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Tree Growth Dynamics, Fire History, and Fire-Climate Relationships in Pine Rocklands of the Florida Keys, U.S.A.

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To the Graduate Council:

I am submitting herewith a dissertation written by Grant Logan Harley entitled "Tree Growth Dynamics, Fire History, and Fire-Climate Relationships in Pine Rocklands of the Florida Keys, U.S.A.." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Geography.

Henri D. Grissino-Mayer, Major Professor

We have read this dissertation and recommend its acceptance:

Sally P. Horn, Carol P. Harden, Jennifer A. Franklin

Accepted for the Council:
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Vice Provost and Dean of the Graduate School

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

Tree Growth Dynamics, Fire History, and Fire-Climate Relationships in Pine Rocklands of the Florida Keys, U.S.A.

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

Grant Logan Harley
May 2012

DEDICATION

This dissertation is dedicated to my wife, Mandi, for her unconditional love and support; to my parents for instilling in me a strong work ethic and commitment to my passion; and to my friends for their love, support, and humor.

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ABSTRACT

Pine rocklands are globally endangered, fire-maintained communities currently restricted to small habitat areas in southern Florida, Cuba, and the Bahamas. The purpose of this dissertation research was to identify the long-term ecological disturbance regimes and climatic trends responsible for the persistence of pine rocklands, and examine how human-induced changes during the 20th century contributed to decline of these communities. This research applied techniques of dendrochronology in extreme southern Florida, in a subtropical region where tree-ring science has never been applied, to increase the understanding of how anthropogenic and natural disturbance events have decreased the spatial distribution of South Florida slash pine (*Pinus elliottii* Engelm. var. *densa* Little and Dorman; hereafter slash pine), the foundation species of pine rocklands.

To investigate the complex dynamics of declining pine rockland communities, I analyzed (1) the dendrochronological potential and climate response of slash pine, (2) the intra-annual ring formation characteristics and relationships to monthly climatic conditions, (3) the influence of historical fire regimes and varied fire management practices since the 1950s on the structure of slash pine savannas on adjacent islands in the Lower Florida Keys, and (4) the control of global-scale oceanic/atmospheric oscillations on historical wildfire occurrence.

The analyses presented here demonstrate that slash pine forms anatomically distinct, annual growth rings with the consistent year-to-year variability necessary for rigorous dendrochronological studies. Annual radial growth of slash pine is primarily influenced by water availability during the growing season; however intra-annual cellular growth is driven by daily insolation. In the Lower Florida Keys, the growing season of slash pine occurs between February and November, with trees experiencing dormancy between November and January. Reconstructions of fire history and savanna structure revealed that, over the past 150 years, frequent fires occurring every *ca.* 6 years promoted pine recruitment and ensured the persistence of pine rockland habitat. However, the recent lack of fire in some areas could result in the loss of pine rockland habitat, as pine savannas are currently succeeding to tropical hardwood hammock. Over the past several centuries, interacting effects of two Pacific climatic forcing mechanisms (El Niño-Southern Oscillation, Pacific Decadal Oscillation) drove wildfire occurrence in the Lower Florida Keys.

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1.1 Purpose

The purpose of this dissertation research was to investigate the structure and fire disturbance history of declining pine rockland communities in the Lower Florida Keys. The ecological and climatological factors contributing to the distribution of South Florida slash pine (*Pinus elliottii* Engelm. var. *densa* Little and Dorman; hereafter slash pine) at the southern extent of its range were also examined because slash pine is the foundation species of endangered pine rockland communities. Information generated by this research will aid local and regional officials in efforts to maintain pine rocklands in South Florida, where fire suppression and urbanization have led to widespread succession from pine rockland communities to tropical hardwood hammock. Additionally, I examined the interactions between climate mechanisms (*e.g.* El Niño-Southern Oscillation and Pacific Decadal Oscillation) and wildfire, and determined how these interactions affected the current distribution of pine rocklands. An interest in the vegetation history and structure of pine rockland communities by local officials, along with the need to understand how slash pine responds to regional variations in climate, serve as the impetus for this research.

Pine rockland communities are globally endangered (Noss *et al*. 1995). These communities are fire-maintained and provide important habitats for several federal and state-listed endangered species, such as the Key deer (*Odocoileus virginianus clavium* Barbour and Allen) and Florida leafwing butterfly (*Anaea troglodyta floridalis* Johnson & Comstock). The following research increases the understanding of how anthropogenic and natural disturbance events have decreased the distribution of slash pine, the foundation species of pine rockland communities. This research is novel because it applies techniques of dendrochronology in southern Florida, which is located in a subtropical region where tree-ring science has never been applied. This research produces climate proxy datasets that add to the growing global network of low-latitude climate proxy data.

1.2 Pine rocklands

Pine rockland vegetation communities contain savanna-like structure and are located on karstic areas where thin to nonexistent soils overlie limestone substrate in southern Florida, Cuba, and The Bahamas. In the United States, these communities are unique to three areas in South Florida: Everglades National Park, Big Cypress National Preserve, and the Lower Florida Keys (Snyder *et al*. 1990). Pine rocklands are characterized by a single canopy species, slash pine, a diverse subcanopy of West Indian hardwoods and palms, and a variety of endemic herbs (Sah *et al*. 2004). Pine rocklands once covered a vast contiguous area of South Florida of over 75,000 ha, but fire suppression and agricultural and residential development during the 20th century have fragmented and reduced the original range by 90% (Doren *et al*. 1993, O'Brien

1998). Hence, these vegetation communities are considered globally endangered (Noss *et al*. 1995).

Slash pine is the foundation species in pine rockland communities. In the Lower Florida Keys, pine rocklands provide an important habitat for several federal and state listed endangered species, including the Key deer (*Odocoileus virginianus clavium*), Kirtland's warbler (*Dendroica kirtlandii* Baird), Florida atala butterfly (*Eumaus atala* Aloy), and Florida leafwing butterfly (*Anaea troglodyta floridalis*) (Snyder *et al*. 1990). Frequent burning maintains food resources for Key deer and prevents succession of pine rocklands to tropical hardwood hammocks. However, urbanization and fire suppression during the 20th century have led to widespread loss of habitat.

1.3 Ecology of pine rockland savannas

Fire is an important process in pine rocklands as it prevents the invasion of hardwoods, maintains the presence of endemic herbs, and ensures the continuance of Key deer habitat (Robertson 1953; Alexander 1967; Wade *et al.* 1980; Snyder *et al*. 1990). Wildfires have been suppressed as a fire management practice in the Lower Florida Keys since the 1950s (Bergh and Wisby 1996), and some disagreement exists regarding the natural fire regime in these communities. Most studies have suggested that pine rocklands experienced low-intensity surface fires about once every decade (Craighead 1971; Wade *et al*. 1980; Snyder 1986). However, Snyder *et al*. (1990) argued that surface fires occurred within the range of once every 3 to 7 years, the maximum of which is in agreement with the 8-year fire interval argued by Taylor (1981). Low-intensity/severity fires early in the growing season promote height growth in slash pine seedlings, and encourage recruitment to canopy. These fires also synchronize the flowering of many herbaceous plants. Frequent fire tends to discourage broadleaved woody vegetation and favors a rich assortment of plant life on the savanna floor, including nitrogen-fixing legumes, low shrubs, and soil organisms (Landers and Boyer 1999).

Microscopic and macroscopic charcoal fragments in sediment cores from small ponds in the Florida Keys demonstrate repeated fire during the late Holocene (Albritton 2009, Kocis 2012, Horn *unpublished data*). High percentages of pine pollen at Key Deer Pond (Albritton 2009), and macroscopic charcoal identified as pine charcoal at Blue Hole Wetland (Horn *unpublished data*), demonstrate a long relationship between fire and pines in the Florida Keys.

