the expense of diameter growth. Also, the tendency toward growth release in the moist sites may be related to the nutrients released or the ability to take up those nutrients. Fires convert organic material to ash, which makes the nutrients more soluble and readily available to plants (Komarek 1967).

On drier sites, longleaf pine trees seem to be more adversely affected by fire. Fires can have an adverse affect on longleaf pine growth, particularly for latewood production (Wahlenberg 1946). Studies in forest laboratories in sandy, upland soils of the Coastal Plain have shown that fire can reduce the growth rate of longleaf pine for 14-year-old saplings subjected to biennial burns, even when hardwood competition is eliminated (Boyer 1987). This study shows that in sandhill sites, a fire interval of between 3 and 10 years may be sufficient to slow the rate of growth in the first few years after the fire. The trees at the Donut site seemed to be more stressed by fire than those at Brandt Pond. Assuming that the Brandt Pond fire chronology contains a more complete record of all fires at EAFB, the fires recorded in the Donut samples may have been more representative of the hotter fires that placed greater stress on the trees.

One study that compared wet and dry sites in longleaf pine forests appears to disagree with these findings on the effects of fire on longleaf pine growth. In a study of longleaf pines growing in flatwoods versus sandhills, Glitzenstein *et al.* (1995) found that biennial burning significantly reduced growth in the mesic flatwoods and not the sandhills. The slower growth rates in the flatwoods were attributed to a greater fuel accumulation and crown scorch. In this study, however, the fire interval was not the same at all sites. Therefore, the results are not comparable, but the effects of fuel accumulation and related fire intensities may be just as important in this study. In any event, if the interpretation of post-fire effects on growth is correct, the influence of fire on diameter growth in the years after a fire event obviously adds noise to any climate reconstruction.

6.5.5 Fire Extent

The relatively high fire frequencies at sites such as EAFB seem to be indicative of extensive fires, but few fires are synchronous between the Donut and Brandt Pond. Widespread fires that occurred at both the Donut and Brandt Pond happened during wet years that were typically preceded by one or two wet years. The buildup of fine fuels evidently made the fires more capable of spreading between sites. Moreover, the wet years may have resulted in more litter production and hotter fires, making more trees at both sites more susceptible to scarring. Interestingly, all of these widespread fires occurred during the growing season, and three of the four were during the early season. An extended drought is apparently not necessary for fires to spread in the Florida panhandle, as surface fuels can become quite dry in the growing season when temperatures are high. Because fires in the growing season are hotter than dormant-season fires as fuels are drier (Hodgkins 1958), more trees could record the fire because intense fires are more likely to scar trees. The lack of synchronous fires between the two sites at Eglin is probably indicative of the sensitivity of tree samples at Brandt Pond compared to the Donut. Nonetheless, the differences could represent an actual variation in fire regimes that may have been a characteristic of this area. Variability in the height and density of grasses and other surface fuels can affect the spread and intensity of fires (Komarek 1965), and these sites could have had different densities of groundcover in the past. However, this theory is unlikely, given the similarities between the sites (soil and topography) and their close proximity.

Looking at regional scale climate relationships between sites, the fact that only six fire years were synchronous is not surprising because, as the climate analysis showed, climate conditions can vary markedly over different portions of the Southeastern Coastal Plain. No similarities in climate conditions between sites are apparent during the years of synchronous fires, except for 1951. Conditions were dry in both the Big Thicket and Sandy Island during that year. In general, however, the fact that fires occurred in the same year between any of these sites appears to be purely coincidental.

6.6 Conclusions and Recommendations

6.6.1 Major Conclusions

"The proper use of fire, and not complete fire prevention, is the only solution of the problem of future forestry in the South."

- H.H. Chapman, forester, 1912

This study documents for the first time the historical fire regime of various sites in the Southeastern Coastal Plain using fire-scar data. The major conclusions from this study include:

1. Fire history can be reconstructed using fire scars from longleaf pine trees.

This study is the first to use fire scars from longleaf pine trees to reconstruct fire history in the Southeastern Coastal Plain. Fire scars and other indicators of fire injury are present in longleaf pine wood, but the samples are not particularly abundant. Living, fire-scarred longleaf pine trees can be seen in many stands, and partial cross-sections can be extracted with minimal damage to the tree. Most fire scars are found embedded deep inside the tree in stumps and other remnants.

2. Trauma rings may yield valuable fire history information that might be preserved at the "root-stem" interface.

Although the evidence is preliminary and includes only two samples, the abundance of trauma rings in the wood near the "root-stem" interface may be an indicator of fire. These trauma rings are often associated with fire scars, so although these rings could be produced by other causes, the available evidence points toward an association between fire and trauma rings. More intensive sampling and examination of "root-stem" samples is necessary to validate the consistent abundance of trauma rings in this portion of the tree and the utility of their signature as an indicator of fire events.

3. Based on the fire-scar record, fire was frequent at several sites in the Southeastern Coastal Plain prior to the practice of fire suppression.

This study confirms the commonly held belief that frequent fires of low to moderate severity occurred in the Southeastern Coastal Plain before and after settlement by Euro-Americans. As the results of this study are a conservative estimate of fire frequency, fires were probably more frequent than these findings indicate. Fire suppression drastically altered the frequency of fire in longleaf pine forests in the 20th century. Vegetative changes in the Southeastern Coastal Plain caused by changes in the disturbance regime (*i.e.*, fire) can occur quite rapidly, so the importance of fire in maintaining longleaf pine forests is clear.

4. Historic fires varied according to site conditions and human population and practices.

Fires were an integral part of maintaining longleaf pine ecosystems, but the effects of fire were not the same across the region because of differences in climate conditions, human culture and population, topographic barriers, and site conditions (Glitzenstein *et al.* 2003). The frequency of fire was largely controlled by moisture conditions at each site that are related to edaphic factors. Dry mesic settings were most conducive to frequent fire because of the faster accumulation of fuels compared to xeric sandhills. Fires may have been more frequent at xeric sites than is reported here, but the fire severity may have been lower in general. The cooler fires would not have scarred as many trees as in moist settings. Lowland sites adjacent to riparian areas seemed to be affected by moisture conditions because, although fuels were plentiful, these sites were not dry enough to carry fire as often as the dry mesic sites. In some areas, cultural practices, such as game hunting, influenced the frequency and seasonality of fires.

5. The size of fire compartments directly affected fire frequency.

The lowest fire frequency was at Sandy Island, a small fire compartment, while the most frequent fires occurred at EAFB where fire compartments were large. Where fire compartments are large, fire can spread over a broad area from a single ignition. Therefore, fewer ignitions are required to produce fire effects over the entire area. Moreover, lightning ignitions are more likely to occur over a large fire compartment than a small one.

6. A mix of lightning and anthropogenic ignitions characterized the historical fire regime at all sites.

Lightning-ignited fires during the growing season were evident at all sites, although lightning fires were clearly more prevalent in the Florida panhandle than at the other sites. Fires during the growing season also appeared to be more widespread and indicative of drier fuels across the landscape. Fires in the dormant season were dominant at two sites, and this finding demonstrates the significant effect of anthropogenic ignitions in some areas of the region. Human-caused fires at isolated sites such as Sandy Island increased the occurrence of fire in areas that were small lightning targets. The combination of dormant- and growing-season fires over the centuries in the Southeastern Coastal Plain was sufficient to maintain relatively open longleaf pine forests that were relatively free of a dense oak midstory. However, where dormant-season fires were dominant and soils were relatively moist, such as in the Turkey Creek Unit of the Big Thicket, a mix of pines and hardwoods resulted. Whether or not climate change, changes in fire regimes, or a combination of the two caused shifts in the relative abundance of pines and oaks in the palynological record is not known because of the long and complex influence of human cultures on historic fire regimes (Clark and Robinson 1993). Also, the temporal scale of this study is limited, and the natural and anthropogenic disturbance regime immediately preceding European settlement cannot necessarily be accepted as representative of a long-term baseline value (Lorimer 2001).

7. Short-term climate conditions were not particularly important to fire occurrence.

Currently, fire frequency in portions of the Southeastern Coastal Plain is controlled by social behavior rather than climate or weather (Brenner 1991). Likewise, climate conditions do not have a particularly significant effect on fire occurrence from a historical perspective. Site conditions seem to play a role, albeit minor, in how trees respond to fire events. At moist sites, trees tend to recover more quickly from the stress of fire compared to more xeric settings.

6.6.2 Management Implications and Future Research

6.6.2.1 Management Implications

> *...Human-generated changes must be constrained because nature has functional, historical, and evolutionary limits. Nature has a range of ways to be, but there is a limit to those ways, and therefore, human changes must be within those limits.*
>
> *- Christensen et al. (1996)*

The long-term importance of fire is only beginning to be understood (Clark and Robinson 1993), but extensive field experimentation, coupled with the knowledge of historic fire regimes gleaned from fire-scar studies, is increasing our ability to successfully manage fire in longleaf pine forests. For successful recruitment to occur, fire regimes consistent with historical fire patterns are desirable (Glitzenstein *et al.* 1995). The knowledge gained from this study on "natural" fire regimes reveals three important considerations for fire managers. First, fire management plans must be designed for specific sites, as different types of longleaf pine ecosystems have varied natural fire regimes. Second, fire was historically frequent, but the interval varied. At all sites, the minimum fire interval was one year, but the average fire interval differed considerably. Third, a mix of dormant- and growing- season fires is important, but growing-season fires are less important on dry sites where competitors are few.

The first step in developing a prescribed fire plan is to develop a specific goal. In other words, land managers must decide what they want the forest to look like. Ultimately, decisions about what is "natural" or desirable about past landscapes are inherently subjective and are dependent on the values of the decision-makers (Swetnam *et al.* 1999). In many cases, high species diversity, a sparse or nonexistent understory of oaks, and a healthy environment for regenerating and sustaining longleaf pine are desirable. For communities such as longleaf pine flatwoods, burning as frequently as fuels will allow is the best method for achieving these effects (Glitzenstein *et al.* 2003). The literature is replete with prescribed fire studies of varied frequency, seasonality, and intensity in a variety of longleaf pine ecosystems, so matching the overall goal with the specific fire prescription described in these studies seems to be a reasonable approach. The historic fire frequencies found in this study may yield the desired effects, but the changes may take longer than land managers are willing to wait. The reconstructed fire histories in this study could be useful to fire managers and fire scientists in an experimental fire regime that tests these results. Because the fire intervals are probably conservative estimates, the results may be unacceptable, however, in terms of herb diversity and the possible overabundance of shrubs (Glitzenstein, pers.comm.).

Plant community changes that occur as a result of changes in the fire regime (both prescribed and natural) can be slow and dependent on the frequency and season of burning (Waldrop *et al.* 1992). As field experimentation has shown, annual or biennial fires can produce desirable effects, but the shortest mean fire interval in this study was greater than three years. Therefore, managers may wish to "speed up" the natural process of vegetative adjustment by regular and frequent fires. Moreover, natural fires were not regulated events that occurred on a consistent schedule, as is the common practice for prescribed fire. The seasonality of fires varied and the intensities probably ranged from low to moderate. Therefore, varying the interval and seasonality of fires in order to mimic the "natural" fire regime may complicate the management process.

Special care must be taken when burning in certain situations. When reintroducing fire to stands that have been fire suppressed, prescribed burns can be counterproductive because of thick duff and ladder fuels that can create hot fires that kill mature trees (Kush *et al.* 2004; Varner *et al.* 2005). Winter burns with moist conditions are recommended to begin the process because the intensity of fire will be low (Masters *et al.* 1995). Once the dangerous fuel loads have been reduced, growing season fires can be introduced to accommodate seed-production in wiregrass (Conner *et al.* 2001). For pine plantations, the burning schedule should be tailored to the stage of growth, being particularly sensitive to trees in the vulnerable height-growth stage (Grelen 1983). Burning in the summer and other seasons when the fuels are exceptionally dry brings a greater risk of mortality because the fires tend to be hotter. However, growing season burns are important for species diversity and the vitality of wiregrass.

6.6.2.2 Future Research

An immense void of fire-scar data exists across the Southeastern Coastal Plain, and this study was essentially an exploratory effort to reconstruct fire history in longleaf pine forests using fire scars. Unfortunately, the availability of fire-scarred remnants will continue to decline because of prescribed and natural fires, the extraction of longleaf pine stumps for distillation, and natural decay. The need to obtain samples in areas where remnant wood is available is urgent.

Several considerations are important in sampling for fire-scarred wood. First, partial cross-sections from living trees are ideal for comparing fire-scar information to known fire events. Second, extensive sampling of all available remnants at a site is recommended because fire scars are not readily visible on stumps and logs that have deteriorated over time. Many of the samples will contain no scars, so in order to obtain a statistically significant sample size, a large number of samples must be collected. Third, cross-sections from the root-stem interface may yield the best fire history information, so cutting as close to the base of the trunk where the roots begin to protrude is recommended. Fourth, samples from a variety of different settings will help to clarify the relationship between site conditions and fire regimes.

With regard to other techniques of studying fire history, the charcoal record in lakes and soils has been woefully underutilized in the Southeastern Coastal Plain. The charcoal record may reveal important information on fire regimes at much longer timescales than the tree-ring record. For example, a comparison of early to late Holocene charcoal records may indicate whether thundershowers and associated lightning fires were more significant in the late Holocene (Watts *et al.* 1996). The synthesis of fire-scar and fossil charcoal data will further our understanding of the historic role of fire in shaping the vegetation of the Southeastern Coastal Plain.

Chapter 7

Conclusions and Future Research

"The blind acceptance of a reconstruction without some indications of its limitations will surely lead to some erroneous conclusions about climate."

G.A.Gordon, 1980

The overall purpose of this study was to interpret data obtained from longleaf pine trees to reconstruct climate and fire history in the Atlantic and Gulf Coastal Plain over the past several centuries. In addition, this study examined the climate response of longleaf pine to a number of variables that included atmospheric teleconnections. Longleaf pine has been an essentially untapped resource for exploring the climate and fire history of the Southeastern Coastal Plain. As such, this research is a seminal effort in the application of dendroclimatology and dendropyrochronology using this tree species. This chapter summarizes the major findings of the research.

7.1 Climate Response and Climate Reconstructions

1. Longleaf pine is an excellent species for dendroclimatological reconstructions because the tree is long-lived and multiple remnants persist on the landscape.

The results of this study demonstrate the feasibility of reconstructing past climate in the Southeastern Coastal Plain using longleaf pine trees. The trees are sensitive to climate conditions and crossdate readily, although missing and false rings can sometimes be problematic. Longleaf pine trees are long-lived (400–500 years maximum ages) and their remnants are well preserved in many areas of the coastal region because of their high resin content. Living longleaf pine trees of considerable age can still be found in many areas of the Southeastern Coastal Plain. Trees in excess of 200 years of age were not uncommon at EAFB and at Pine Park in eastern Texas, and trees that exceed 150 years of age were fairly abundant at all sites in South Carolina. The oldest living tree from all chronologies dated to the year 1741. In addition to the living trees, numerous remnants of long-lived trees were found at all sites, but the remnants were scarcer in eastern Texas. The most long-lived tree in all the chronologies came from Eglin AFB and contained 437 rings, but some of the sapwood was missing from the sample.

2. The longleaf pine samples collected on all three sites produced some of the longest, continuous tree-ring chronologies obtained from southern pine in the entire Southeast.

The final chronologies dated to 1458 in South Carolina, 1507 in Florida, and 1632 in Texas. In the Southeastern Coastal Plain, the age of the EAFB and South Carolina chronologies are only exceeded by a network of baldcypress chronologies, and only by an 850-year long eastern red cedar chronology from the Missouri Ozarks in the interior southeastern U.S. The chronologies developed for this study filled some major gaps in the coverage of longleaf pine chronologies in the Southeast and are an excellent complement to the existing baldcypress chronologies from the region.

3. The amount of variance explained by the climate reconstructions is comparable to other climatic models using southern pine in the southeastern U.S.

The reconstructions that predicted climate as a function of tree growth explained from 31% to 45% of the variance in September PHDI. Grissino-Mayer and Butler (1993) used a multiple regression model to predict shortleaf pine growth in northern Georgia, and 46% of pine growth was accounted for by their model. All models in this study verified with a statistically significant Pearson correlation coefficient ($p < 0.001$), and a relatively close fit between actual and estimated PHDI values was apparent for all models. A comparison of my chronologies to other chronologies in the Southeastern Coastal Plain revealed statistically significant correlations and a common climate signal with certain tree species.

4. The correlation between longleaf pine growth and Palmer indices was the highest among all climate variables analyzed in this study.

PDSI and PHDI from July to November of the current year were more strongly correlated with longleaf pine growth than the other variables because these indices integrate the water content of the soil, temperature, and precipitation. Moreover, the high degree of autocorrelation that is inherent in the Palmer indices contributed to the high correlations with pine growth over several consecutive months of the growing season. The composite variables correlated most highly with latewood width indices. August PDSI in Texas ($r = 0.57$, $p < 0.0001$) provided the greatest correlation between latewood width and any monthly climate variable.

5. The correlation between longleaf pine growth and precipitation was moderate to high, and tree growth was most affected by rainfall in the spring and summer.

Precipitation in the current spring and summer was also a key factor associated with longleaf pine growth. Earlywood formation was most strongly correlated with current spring precipitation, and latewood formation depended heavily on current summer precipitation. The correlations between summer precipitation and latewood width in Texas ($r = 0.54, p < 0.0001$) and South Carolina ($r = 0.49, p < 0.0001$) were exceptional. Longleaf pine growth in Florida correlated most strongly with precipitation in the spring season ($r = 0.32, p < 0.001$), but the results for Florida only included an analysis of total ring width.

6. The correlation between longleaf pine growth and temperature was rather weak, and summer temperatures had the strongest effect on longleaf pine growth.

The relationship between temperature and pine growth was the weakest among all climate variables. However, warm summer temperatures in the current year adversely affected latewood growth in Texas and South Carolina. High temperatures in the summer are negatively related to longleaf pine growth because of high rates of evapotranspiration that favor respiration over net carbon assimilation. The correlations between July temperature and latewood width for Texas ($r = -0.42, p < 0.0001$) and South Carolina ($r = -0.33, p < 0.0005$) were highly significant.

7. Climate response was generally strongest in Texas, and trees in Florida and South Carolina displayed a roughly equal association with climate.

The correlation between climate and ring widths of longleaf pine trees varied between the different regions of the Coastal Plain. The mean sensitivity of the tree-ring chronologies varied substantially and was highest in Texas (0.35 for total ring width, 0.57 for latewood width). The climate response of longleaf pine trees in Texas was generally more significant for all variables, particularly for temperature. The warmer and drier conditions in the summer coupled with the loamy condition of the soil likely contributed to the distinct difference in the level of climate sensitivity in Texas. Summer rainfall is critical at the far western edge of the range of longleaf pine where summer temperatures are approximately 1^{0} C warmer than the Florida panhandle.

The longleaf pine trees in Florida and South Carolina grow in Quartzipsamment soils that have low moisture retention. The effectiveness of a particular precipitation event is probably less on the sandy sites because the water tends to drain more quickly through the soil profile to the groundwater table. As a result, the amount of water that a longleaf pine tree would be able to take up in its root system would be less than in a more loamy soil. Therefore, the climate response was generally weaker in the eastern sites, and the mean sensitivity values found for the Florida chronology (0.31 for total ring width) and for the South Carolina chronology (0.27 for total ring width) were also lower.

8. Various disturbances affected longleaf pine growth at all sites, and these disturbances were evident in the tree-ring record.

A variety of disturbances affected tree growth at all sites, so climate was not solely responsible for changes in growth rates. A comparison of chronologies within the region helped distinguish between climatic and non-climatic forcings. The major disturbances detected in the tree rings may have included logging, a major earthquake, ice storms, beetle outbreaks, and fire. Logging produced growth releases in Texas and South Carolina in the 1920s. The great Charleston earthquake of August 31, 1886, which registered between 6 and 7 on the Modified Mercalli Intensity scale, appears to have caused a growth suppression in 1887 in South Carolina. An arctic outbreak and ice storm in February 1835 slowed the growth of trees in the Florida panhandle considerably for a period of 4 years. Similarly, an ice storm that struck the Sandhill region of South Carolina in February 1969 seems to have slowed the growth of longleaf pine trees at Poinsett Electronic Combat Range during that year. A pine beetle outbreak in the Big Thicket in the mid-1970s may have caused below-average growth in years when precipitation was exceptionally high. Prescribed fire early in the growing season diminished growth at Sandy Island in 1999, and fires probably affected growth rates at all sites.

9. Fluctuations in wet and dry periods were rarely synchronous across the Southeastern Coastal Plain, but certain periods showed spatially extensive drought.

The three reconstructions provide some insight into the limitations of our interpretations of climate patterns and climate extremes in the Southeastern Coastal Plain over the past 500 years. Over much of the period of the reconstructions, extreme climate conditions were not synchronous among all sites. The Texas chronology at times seemed more in synchrony with South Carolina than with Florida. However, at annual and multi-annual scales, a few events stand out in terms of the breadth and severity of their effects. The year 1925 was perhaps the driest year at all sites in the past 300 years. Similarly, the drought of 1860 that affected large areas of the central U.S. brought drought conditions to the Southeastern Coastal Plain as far east as southern Georgia. The prevailing position and extent of the Bermuda High is likely responsible for the changes in moisture conditions between sites.

At the multi-annual and decadal time scales, the period 1951 to 1955 was one of the driest 5-year episodes among all reconstructions. Other droughts that were spatially extensive included the drought in the mid-1500s in coastal Carolina (that affected the Santa Elena colony), southern Georgia, and the Florida panhandle. Also worthy of note was the bipolar nature of moisture extremes between the southwestern U.S. and the Southeastern Coastal Plain. The decade 1778 to 1787 was one of the driest decades in northwestern New Mexico since AD 985, but this period corresponded to the wettest decade in the entire South Carolina reconstruction.

At multi-decadal time scales, moisture conditions in the growing season shifted on average every 67, 61, and 47 years in Texas, Florida, and South Carolina, respectively. The greater persistence of moisture regimes in eastern Texas is probably related to its climatic relationship with the Midcontinent region where climate patterns are more persistent. At decadal scales, the climate conditions in Florida showed the lowest tendency to swing into extreme conditions, and this characteristic is probably attributable to the more consistent supply of growing season thunderstorms and sea-breeze gust front precipitation in the Florida panhandle.

10. In addition to total ring width, measurements of earlywood and latewood width helped to better understand in more detail the response of longleaf pine to climatic variations.

Data on earlywood and latewood were extremely informative by providing more details of the intra-annual climatic response of longleaf pine trees. In some cases, total ring width would show no statistically significant relationships with climate, while earlywood and latewood would have significant associations. For example, summer temperatures in South Carolina showed no significant relationships with total ring width, but the association between latewood width and summer temperatures was statistically significant ($r = -0.28, p < 0.003$). The associations between these monthly climate variables and the specific responses in earlywood and/or latewood formation helped clarify the mechanisms involved in growth initiation and termination within the growing season. Furthermore, latewood is more sensitive to most climate variables than earlywood, suggesting that the latewood width should be targeted in future studies to produce more statistically robust reconstructions.

7.2 Effects of Atmospheric Teleconnections

1. Longleaf pine growth was generally directly related with ENSO conditions in the year that preceded growth, while an inverse relationship was evident between tree growth and ENSO in the current year.

The most salient effect in Texas was a lag or preconditioning relationship with ENSO in the year prior to growth, while ENSO conditions concurrent with the growth year had the most effect on trees growing in Florida and South Carolina. Why a lag exists in the ENSO teleconnection in Texas and not in South Carolina and Florida is not clear. The most statistically significant correlations between ENSO and tree growth in both Texas and South Carolina were normally from July through September ($r = 0.17, p < 0.05$ for previous July in Texas, 1868–2003; $r = -0.19, p < 0.05$ for current August in South Carolina). This finding indicates that, although the effects of the ENSO teleconnection are most prominent in winter and early spring, summer and late fall conditions are also influenced by ENSO in the Southeastern Coastal Plain.

2. The PDO affected longleaf pine growth most strongly, on average, in Texas, while the growth response of trees in South Carolina and Florida often resembled the response to ENSO.

The effects of PDO were rather similar to the effects of ENSO, so the relative effects of these two teleconnections is difficult to determine. Positive relationships with PDO in the year prior to growth preceded negative relationships in the current year in South Carolina and Florida. Also, the association between tree growth and the PDO in Florida was generally weak, while the PDO signal was more pronounced in longleaf pine growth in Texas and South Carolina. Finally, the pattern of tree-growth response to ENSO from 1959 to 2003 is remarkably similar to the pattern of growth response to PDO from 1976 to 2000 for South Carolina. A major difference between the effects of PDO and ENSO was in Texas, where the relationship between PDO and longleaf pine growth was generally positive and stronger, on average, than the ENSO effect.

3. The association of the NAO with longleaf pine growth was generally weak except for consistent relationships between NAO in August of the previous year and May in the current year.

At all sites, NAO for August of the previous year had a statistically significant and negative relationship with longleaf pine growth ($r = -0.17$, $p < 0.05$ for latewood in Texas; $r = -0.24$, $p < 0.006$ for Florida; $r = -0.24$, $p < 0.001$ for total ring width in South

Carolina), and this association could be explained by changes in hurricane activity. The NAO in May of the current year was also inversely related to longleaf pine growth at all sites ($r = -0.21, p < 0.01$ for Florida; $r = -0.20, p < 0.007$ for total ring width in South Carolina), and this relationship may bear on the effects of NAO on springtime temperatures.

4. The AMO affected longleaf pine growth most significantly in South Carolina, and on average, the positive phase of the AMO produced favorable conditions for tree growth.

The association between the AMO and tree growth was generally positive in most months of the year, if the average condition over the full period of the instrumental record is considered. Although some studies suggest that the positive phase of the AMO generally brings less summer rainfall in the U.S., the warm phase of the AMO normally produced favorable moisture conditions for longleaf pine growth. Conditions during all portions of the growing season may be affected by AMO, but the strongest overall signature in both Florida and South Carolina was between February and April.

5. Although the growth response of longleaf pine trees to all atmospheric teleconnections was relatively subdued, the consistency of certain relationships revealed clear but weak relationships.

The longleaf pine trees in Florida showed the least degree of statistical significance in response to all teleconnections compared to Texas and South Carolina. Despite the weakness in many of the relationships, consistent patterns of tree growth response were still evident. For example, the negative relationship between tree growth and ENSO in the current year was a fairly consistent trend at EAFB. The analysis of the relationship between teleconnections and longleaf pine growth in Florida illustrates the importance of examining all correlation results and not just the statistically significant values.

6. The effects of teleconnections varied temporally, as certain periods of analysis were characterized by particularly robust correlations between tree growth and particular teleconnections.

Although understanding how climate affects a region in the past provides some insight into the workings of the climate system, climate will never precisely show the same patterns through time (Burroughs 1996). This statement is particularly true for teleconnections that interact with each other as well as the prevailing "background" climate of the local area in complex relationships. The effects of atmospheric teleconnections on longleaf pine growth in the Southeastern Coastal Plain are complicated and unstable through time. During certain periods of analysis, teleconnections asserted a stronger influence on tree growth than in other periods. For example, ENSO B (1914–1958) showed the strongest effects of the ENSO teleconnection at all sites for any period under study. Correlations between tree growth and the PDO in PDO D were exceptionally high in South Carolina ($r = -0.56$, $p < 0.003$ for current October indices and latewood). The effects of the AMO were particularly pronounced from 1961 to 1990, while the influence of both PDO and NAO was fairly weak during the same general period, particularly in Texas and Florida. These teleconnections evidently have competing influences, which cause these relationships to be temporally variable depending on their relative strengths during particular points in time.

7. In general, the dominant phase of a teleconnection did not produce a distinct signature in tree growth response.

This study examined the temporal changes in teleconnection effects on time scales that roughly equated to the dominant phase of the teleconnection, but the prevailing phase rarely produced a unique response in tree growth. Moreover, the effects of the prevailing phase of a teleconnection were opposite in sign for some sites. For example, in South Carolina, the effects of the prevailing phase of the teleconnection were opposite in sign for NAO B (1901–1935) and D (1971–2002) (both positive phases) and PDO B (1926–1950) and D (1976–2000) (both warm phases). In some cases, however, the predominant phase of a teleconnection produced a distinct response in longleaf pine growth. To illustrate, the highest correlations between the AMO and tree growth in South Carolina were found in the predominantly cold phases of the AMO (AMO B (1901–1930) ($r = 0.61$, $p < 0.001$ for previous July indices and latewood) and D (1961–1990) ($r = 0.53$, $p < 0.002$ for current September indices and earlywood).

8. The importance of measuring earlywood and latewood was reinforced in this portion of the study because earlywood and latewood widths revealed intra-annual relationships between tree growth and teleconnections that were not apparent using total ring width as the sole measure of growth response.

The correlations between teleconnection indices and total ring width, earlywood width, and latewood width revealed distinct differences in the strength of the climate response. For example, the relationship between longleaf pine growth and ENSO in the year prior to growth was most evident in the earlywood width in Texas ($r = 0.21, p < 0.02$ for previous October). On the other hand, latewood width was most highly correlated with ENSO in the current year in South Carolina ($r = -0.28, p < 0.001$ for current August). In like manner, the influence of the PDO is most strongly manifested in the earlywood width in Texas, but in the latewood width in South Carolina. Efforts to reconstruct teleconnections using tree-ring chronologies would benefit from the inclusion of earlywood and latewood data that capture the subtleties of the intra-annual association between climate and tree growth.

7.3 Historic Fire Regimes

1. Longleaf pine trees produce fire scars that can be used to reconstruct fire history.

This study is the first published use of fire scars of longleaf pine trees in dendropyrochronology and demonstrates that fire history in longleaf pine ecosystems can be reconstructed using fire scars. Fire scars can be found in longleaf pine wood, both in visible catfaces and as internal scars buried deep inside the wood. The internal scars tend to heal over rapidly after recording a few fires. Fire-scarred samples are not prevalent, however, presumably because most fires were low severity and thick bark protected the wood from injury. Partial cross-sections can be extracted from living, fire-scarred trees with minor damage to the tree. Trauma rings, which are particularly abundant at the root-stem interface, may be an important indicator of fire activity.

2. Even though the number of fire-scarred samples from each site was rather low, the length of the fire chronologies was exceptional for fire history studies in the southeastern U.S.