Myers (2010) provided a conceptual ecological model for pine rocklands in the NKDR that included three seral, or successional, stages: early-seral, mid-seral, and late-seral (Figure 1.1). In this model, each seral stage represents the degree of change in vegetation structure, development, or composition in the absence of fire. Myers (2010) classified each stage based on differences in fire frequency, mid-story vegetation cover and height, herbaceous layer abundance and diversity, pine regeneration, and duff layer (Table 1.1). Although the conceptual ecological model presented by Myers (2010)

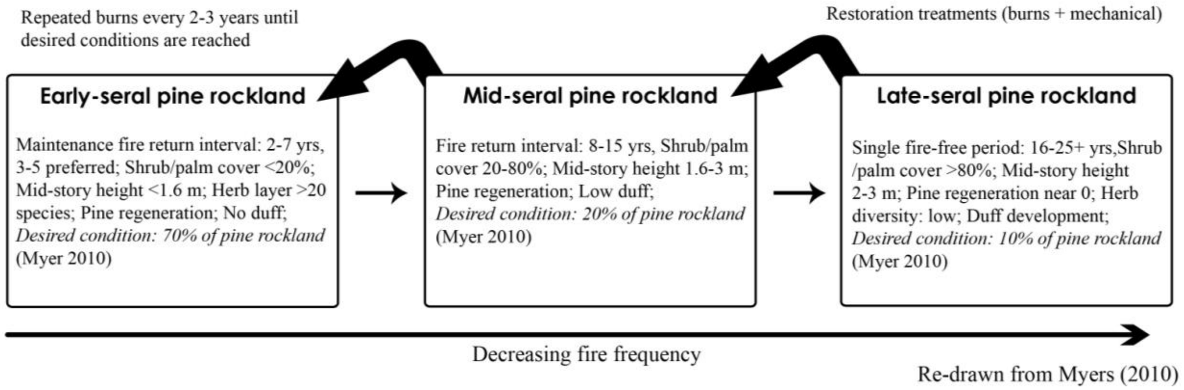

Figure 1.1. Conceptual ecological model for pine rockland ecosystems in the National Key Deer Refuge, Lower Florida Keys (redrawn from Myers 2010).

Table 1.1. Description of the successional (seral) stages identified for pine rockland ecosystems in the National Key Deer Refuge, Lower Florida Keys (from Myers 2010).

Stage	**Description**
Early-seral	Minimal mid-story (shrub layer). Woody shrubs compose >20% cover; average shrub height >1.6 m; highly diverse herbaceous layer (<20 species). Palm species present but widely scattered with some regeneration. Pine stands are open and multi-aged with density and age structure that vary widely; scattered pine regeneration of varying density primarily in gaps and other open areas. Little or no duff accumulation. Fire regime: frequent 3–7 years; low intensity/low severity surface fires; variability in season of burn.
Mid-seral	Woody shrubs and palms compose between 20–80% cover; average shrub/palm height 1.6–3 m. Pine stands open and multi-aged with limited regeneration. Duff accumulating. Fire history: unburned for more than 7 years, but less than 15 years. Probably can be maintained with a fire return interval of 7–15 years, but may require a return to early-seral stage through a period of frequent burning, especially if the interval has been in the upper end of that range for an extended period.
Late-seral	Tall broadleaf and palm component compose >80% cover; average shrub/palm height 2–3 m. Lower diversity ground cover than early- and mid-seral stages. Not sufficient pine regeneration to replace older trees; pine regeneration might be lacking altogether. Most herbaceous species will be absent. Little exposed rock. A transitional stage hammock. Fire history: unburned for more than 15 years. There is probably not a fire regime that can maintain the late-seral stage with pine at a particular place on the landscape. To maintain this stage in the landscape, the site would need to return to an earlier successional stage to allow pine establishment (i.e. to have this stage always present, it may need to move around the landscape).

is important for deciding desired future conditions in NKDR, fire return intervals were not based on quantitative fire history or stand structure data.

Dendroecological techniques can be used to provide accurate information regarding the disturbance history during the development of a stand, including the spatial and temporal variability of past fires (Abrams *et al*. 1997; Druckenbrod 2005). Since the inception of the National Key Deer Refuge on Big Pine Key in 1957, prescribed burning has been applied inconsistently (Bergh and Wisby 1996). This has resulted in a variety of stand structures in various stages of development (Sah *et al*. 2004). To my knowledge, no published study has applied techniques of dendroecology in the Lower Florida Keys; hence, the age structure and patterns of tree growth related to fire disturbance events are unknown and the natural fire regime prior to the 1950s is unclear due to a lack of historic documentation or high-resolution, tree-ring based reconstructions of past fire.

1.3.1 Fire regimes in pine rocklands

1.3.1.1 Fire season

The wet/lightning season in South Florida exists between the months of May and October. In the Lower Keys, convective thunderstorms are most common during this period, with an average peak of 14.5 thunderstorm days in August (Bergh and Wisby 1996). Taylor (1981) found that in Everglades National Park, lightning-caused fires burned the greatest number of acres in May, June, and July, when convective thunderstorms were most common, yet standing water and fuel moisture content were still low due to evaporation.

On average, the Lower Keys receive less precipitation than mainland Florida. During the period 1895–2009, average annual precipitation was 990 mm for the Lower Keys and 1397 mm for the South Florida mainland (NCDC 2009). As a result, lower fuel production may result in both a slower rate of hardwood succession (Alexander and Dickson 1972) and longer fire return interval (Snyder *et al*. 1990). Karl *et al*. (1983) reported that extreme to severe droughts (Palmer Drought Severity Index and Palmer Hydrological Drought Index values < –3) affected both the Lower Keys and Everglades in 1971 and 1974/1975. These droughts corresponded to extreme fire years in the Everglades (Taylor 1981) but did not have the same effect in the Lower Keys (see Bergh and Wisby 1996). It is possible that the differences in acreage burned per fire season between the Lower Keys and the Everglades were due to the fragmented condition and sparse distribution (limited area) of slash pine forests on islands of the Lower Keys.

The only long-term weather data readily available for the Lower Keys region are collected at Key West. This is a problem because precipitation varies greatly from the southern portion of peninsular Florida to Key West. Hence, not all storms recorded at Key West are experienced on other islands, and an individual storm often affects areas of a particular island differently, especially on large islands such as Big Pine Key.

However, if an equal number of storm days per island in the Lower Keys is assumed, Big Pine Key might have a higher frequency of lightning strikes, and hence fires, than any other island in the area simply because it has the largest land mass.

Sah *et al*. (2006) conducted a burning experiment in six blocks in the pine forests of National Key Deer Refuge, Big Pine Key, Lower Florida Keys to examine the distribution of fuel components before fire, their effects on fire behavior and seasonality, and the dynamics associated with fuel recovery following fire. Within each of the blocks, they subjected 1-ha plots to three treatments over a 4-year period from 1998 to 2001: control, summer, and winter burning. They used path analysis to model the effects of fuel type and char height, an indicator of fire intensity, on fuel consumption. They found that fire intensity increased with surface fuel loads, but was negatively related to the quantity of hardwood shrub fuels, probably because these fuels were associated with a moist microenvironment within hardwood patches, and therefore tended to resist fire. Winter fires were milder than summer fires and were less effective at controlling the encroachment of hardwoods, a finding that agreed with the findings of Snyder *et al*. (1990). The authors suggested a mixed seasonal burning regiment for fire management, with burns applied opportunistically under a range of winter and summer conditions.

A similar study was conducted by Menges and Deyrup (2001) in South Florida on ways in which the dynamics of fire seasonality, regime, and intensity affect the distribution of slash pine. They examined the post-fire survival of slash pine by considering the interacting factors of bark beetle outbreaks, fire seasonality, fire intensity, acres burned, and vegetation structure and composition. Slash pines were sampled in 24 burned areas for three years following each fire. Season of burn most affected the survival of pines; fall burns resulted in the highest mortality because fires tended to be more intense during this time.

1.3.1.2 Fire frequency

In the Lower Florida Keys, wildfires have been suppressed as a fire management practice since the 1950s (Bergh and Wisby 1996), and previous investigations report a variety of historical wildfire frequencies. Most studies suggested that pine rocklands experienced low-intensity surface fires about once every decade (Craighead 1971; Wade *et al*. 1980; Snyder 1986), which is in agreement with Snyder *et al*. (1990), who argued that surface fires occurred about once every 3 to 7 years, and with the 8-year fire interval argued by Taylor (1981). Currently, the natural fire regime prior to the 1950s is unknown due to a lack of historical records and a lack of tree-ring based fire reconstruction research.