Although the sample size was relatively small at all sites, the samples contained well-preserved fire scars. I obtained 10 samples for the Big Thicket, 14 samples for EAFB, and 18 samples for Sandy Island. The maximum number of scars on any sample was 26, but the average sample contained between 3 and 4 scars. The earliest scars dated to 1626 at EAFB, 1674 at Sandy Island, and 1714 in the Big Thicket, but the sample depth is very low until the 1800s for Florida and South Carolina, and until the 1900s in Texas. Nevertheless, the length of the fire chronologies is exceptional for the southeastern United States.

3. Fire was frequent in longleaf pine forests before the practice of fire suppression.

Notwithstanding the statistical limitations of a small sample size, this research validates the speculation concerning frequent fires in longleaf pine forests of the past. Before fire suppression in the 20th century, fires occurred approximately once every 4 years at EAFB, once every 5 years in the Big Thicket, and once every 12 years at Sandy Island. However, fires were probably more frequent than the results indicate because fire-scar data generally produces conservative estimates (trees do not record all fires). Minimum fire intervals ranged between 1 and 2 years, and maximum fire intervals ranged from 13 to 74 years. Because the fires were relatively frequent, the severity was probably low to moderate. In the 20th century, fire suppression drastically altered the fire regime of longleaf pine forests in the Southeastern Coastal Plain. As a result, longleaf pine trees declined in abundance and hardwoods invaded many stands formerly dominated by longleaf pine.

4. Both natural and anthropogenic ignitions characterized historic fire regimes, but human-caused fires were particularly important at some sites.

Fire regimes in the Southeastern Coastal Plain are determined by a complex combination of factors that include climate and atmospheric conditions and cultural practices. Lightning-ignited fires likely occurred at all sites, but the highest percentage of naturally-ignited fires occurred in the Florida panhandle. The relative frequency of lightning fires at EAFB is probably related to the greater frequency of thunderstorms in this area relative to the West Gulf Coastal Plain and the Atlantic Coastal Plain. Anthropogenic ignitions were likely dominant in Texas and Sandy Island as indicated by the preponderance of fires in the dormant season. During the period of the fire record in the Big Thicket, open range burning was common and may have been the cause of most human-caused fires. Fires peaked at Sandy Island in the mid-1800s when rice production and slave population was high. At all sites, fire frequency decreased dramatically in the 1900s because of fire suppression. The end of the open range in Texas in the 1950s and in the 1930s in Florida probably contributed to the reduction in fire frequency. The logging of numerous old-growth longleaf pines at Sandy Island in the early 1900s probably contributed to the reduced incidence of fire because of the reduction in needle fall from the removal of many large trees.

5. Fire frequency may have been influenced by soil moisture conditions, the size of fire compartments, and, to a lesser degree, short-term climate conditions.

Not only did prevailing atmospheric conditions and human activity affect historic fire regimes, but site conditions may have been important as well. The frequency of fire seemed to be controlled in some degree by moisture conditions at each site that are related to edaphic factors. Dry mesic settings appeared to be most conducive to frequent fire because of the faster accumulation of fuels compared to xeric sandhills. Fires may have been more frequent at xeric sites than is reported here, but the less-plentiful fuels would have produced cooler fires that would not have scarred as many trees as in moist settings. Lowland sites adjacent to riparian areas probably supported lower fire frequencies because, on average, the moisture content of the fuels was higher, so the fuels could not burn easily.

6. The size of fire compartments showed a direct relationship with fire frequency.

Areas where the fire compartments were small, such as Sandy Island and the Big Thicket, had lower fire frequencies than EAFB, where fire compartments were larger. When fire compartments are large, the chance that an ignition may occur in the area is higher, so the possibility that fire will spread throughout the compartment is greater than in an area that is highly dissected by barriers to fire. In the case of both Sandy Island and the Big Thicket, the major barriers that separated fire compartments were rivers.

7. Short-term climate conditions may have influenced fire activity, but the effects of climate were probably weak.

Few statistically significant relationships were evident in the Superposed Epoch Analysis. However, during the fire year, average to dry moisture conditions tended to prevail. At Brandt Pond, a statistically significant ($p < 0.05$) and inverse relationship was evident between moisture conditions and the incidence of fire when a minimum of two trees scarred was considered. Therefore, at this site, drought conditions likely favored fires of relatively higher severity that scarred multiple trees. The general lack of a statistically significant relationship between moisture conditions in the year of fire and fire occurrence at all sites could be related to soil type, because sandy soils are almost always dry, even within a few days of a substantial rain event. As a result, short-term climate conditions may have less effect on soil and fuel moisture. After a fire event, longleaf pine trees at more moist sites (*e.g.*, Big Thicket) appeared to recover more quickly, presumably because the trees are less stressed for water than those at more xeric sites.

7.4 Recommendations for Fire Management

Fire management plans for longleaf pine forests have usually been based on prescribed burning experiments, but the information available from this study may have some utility as well. Although reconstructions of past wildfires are important to justify the need for fire restoration, the specific characteristics of past fire regimes may also serve as a guide to fire restoration programs (Swetnam *et al.* 1999). Fire management programs designed to mimic natural processes can use fire history information as a basis for modeling, planning, and implementing fire management programs (Swetnam *et al.* 1999).

Land managers interested in using this study as a guide to fire management must keep the following elements in mind. First, these data are based on a fairly small sample size and therefore represent a preliminary study. More work is necessary to provide more robust statistical results. Second, the estimates of fire frequency are probably conservative, as is the case with most studies based on fire-scar analysis. Third, the overall goal of the fire management plan must be considered, and this goal must include the type of vegetative assemblage desired. Fourth, the pace of restoration desired in the plan will dictate the frequency and seasonality of fire, in large measure. Frequent (biennial to annual) fires in the growing season will reduce hardwoods and increase the growth of herbaceous plants more rapidly than the "natural" fire regime, which may produce similar effects but may take much longer to achieve. Finally, recent studies have demonstrated the "pitfalls" inherent in restoring fire to old-growth stands that have had fires suppressed during the 20th century. The utmost care must be taken to reduce accumulated fuels before reintroducing fire in these valuable stands to avoid the undue mortality of ancient longleaf pines.

In any event, the current fire management practices in some sites that I visited are quite close to the historic fire regime. For example, the current fire rotation at EAFB is roughly 4 years for most sites, and the computed fire return interval for Brandt Pond was approximately 3.5 years. Knowing that current management practices roughly approximate the fire regime of the past gives land managers the sense that they are, indeed, restoring the "natural" fire conditions.

7.5 Future Studies using Longleaf Pine

While this study demonstrates the usefulness of longleaf pine for research in climate and fire history of the Southeastern Coastal Plain, much remains to be answered, and the opportunities for future research are many. Four major areas for future study include (1) expanding the length and coverage of existing chronologies, (2) relating climate history to archaeological/historical research, (3) examining the effects of teleconnections based on historical reconstructions, and (4) analyzing the effects of teleconnections on fire regimes.

While several longleaf pine chronologies are available from the International Tree Ring Data Bank, these chronologies, combined with those in this study, are few, relative to the spatial extent of the Southeastern Coastal Plain and the potential abundance of remnant wood in the region. Coverage is particularly sparse in Florida, even though several sites contain old-growth longleaf pines. Furthermore, longleaf pine trees from the Piedmont and Ridge and Valley provinces have yet to be exploited fully. Expanding the number of chronologies across the Southeast will increase our knowledge of past climates by improving the spatial resolution of available data.

Much larger datasets of fire-scarred samples are needed to better characterize the historic frequency and seasonality of fire. Moreover, the fire regimes across the Coastal Plain and surrounding regions were not homogeneous because of variations in local topography, edaphic conditions, human populations and practices, and other factors. Therefore, much work in dendropyrochronology is necessary to further our understanding of these historic fire regimes.

My chronologies extend into the 15th century, but I believe that longleaf pine wood that dates several centuries older may exist in certain sites. Stumps and remnants from the sites of early logging in Virginia and North Carolina during the 17th and 18th century could yield samples of considerable age. “Dead-head” logs extracted from the bottom of rivers in the Coastal Plain are well preserved and could be another source of samples. Moreover, virtually no research has investigated longleaf pine samples from archaeological sites. Because longleaf pine trees were used in construction by Native Americans and Euro-American settlers, samples from archaeological sites may prove useful for extending chronologies into the distant past. As in this study, TRW, EWW, and LWW chronologies should be developed. Oxygen isotope data should be further refined and incorporated as well. For fire history studies, samples from the root-stem interface are recommended to find evidence of trauma rings, which require further examination to prove their validity as indicators of fire activity.

Expanding the coverage and length of longleaf pine chronologies will enable more interdisciplinary research between dendrochronology, archaeology, and history. Tree-ring data provide an enhanced level of temporal resolution that can be useful in connecting climatic events to the history of humans in the Southeastern Coastal Plain. Anderson *et al.* (1992) is one of the few studies that incorporate tree-ring research with archaeology; further cooperation between these two disciplines could be fruitful. As in this study, research on how tree growth was affected by catastrophic disturbances that were recorded in history is another avenue for future investigation.

Teleconnections and their effects on longleaf pine growth in the past should also be explored. Several reconstructions of ENSO and the NAO have been developed in the past decade, and longleaf pine growth trends in the past can be compared to these reconstructions. These studies would have the potential to increase our understanding of temporal and spatial changes of atmospheric teleconnections and their effects on tree growth in the Coastal Plain. Perhaps more importantly, to better define the relationship between teleconnections and tree growth, more information is necessary on precisely how these teleconnections affect climate in various regions of the Southeast. While my study adds to our knowledge of how teleconnections affect tree growth, the particular climate parameters that are causing these growth responses are not well understood.

Another area that shows promise for future research concerns long-term teleconnections and their effects on fire regimes in the Southeastern Coastal Plain. This study has shown that a number of teleconnections affect longleaf pine growth. These relationships are undoubtedly linked to climate conditions, and climate conditions help to shape fire regimes to some degree. I suspect that some significant relationships may exist between fire activity and teleconnections in some areas of the Southeastern Coastal Plain.

In conclusion, valuable climate proxies, such as coral colonies and glacial ice, are threatened worldwide, so a pressing need exists for more research using these proxies. Likewise, the need to exploit available longleaf pine wood is urgent because of the demand for these pine remnants in wood distillation and other industries. Many sites that I investigated during this research had already been cleared of most of their longleaf pine stumps. Moreover, prescribed burning, while preserving and restoring longleaf pine trees, can consume the available remnants. As burning for the management of longleaf pine forests becomes more widespread, the likelihood that valuable remnants might be destroyed increases. Therefore, research in climate and fire history using this valuable scientific resource should be a priority.

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APPENDICES

APPENDIX A1. Statistical descriptions for the 125 series in the Texas total ring width chronology. AR( ) represents the order of the autoregressive model used in the detrending. Higher values are indicative of persistence over several years, and the normal range for AR coefficients is between 1 and 4 (Grissino-Mayer 2001a).

Seq	Series	Interval		No. Years	Corr. w/ master	Mean sens	Std dev	Auto corr	AR ( )
1	TCF01	1938	1994	57	0.322	0.357	0.500	-0.018	2
2	TCF02	1890	1994	105	0.539	0.290	0.606	0.033	1
3	TCF03	1954	1994	41	0.358	0.201	0.578	-0.042	1
4	TCF04	1912	1994	83	0.406	0.458	0.578	-0.028	1
5	TCF05	1938	1994	57	0.512	0.352	0.495	0.004	1
6	TCF06	1895	1994	100	0.616	0.377	0.450	0.049	1
7	TCF07	1924	1994	71	0.559	0.319	0.607	-0.063	1
8	TCF08	1915	1994	80	0.609	0.328	0.480	-0.022	1
9	TCF09	1956	1994	39	0.372	0.242	0.630	-0.107	1
10	TCF10	1961	1994	34	0.538	0.296	0.738	0.080	1
11	TCF11	1923	1994	72	0.479	0.326	0.437	-0.026	1
12	TCF13	1935	1994	60	0.426	0.292	0.553	-0.005	3
13	TCP01	1897	1994	98	0.459	0.269	0.489	-0.019	2
14	TCP02	1928	1994	67	0.484	0.395	0.515	-0.002	2
15	TCP03	1932	1994	63	0.603	0.231	0.528	0.113	1
16	TCP04	1919	1994	76	0.544	0.459	0.521	-0.070	1
17	TCP05	1909	1994	86	0.553	0.311	0.553	0.027	2
18	TCP06	1921	1994	74	0.509	0.330	0.509	0.043	1
19	TCP07	1943	1994	52	0.564	0.341	0.483	0.039	2
20	TCP08	1929	1994	66	0.591	0.315	0.519	0.116	1
21	TCP09	1929	1994	66	0.457	0.292	0.545	0.007	2
22	TCP10	1922	1994	73	0.581	0.297	0.472	0.001	2
23	TCP11	1909	1994	86	0.473	0.507	0.594	0.025	1
24	TCP12	1930	1994	65	0.473	0.382	0.623	-0.126	1
25	TC10A	1791	1892	102	0.470	0.261	0.449	0.018	2
26	TC10B	1794	1885	92	0.290	0.369	0.347	0.015	1
27	TC11a	1896	2003	108	0.489	0.358	0.445	0.081	4
28	TC11b	1916	2003	88	0.461	0.331	0.520	-0.003	2
29	TC12a	1925	2003	79	0.585	0.301	0.500	0.075	1
30	TC12b	1921	2003	83	0.636	0.335	0.544	0.013	1
31	TC016b	1629	1736	108	0.366	0.309	0.458	-0.035	2
32	TC019a	1903	2003	101	0.585	0.343	0.471	0.035	2
33	TC28A	1895	2002	108	0.436	0.326	0.315	-0.118	1
34	TC28B	1900	2003	104	0.604	0.307	0.407	-0.057	1
35	TC29A	1900	2003	104	0.472	0.394	0.616	-0.016	1
36	TC29b2	1930	2003	74	0.658	0.446	0.608	0.095	2

APPENDIX A1. *continued*

Seq	Series	Interval		No. Years	Corr. w/ master	Mean sens	Std dev	Auto corr	AR ( )
37	TC30A2	1910	2003	94	0.529	0.407	0.508	0.078	2
38	TC30B2	1910	2003	94	0.507	0.318	0.606	-0.032	1
39	TC30A	1685	1789	105	0.327	0.420	0.476	-0.002	1
40	TC30B	1660	1798	139	0.380	0.442	0.483	-0.026	1
41	TC30C	1700	1802	103	0.543	0.442	0.584	-0.093	2
42	TC31	1920	1974	55	0.510	0.386	0.443	-0.075	1
43	TC032	1694	1861	168	0.425	0.311	0.468	0.065	1
44	TC035	1668	1734	67	0.360	0.398	0.516	0.123	2
45	TC36A	1772	1844	73	0.566	0.385	0.539	0.050	2
46	TC036B	1777	1841	65	0.707	0.397	0.577	0.042	2
47	TC368	1751	1825	75	0.321	0.314	0.495	0.094	1
48	TC037	1710	1790	81	0.297	0.366	0.526	0.018	1
49	TC38	1777	1864	88	0.674	0.378	0.466	0.032	1
50	TC70a	1743	1847	105	0.521	0.305	0.452	0.005	2
51	TC70b	1749	1863	115	0.506	0.278	0.581	0.015	2
52	TC71a	1676	1870	195	0.585	0.394	0.457	-0.015	2
53	TC71b	1676	1819	144	0.535	0.410	0.444	0.006	2
54	TC72a	1720	1892	173	0.514	0.434	0.379	-0.019	3
55	TC72b	1720	1872	153	0.653	0.383	0.352	-0.004	1
56	TC73a	1750	1867	118	0.472	0.422	0.539	-0.034	1
57	TC73b	1754	1860	107	0.531	0.376	0.426	-0.001	1
58	TC74	1657	1762	106	0.530	0.413	0.561	0.078	1
59	TC75	1767	1866	100	0.399	0.260	0.392	-0.006	2
60	HC04	1907	1982	76	0.450	0.367	0.528	-0.076	1
61	CLL.08	1851	1993	143	0.438	0.391	0.449	0.015	1
62	CLL.06	1900	1993	94	0.653	0.338	0.494	0.087	1
63	CLL.07	1843	1992	150	0.621	0.317	0.554	0.000	2
64	CLL.11	1826	1993	168	0.496	0.360	0.530	-0.018	2
65	CLL.05	1922	1992	71	0.596	0.338	0.377	-0.041	1
66	CLL.04	1860	1993	134	0.541	0.308	0.488	0.001	1
67	CLL.13	1862	1993	132	0.600	0.288	0.393	0.033	1
68	CLL.14	1891	1993	103	0.615	0.300	0.570	-0.032	1
69	CLL.20	1907	1993	87	0.614	0.295	0.527	0.014	1
70	CLL.21	1848	1993	146	0.568	0.271	0.438	0.001	1
71	CLL.03	1819	1993	175	0.544	0.323	0.287	-0.017	1
72	CLL.16	1883	1993	111	0.578	0.307	0.468	-0.075	3
73	CLL.01	1795	1993	199	0.400	0.322	0.497	-0.025	1
74	CLL.09	1847	1993	147	0.546	0.309	0.406	0.035	1
75	CLL.02	1806	1993	188	0.468	0.318	0.449	-0.003	1

APPENDIX A1. *continued*

Seq	Series	Interval		No. Years	Corr. w/ master	Mean sens	Std dev	Auto corr	AR ( )
76	CLL.12	1828	1993	166	0.555	0.377	0.550	-0.044	1
77	CLL.15	1870	1988	119	0.543	0.286	0.420	-0.022	1
78	CLL.10	1850	1993	144	0.586	0.362	0.493	0.035	1
79	SAPP01	1890	1994	105	0.483	0.336	0.556	-0.010	1
80	SAPP04	1890	1994	105	0.433	0.366	0.510	0.003	1
81	SAPP05	1931	1994	64	0.502	0.294	0.445	-0.053	1
82	SAPP10	1909	1994	86	0.426	0.261	0.454	-0.054	1
83	SAPP07	1898	1994	97	0.526	0.407	0.402	0.014	2
84	SAPP08	1890	1994	105	0.498	0.317	0.470	-0.100	1
85	SAPP12	1911	1994	84	0.473	0.354	0.442	-0.033	1
86	SAPP03	1899	1992	94	0.412	0.333	0.604	-0.005	2
87	SAPP11	1917	1994	78	0.529	0.342	0.352	-0.036	1
88	SAPP02	1893	1994	102	0.360	0.282	0.548	-0.067	1
89	PP01a	1844	2003	160	0.494	0.372	0.497	0.019	1
90	PP01b	1900	2003	104	0.566	0.355	0.562	-0.016	1
91	PP02a	1790	2003	214	0.389	0.377	0.441	-0.023	2
92	PP02b	1805	2003	199	0.447	0.404	0.489	0.067	1
93	PP03a	1865	2003	139	0.562	0.328	0.471	-0.005	2
94	PP03b	1814	2003	190	0.354	0.393	0.412	-0.019	2
95	PP05a	1910	1940	31	0.424	0.347	0.731	0.024	1
96	PP05b	1916	1947	32	0.606	0.424	0.643	-0.030	1
97	PP06a	1787	2003	217	0.505	0.378	0.511	0.047	1
98	PP06b	1804	2003	200	0.501	0.397	0.435	0.057	1
99	PP07a	1964	2003	40	0.313	0.336	0.655	-0.071	1
100	PP07b	1902	2003	102	0.402	0.313	0.442	-0.066	1
101	PP08a	1887	2003	117	0.557	0.396	0.568	-0.063	1
102	PP08b	1928	2003	76	0.480	0.330	0.443	0.045	1
103	PP09a	1814	2003	190	0.489	0.335	0.379	-0.020	1
104	PP09b	1816	2003	188	0.582	0.334	0.468	-0.016	1
105	PP10a	1820	2003	184	0.576	0.321	0.405	0.010	1
106	PP10b	1833	2002	170	0.561	0.370	0.465	0.098	1
107	PP11a	1819	2003	185	0.500	0.358	0.570	0.037	1
108	PP11b	1830	2003	174	0.487	0.371	0.512	0.042	1
109	PP12a	1821	2003	183	0.497	0.286	0.302	-0.024	1
110	PP12b	1822	2003	182	0.558	0.313	0.290	-0.028	1
111	PP13a	1808	2003	196	0.609	0.367	0.491	0.052	2
112	PP13b	1820	2003	184	0.648	0.319	0.454	0.050	1
113	PP14o	1865	2003	139	0.607	0.321	0.485	-0.057	1
114	PP15a	1813	2003	191	0.578	0.415	0.498	-0.049	1

APPENDIX A1. *continued*

Seq	Series	Interval		No. Years	Corr. w/ master	Mean sens	Std dev	Auto corr	AR ( )
115	PP15b	1779	2003	225	0.419	0.451	0.477	0.013	2
116	PP16a	1780	2003	224	0.514	0.351	0.420	-0.006	1
117	PP16b	1780	2003	224	0.501	0.369	0.326	-0.004	1
118	PP17a	1829	2003	175	0.678	0.393	0.569	0.047	2
119	PP17b	1836	2003	168	0.672	0.355	0.473	-0.041	2
120	PP18a	1896	2003	108	0.585	0.358	0.470	-0.063	2
121	PP18b	1840	2003	164	0.488	0.357	0.462	-0.034	1
122	PP19a	1904	2003	100	0.619	0.335	0.490	0.011	1
123	PP19b	1907	2003	97	0.465	0.333	0.427	-0.033	1
124	PP20a	1848	2003	156	0.519	0.338	0.531	-0.008	1
125	PP20b	1837	2002	166	0.526	0.383	0.572	0.074	1
Total or mean:				14612	0.515	0.352	0.477	0.001	

APPENDIX A2. Statistical descriptions for the 32 series in the Texas latewood width chronology.

Seq	Series	Interval		No. Years	Corr. w/ master	Mean sens	Std dev	Auto corr	AR ( )
1	GR01BL	1910	2003	94	0.487	0.581	0.595	-0.027	1
2	CN01BL	1931	2003	73	0.609	0.664	0.653	0.000	1
3	GR01AL	1890	2001	112	0.567	0.581	0.507	0.024	1
4	GR03AL	1917	2003	87	0.664	0.629	0.558	-0.018	1
5	GR03BL	1920	2003	84	0.655	0.608	0.517	-0.032	1
6	GR04L	1922	2003	82	0.501	0.638	0.501	-0.019	1
7	GR05AL	1922	2003	82	0.584	0.668	0.605	-0.003	1
8	GR05BL	1941	2004	64	0.643	0.738	0.550	0.043	1
9	PP02BL	1805	1909	105	0.547	0.613	0.50	0.014	1
10	PP06AL	1787	2003	217	0.544	0.589	0.420	0.047	1
11	PP06BL	1830	2003	174	0.535	0.592	0.555	0.004	3
12	PP10AL	1820	2003	184	0.720	0.526	0.559	-0.001	2
13	PP10BL	1833	2003	171	0.678	0.534	0.505	0.036	1
14	PP12BL	1819	2003	185	0.518	0.498	0.376	-0.022	1
15	PP13AL	1807	2002	196	0.628	0.607	0.465	-0.012	2
16	PP15AL	1811	2003	193	0.635	0.676	0.544	-0.037	2
17	PP15BL	1779	2003	225	0.475	0.674	0.508	0.023	2
18	PP17AL	1829	2002	174	0.606	0.557	0.535	0.026	2
19	PP17BL	1836	2003	168	0.695	0.574	0.421	-0.011	3
20	PP19AL	1904	2003	100	0.581	0.557	0.487	-0.014	1
21	PP20BL	1836	2003	168	0.498	0.602	0.612	0.032	2
22	TC32L	1694	1861	168	0.414	0.469	0.444	0.050	1
23	TC38L	1777	1863	87	0.651	0.559	0.518	-0.019	1
24	TC70AL	1743	1843	101	0.484	0.414	0.514	0.061	2
25	TC70BL	1749	1863	115	0.536	0.33	0.452	0.020	1
26	TC71BL	1676	1818	143	0.520	0.565	0.461	0.029	2
27	TC72A2L	1755	1893	139	0.524	0.568	0.458	0.028	1
28	TC72BL	1721	1872	152	0.453	0.498	0.500	-0.008	1
29	TC73AL	1760	1862	103	0.494	0.531	0.466	-0.004	1
30	TC73BL	1755	1860	106	0.452	0.545	0.512	-0.017	1
31	TC74AL	1660	1763	104	0.620	0.594	0.445	0.084	1
32	TC75L	1767	1866	100	0.346	0.376	0.403	0.060	1
Total or mean:				4256	0.558	0.566	0.498	0.011	

APPENDIX A3. Statistical descriptions for the 25 series in the Texas earlywood width chronology.

Seq	Series	Interval		No. Years	Corr. w/ master	Mean sens	Std dev	Auto corr	AR ()
1	TC32E	1694	1758	65	0.393	0.250	0.399	-0.002	1
2	TC38E	1777	1863	87	0.502	0.318	0.451	0.073	1
3	TC70AE	1743	1846	104	0.444	0.349	0.492	-0.005	1
4	TC71BE	1676	1818	143	0.296	0.409	0.459	0.010	2
5	TC72A2E	1755	1893	139	0.504	0.389	0.432	0.039	2
6	TC72BE	1721	1872	152	0.565	0.429	0.456	0.032	1
7	TC73AE	1760	1862	103	0.535	0.420	0.519	-0.023	2
8	TC73BE	1755	1860	106	0.639	0.352	0.379	-0.022	2
9	TC74AE	1660	1763	104	0.299	0.475	0.465	0.020	1
10	GR01AE	1910	2001	92	0.492	0.294	0.392	0.120	1
11	GR01BE	1935	2003	69	0.536	0.277	0.471	-0.035	1
12	GR03AE	1917	2003	87	0.625	0.365	0.462	-0.066	1
13	GR03BE	1920	2003	84	0.652	0.330	0.505	-0.038	1
14	GR04E	1922	2003	82	0.468	0.261	0.409	-0.092	1
15	GR05AE	1922	2003	82	0.620	0.403	0.336	-0.048	1
16	GR05BE	1941	2004	64	0.691	0.468	0.671	-0.018	1
17	PP02BE	1805	1909	105	0.377	0.359	0.471	0.046	1
18	PP06AE	1787	2003	217	0.552	0.313	0.401	0.046	1
19	PP06BE	1797	2003	207	0.418	0.347	0.424	0.056	1
20	PP10BE	1833	2003	171	0.442	0.318	0.297	0.039	1
21	PP12BE	1819	1969	151	0.533	0.234	0.422	0.004	1
22	PP13AE	1807	2002	196	0.483	0.296	0.451	0.020	1
23	PP15AE	1811	2003	193	0.583	0.310	0.441	0.014	1
24	PP15BE	1810	2003	194	0.483	0.300	0.458	0.017	1
25	PP17AE	1829	1969	141	0.557	0.227	0.488	0.030	1
Total or mean:				3138	0.502	0.336	0.439	0.016	

APPENDIX A4. Statistical descriptions for the 144 series in the Florida chronology.

Seq	Series	Interval		No. Years	Corr. w/ master	Mean sens	Std dev	Auto corr	AR ( )
1	dn01a	1764	1926	163	0.460	0.282	0.278	-0.038	6
2	dn01b	1764	1945	182	0.482	0.322	0.380	-0.048	3
3	dn02	1797	1942	146	0.582	0.269	0.344	0.017	1
4	dn02b	1797	1915	119	0.409	0.334	0.253	-0.014	3
5	dn003a	1517	1941	425	0.531	0.309	0.299	-0.007	1
6	dn003b	1517	1953	437	0.486	0.295	0.393	0.017	1
7	dn05a	1678	1911	234	0.566	0.226	0.342	-0.007	1
8	dn05b	1668	1898	231	0.654	0.234	0.330	-0.060	2
9	dn007a	1810	1919	110	0.622	0.276	0.364	-0.024	1
10	dn007b	1810	1937	128	0.559	0.254	0.366	-0.001	4
11	dn08	1593	1904	312	0.418	0.284	0.231	-0.022	1
12	dn008b	1593	1769	177	0.402	0.316	0.446	-0.025	3
13	dn011b	1555	1916	362	0.533	0.373	0.331	-0.022	5
14	dn011c	1534	1910	377	0.459	0.379	0.314	-0.007	2
15	dn011d	1634	1918	285	0.498	0.391	0.349	-0.005	2
16	dn012a	1767	1936	170	0.472	0.303	0.473	0.019	1
17	dn012b	1767	1943	177	0.559	0.339	0.442	0.025	1
18	dn013ba	1617	1801	185	0.516	0.359	0.399	0.065	1
19	dn013bb	1617	1785	169	0.564	0.371	0.435	0.093	1
20	dn013c	1627	1783	157	0.453	0.343	0.309	-0.007	5
21	dn014	1642	1735	94	0.699	0.408	0.478	-0.022	2
22	dn014b	1642	1812	171	0.513	0.382	0.450	0.008	1
23	dn015a	1732	1907	176	0.584	0.244	0.354	-0.008	1
24	dn015b	1734	1897	164	0.561	0.264	0.475	-0.033	1
25	dn016a	1608	1787	180	0.538	0.382	0.472	0.028	1
26	dn016b	1647	1787	141	0.553	0.343	0.503	-0.006	3
27	dn017b	1710	1762	53	0.482	0.215	0.385	0.037	1
28	dn017c	1687	1837	151	0.672	0.265	0.426	-0.002	1
29	dn018a	1652	1843	192	0.503	0.340	0.427	-0.036	2
30	dn018b	1706	1873	168	0.649	0.287	0.399	-0.080	2
31	dn018c	1734	1851	118	0.642	0.265	0.442	-0.066	2
32	dn019c	1503	1652	150	0.286	0.355	0.498	0.019	1
33	dn020	1925	2003	79	0.492	0.395	0.533	-0.033	1
34	dn021a9	1657	1767	111	0.639	0.327	0.355	-0.028	1
35	dn021a	1769	1858	90	0.514	0.275	0.400	0.014	2
36	dn021b	1637	1877	241	0.552	0.309	0.343	0.042	1
37	dn022a	1820	2003	184	0.529	0.292	0.368	-0.018	1
38	dn022b	1826	2003	178	0.562	0.331	0.405	0.050	1
39	dn023a	1762	1946	185	0.428	0.290	0.383	-0.027	1