Bergh and Wisby (1996) represented the most comprehensive report to date on fire history in the Lower Keys pine rocklands. Their report was based on GIS-based images and data, and was intended to help plan prescribed burning activities in the Lower Keys. Their fire history data derived from several sources, including historical fire reports and descriptions noted in the Annual Narrative Reports of the United States Fish and Wildlife Service's (USFWS) Florida Keys Refuges, Key West Citizen newspaper articles, and reports from volunteer fire departments in the Lower Keys. Once fire dates and respective areas were analyzed, images were digitized in GIS and georeferenced with coinciding aerial photographs. The resulting GIS files demonstrated that 58 fires occurred in the Lower Keys between 1961 and 1996. Of these, 27 were wildfires and 31 were prescribed burns. In addition to the 58 well-documented fires, 21 fires were mentioned between 1944 and 1980 in reports that could not be corroborated or documented. Of the 58 documented fires in the Lower Keys, Bergh and Wisby (1996) found that six were clearly started by lightning and occurred between April–September, with the greatest number of fires (3) occurring in July. Bergh and Wisby (1996) mentioned that an unknown, and possibly large, number of fires went unreported or undetected. Therefore, a tree-ring based fire history study would be beneficial to efforts to compile a complete fire history in the Lower Keys.

Beckage and Platt (2003) demonstrated linkages between fire regimes and the El Niño-Southern Oscillation (ENSO) in pine rocklands of the Florida Everglades. Using historical fire data from 1948 to 1999, they found that the El Niño phase was associated with increased dry-season rainfall, higher surface water levels, decreased lightning strikes, fewer fires, and smaller areas burned. Conversely, the La Niña phase of ENSO was associated with decreased dry-season precipitation, lower surface water levels, increased lightning strikes, more fires, and larger areas burned. They hypothesized that frequent shifts between ENSO phases influenced vegetation through periodic large-scale fires and resulted in a widespread occurrence of fire-influenced communities in the Everglades landscape; however, their results were based solely on historically documented fires and assumptions of how fire behaved during ENSO phases without having tree-ring data to support claims.

1.3.1.3 Fire ecology

Fire is required for the maintenance and persistence of pine rockland communities. Robertson (1954) and Wade *et al.* (1980) reviewed fire effects in these communities and reported that fires usually occurred as low-intensity surface fires that consumed only litter and some understory vegetation. The pine stem density was usually too sparse and the canopy too open to support stand-replacing crown fires. Fires that carried across pine rocklands usually burned out when they encountered a hardwood hammock margin, yet soil fires smoldered in hammocks, especially during drought conditions (Wade *et al.* 1980). Snyder *et al.* (1990) stated that fuel conditions favored frequent fire in rockland communities. The herbaceous layer acted to carry surface fires across the landscape. Pine needles accumulated as a duff layer and decomposed slowly, as did other fuels (*e.g.* snags, stump, logs) because of rapid drying due to open canopy conditions. In contrast, hammocks contained broadleaf litter lying directly on moist organic soil and sparse herbaceous fuel. Fuels did not dry as rapidly under shaded hammocks, and the humid microclimate did not favor spreading fire (Snyder *et al*. 1990).

South Florida slash pine has evolved certain characteristics that are fire adaptive. Like its sister taxon longleaf pine (*Pinus palustris* Mill.), slash pine establishes in a “grass stage,” with long needles that shield apical buds and a thick insulating bark that shields the vascular cambium from fires. Following fire during the grass stage, seedlings grow rapidly to establish a height above normal surface fires (sapling stage). Typically, pine seedling establishment is increased when fires occur before seed release (Snyder 1986). Within the rockland community, fire commonly kills the aboveground portion of hardwood shrubs, but all species typically resprout from below ground (Robertson 1953). Shrub layer palms (mostly *Sabal palmetto* and *Serenoa repens*) have a similar fire adaptation, as fire kills aboveground biomass, but sub-surface apical buds are unharmed and protected on the stem, allowing them to quickly resprout (Snyder *et al*. 1990).

When native species, as mentioned above, have positive fire feedback mechanisms, the result is a healthy community. However, some non-native species were shown to facilitate their own invasions in rockland communities. Stevens and Beckage (2009) considered the invasive species Brazilian pepper (*Schinus terebinthifolius*) growing in the rockland communities on Long Pine Key (Upper Florida Keys) and investigated whether this invasive shrub initiated a fire-suppression feedback that ultimately resulted in the conversion of pine rockland savanna to tropical hardwood hammock. By applying controlled burns to selected plots, they found that prescribed burns caused significant mortality of Brazilian pepper at low densities and that savannas with more frequent fires contained less Brazilian pepper. However, high densities of Brazilian pepper reduced fire temperature by up to 200 °C, and under these conditions the plant experienced mortality as much as 80%. Stevens and Beckage (2009) used a cellular automaton model to show that frequent fire may control low-density populations, but that Brazilian pepper may reach a sufficient density during fire-free periods to initiate a positive feedback that reduces the frequency of fire and converts savannas to an invasive-dominated forest.

Platt *et al*. (2002) demonstrated that certain fire regimes strongly influenced the number of pines killed by hurricanes. In remnant pine savannas of the Everglades, the authors measured direct mortality of slash pines during Hurricane Andrew in 1992 and extended mortality over the following 24–30 months. To study possible effects of prior fire regimes on subsequent hurricane-related mortality in pine savannas, they examined savannas that were unburned, burned during the wet (lightning fire) season, or burned during the dry (anthropogenic fire) season in the decade before Andrew. Doren *et al*. (1993) found that anthropogenic changes to dry-season fires strongly influenced the effects of hurricanes on the mortality of pines in the Everglades.

Savannas dominated by slash pine are one of the most threatened habitats in Florida. Doren *et al*. (1993) measured pine density and size-class distribution in three slash pines stands in Everglades National Park and Big Cypress National Preserve to gain an understanding of the effects of how these were affected by past fire management practices. All three stands differed in fire management and logging history. Doren *et al*. (1993) found that even in the absence of logging, past fire management practices converted an uneven sized, variable density stand to an even-sized, uniform density stand. Intense dry-season fires, caused by long-term fire suppression, were probably responsible for the loss of large individual trees in non-logged stands. Furthermore, they proposed that restoration of second-growth stands to uneven-sized, variable density states would require reintroduction of fires more characteristic of those in presettlement environments. Intense and numerous early wet season fires (April–June) were probably the only fires that thinned established trees and opened space for recruitment into populations.

1.4 Dendrochronology in the subtropics and tropics

Dendrochronology has a wide range of applications and is used to reconstruct both environmental and anthropogenic histories (Fritts 1976; Dean *et al*. 1996). Most studies that involve dendrochronology are conducted in temperate regions, where the majority of tree species produce a single and explicit growth ring each year (Speer *et al*. 2004, Speer 2010). Most species located in tropical and subtropical areas do not experience strong enough seasonality in temperature or precipitation to cause tree growth to enter dormancy each year. The lack of seasonality prevents trees from entering into a dormant state, which results in the production of growth rings with diffuse and indistinct boundaries. However, recent studies show that certain tree species located in tropical and subtropical regions produce annual rings (Speer *et al*. 2004; Brienen and Zuidema 2006; Buckley *et al*. 2007; Baker *et al*. 2008). Tree-ring records from these regions are important because the tropics are the center of action for many broad-scale climate phenomena (*e.g.* ENSO; D'Arrigo *et al*. 2006) and these data provide rare opportunities for understanding the ecological dynamics of tropical and subtropical communities (Brienen *et al*. 2009).

South Florida remains a substantially under-represented region for dendrochronological research due to the difficulty of finding species with annual growth rings. To study the growth patterns of slash pine, Langdon (1963) installed dendrometer bands on 10 mature individuals in the Corkscrew Experimental Forest, Fort Meyers, Florida, and measured incremental radial growth for four years. Langdon found that, for the growing season, cambial activity first occurred in early February, and 37% of the annual growth occurred from February to April, 35% from May to August, 25% from September to November, and 3% from December to January.