APPENDIX A4. *continued*

Seq	Series	Interval		No. Years	Corr. w/ master	Mean sens	Std dev	Auto corr	AR ( )
40	dn023b	1791	1927	137	0.565	0.289	0.469	-0.017	1
41	dn023c	1771	1878	108	0.630	0.271	0.410	-0.037	1
42	dn024a	1830	2003	174	0.585	0.270	0.433	-0.037	3
43	dn024b	1790	2003	214	0.560	0.292	0.380	0.005	3
44	dn025a	1820	1918	99	0.498	0.252	0.413	-0.014	1
45	dn025b	1820	1878	59	0.586	0.284	0.584	-0.069	2
46	dn026a9	1589	1828	240	0.531	0.326	0.329	-0.008	1
47	dn026b9	1582	1915	334	0.525	0.322	0.443	-0.038	2
48	dn028a	1786	2003	218	0.471	0.279	0.362	-0.018	1
49	dn028b	1800	2003	204	0.582	0.281	0.349	-0.048	1
50	dn029a	1773	1837	65	0.458	0.394	0.530	0.015	2
51	dn029a2	1880	2003	124	0.630	0.378	0.402	-0.074	1
52	dn029b	1772	1837	66	0.495	0.335	0.447	-0.030	1
53	dn029b2	1880	2003	124	0.603	0.326	0.399	-0.037	1
54	dn030a5	1772	1864	93	0.606	0.422	0.501	-0.032	2
55	dn030a	1900	2003	104	0.468	0.300	0.538	-0.053	1
56	dn030b	1900	2002	103	0.458	0.304	0.466	-0.011	1
57	dn031b	1770	1948	179	0.404	0.335	0.402	-0.007	1
58	dn032a	1768	2003	236	0.519	0.299	0.387	-0.012	3
59	dn032b	1810	2003	194	0.465	0.349	0.291	-0.010	1
60	dn033a	1870	2003	134	0.473	0.286	0.486	0.010	1
61	dn033b	1820	2003	184	0.535	0.331	0.348	0.016	1
62	dn034a	1769	1865	97	0.549	0.253	0.483	0.039	1
63	dn034b	1773	1864	92	0.540	0.290	0.527	-0.096	1
64	dn035b	1870	2003	134	0.499	0.267	0.369	-0.010	4
65	dn037a	1780	1978	199	0.515	0.330	0.412	-0.008	1
66	dn037b	1800	1978	179	0.464	0.341	0.354	0.001	1
67	dn038a	1780	1858	79	0.642	0.347	0.546	0.080	1
68	dn038b	1758	2003	246	0.501	0.292	0.377	0.047	1
69	dn039a	1900	2003	104	0.480	0.287	0.426	-0.037	1
70	dn039b	1900	2003	104	0.532	0.296	0.439	-0.001	1
71	dn040a	1810	1958	149	0.497	0.359	0.362	-0.033	1
72	dn040b	1827	1958	132	0.633	0.372	0.333	-0.022	1
73	af002a	1800	1910	111	0.574	0.263	0.335	-0.006	1
74	af004a	1790	2003	214	0.495	0.275	0.433	-0.020	1
75	af004b	1790	2003	214	0.558	0.304	0.330	0.009	1
76	af005a	1850	2003	154	0.453	0.231	0.447	0.059	1
77	af005b	1880	2003	124	0.467	0.233	0.351	-0.008	1
78	af006a	1830	2000	171	0.519	0.292	0.397	-0.047	3

APPENDIX A4. *continued*

Seq	Series	Interval		No. Years	Corr. w/ master	Mean sens	Std dev	Auto corr	AR ( )
79	af006b	1840	2003	164	0.544	0.311	0.475	0.051	1
80	af007a	1811	2003	193	0.475	0.245	0.414	-0.041	2
81	af007b	1820	2003	184	0.498	0.258	0.377	-0.010	1
82	af008a	1820	2003	184	0.571	0.245	0.334	0.002	1
83	af008b	1750	2003	254	0.432	0.289	0.280	-0.045	3
84	af009a	1790	2003	214	0.572	0.307	0.378	-0.042	1
85	af009b	1770	2003	234	0.615	0.288	0.375	-0.059	3
86	af010a	1770	2003	234	0.510	0.349	0.320	-0.022	1
87	af010b	1770	2003	234	0.494	0.312	0.377	0.023	1
88	jg001b	1880	2003	124	0.578	0.320	0.423	0.012	3
89	jg001c	1859	1919	61	0.430	0.345	0.455	0.050	1
90	wp01b2	1877	1948	72	0.426	0.269	0.470	0.013	2
91	wp03b2	1814	1950	137	0.426	0.269	0.429	-0.022	3
92	wp06a2	1850	1982	133	0.409	0.197	0.391	-0.021	1
93	wp06b	1850	2001	152	0.483	0.202	0.557	0.041	1
94	wp08a	1794	1878	85	0.444	0.316	0.522	-0.007	3
95	wp08a2	1920	1958	39	0.472	0.277	0.511	-0.052	1
96	wp08b	1819	1878	60	0.515	0.266	0.467	-0.036	1
97	wp08b2	1920	1988	69	0.452	0.342	0.460	0.016	1
98	wp09a2	1870	2001	132	0.435	0.303	0.551	0.022	1
99	wp09b2	1801	2003	203	0.432	0.399	0.480	0.014	5
100	wp012a3	1741	1808	68	0.478	0.315	0.503	0.025	1
101	wp012a2	1810	1978	169	0.424	0.303	0.443	-0.021	2
102	wp13a2	1814	2003	190	0.482	0.257	0.364	-0.012	1
103	wp013b2	1814	2003	190	0.443	0.285	0.395	0.024	1
104	wp014a3	1880	2003	124	0.536	0.291	0.445	-0.036	1
105	wp014b2	1820	2003	184	0.479	0.336	0.473	-0.049	2
106	wp015a	1920	2004	85	0.444	0.268	0.441	0.004	1
107	wp015b	1890	2004	115	0.435	0.240	0.393	-0.060	1
108	wp016a	1828	2004	177	0.441	0.293	0.409	-0.062	1
109	wp017b2	1870	2003	134	0.441	0.335	0.525	0.053	1
110	wp018a2	1880	2003	124	0.421	0.281	0.434	-0.028	1
111	wp018b2	1880	2003	124	0.439	0.344	0.397	0.004	1
112	wp019a2	1880	2003	124	0.530	0.291	0.538	-0.033	2
113	wp019b2	1820	2003	184	0.499	0.293	0.470	0.013	1
114	wp020b	1870	2004	135	0.497	0.282	0.433	-0.032	1
115	bp001a	1809	1948	140	0.494	0.296	0.413	-0.021	1
116	bp001b	1759	2003	245	0.371	0.293	0.407	-0.014	1
117	bp002a	1808	1939	132	0.595	0.317	0.374	0.020	1

APPENDIX A4. *continued*

Seq	Series	Interval		No. Years	Corr. w/ master	Mean sens	Std dev	Auto corr	AR ( )
118	bp002b	1890	1959	70	0.555	0.277	0.630	-0.043	1
119	bp003a	1819	2003	185	0.545	0.336	0.348	0.036	1
120	bp003b	1814	2003	190	0.461	0.313	0.438	0.035	1
121	bp004a	1830	1984	155	0.483	0.374	0.597	-0.010	1
122	bp005b	1788	1958	171	0.459	0.403	0.353	0.002	1
123	bp006b	1850	2003	154	0.474	0.285	0.560	0.014	1
124	bp007a	1860	2003	144	0.449	0.319	0.435	-0.041	1
125	bp008a	1800	1934	135	0.556	0.309	0.521	-0.009	1
126	bp008b	1820	1942	123	0.504	0.255	0.562	0.075	1
127	bp011	1674	1748	75	0.443	0.366	0.554	-0.035	1
128	bp011d	1527	1619	93	0.349	0.273	0.495	0.004	1
129	bp012a	1820	1914	95	0.622	0.431	0.424	-0.036	2
130	bp012b	1820	1908	89	0.723	0.340	0.530	-0.053	2
131	bp013a	1820	1892	73	0.590	0.372	0.519	0.057	1
132	bp013b	1820	1868	49	0.572	0.393	0.494	0.180	1
133	bp014a	1820	2003	184	0.539	0.263	0.422	-0.003	3
134	bp014b	1820	1968	149	0.626	0.326	0.432	-0.020	1
135	bP015A	1792	1908	117	0.490	0.543	0.554	-0.048	1
136	bp015b	1803	1910	108	0.582	0.433	0.384	0.003	1
137	bp017a	1834	2003	170	0.515	0.316	0.446	-0.020	1
138	bp017b	1850	2003	154	0.563	0.295	0.560	-0.002	7
139	bp018a	1830	1968	139	0.536	0.349	0.364	-0.004	1
140	bp018b	1860	2003	144	0.562	0.301	0.501	-0.021	1
141	bp019a	1809	2003	195	0.579	0.342	0.442	0.017	2
142	bp019b	1809	2003	195	0.511	0.355	0.455	0.004	2
143	bp022a	1800	2003	204	0.512	0.275	0.391	-0.036	1
144	bp022b	1786	2003	218	0.487	0.270	0.377	0.005	1
Total or mean:				22852	0.513	0.310	0.408	-0.008	

APPENDIX A5. Statistical descriptions for the 102 series in the South Carolina TRW chronology.

Seq	Series	Interval		No. Years	Corr. w/ master	Mean sens	Std dev	Auto corr	AR ( )
1	pr001b	1930	2003	74	0.449	0.266	0.491	0.038	1
2	pr010a	1946	2003	58	0.469	0.279	0.569	0.037	3
3	pr011b	1947	2003	57	0.526	0.363	0.486	-0.085	3
4	pr012a	1920	2003	84	0.551	0.378	0.546	-0.045	1
5	pr012b	1946	2003	58	0.542	0.369	0.449	-0.027	1
6	dp001a	1900	2003	104	0.372	0.310	0.495	0.036	1
7	dp001b	1843	2003	161	0.384	0.280	0.391	0.015	1
8	dp002a	1851	2003	153	0.352	0.261	0.404	0.027	2
9	dp002b	1905	2003	99	0.473	0.257	0.438	-0.046	1
10	dp004	1920	2002	83	0.531	0.284	0.495	0.019	1
11	dp005a	1848	2003	156	0.550	0.269	0.288	-0.074	1
12	dp005b	1900	2003	104	0.527	0.289	0.530	-0.039	1
13	dp006a	1880	2003	124	0.397	0.272	0.426	-0.070	1
14	dp006b	1878	2003	126	0.477	0.229	0.484	-0.039	1
15	dp007a	1900	2001	102	0.359	0.298	0.484	-0.041	2
16	dp008b	1900	2003	104	0.383	0.269	0.453	-0.050	2
17	dp009a	1866	1950	85	0.468	0.223	0.527	-0.045	1
18	dp009b	1883	1950	68	0.632	0.296	0.520	-0.044	2
19	dp010a	1868	2003	136	0.476	0.233	0.464	0.003	1
20	dp011a	1899	2003	105	0.525	0.273	0.644	-0.080	1
21	dp011b	1916	2003	88	0.555	0.339	0.589	-0.015	1
22	dp012a	1918	2003	86	0.535	0.366	0.492	-0.036	1
23	dp013a	1886	2003	118	0.441	0.279	0.473	-0.029	3
24	dp014a	1863	2003	141	0.467	0.247	0.547	-0.053	1
25	dp015a	1875	2003	129	0.417	0.230	0.391	0.000	1
26	dp015b	1876	2003	128	0.445	0.249	0.414	-0.055	2
27	hb07a	1841	1994	154	0.394	0.337	0.418	0.006	1
28	hb07b	1837	2003	167	0.554	0.277	0.488	0.005	1
29	hg01b	1911	2000	90	0.428	0.279	0.528	-0.032	2
30	hg06a	1874	2003	130	0.444	0.294	0.539	0.002	1
31	hg06b	1855	2003	149	0.384	0.295	0.466	-0.027	1
32	hg07a	1863	1964	102	0.477	0.391	0.518	-0.028	1
33	hg016a	1869	1940	72	0.475	0.221	0.508	0.009	1
34	hg016b	1868	1932	65	0.630	0.275	0.391	-0.003	1
35	hg017a	1843	1909	67	0.425	0.377	0.391	-0.028	3
36	si01	1916	2003	88	0.608	0.238	0.371	-0.011	1

APPENDIX A5. *continued*

Seq	Series	Interval		No. Years	Corr. w/ master	Mean sens	Std dev	Auto corr	AR ( )
37	si004b	1873	2003	131	0.621	0.295	0.520	-0.006	1
38	si007a	1868	2003	136	0.560	0.198	0.374	0.016	1
39	si008	1898	1989	92	0.397	0.214	0.418	-0.110	1
40	si009a	1920	2003	84	0.474	0.292	0.476	-0.050	1
41	si009b	1888	2003	116	0.436	0.280	0.356	-0.022	1
42	si010a	1917	2003	87	0.546	0.238	0.490	0.020	1
43	si010b	1912	2003	92	0.353	0.244	0.452	-0.018	2
44	si012a	1902	2003	102	0.518	0.239	0.401	-0.027	2
45	si012b	1910	2003	94	0.578	0.270	0.607	-0.045	1
46	si013a	1916	2003	88	0.429	0.274	0.658	-0.040	2
47	si013b	1923	2003	81	0.471	0.214	0.471	0.068	1
48	si016	1846	2003	158	0.428	0.229	0.383	-0.025	1
49	si017a	1915	2003	89	0.498	0.237	0.525	-0.008	1
50	si17b	1924	2003	80	0.579	0.269	0.497	-0.013	1
51	si019	1912	2003	92	0.476	0.252	0.524	0.024	1
52	si019	1870	2003	134	0.649	0.214	0.437	-0.019	1
53	si020	1892	2003	112	0.509	0.263	0.461	-0.033	1
54	si022	1868	2003	136	0.453	0.258	0.438	-0.026	1
55	si025a	1850	2003	154	0.383	0.286	0.472	-0.028	1
56	si025b	1841	2003	163	0.438	0.320	0.466	-0.079	1
57	si028b	1893	2003	111	0.393	0.238	0.355	0.075	2
58	si030a	1675	1775	101	0.414	0.277	0.487	-0.048	1
59	si030b	1675	1766	92	0.529	0.271	0.487	-0.057	2
60	si031a	1679	1867	189	0.546	0.235	0.453	-0.007	1
61	si031b	1747	1856	110	0.495	0.211	0.474	-0.029	4
62	si032a	1688	1841	154	0.606	0.241	0.369	-0.018	2
63	si032b	1694	1817	124	0.617	0.329	0.480	-0.016	1
64	si033a	1840	1904	65	0.482	0.185	0.519	0.087	1
65	si034a	1850	1922	73	0.497	0.373	0.474	-0.059	1
66	si034b	1850	1915	66	0.545	0.353	0.438	0.004	1
67	si035a	1624	1779	156	0.551	0.193	0.397	0.016	1
68	si036a	1842	1932	91	0.364	0.299	0.412	-0.050	1
69	si037a	1598	1758	161	0.590	0.217	0.407	-0.071	1
70	si037b	1613	1776	164	0.490	0.252	0.499	-0.025	2
71	si040a	1577	1886	310	0.566	0.255	0.309	-0.028	3
72	si040b	1547	1870	324	0.506	0.274	0.360	-0.005	1
73	si040c	1548	1647	100	0.468	0.294	0.387	-0.040	1
74	si043a	1689	1885	197	0.585	0.318	0.489	0.014	1
75	si043b	1692	1878	187	0.595	0.310	0.416	-0.055	2

APPENDIX A5. *continued*

Seq	Series	Interval		No. Years	Corr. w/ master	Mean sens	Std dev	Auto corr	AR ( )
76	si045a	1624	1886	263	0.568	0.332	0.331	0.027	1
77	si045b	1629	1742	114	0.593	0.312	0.364	-0.035	2
78	si045c	1743	1880	138	0.611	0.289	0.421	-0.047	1
79	si046a	1567	1683	117	0.405	0.207	0.422	-0.052	1
80	si046b	1567	1689	123	0.593	0.251	0.519	-0.029	2
81	si047a	1847	1929	83	0.255	0.281	0.591	0.037	1
82	si048b	1876	1942	67	0.618	0.306	0.504	-0.097	1
83	si050a	1738	1817	80	0.489	0.338	0.404	0.018	1
84	si051a	1615	1778	164	0.423	0.262	0.484	-0.008	2
85	si052a	1781	1887	107	0.519	0.253	0.434	-0.021	2
86	si052b	1777	1891	115	0.567	0.260	0.440	0.070	1
87	si070a	1711	1887	177	0.485	0.355	0.384	0.016	1
88	si070b	1711	1874	164	0.511	0.314	0.393	0.002	1
89	si073a	1621	1851	231	0.463	0.278	0.370	-0.063	1
90	si073b	1621	1855	235	0.476	0.283	0.322	-0.030	1
91	si074a	1738	1866	129	0.573	0.229	0.456	0.027	1
92	si074b	1750	1857	108	0.533	0.227	0.394	-0.037	1
93	si075b	1603	1886	284	0.515	0.299	0.449	-0.040	1
94	si075a	1595	1908	314	0.523	0.310	0.487	-0.016	1
95	si077b1	1670	1876	207	0.491	0.239	0.464	-0.019	1
96	si078a	1684	1858	175	0.493	0.247	0.391	-0.035	2
97	si078b	1768	1882	115	0.476	0.184	0.414	-0.005	2
98	si079	1610	1845	236	0.525	0.335	0.316	0.030	1
99	si079b	1606	1848	243	0.465	0.384	0.441	0.008	1
100	si080a	1712	1886	175	0.613	0.211	0.409	-0.013	3
101	si080b	1712	1886	175	0.479	0.264	0.494	-0.042	1
102	si082a	1512	1781	270	0.440	0.220	0.363	-0.072	1
103	si082b	1512	1741	230	0.528	0.259	0.382	-0.028	1
104	si083a	1464	1820	357	0.542	0.248	0.409	-0.017	1
105	si083b	1455	1804	350	0.532	0.267	0.468	-0.031	1
Total or mean:				14357	0.499	0.274	0.438	-0.020	

APPENDIX A6. Statistical descriptions for the 48 series in the South Carolina LWW chronology.

Seq	Series	Interval		No. Years	Corr. w/ master	Mean sens	Std dev	Auto corr	AR ( )
1	HG01BL	1911	2000	90	0.512	0.467	0.613	0.009	2
2	HB07BL	1836	2003	168	0.460	0.410	0.466	0.019	1
3	HG04AL	1925	2003	79	0.441	0.409	0.550	0.082	1
4	DP14AL	1863	2003	141	0.335	0.400	0.565	0.008	1
5	DP02BL	1903	2003	101	0.279	0.402	0.470	-0.052	1
6	DP05AL	1860	2003	144	0.351	0.407	0.470	-0.066	1
7	DP05BL	1920	2002	83	0.463	0.479	0.442	-0.004	1
8	DP11AL	1896	2002	107	0.338	0.424	0.471	-0.018	1
9	DP11BL	1911	2003	93	0.426	0.514	0.481	-0.034	1
10	FMF002	1944	2002	59	0.456	0.522	0.629	-0.030	1
11	FMF003	1941	2003	63	0.435	0.372	0.622	-0.017	1
12	FMF005	1941	2002	62	0.491	0.551	0.533	0.007	1
13	FMF008	1946	2003	58	0.607	0.406	0.574	-0.069	1
14	FMF009	1943	2003	61	0.450	0.382	0.599	-0.049	1
15	FMF010	1943	2003	61	0.364	0.388	0.518	-0.091	2
16	FMF013	1942	2003	62	0.611	0.478	0.476	-0.001	1
17	FMF014	1941	2002	62	0.433	0.439	0.526	0.170	1
18	FMF020	1940	2003	64	0.458	0.467	0.625	-0.033	1
19	SI01L	1916	2003	88	0.681	0.481	0.488	0.008	1
20	SI03AL	1947	2001	55	0.379	0.461	0.512	0.031	3
21	SI04BL	1873	2003	131	0.543	0.416	0.433	-0.026	2
22	SI07AL	1868	2003	136	0.372	0.280	0.490	0.037	1
23	SI10AL	1917	2003	87	0.410	0.410	0.608	0.087	1
24	SI11L	1855	1999	145	0.340	0.444	0.364	-0.060	3
25	SI12BL	1910	2003	94	0.591	0.360	0.469	-0.028	1
26	SI17BL	1924	2003	80	0.347	0.387	0.467	-0.022	1
27	SI19L	1871	2003	133	0.521	0.367	0.577	0.010	1
28	SI19BL	1912	2003	92	0.668	0.385	0.486	-0.026	
29	SI22L	1868	2003	136	0.514	0.423	0.423	-0.059	1
30	SI25BL	1841	2003	163	0.433	0.438	0.399	-0.024	1
31	SI31AL	1679	1866	188	0.520	0.370	0.432	0.025	1
32	SI31BL	1750	1854	105	0.623	0.407	0.458	0.060	2
33	SI32AL	1688	1841	154	0.536	0.345	0.366	-0.050	1
34	SI32BL	1694	1811	118	0.535	0.392	0.347	-0.010	1
35	SI37AL	1602	1759	158	0.538	0.359	0.430	0.014	1
36	SI37BL	1613	1751	139	0.500	0.448	0.476	0.037	1
37	SI40AL	1580	1879	300	0.440	0.355	0.443	0.008	1
38	SI40BL	1540	1871	332	0.513	0.453	0.534	-0.002	1

APPENDIX A6. *continued*

Seq	Series	Interval		No. Years	Corr. w/ master	Mean sens	Std dev	Auto corr	AR ( )
39	SI43AL	1720	1855	136	0.547	0.454	0.542	-0.003	1
40	SI43BL	1692	1876	185	0.533	0.545	0.489	-0.010	1
41	SI45L	1628	1885	258	0.598	0.456	0.370	0.027	1
42	SI45BL	1631	1750	120	0.589	0.457	0.428	-0.034	1
43	SI45CL	1744	1880	137	0.624	0.432	0.472	-0.040	1
44	SI73AL	1622	1831	210	0.435	0.454	0.415	-0.062	1
45	SI75AL	1609	1851	243	0.590	0.519	0.516	0.007	1
46	SI75BL	1611	1758	148	0.428	0.398	0.594	-0.019	1
47	SI83AL	1468	1794	327	0.543	0.465	0.463	0.011	1
48	SI83B2L	1479	1803	325	0.526	0.462	0.411	0.011	1
Total or mean:				6481	0.494	0.429	0.474	-0.005	

APPENDIX A7. Statistical descriptions for the 32 series in the South Carolina EWW chronology.

Seq	Series	Interval		No. Years	Corr. w/ master	Mean sens	Std dev	Auto corr	AR ( )
1	HB07BE	1836	2003	168	0.489	0.309	0.450	-0.016	1
2	DP02BE	1903	2003	101	0.426	0.240	0.531	-0.069	2
3	DP05AE	1840	2003	164	0.463	0.318	0.446	-0.061	1
4	DP05BE	1890	2002	113	0.479	0.302	0.454	-0.010	1
5	DP11AE	1896	2002	107	0.469	0.280	0.529	0.003	1
6	DP11BE	1911	2003	93	0.488	0.273	0.507	0.010	1
7	DP14AE	1863	2003	141	0.380	0.273	0.454	0.022	2
8	SI01E	1916	2003	88	0.411	0.218	0.586	-0.052	2
9	SI04BE	1873	2003	131	0.549	0.325	0.420	-0.022	1
10	SI07AE	1868	2003	136	0.542	0.224	0.322	0.001	1
11	SI10AE	1917	2003	87	0.492	0.265	0.517	-0.013	1
12	SI12BE	1910	2003	94	0.498	0.306	0.478	-0.030	1
13	SI17BE	1924	2003	80	0.590	0.272	0.557	0.008	1
14	SI19E	1871	2003	133	0.613	0.232	0.444	-0.062	1
15	SI19BE	1912	2003	92	0.406	0.247	0.549	-0.039	1
16	SI22E	1868	2003	136	0.389	0.250	0.478	0.015	1
17	SI25BE	1841	2003	163	0.532	0.276	0.498	-0.029	1
18	SI31AE	1679	1866	188	0.416	0.185	0.420	-0.016	1
19	SI31BE	1750	1854	105	0.513	0.195	0.533	0.035	3
20	SI32AE	1730	1841	112	0.533	0.354	0.420	-0.007	1
21	SI32BE	1694	1811	118	0.560	0.249	0.486	0.006	1
22	SI37AE	1602	1759	158	0.500	0.233	0.463	0.003	1
23	SI37BE	1613	1751	139	0.497	0.245	0.457	-0.014	1
24	SI40BE	1540	1871	332	0.413	0.275	0.412	-0.023	1
25	SI43AE	1689	1880	192	0.487	0.362	0.439	-0.021	1
26	SI43BE	1692	1876	185	0.358	0.281	0.342	-0.029	1
27	SI45E	1628	1839	212	0.456	0.273	0.292	-0.012	1
28	SI45BE	1631	1750	120	0.502	0.230	0.381	0.011	1
29	SI45CE	1744	1880	137	0.528	0.225	0.335	-0.012	1
30	SI75AE	1609	1869	261	0.436	0.297	0.328	-0.047	2
31	SI83B2E	1479	1716	238	0.426	0.250	0.356	0.011	2
32	SI83AE	1468	1668	201	0.501	0.297	0.513	-0.041	1
Total or mean:				4725	0.472	0.270	0.434	-0.017	

APPENDIX B1. Residual Index Chronology for Texas TRW chronology. These values are the tree-ring indices for each year in the chronology. The indices are displayed without the decimal points, but the actual value can be obtained by dividing the numbers by 100. Thus, the mean value for all indices is 1.0. Each line represents a decade of indices, and the decades are shown in the lefthand column. The numbers across the top of the table are the last numbers in the year for that particular decade. This format, known as the "Tucson format", is the internationally accepted format of the World Data Center for Palaeoclimatology.

Year	0	1	2	3	4	5	6	7	8	9
1632			56	79	117	126	43	71	99	101
1640	111	112	18	52	71	109	90	83	92	149
1650	129	150	125	107	108	80	106	111	61	97
1660	103	139	91	83	64	86	95	82	119	113
1670	115	85	102	97	113	70	113	96	88	56
1680	85	65	85	51	79	87	119	128	82	89
1690	59	109	103	101	95	86	98	110	109	99
1700	87	61	89	121	108	108	101	126	103	126
1710	127	112	114	80	88	75	84	84	73	142
1720	60	84	123	76	116	101	96	83	136	98
1730	108	89	72	61	107	110	87	130	62	100
1740	104	105	84	125	109	84	122	95	132	67
1750	81	104	108	132	75	66	75	110	99	141
1760	134	108	99	127	94	109	79	69	69	86
1770	123	112	73	92	111	110	141	92	83	127
1780	103	142	85	64	72	97	121	83	100	115
1790	85	107	110	89	97	165	92	102	119	128
1800	88	86	80	113	95	83	83	112	114	91
1810	78	107	109	107	81	103	104	85	113	120
1820	109	93	87	114	79	88	94	90	109	114
1830	73	75	113	119	105	116	113	90	76	75
1840	68	88	90	102	86	97	134	67	92	107
1850	93	78	119	117	94	82	74	101	111	87
1860	61	120	79	109	97	121	118	137	102	104
1870	125	111	79	86	75	82	115	78	98	73
1880	80	73	131	63	71	85	108	96	78	86
1890	110	103	117	91	126	84	90	77	129	83
1900	148	119	123	101	102	101	107	110	125	82
1910	83	90	100	119	100	99	88	79	88	107
1920	86	102	116	108	74	59	132	91	84	126
1930	90	116	83	131	67	115	96	108	124	82

APPENDIX B1. *continued*

Year	0	1	2	3	4	5	6	7	8	9
1940	134	135	112	72	90	107	111	58	68	122
1950	96	68	99	123	75	116	66	120	100	106
1960	92	131	89	88	95	105	104	86	115	73
1970	92	107	107	76	87	122	91	108	78	95
1980	79	139	85	126	90	82	100	95	98	116
1990	106	96	73	90	116	83	89	108	131	88
2000	106	130	97	87						

APPENDIX B2. Residual Index Chronology for Texas LWW chronology.

Year	0	1	2	3	4	5	6	7	8	9
1662			60	60	64	83	221	92	154	153
1670	75	62	62	117	133	90	102	72	80	130
1680	26	45	30	58	37	99	166	36	122	49
1690	90	141	88	130	141	93	128	137	66	92
1700	106	35	84	123	117	120	147	156	94	164
1710	94	159	93	96	93	87	35	80	64	212
1720	51	170	136	29	96	117	87	86	145	69
1730	81	69	93	37	117	130	98	115	36	76
1740	148	77	78	128	78	64	150	114	85	59
1750	56	81	96	104	130	43	105	107	89	130
1760	115	116	126	93	95	113	94	73	68	73
1770	116	97	105	101	98	106	140	76	69	188
1780	91	157	84	69	75	129	110	60	78	107
1790	100	111	100	85	121	157	101	92	124	127
1800	86	73	83	118	101	78	88	148	146	91
1810	63	91	104	98	87	107	96	69	128	120
1820	113	78	91	125	80	58	97	84	102	137
1830	54	50	156	137	98	94	106	69	69	63
1840	70	99	97	113	80	98	155	54	107	107
1850	91	66	131	122	99	98	54	116	97	75
1860	42	144	66	125	79	130	124	163	96	74
1870	151	164	40	92	48	90	151	56	100	60
1880	78	44	205	36	49	79	162	119	71	76
1890	93	61	95	96	154	72	43	56	146	45
1900	192	137	124	97	98	125	107	124	214	54
1910	71	93	110	105	81	131	94	75	88	132
1920	103	95	154	151	37	42	145	102	46	143
1930	101	55	64	155	24	108	95	74	122	43
1940	131	156	116	39	111	152	101	32	48	142
1950	86	38	68	98	41	112	36	161	108	117
1960	138	154	76	67	93	82	119	84	126	58
1970	60	95	112	70	70	106	85	83	76	119
1980	28	161	71	152	82	72	127	84	65	142
1990	112	166	46	64	150	91	66	114	112	83
2000	70	135	108	90	91					

APPENDIX B3. Residual Index Chronology for Texas EWW chronology.