Tomlinson and Craighead (1972) conducted visual observations of wood anatomy of many plant species found in South Florida. They reported a small number of species possessed anatomically distinct growth rings, including slash pine, which they mentioned as the clearest example of annual growth rings of any species observed. Yet, neither Langdon (1963) nor Tomlinson and Craighead (1972) offered any evidence (*e.g.* ring counts between known events, crossdating) to show that growth rings in this species are truly annual, which cannot be assumed given its subtropical location.

Slash pine persists on a surface of exposed limestone with poorly developed soils, and the study area experiences a distinct summer-wet and winter-dry season, with an average of 80% of the precipitation occurring in the summer (Winsberg 2003). These factors are imperative for successful subtropical tree-ring studies (Speer *et al*. 2004; Baker *et al*. 2008; Heinrich *et al*. 2008; Sano *et al*. 2009). Data generated by this research will be used to determine the structure and dynamics of pine rockland communities.

1.5 Motivation for the research

I had several reasons for conducting research in Florida Keys pine rocklands. First, slash pine is the southernmost distributed native conifer in the United States, and slash pine located in the Lower Florida Keys exists at the southernmost limit of its geographical distribution. Moreover, the Lower Florida Keys have a unique geography, located along the Florida Straits between the Gulf of Mexico and Atlantic Ocean, so old-growth slash pines here could potentially reveal climate information about various oceanic/atmospheric climate phenomena (e.g. ENSO, Pacific Decadal Oscillation (PDO)), and add a much needed data point within the network of climate proxies.

Previous investigations have shown that various climate-forcing mechanisms (such as ENSO and PDO) influence Florida weather and climate, and control the occurrence of wildfire, which is a major disturbance in pine rocklands. Wildfires in the Lower Florida Keys (LFK) have been suppressed since the 1950s, and a considerable amount of dead material has accumulated on the ground. To complicate matters, inhabitants in the LFK have built their houses adjacent to slash pine trees that contain many fire scars, which is direct evidence that fires once burned frequently on the islands. Hence, the combination of prolonged drought and lightning is all it would take to potentially result in widespread loss of property and endangered wildlife species. Finally, the *ca.* 100,000 people living in the Florida Keys receive their drinking water through the Florida Keys Aqueduct Authority (FKAA), which pumps freshwater all the way from Miami to Key West (*ca.* 650 km). The source of this freshwater comes from groundwater aquifers, which are vulnerable to over-pumping and saltwater intrusion during periods of drought. From 2005 to 2008, the Florida Keys experienced one of the most severe droughts in recorded history. Yet, without the knowledge of drought severity before the 1900s, it is impossible to know the historical connotation of this most recent drought. As we head into an era of uncertain climatic conditions and unprecedented warming, reconstructions of regional precipitation using slash pines could help reveal the historical context of this most recent drought and aid the FKAA in refining its water-use policies to be better suited for dealing with future droughts.

1.6 Objectives

Knowledge of the long-term patterns of ecological disturbance and climatic trends responsible for the persistence of pine rocklands and how human-induced changes during the 20th century are currently contributing to their decline is crucial to the management and conservation of these globally endangered communities. The primary objectives of my research are to:

1. Determine if slash pine at its southern range limit forms anatomically distinct growth rings (Chapter 2).
2. Establish whether growth rings are consistently annual throughout the life of trees (Chapter 2).
3. Verify if crossdating is possible within and among trees (Chapter 2).
4. Examine which climatic factors influence slash pine radial growth in the Lower Florida Keys (Chapter 2).
5. Examine the timing of growth ring formation in slash pine using anatomical evidence (Chapter 3).
6. Investigate the relationship between climatic variables and intra-annual xylem differentiation at the southernmost range limit of slash pine (Chapter 3).

7. Describe the characteristics of the historical fire regimes in the pine rocklands of the Lower Florida Keys and determine whether fire regimes differed across islands (Chapter 4).
8. Determine whether fire regimes changed during the 20th century after the establishment of the National Key Deer Refuge (NKDR) (Chapter 4).
8. Investigate how historical fire regimes and varied fire management practices since establishment of the NKDR affected the stand structure of the two islands (Chapter 4).
9. Provide pine rockland management suggestions based on historical fire history and stand structure data (Chapter 4).
10. Characterize the historical fire regime in slash pine savannas on Big Pine Key, including return interval, fire season, and relative spatial extent (Chapter 5).
11. Determine whether detectable fire years were associated with El Niño-Southern Oscillation and/or Pacific Decadal Oscillation (Chapter 5).

1.7 Organization of the dissertation

My dissertation consists of five chapters. Chapters 2–5 are included as stand-alone manuscripts that are either already published or in review at an ISI peer-viewed journal. In Chapter 2, I tested the hypothesis that slash pine produces annual growth rings in the Lower Florida Keys by counting the number of rings on samples that contained a fire scar from a known wildfire and a known date for hurricane-induced tree mortality. In addition, a crossdated tree-ring chronology (1871–2009) was developed from living trees and remnant wood and compared to divisional climate data to determine how the regional climate regime influences radial growth. The goal of this chapter was to reveal the potential of producing high-quality dendrochronological data in southern Florida from slash pine. This should prove useful in further studies on fire history and tree phenology, and for assessing the projected impacts of impending climate change on the pine rockland community.

In Chapter 3, I determine the temporal and seasonal dynamics of intra-annual cell formation of slash pine in the Florida Keys, and examine possible relationships between monthly cell production and climatic factors, such as temperature, precipitation, solar radiation, potential evapotranspiration, and day length. During the period March 2010 to March 2011, wood micro-cores containing the outermost layers of bark, phloem, vascular cambium, and xylem were extracted monthly from six trees and used to identify the growing season of slash pine in the Florida Keys.

Chapter 4 explores how historical fire disturbance and varied fire management practices influenced pine rockland structure in habitat areas on adjacent islands. I reconstructed fire history in two stands from fire scars on slash pine that were accurately dated using dendrochronology, and quantified stand structure to infer successional trajectories on both islands.

In Chapter 5, I investigate relationships between climatic variability and historical wildfires in pine rockland communities in the Florida Keys. Using the dominant tree, slash pine, I developed a new set of crossdated fire-scar chronologies spanning 1707–2010 from four sites on Big Pine Key and compared the fire chronology to measured values of the ENSO (NIÑO3.4 region), PDO, and divisional temperature and precipitation. This chapter adds much needed data for analyzing fire-climate relationships within the network of fire history sites in the southeastern United States, and results have implications for other pine rockland communities in southern Florida and the Bahamas. I summarize the major findings of my dissertation work in the Florida Keys and suggest recommendations for future research. The Appendices contains details of the slash pine chronologies developed from my work.

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Chapter 2

The Dendrochronology of *Pinus elliottii* in the Lower Florida Keys: Chronology Development and Climate Response

Chapter 2

The Dendrochronology of *Pinus elliottii* in the Lower Florida Keys: Chronology Development and Climate Response

This chapter is a slightly revised version of a paper published in a peer-reviewed journal: Grant L. Harley, Henri D. Grissino-Mayer, and Sally P. Horn (2011). The Dendrochronology of Pinus elliottii in the Lower Florida Keys: Chronology development and climate response. *Tree-Ring Research,* 67(1): 39–50. The revisions follow suggestions made be members of my dissertation committee. The use of "we" in this chapter refers to my co-authors and myself. As the first author, I was lead on designing the study, obtaining the data, performing analyses, and writing the manuscript.