Year	0	1	2	3	4	5	6	7	8	9
1661		155	92	69	39	77	81	57	101	95
1670	118	96	129	86	134	15	61	75	94	126
1680	73	44	58	71	112	46	98	106	96	98
1690	47	120	139	124	110	108	87	112	86	89
1700	82	77	130	114	158	99	129	167	90	142
1710	139	107	161	91	92	81	104	53	108	157
1720	67	64	115	74	98	101	101	89	89	91
1730	128	87	58	67	118	124	79	93	65	92
1740	94	136	83	147	117	71	65	83	99	75
1750	76	90	139	169	61	65	82	114	109	147
1760	119	114	90	131	84	92	92	61	81	101
1770	162	127	50	95	133	105	143	52	85	109
1780	102	99	72	42	83	104	99	88	110	91
1790	82	110	102	94	68	214	65	118	147	142
1800	89	71	79	113	94	81	82	116	124	71
1810	70	125	105	112	92	104	106	80	124	109
1820	89	84	81	118	77	90	98	99	127	96
1830	72	77	109	118	97	115	99	84	82	82
1840	73	94	87	121	104	94	116	77	90	117
1850	119	91	113	104	81	69	97	111	121	87
1860	84	120	89	109	89	123	96	138	91	115
1870	125	106	98	58	102	102	111	83	111	74
1880	69	99	129	78	94	117	101	104	66	91
1890	101	105	91	79	122	74	107	78	110	100
1900	111	94	125	100	101	87	106	89	115	117
1910	81	92	101	138	117	70	94	100	87	87
1920	87	93	121	99	111	48	133	87	80	136
1930	89	140	67	114	81	81	104	123	92	89
1940	105	134	79	76	103	109	133	72	84	116
1950	93	72	111	115	86	107	90	104	112	104
1960	111	124	91	67	103	109	95	97	100	96
1970	94	95	78	66	72	123	70	138	64	111
1980	89	123	70	138	76	87	113	96	111	106
1990	106	105	83	116	115	85	76	95	135	92
2000	108	119	62	93	41					

APPENDIX B4. Residual Index Chronology for Florida TRW chronology.

Year	0	1	2	3	4	5	6	7	8	9
1507								127	79	90
1510	60	121	105	158	83	138	148	174	54	104
1520	109	69	70	96	112	131	60	79	85	82
1530	135	47	105	105	82	63	97	84	77	90
1540	65	106	147	84	87	92	87	81	123	111
1550	101	179	84	100	47	159	151	118	64	94
1560	96	83	74	95	94	144	78	53	92	75
1570	162	127	110	114	138	123	117	129	131	109
1580	136	81	88	71	70	92	112	111	73	75
1590	135	111	85	105	97	78	107	87	107	72
1600	69	80	59	99	123	95	45	129	103	83
1610	74	99	85	114	92	98	114	94	103	94
1620	93	83	112	119	80	108	43	82	79	95
1630	85	100	96	90	87	93	105	96	94	92
1640	100	86	91	91	114	90	97	137	82	125
1650	119	119	123	80	109	87	121	77	121	90
1660	139	137	123	121	92	113	94	100	153	114
1670	84	88	69	59	119	77	63	100	77	82
1680	129	89	98	80	106	120	99	143	148	134
1690	36	113	123	63	114	92	101	114	98	100
1700	94	92	93	98	92	170	83	109	71	99
1710	116	87	114	98	89	103	130	29	81	97
1720	88	101	93	96	100	101	85	83	86	91
1730	98	96	117	115	85	85	94	74	101	100
1740	93	102	114	86	76	116	77	91	80	104
1750	65	102	97	134	92	93	103	100	71	102
1760	110	118	111	101	94	124	121	102	93	108
1770	99	122	106	88	114	116	111	98	105	108
1780	72	100	116	98	98	118	101	77	105	102
1790	96	101	105	106	103	103	82	77	88	99
1800	83	98	111	86	104	88	117	109	72	68
1810	95	79	122	93	133	88	98	119	91	114
1820	98	131	87	88	104	111	102	98	89	107
1830	78	113	159	99	67	73	101	88	84	89
1840	116	120	121	114	92	89	117	91	77	112
1850	99	98	106	63	108	89	131	112	79	113
1860	68	119	96	111	85	88	102	122	78	125
1870	126	97	73	109	89	92	90	103	108	104
1880	108	101	121	78	90	86	115	97	119	89

APPENDIX B4. *continued*

Year	0	1	2	3	4	5	6	7	8	9
1890	100	85	97	97	117	104	127	84	84	66
1900	84	103	81	82	85	96	102	111	103	108
1910	97	99	113	93	84	101	141	103	103	97
1920	81	93	78	93	100	66	129	76	87	113
1930	99	87	81	103	98	87	154	96	74	117
1940	80	99	96	102	112	111	107	121	106	97
1950	92	103	98	114	91	106	89	109	105	94
1960	120	126	83	77	119	104	89	84	95	138
1970	110	97	99	110	80	116	83	102	118	95
1980	95	100	103	104	88	95	75	98	91	102
1990	95	116	67	109	118	99	116	72	107	78
2000	90	93	91	102	69					

APPENDIX B5. Residual Index Chronology for South Carolina TRW chronology.

Year	0	1	2	3	4	5	6	7	8	9
1458									82	114
1460	57	164	36	103	209	93	94	72	71	86
1470	78	90	103	165	72	72	137	87	56	73
1480	68	83	94	88	200	62	89	183	51	131
1490	79	80	126	85	126	137	106	109	123	71
1500	172	28	129	120	38	95	130	169	161	61
1510	73	78	78	82	123	90	96	112	61	87
1520	87	140	108	106	91	105	115	183	110	52
1530	108	106	112	122	100	66	129	89	79	95
1540	109	110	116	100	85	87	86	97	86	102
1550	124	66	110	81	74	95	87	143	87	164
1560	99	55	103	87	61	122	79	73	92	86
1570	78	80	86	106	81	122	85	104	113	88
1580	89	91	113	90	121	61	78	104	84	105
1590	113	118	124	116	99	82	86	102	79	90
1600	77	74	127	74	103	98	97	91	83	98
1610	128	125	113	145	79	89	99	139	129	92
1620	105	109	84	91	98	108	88	87	93	99
1630	101	103	87	85	78	118	107	114	96	117
1640	83	106	151	96	81	107	94	73	107	115
1650	109	126	59	110	115	99	96	93	94	108
1660	86	100	99	97	69	97	112	99	113	85
1670	131	85	95	83	86	96	83	89	95	122
1680	100	109	89	65	100	74	110	153	86	100
1690	99	83	82	93	82	80	95	96	86	85
1700	118	94	88	92	117	93	102	107	112	95
1710	97	130	98	106	110	115	111	83	90	91
1720	90	93	54	110	96	115	103	107	128	90
1730	118	85	107	145	97	110	84	102	78	121
1740	102	77	99	119	88	108	81	121	111	107
1750	77	97	111	86	82	108	77	101	85	97
1760	107	105	94	100	107	86	116	74	88	94
1770	116	102	92	67	90	106	102	111	118	125
1780	137	107	110	99	94	96	106	124	92	93
1790	89	48	94	108	93	83	108	86	128	103
1800	87	101	106	90	112	93	123	115	126	121
1810	96	68	98	105	108	89	107	85	127	59
1820	84	73	88	95	89	106	105	104	97	94
1830	87	127	109	102	94	103	127	101	93	90

APPENDIX B5. *continued*

Year	0	1	2	3	4	5	6	7	8	9
1840	95	109	83	124	74	87	102	80	89	92
1850	105	111	87	94	88	105	92	102	103	101
1860	118	113	88	109	115	90	112	98	96	98
1870	97	120	81	94	101	97	101	99	101	89
1880	96	93	110	97	102	100	121	46	95	103
1890	102	102	99	118	90	91	90	105	87	89
1900	87	107	103	113	90	100	121	119	100	105
1910	82	90	106	92	95	99	115	104	75	91
1920	84	105	123	97	107	107	104	98	118	130
1930	83	88	99	93	72	103	95	101	104	116
1940	74	90	89	100	103	117	102	112	95	123
1950	82	87	98	112	67	99	107	99	93	124
1960	112	114	98	77	124	104	97	86	86	104
1970	90	117	96	107	77	100	84	104	89	101
1980	90	111	98	77	114	90	71	100	118	127
1990	109	78	84	133	98	69	102	120	119	82

APPENDIX B6. Residual Index Chronology for South Carolina LWW chronology.

Year	0	1	2	3	4	5	6	7	8	9
1470	60	80	74	49	67	120	181	67	62	54
1480	91	92	102	198	28	76	208	68	146	53
1490	75	84	125	154	147	77	163	154	55	170
1500	-3	202	42	25	114	134	152	245	2	62
1510	71	78	87	214	134	115	100	30	74	102
1520	86	108	109	50	111	166	373	-44	9	83
1530	141	160	165	36	76	74	97	53	56	112
1540	134	126	146	83	40	139	128	90	86	115
1550	142	42	112	86	62	120	46	162	69	289
1560	123	-14	97	115	52	157	44	73	60	109
1570	55	68	70	154	58	91	68	131	124	118
1580	69	135	117	94	88	31	66	88	80	133
1590	72	88	163	113	89	85	50	94	69	60
1600	63	66	225	54	70	66	109	78	70	72
1610	167	104	160	177	75	65	73	194	141	162
1620	69	94	66	83	107	122	105	78	77	91
1630	84	77	80	70	72	100	126	113	91	99
1640	80	105	213	101	67	109	99	70	88	125
1650	122	123	42	135	137	86	70	75	107	95
1660	73	82	138	89	51	86	122	95	107	88
1670	154	65	103	66	106	74	91	90	70	160
1680	90	142	80	45	95	52	114	218	60	84
1690	116	81	58	87	67	76	87	85	94	88
1700	122	72	92	68	143	92	77	85	117	94
1710	99	144	99	115	95	154	176	65	75	86
1720	99	98	34	102	84	105	98	100	147	75
1730	130	69	101	181	86	117	80	94	71	110
1740	115	61	87	125	82	96	73	119	106	146
1750	74	95	118	80	56	105	85	98	76	101
1760	104	111	83	101	108	86	98	85	72	81
1770	119	119	77	47	89	87	75	95	118	138
1780	186	100	131	110	93	104	85	145	112	100
1790	78	41	82	100	76	65	98	67	144	93
1800	84	96	100	96	115	88	133	160	129	141
1810	91	61	82	118	94	79	124	104	165	48
1820	73	59	88	85	89	130	92	107	92	90
1830	89	124	117	93	68	124	109	120	76	129
1840	83	115	65	133	67	69	87	62	79	84
1850	94	115	85	74	111	93	105	104	147	92

APPENDIX B6. *continued*

Year	0	1	2	3	4	5	6	7	8	9
1860	142	99	85	94	98	87	92	123	101	67
1870	77	113	69	94	90	95	108	95	123	66
1880	89	84	113	99	115	123	100	52	71	114
1890	110	87	83	203	63	89	92	97	88	95
1900	61	93	86	107	91	82	147	154	109	98
1910	87	90	91	78	89	111	173	112	61	84
1920	100	70	154	102	90	90	102	115	130	135
1930	74	58	111	85	68	122	80	86	101	103
1940	71	72	103	93	114	131	84	136	88	110
1950	82	83	102	94	47	145	104	97	99	139
1960	118	113	83	64	128	111	95	92	68	102
1970	94	117	87	110	99	101	94	82	82	86
1980	74	97	109	54	88	115	48	78	98	112
1990	105	77	89	85	140	76	90	96	125	88
2000	122	104	103	119						

APPENDIX B7. Residual Index Chronology for South Carolina EWW chronology.

Year	0	1	2	3	4	5	6	7	8	9
1469										128
1470	61	60	81	141	88	254	40	20	81	75
1480	52	76	84	114	126	71	162	79	45	132
1490	66	105	124	64	131	191	42	113	101	160
1500	68	61	191	39	75	128	175	127	128	79
1510	87	89	74	124	92	95	156	61	76	112
1520	99	164	122	107	119	101	178	102	48	105
1530	93	97	154	92	55	123	100	65	103	91
1540	115	97	140	117	116	105	81	107	69	111
1550	115	67	108	73	71	79	100	116	109	106
1560	105	102	91	100	55	98	102	68	96	97
1570	84	75	87	108	79	88	111	92	76	87
1580	101	121	112	103	99	69	52	100	90	99
1590	109	106	122	118	80	75	87	96	91	68
1600	73	55	100	87	93	118	90	103	87	112
1610	132	129	131	109	92	83	124	99	146	114
1620	102	81	115	86	106	116	83	84	83	91
1630	89	92	92	92	73	124	94	124	139	92
1640	77	116	100	115	97	88	101	84	118	92
1650	107	113	74	79	90	108	100	102	84	107
1660	105	118	84	80	82	104	109	97	113	84
1670	131	107	100	92	72	133	66	109	115	113
1680	108	80	102	77	95	91	101	118	118	89
1690	91	87	83	79	97	86	90	97	88	84
1700	105	104	92	92	108	110	101	99	103	101
1710	105	131	110	99	111	94	98	119	79	100
1720	90	85	60	100	89	99	111	110	107	92
1730	109	82	101	100	132	105	80	96	79	102
1740	108	76	96	107	95	98	96	116	121	110
1750	92	123	122	77	102	98	75	106	95	85
1760	109	94	116	89	103	81	142	59	94	97
1770	115	102	116	83	92	107	102	106	102	151
1780	113	103	110	109	102	95	109	111	92	97
1790	98	48	88	88	99	71	114	88	102	97
1800	88	127	105	92	92	97	124	116	108	127
1810	107	66	101	106	117	87	108	85	118	85
1820	91	71	75	109	89	96	119	112	110	78
1830	92	135	114	93	93	82	125	87	98	97
1840	103	93	86	102	72	89	82	86	76	101
1850	117	88	100	82	89	102	94	105	100	106

APPENDIX B7. *continued*

Year	0	1	2	3	4	5	6	7	8	9
1860	134	103	118	106	119	83	100	90	97	109
1870	88	113	85	91	108	104	105	114	91	102
1880	94	97	99	90	103	93	124	48	79	110
1890	102	105	109	87	116	100	83	100	82	89
1900	83	98	97	109	94	129	79	153	110	102
1910	71	94	99	95	92	102	93	125	89	87
1920	86	113	111	129	109	116	116	82	112	121
1930	95	118	84	88	74	100	90	95	85	123
1940	79	100	74	100	109	107	103	125	89	121
1950	85	82	97	114	82	92	101	103	94	118
1960	97	121	98	90	113	104	92	99	102	111
1970	81	104	101	95	76	89	84	113	94	106
1980	88	119	80	85	118	70	76	123	127	115
1990	107	69	91	140	83	60	90	131	104	92

APPENDIX C1. Fire-scar data from fire-scarred cross sections from Texas sites.

Series 1 : HC003
Inner Ring : 1875
Outer Ring :1955
Length of sample : 81
Number in final analysis : 24
Information on fire history :
  1924 D fire scar
  1931 U fire scar FI = 7
  1933 A fire scar FI = 2
  1937 U fire scar FI = 4
  1939 U fire scar FI = 2
  1951 U fire scar FI = 3
Total number of fire scars : 6
Total number all indicators : 6
Average number years per fire : 4.0
Sample mean fire interval : 3.6

Series 2 : HC070
Inner Ring : 1890
Bark Date : 1984
Length of sample : 95
Number in final analysis : 38
Information on fire history :
  1902 U fire scar
  1913 U fire scar FI = 11
  1927 U fire scar FI = 14
  1931 D fire scar FI = 4
  1937 U fire scar FI = 6
Total number of fire scars : 5
Total number all indicators : 5
Average number years per fire : 7.6
Sample mean fire interval : 8.8

Series 3 : HC022
Inner Ring : 1834
Outer Ring : 1932
Length of sample : 99
Number in final analysis : 35
Information on fire history :
  1898 U fire scar
  1901 D fire scar FI = 3
  1902 D fire scar FI = 1
  1903 D fire scar FI = 1
  1921 D fire scar FI = 18
Total number of fire scars : 5
Total number all indicators : 5
Average number years per fire : 7.0
Sample mean fire interval : 5.8

Series 4 : HC027
Inner Ring : 1946
Bark Date : 1984
Length of sample : 39
Number in final analysis : 34
Information on fire history :
  1951 L fire scar
Total number of fire scars : 1
Total number all indicators : 1
Average number years per fire : 34.0

Series 5 : HC841
Inner Ring : 1876
Bark Date : 1984
Length of sample : 109
Number in final analysis : 45
Information on fire history :
  1927 U fire scar
  1937 U fire scar FI = 10
  1939 D fire scar FI = 2
  1944 D fire scar FI = 5
  1947 D fire scar FI = 3
  1949 D fire scar FI = 2
  1956 U fire scar FI = 7
  1969 U fire scar FI = 13
Total number of fire scars : 8
Total number all indicators : 8
Average number years per fire : 5.6
Sample mean fire interval : 6.0

APPENDIX C1. *continued*

Series 6 : TC34
Inner Ring : 1792
Outer Ring : 1944
Length of sample : 153
Number in final analysis : 1
Information on fire history :
  1903 U injury
No information in this range.
Total number all indicators : 1

Series 7 : TC035
Inner Ring : 1668
Outer Ring : 1734
Length of sample : 67
Number in final analysis : 6
Information on fire history :
  1714 A fire scar
  1716 D fire scar FI = 2
Total number of fire scars : 2
Total number all indicators : 2
Average number years per fire : 3.0
Sample mean fire interval : 2.0

Series 8 : TC70
Inner Ring : 1743
Outer Ring : 1863
Length of sample : 121
Number in final analysis : 1
Information on fire history :
  1850 U injury
No information in this range.
Total number all indicators : 1

Series 9 : TC071
Inner Ring : 1715
Outer Ring : 1870
Length of sample : 156
Number in final analysis : 10
Information on fire history :
  1784 D fire scar
  1824 U fire scar FI = 4
Total number of fire scars : 2
Total number all indicators : 2
Average number years per fire :
5.0
Sample mean fire interval : 4.0

Series 10 : TC072
Pith Date : 1718
Outer Ring : 1873
Length of sample : 156
Number in final analysis : 14
Information on fire history :
  1719 E fire scar
  1723 D fire scar FI = 4
  1727 D fire scar FI = 4
Total number of fire scars : 3
Total number all indicators : 3
Average number years per fire :
4.7
Sample mean fire interval : 4.0

APPENDIX C2. Fire-scar data from fire-scarred cross sections from Florida sites.

Series 1 : DN020
Inner Ring : 1925
Bark Date : 2004
Length of sample : 80
Number in final analysis : 29
Information on fire history :
  1991 D fire scar
  1998 A fire scar FI = 7
  2001 D fire scar FI = 3
Total number of fire scars : 3
Total number all indicators : 3
Average number years per fire : 9.7
Sample mean fire interval : 5.0

Series 2 : DN009
Inner Ring : 1780
Bark Date : 1961
Length of sample : 182
Number in final analysis : 114
Information on fire history :
  1789 U fire scar
  1837 U fire scar
  1862 U fire scar FI = 12
  1870 U fire scar FI = 8
  1872 U fire scar FI = 2
  1881 U fire scar FI = 9
  1883 U fire scar FI = 2
  1895 U fire scar FI = 12
  1907 U fire scar FI = 12
  1947 E fire scar FI = 40
Total number of fire scars : 10
Total number all indicators : 10
Average number years per fire : 11.4
Sample mean fire interval : 12.1

Series 3 : DN10A
Pith Date : 1756
Outer Ring : 1969
Length of sample : 214
Number in final analysis : 2
Information on fire history :
  1833 U fire scar
  1921 U fire scar
Total number of fire scars : 2
Total number all indicators : 2
Average number years per fire :
1.0

Series 4 : DN002
Pith Date : 1749
Outer Ring : 1940
Length of sample : 192
Number in final analysis : 1
Information on fire history :
  1862 A fire scar
Total number of fire scars : 1
Total number all indicators : 1
Average number years per fire :
1.0

Series 5 : DN005
Inner Ring : 1668
Outer Ring : 1988
Length of sample : 321
Number in final analysis : 23
Information on fire history :
  1899 E fire scar
  1908 D fire scar FI = 9
  1918 E fire scar FI = 10
  1921 D fire scar FI = 3
Total number of fire scars : 4
Total number all indicators : 4
Average number years per fire :
5.8
Sample mean fire interval : 7.3

Series 6 : DN014
Inner Ring : 1642
Outer Ring : 1839
Length of sample : 198

APPENDIX C2. *continued*

Number in final analysis : 1
Information on fire history :
1736 A fire scar
Total number of fire scars : 1
Total number all indicators : 1
Average number years per fire : 1.0

Series 7 : DN011
Pith Date : 1533
Outer Ring : 1971
Length of sample : 439
Number in final analysis : 31
Information on fire history :
1694 L fire scar
1907 A fire scar
1914 D fire scar FI = 7
1918 A fire scar FI = 4
1921 D fire scar FI = 3
1936 U fire scar FI = 15
Total number of fire scars : 6
Total number all indicators : 6
Average number years per fire : 5.2
Sample mean fire interval : 7.3

Series 8 : DN003
Inner Ring : 1517
Outer Ring : 1953
Length of sample : 437
Number in final analysis : 11
Information on fire history :
1626 M fire scar
1627 L injury
1636 E fire scar FI = 10
Total number of fire scars : 2
Total number all indicators : 3
Average number years per fire : 5.5
Sample mean fire interval : 10.0

Series 9 : BP012
Inner Ring : 1827
Outer Ring : 1908
Length of sample : 82
Number in final analysis : 1
Information on fire history :
1827 E fire scar
Total number of fire scars : 1
Total number all indicators : 1
Average number years per fire :
1.0

Series 10 : BP009
Pith Date : 1804
Outer Ring : 1956
Length of sample : 153
Number in final analysis : 4
Information on fire history :
1819 E fire scar
1820 E fire scar FI = 1
1822 E fire scar FI = 2
Total number of fire scars : 3
Total number all indicators : 3
Average number years per fire :
1.3
Sample mean fire interval : 1.5

Series 11 : BP020
Inner Ring : 1801
Outer Ring : 1925
Length of sample : 125
Number in final analysis : 105
Information on fire history :
1821 M injury
1822 U injury
1823 A injury
1825 M injury
1827 M injury
1828 A fire scar
1830 D fire scar FI = 2
1833 M injury
1834 L fire scar FI = 4

1837 A injury
1839 M injury
1840 A injury
1842 L injury
1843 L fire scar FI = 9
1844 L injury
1845 A fire scar FI = 2
1846 D fire scar FI = 1
1847 D fire scar FI = 1
1848 M injury
1850 U injury
1853 A injury
1854 E injury
1855 D fire scar FI = 8
1856 L fire scar FI = 1
1857 A fire scar FI = 1
1858 A fire scar FI = 1
1860 E fire scar FI = 2
1861 D injury
1862 M fire scar FI = 2
1864 M injury
1865 A fire scar FI = 3
1867 A fire scar FI = 2
1868 A fire scar FI = 1
1870 E fire scar FI = 2
1873 M fire scar FI = 3
1874 E injury
1881 E injury
1882 D fire scar FI = 9
1884 U fire scar FI = 2
1885 U fire scar FI = 1
1886 D injury
1889 A fire scar FI = 4
1890 U injury
1893 M injury
1894 A fire scar FI = 5
1895 U injury
1896 A injury
1897 U injury
1898 M fire scar FI = 4
1901 L injury
1909 A fire scar FI = 11
1910 M injury
1911 M injury
1913 M injury
1918 E fire scar FI = 9
Total number of fire scars : 26
Total number all indicators : 55
Average number years per fire :
4.0
Sample mean fire interval : 3.6

Series 12 : BP015
Inner Ring : 1792
Outer Ring : 1910
Length of sample : 119
Number in final analysis : 28
Information on fire history :
1814 A injury
1819 U injury
1820 E injury
1822 D injury
1825 U injury
1828 A fire scar
1834 M fire scar FI = 6
1840 A injury
1868 U fire scar FI = 6
Total number of fire scars : 3
Total number all indicators : 9
Average number years per fire :
9.3
Sample mean fire interval : 6.0

Series 13 : BP008
Pith Date : 1777
Outer Ring :1830
Length of sample : 54
Number in final analysis : 39
Information on fire history :
1792 M fire scar

1793 L fire scar FI = 1
1806 A fire scar FI = 13
1814 U fire scar FI = 8
1830 U fire scar FI = 16
Total number of fire scars : 5
Total number all indicators : 5
Average number years per fire : 7.8
Sample mean fire interval : 9.5

Series 14 : BP021
Inner Ring : 1589
Outer Ring : 1819
Length of sample : 231
Number in final analysis : 43
Information on fire history :
1747 E fire scar
1749 E injury
1753 E fire scar FI = 6
1761 D fire scar FI = 8
1767 D fire scar FI = 6
1780 D fire scar FI = 13
1789 E fire scar FI = 9
Total number of fire scars : 6
Total number all indicators : 7
Average number years per fire : 7.2
Sample mean fire interval : 8.4

APPENDIX C3. Fire-scar data from fire-scarred cross sections from South Carolina site.

Series 1 : SI030
Pith Date : 1671
Outer Ring : 1775
Length of sample : 105
Number in final analysis : 1
Information on fire history :
  1674 D fire scar
Total number of fire scars : 1
Total number all indicators : 1
Average number years per fire : 1.0

Series 2 : SI032
Inner Ring : N/A
Outer Ring : N/A

Series 3 : SI036
Pith Date : 1840
Outer Ring : 1932
Length of sample : 93
Number in final analysis : 2
Information on fire history :
  1860 U injury
  1910 D fire scar
Total number of fire scars : 1
Total number all indicators : 2
Average number years per fire : 2.0

Series 4 : SI041
Inner Ring : 1789
Outer Ring : 1893
Length of sample : 105
Number in final analysis : 6
Information on fire history :
  1855 U injury
  1860 D fire scar
Total number of fire scars : 1
Total number all indicators : 2
Average number years per fire : 6.0

Series 5 : SI042
Inner Ring : 1822
Outer Ring : 1897
Length of sample : 76
Number in final analysis : 1
Information on fire history :
  1860 U fire scar
Total number of fire scars : 1
Total number all indicators : 1
Average number years per fire :
1.0

Series 6 : SI044
Inner Ring : 1825
Outer Ring : 1879
Length of sample : 55
Number in final analysis : 2
Information on fire history :
  1855 U injury
  1870 D fire scar
Total number of fire scars : 1
Total number all indicators : 2
Average number years per fire :
2.0

Series 7 : SI045
Pith Date : 1624
Outer Ring : 1886
Length of sample : 263
Number in final analysis : 3
Information on fire history :
  1759 D fire scar
  1781 D fire scar
  1817 D fire scar
Total number of fire scars : 3
Total number all indicators : 3
Average number years per fire :
1.0

Series 8 : SI049
Inner Ring : 1775

Outer Ring : 1883
Length of sample : 109
Number in final analysis : 24
Information on fire history :
  1860 D fire scar
  1870 D fire scar FI = 10
Total number of fire scars : 2
Total number all indicators : 2
Average number years per fire : 12.0
Sample mean fire interval : 10.0

Series 9 : SI050
Inner Ring : 1738
Outer Ring : 1817
Length of sample : 80
Number in final analysis : 2
Information on fire history :
  1774 D fire scar
  1781 U fire scar
Total number of fire scars : 2
Total number all indicators : 2
Average number years per fire : 1.0

Series 10 : SI070
Pith Date : 1711
Outer Ring : 1971
Length of sample : 261
Number in final analysis : 2
Information on fire history :
  1951 M fire scar
  1962 U fire scar
Total number of fire scars : 2
Total number all indicators : 2
Average number years per fire : 1.0

Series 11 : SI70A
Inner Ring : 1955
Bark Date : 2004
Length of sample : 50
Number in final analysis : 28
Information on fire history :
  1977 E fire scar
  2002 D fire scar FI = 25
Total number of fire scars : 2
Total number all indicators : 2
Average number years per fire :
14.0
Sample mean fire interval : 25.0

Series 12 : SI071
Inner Ring : 1914
Bark Date : 2004
Length of sample : 91
Number in final analysis : 28
Information on fire history :
  1977 E fire scar
  1985 A fire scar FI = 8
Total number of fire scars : 2
Total number all indicators : 2
Average number years per fire :
14.0
Sample mean fire interval : 8.0

Series 13 : SI072
Pith Date : 1812
Outer Ring : 1904
Length of sample : 93
Number in final analysis : 37
Information on fire history :
  1855 D fire scar
  1860 D fire scar FI = 5
  1864 D fire scar FI = 4
Total number of fire scars : 3
Total number all indicators : 3
Average number years per fire :
12.3
Sample mean fire interval : 4.5

Series 14 : SI027
Inner Ring : 1840

Bark Date : 2004
Length of sample : 165
Number in final analysis : 4
Information on fire history :
1843 U injury
1853 U fire scar
1864 U fire scar
1908 U fire scar
Total number of fire scars : 3
Total number all indicators : 4
Average number years per fire : 1.3

Series 15 : SI011
Inner Ring : 1850
Bark Date : 2004
Length of sample : 155
Number in final analysis : 1
Information on fire history :
1855 U injury
No information in this range.
Total number all indicators : 1

Series 16 : SI075
Inner Ring : 1588
Outer Ring : 1908
Length of sample : 321
Number in final analysis : 4
Information on fire history :
1759 M injury
1774 U injury
1853 M injury
1893 D fire scar
Total number of fire scars : 1
Total number all indicators : 4
Average number years per fire : 4.0

Series 17 : SI076
Pith Date : 1741
Outer Ring : 1896
Length of sample : 156
Number in final analysis : 46
Information on fire history :
1759 M fire scar
1776 D fire scar FI = 17
1791 M fire scar FI = 15
1807 A injury
Total number of fire scars : 3
Total number all indicators : 4
Average number years per fire : 15.3
Sample mean fire interval : 16.0

Series 18 : SI078
Inner Ring : 1676
Outer Ring : 1897
Length of sample : 222
Number in final analysis : 2
Information on fire history :
1692 D fire scar
1722 U injury
Total number of fire scars : 1
Total number all indicators : 2
Average number years per fire : 2.0

Series 19 : SI080
Pith Date : 1669
Outer Ring : 1924
Length of sample : 256
Number in final analysis : 19
Information on fire history :
1843 U fire scar
1891 U injury
Total number of fire scars : 1
Total number all indicators : 2
Average number years per fire : 19.0

Vitae

Joseph P. Henderson was born in Birmingham, Alabama on June 20, 1965. He attended John Carroll High School before moving to Maryville, Tennessee in 1980. He attended Maryville High School and graduated in 1983. He attended the United States Military Academy and graduated with a Bachelor of Science in Geography in 1987. He served in various military assignments before enrolling in the University of Tennessee in 1995 where he received a Master of Science in Geography in 1997. He was an Instructor and Assistant Professor in Geography at the United States Military Academy from 1997 to 2000. Following several military assignments, he again enrolled at the University of Tennessee in 2003. He will return to the United States Military Academy as a member of the faculty in the summer of 2006.