2.1 Abstract

South Florida slash pine (*Pinus elliottii* var. *densa*) is the southernmost pine species in the United States and the foundation species of the globally endangered pine rockland communities in South Florida. To test if slash pine produces annual growth rings in the Lower Florida Keys, we counted the number of rings on samples collected from the North Big Pine Key site (NBP) that contained a fire scar from a known wildfire and a known date for hurricane-induced tree mortality (2006 or 2007). In addition, a crossdated tree-ring chronology (1871–2009) was developed from living trees and remnant wood found at the site and compared to divisional climate data to determine how the regional climate regime influences radial growth. Our analyses demonstrated that slash pine forms anatomically distinct, annual growth rings with the consistent year-to-year variability necessary for rigorous dendrochronological studies. Response function and correlation analysis showed that annual growth of slash pine at NBP is primarily influenced by water availability during the growing season. However, no significant correlations were found between tree growth and the Atlantic Multidecadal Oscillation or the El Niño-Southern Oscillation. Our study reveals the potential of producing high-quality dendrochronological data in southern Florida from slash pine that should prove useful in further studies on fire history and tree phenology, and for assessing the projected impacts of impending climate change on the fragile pine rockland community. *Keywords:* dendrochronology, *Pinus elliottii*, Florida, response function analysis, pine rocklands

2.2 Introduction

The science of dendrochronology relies on precision during the tree-ring dating process to ensure that each growth ring is correctly assigned to the exact calendar year in which it formed (Douglass 1934, 1941). This required precision creates challenges when working in tropical and subtropical regions. Most studies that involve dendrochronology are conducted in temperate regions, where the majority of tree species produce a single and explicit growth ring each year (Fritts 1976; Speer 2010). Many species located in tropical and subtropical regions do not experience strong seasonality in temperature or precipitation that can cause tree growth to cease, resulting in the formation of a well-defined ring. However, recent studies show that certain tree species located in these regions produce annual rings (Speer *et al*. 2004;

Brienen and Zuidema 2006; Buckley *et al*. 2007; Baker *et al*. 2008). Tree-ring records from the tropics and subtropics are important because the tropics are relatively under-represented by proxy data that can be used to infer many broad-scale climate phenomena in the past (*e.g.* El Niño-Southern Oscillation; D'Arrigo *et al*. 2006). These tree-ring data provide rare opportunities for understanding the ecological dynamics of tropical and subtropical communities (Brienen *et al*. 2009).

Pine rockland communities are considered globally endangered because 98% of these communities have been lost worldwide due to land-use conversion and ecological degradation (Noss *et al*. 1995). In the United States, pine rockland communities are unique to three areas in southern Florida: Everglades National Park, Big Cypress National Preserve, and the Lower Florida Keys (Snyder *et al*. 1990). South Florida slash pine (*Pinus elliottii* Engelm. var. *densa* Little and Dorman) is the dominant woody species and sole canopy tree in pine rocklands of the Lower Florida Keys. These communities support a diverse subcanopy of West Indian hardwoods and palms, and a variety of endemic herbs that are alternately encouraged or inhibited by fire (Noss et al. 1995; Sah *et al*. 2004). Pine rocklands once covered a vast contiguous area of southern Florida of over 75,000 ha, but fire suppression and urbanization during the 20th century have fragmented and reduced the original range by 90% (Doren et al. 1993, O'Brien 1998).

Slash pine is the foundation species in pine rockland communities. This species is the southernmost native pine in the United States (Little and Dorman 1954). In the Lower Florida Keys, pine rocklands provide an important habitat for several federal and state listed endangered animal and plant species, including the Key deer (*Odocoileus virginianus clavium* Barbour & Allen), the Lower Keys marsh rabbit (*Sylvilagus palustris hefneri* Lazell), Kirtland's warbler (*Dendroica kirtlandii* Baird), Garber's spurge (*Chamaesyce garberi* (Engelm. ex Chapm.) Small), tiny polygala (*Polygala smallii* R.R. Sm. & Ward), the Big Pine Key ringneck snake (*Diadophis punctatus acricus* Paulson*),* the Florida atala butterfly (*Eumaeus atala* Röber), and the Florida leafwing butterfly (*Anaea troglodyta floridalis* Johnson & Comstock) (Snyder et al. 1990). Frequent burning maintains the associated vegetation of pine rockland communities and prevents succession to tropical hardwood hammocks.

The objectives of this study were to (1) determine if slash pine at its southern range limit forms anatomically distinct growth rings; (2) establish if these growth rings are consistently annual; (3) verify if crossdating is possible within and among trees; and, (4) examine which climatic factors influence slash pine growth in the Lower Florida Keys. Our goal is to provide insights into the potential use of slash pine for future dendrochronological studies in southern Florida that will serve two primary purposes. First, can South Florida slash pine provide useful information on past climate in subtropical locations? Our study reveals which climate variables (such as mean monthly temperature, total monthly precipitation, Atlantic Multidecadal Oscillation (AMO), and El Niño-Southern Oscillation (ENSO)) are important for growth of slash pine. Any statistically significant relationships between climate and pine growth offer the potential for climate reconstruction in a subtropical location. Second, can slash pine yield important information on past fire activity via tree-ring based fire-scar analyses, similar to studies conducted in locations farther north and west in the U.S.? Slash pine is a fire-adapted species, and we discovered hundreds of fire-scarred pines that could provide valuable information on the range of historical variation in fire regimes of the Lower Florida Keys. Should slash pine prove to be a dendrochronologically viable species, reconstructions of fire history would complement ongoing studies on the role of fire in pine rockland ecosystems (Sah *et al*. 2010).

2.2.1 Previous research on South Florida slash pine

Southern Florida remains a substantially under-represented area for dendrochronological research due to the difficulty of finding species with annual growth rings. Langdon (1963), who first attempted to study the growth patterns of slash pine, installed dendrometer bands on 10 mature trees in the Corkscrew Experimental Forest near Naples, Florida (26.4° N, 81.6° W) and measured incremental radial growth during the period 1956–1959. Langdon also monitored groundwater level and soil moisture, and compared radial growth to environmental conditions.

Langdon found that the first spring flush of growth occurred in early February, and 37% of the annual growth occurred from February to April, 35% from May to August, 25% from September to November, and 3% from December to January. Diameter growth had two peaks, one in spring centered on March and another in the fall centered on September; however, radial growth in this study was not separated from seasonal of short-duration shrink-swell cycles.. Langdon found that the 10-month long growing season (February to November) contributed to a high percentage of latewood and therefore high wood density (the specific gravity of South Florida slash pine is 0.845 (Olson 1952), the highest of all pine species in the U.S. (Forest Products Laboratory 1974)). He further discovered that the lack of moisture during drought conditions in 1956 did not affect radial growth considerably, which he attributed to the fact that the wilting point was not reached in the lower soil depths where moisture was still available to trees. Although his study did not specifically correlate radial growth with climate factors, Langdon (1963) was the first to present a basic understanding of the slash pine growing season in South Florida.

Tomlinson and Craighead (1972) made observations of wood anatomy of several tree species found in southern Florida. They speculated that several species form annual growth rings, including slash pine, which they mention as the clearest example of annual growth rings of any species observed. They also noted that the high proportion of latewood to earlywood might be a result of the long growing season that slash pine experiences. Using the results of Langdon (1963) and their own observations, they speculated that the annual reactivation of the cambium corresponds with the first flush of growth during February, at which time the male and female strobili expand. Neither Langdon (1963) nor Tomlinson and Craighead (1972), however, offered any evidence (*e.g.* ring counts between known stand-wide events) to demonstrate that growth rings in this species are annual, which cannot be assumed given its subtropical location.

Specimens of slash pine in Myakka River State Park, Florida (27.2° N, 82.3° W) were successfully crossdated by Ford and Brooks (2002) and used to investigate whether increased levels of the Myakka River, caused by damming, amplified forest stress and decline. Their primary objective was to determine the relationship between historical and present river levels and growth of actively managed forested stands located above and below a dam located within the park. Tree growth and river levels were positively correlated before and after flow increased, suggesting that increased river levels may indirectly cause stress and mortality through increased competition in wet-mesic pine flatwoods. In forested wetland stands, however, Ford and Brooks concluded that increased river levels were the direct cause of extensive mortality upstream from the dam.

Additionally, Ford and Brooks (2003) used tree-ring analyses on slash pine to examine the relationship between radial growth, precipitation minus potential evapotranspiration (P-PET, indicating water availability during times of high demand), and runoff (R, indicating access to groundwater) along a hydrologic gradient at Myakka River State Park. The oldest individual pine established in 1888, but most individuals established in the early decades of active fire suppression (ca. 1930 to 1950). The common period of their three slash pine chronologies spanned 1936–1997 and had interseries correlations of 0.45 ($n = 7$; $p < 0.001$), 0.56 ($n = 31$ $p < 0.001$), and 0.57 ($n = 18$; $p < 0.001$), indicating response within each site to a common climate signal. Tree growth was significantly correlated with current year's spring R and with the current year's spring, summer, and fall P-PET at all three sites.

2.3 Materials and methods

2.3.1 Study area

Big Pine Key (24.6° N, 81.3° W) is the largest of the islands that make up the Lower Florida Keys, and contains the most extensive area of contiguous pine rockland and slash pine habitat (920 ha; Figure 2.1). The pine rocklands on Big Pine Key are located within the National Key Deer Refuge (NKDR), which is managed by the United States Fish and Wildlife Service (USFWS). The tropical savanna climate of the Lower Florida Keys is characterized by hot summers (average maximum August temperature 32.8 °C), cool winters (average minimum January temperature 19.4 °C), and a distinct summer-wet, winter-dry season. The average annual precipitation is 980 mm, with 80% occurring from May to November (NOAA 2010; Figure 2.2). On the rocklands, soil is thin to non-existent and Pleistocene-aged Miami limestone is exposed at the surface (Snyder *et al*. 1990).

2.3.2 Sampling design

To assess the potential of slash pine for dendrochronological research, we conducted a specific sampling design aimed at first determining whether trees on Big Pine Key produce a single and explicit growth ring each year. In August 2009, 36 fire-scarred cross sections from dead and living slash pine trees were collected from a prescribed burn site on North Big Pine Key. The North Big Pine (NBP) site is located on a 25-ha tract of land that last burned on 30 September 1988. According to Bergh and Wisby (1996), this burn was a high-intensity prescribed burn. To determine if slash pine produces a single growth ring each year, we extracted partial sections from dead fire-scarred trees that experienced mortality caused by the 2005 storm surge of Hurricane Wilma and subsequent saltwater impoundment in low-lying areas of the key. The outermost growth ring for these hurricane-killed pines should coincide with calendar year 2006 or 2007. The variability in outermost ring dates occurs because flooding effects from the storm surge (depth and duration) were variable across the island. To test the annual nature of growth rings, a ring count was first conducted with a microscope on samples from the most recent fire scar (1988) to the outermost ring (2006 or 2007).

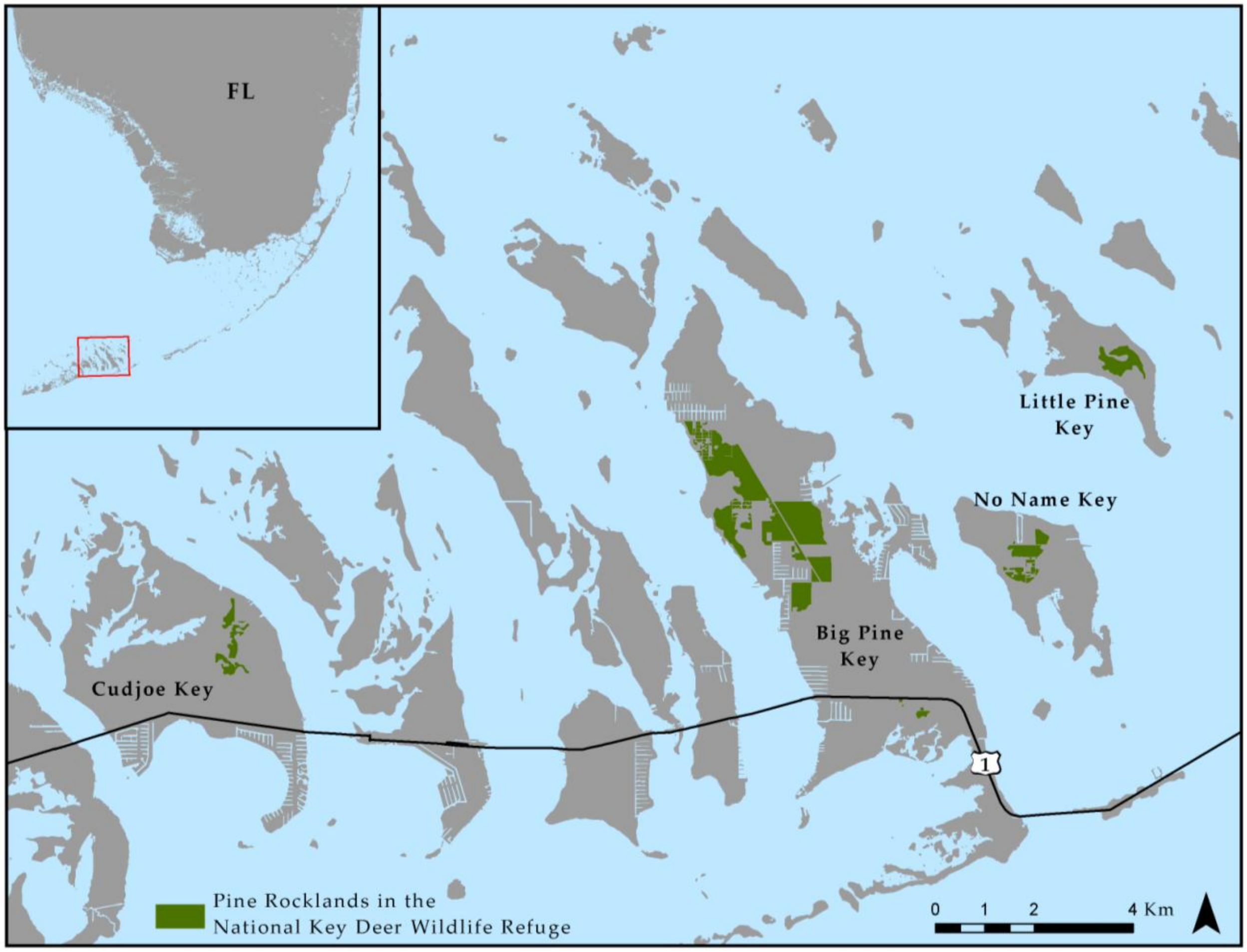

Figure 2.1. Current distribution of pine rocklands and slash pine in the National Key Deer Refuge, Lower Florida Keys.

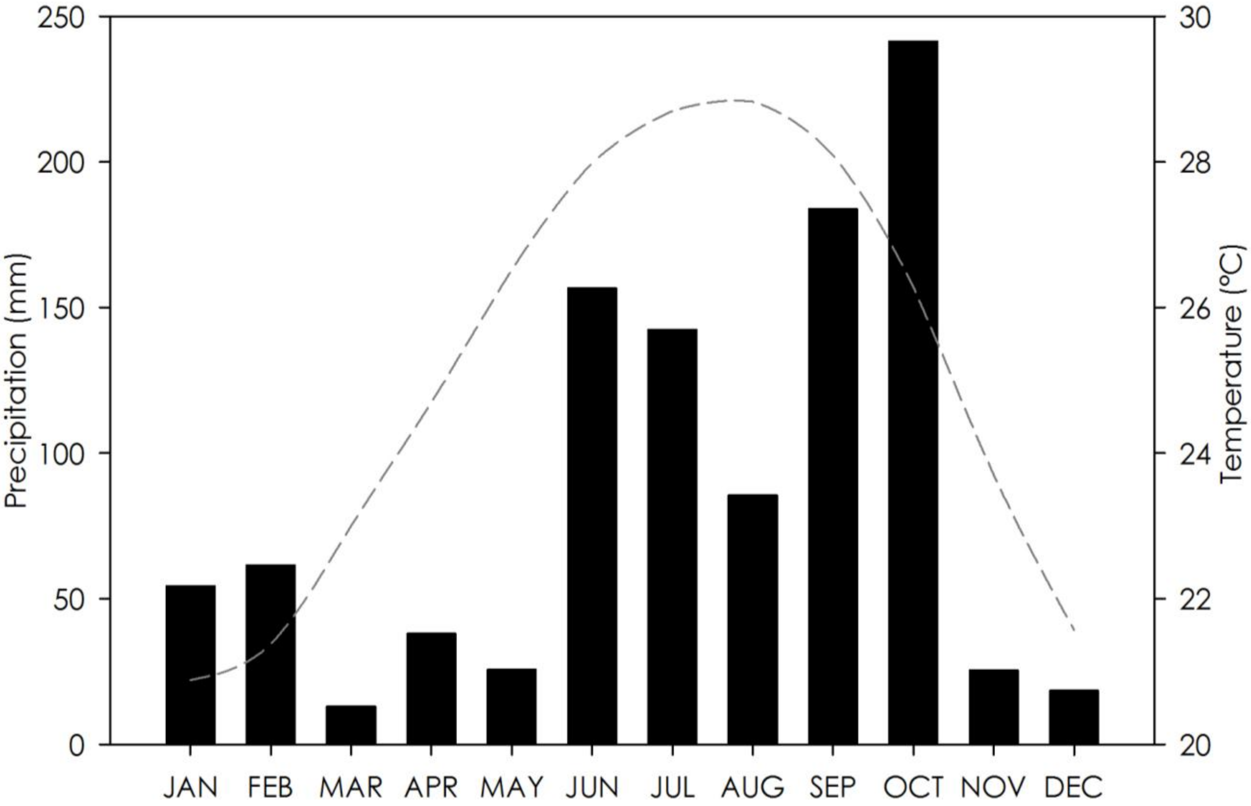

Figure 2.2. Monthly mean temperature (line) and monthly total precipitation (bars) for Florida Climate Division 7 for the period 1895–2009.

A second sampling effort in March 2010 focused on developing a long slash pine chronology for comparison with regional climate variables. A total of 60 slash pine core samples (from 23 trees) were collected from NBP. The cores were taken with a 5.15 mm diameter Haglof increment borer, with 2–4 radii extracted from each tree. Because of the Hurricane Wilma storm surge in 2005, only 23 living trees existed at NBP, all of which had no visible fire injuries. Four radii were necessary on larger trees because the growth rings of older slash pine display poor circuit uniformity. Tree diameters at breast height ranged from 11.7 to 31.5 cm, and increment cores were extracted at 30 cm above ground level.

2.3.3 Laboratory methods

Cores and cross sections were dried then mounted (Stokes and Smiley 1996), then sanded using progressively finer sandpaper, beginning with ANSI 100-grit (125–149 µm) and ending with ANSI 400-grit (20.6–23.6 µm) (Orvis and Grissino-Mayer 2002). The NBP samples were scanned with a high-resolution digital scanner (EPSON, Expression 10000XL) at 1200 dpi and measured and visually crossdated using the WinDENDRO ™ system (version 2009C, Canada). Visual crossdating was confirmed statistically with COFECHA (Holmes 1983; Grissino-Mayer 2001). We used the computer program ARSTAN to standardize tree-ring series to remove the age trend and to minimize effects of autocorrelation in the time series (Cook 1985). Each tree-ring series was detrended with fitted negative exponential curves. Three types of index chronologies were created using the program ARSTAN: standard, residual, and ARSTAN. To determine which chronology best suited our study, we conducted a preliminary correlation analysis between climatic variables (monthly temperature and precipitation from Florida Climate Division 7) and each index chronology. All three index chronologies returned similar results such that the interpretation of the influences of regional climate on tree growth was the same for all chronologies (e.g. Gou et al. 2007). The ARSTAN (ARS) chronology, however, showed the highest correlations between tree growth and climatic variables and therefore was used in all further analyses.

2.3.4 Influences of regional climate on tree growth

To assess the relationship between climate and radial growth of slash pine, we compared the NBP chronology to regional climate data. National Oceanic and Atmospheric Administration (NOAA) divisional data average observations from all climate stations within each division of a state and assign equal weight to each station so that divisional data reduce the effects of micro-site climate variation. We selected monthly mean temperature and monthly total precipitation as variables for analysis. Temperature and precipitation data were obtained for the period 1895–2009 from the National Climatic Data Center (NOAA 2010) for Florida Climate Division 7, which includes the southernmost portion of the peninsula.

Broad-scale atmospheric and oceanic oscillations (such as the El Niño-Southern Oscillation (ENSO) and Atlantic Multidecadal Oscillation (AMO)) can have an effect on the climate of South Florida (Ropelewski and Halpert 1986, 1996; Enfield et al. 2001; Schmidt et al. 2001; Beckage et al. 2003; Laing et al. 2008). ENSO cycles are characterized by alternating periods of warm (El Niño) and cold (La Niña) sea surface temperatures in the central and eastern Pacific and occur with a periodicity of three to seven years (Tudhope et al. 2001). In general, winters in the southeastern United States are cooler and wetter during El Niño periods and warmer and drier during La Niña periods (Ropelewski and Halpert 1986, 1996).

However, because of the latitudinal extent of Florida, the southernmost regions and the rest of the state experience different effects of ENSO (Ropelewski and Halpert 1986, 1996; Laing et al. 2008). In the Everglades of South Florida, Beckage et al. (2003) found that the La Niña phase was correlated with increased winter precipitation and surface water levels. In contrast, the El Niño phase was associated with decreased winter precipitation and surface water levels.

The AMO is a 65–80 year cycle of changes in sea surface temperature anomalies (SSTAs) in the North Atlantic Ocean (Gray et al. 2004). This oscillation is characterized by alternating warm and cool phases, each lasting 20–40 years. Warm AMO phases generally coincide with increased precipitation in Florida and decreased precipitation in the rest of the continental United States. Cool AMO phases correspond with decreased precipitation (drought conditions) in Florida and increased precipitation elsewhere in the U.S. (Enfield et al. 2001).

To determine the effects that ENSO and AMO cycles may have on tree growth in the Lower Florida Keys, we compared the NBP chronology with (1) ENSO: mean monthly SSTAs from the Niño-3.4 Region, east central Tropical Pacific (5° N–5° S, 170–120° W), available from 1871 to 2007 (Trenberth and Stephaniak 2000); and (2) AMO: North Atlantic SSTAs, based on a 5° latitude by 5° longitude global SST grid, unsmoothed, available from 1856 to 2009 (Kaplan et al. 1998).

2.3.5 Response function and correlation analysis

We used response function (RFA) and correlation analysis to examine how regional climatic variables (monthly mean temperature and monthly total precipitation) influence radial growth of slash pine (Fritts *et al*. 1971; Fritts and Xiangding 1986). RFA is a multiple regression technique that estimates indexed values of ring-width using the principal components of monthly climatic data. Correlation analysis produced coefficients that were univariate estimates of Pearson's product-moment correlation (Biondi and Waikul 2004). Similar to the response functions, correlation coefficients were calculated with bootstrapped confidence intervals to reduce potential error and obtain more accurate results (Biondi 1997). We conducted these analyses using climate variables covering a 23-month period (February of the previous year to December of the current year of radial growth). This period was selected because conditions during the previous and current year growing season can affect the amount of carbon fixed and allocated to tree growth (Grissino-Mayer and Butler 1993; Foster and Brooks 2001). Response function and correlation coefficients were produced using the program DENDROCLIM2002, which uses bootstrapping to yield more accurate confidence levels (Biondi 1997; Biondi and Waikul 2004). Coefficients that equaled or exceeded the 95% confidence level were identified by the program. To determine the influence that cycles of ENSO and AMO have on tree growth, correlation coefficients were produced using DENDROCLIM2002.

2.4 Results

2.4.1 Growth ring anatomy of slash pine

In the Lower Florida Keys, slash pine forms anatomically distinct growth rings (Figure 2.3). The growth ring boundaries contain tracheid cells that have thicker cell walls and smaller cell lumen, similar to the latewood cells of the other southern yellow pines (*e.g. Pinus elliottii* Engelm. var. *elliottii, Pinus palustris* Mill.*, Pinus echinata* Mill.*, Pinus taeda* L.). The latewood zone in growth rings occurs when earlywood cells with thin cell walls rapidly transition to latewood cells with thick cell walls. Often, variations in cell dimensions within annual growth rings, generally in the later portions of earlywood zones, occur in which a thin band of tracheid cells with thicker cell walls forms. These variations are numerous and give the appearance of a false ring, but these were easily identified by the gradual transition from latewood to earlywood cells as described by Speer (2010).

2.4.2 Annual ring assessment and chronology development

Samples from NBP demonstrate that the anatomically distinct growth rings formed by slash pine are annual. First, our ring count on samples that contain the 1988 fire scar and then experienced mortality shortly after the 2005 Hurricane Wilma storm surge reveal that these individuals formed a single and explicit growth ring each year from 1988 to 2006/2007 (Table 2.1). Furthermore, we were able to successfully crossdate tree rings from both increment cores and sections from NBP and develop a tree-ring chronology for this site (Figure 2.4). Of the 60 slash pine tree cores that were collected, 24 cores from eight trees could not be crossdated with the master chronology (60% success rate). Fifteen of the 36 fire-scarred cross sections collected from NBP were crossdated against the master chronology, although this process is ongoing and we expect to eventually crossdate tree rings from most cross sections. The 53 dated series (from 31 trees) from NBP produced a 139-year chronology (1871–2009) with a high interseries correlation (0.52) and mean sensitivity (0.39), and only 13 segments were flagged by COFECHA as problematic (8%; Table 2.2). Among the crossdated trees, five distinct marker years were prominent: 1892, 1916, 1942, 1992, and 2003. All five were > 2 standard deviations narrower than the mean ring-width value. Overall, most series

Table 2.1. Ring count results for NBP samples from the most recent fire date at the site (1988; Bergh and Wisby 1996) to the tree death date (2006 or 2007; Morkill 2009).

Sample ID	Most recent fire date	Outermost ring	# rings between fire scar and outermost ring
NBP501	1988	2006	18
NBP503	1988	2007	19
NBP514	1988	2006	18
NBP515	1988	2006	18
NBP516	1988	2006	18
NBP531	1988	2007	19
NBP534	1988	2006	18
NBP538	1988	2006	18
NBP543	1988	2007	19

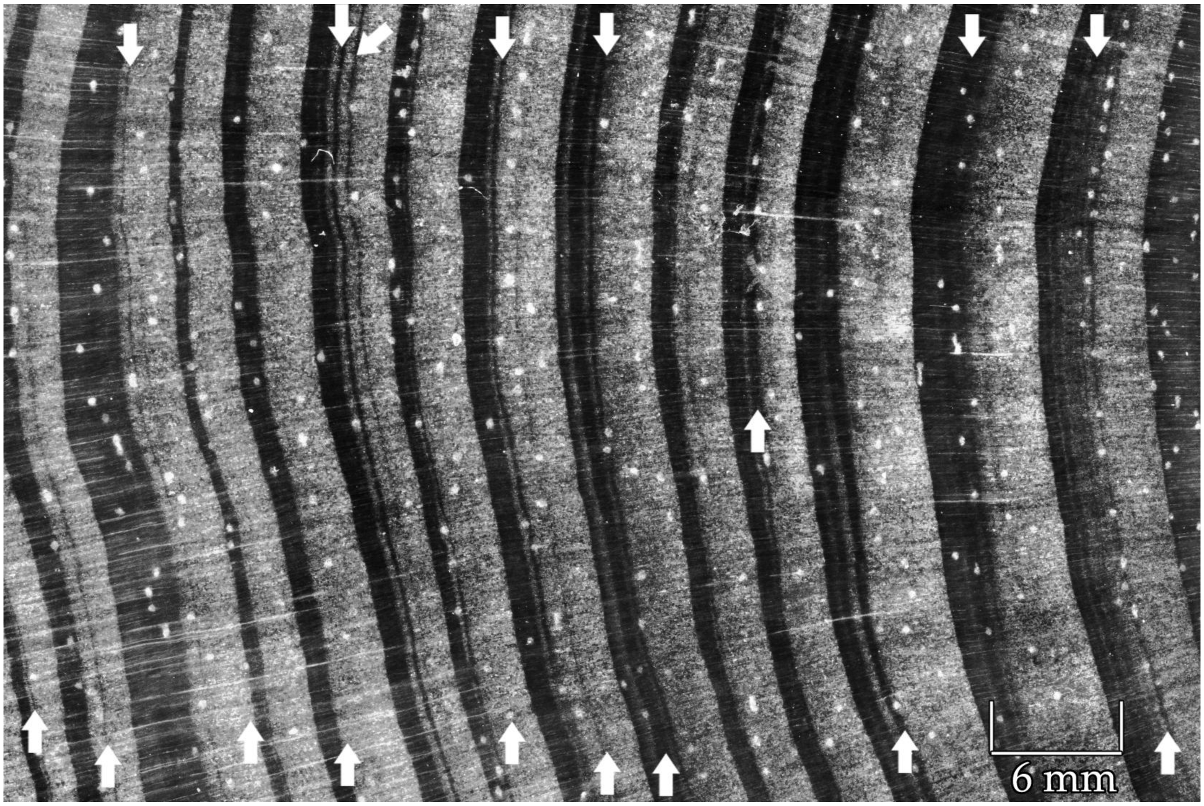

Figure 2.3. Annual growth rings in slash pine (cross section). In many growth rings, a false ring occurred in the late portion of earlywood growth (shown by arrows).

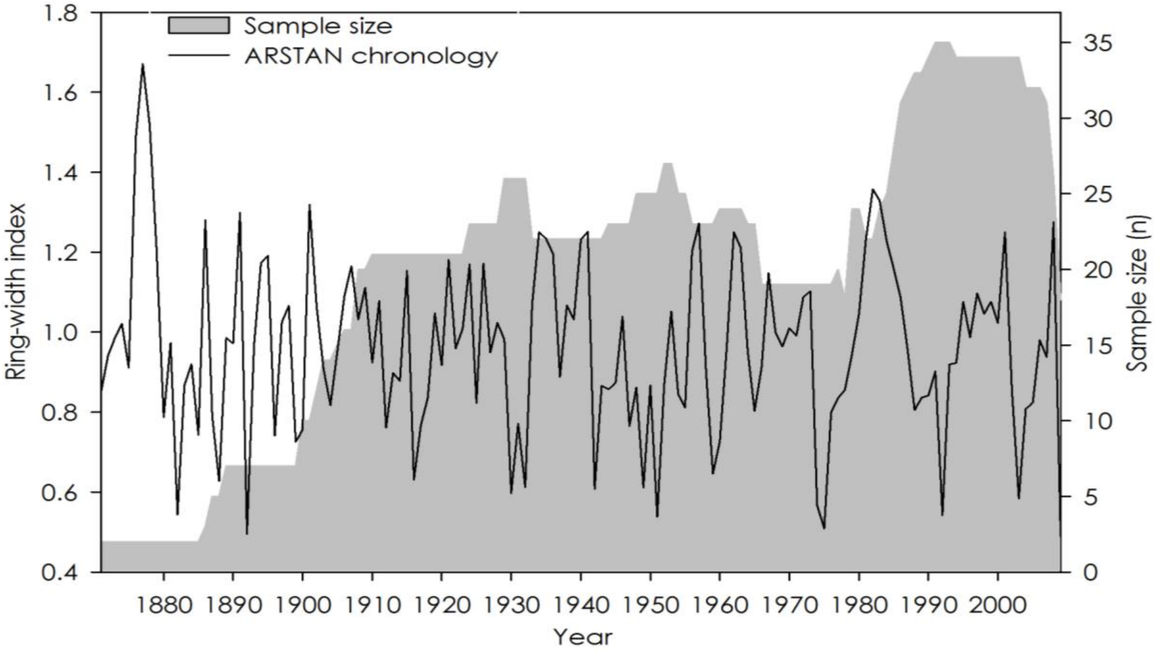

Figure 2.4. ARSTAN chronology and sample depth for slash pine from the NBP site on Big Pine Key.

did not contain locally absent rings, although the 1943 growth ring was missing in several series.

2.4.3 Influence of climatic variables on tree growth

The slash pine chronology from NBP correlated with climate data from Florida Climate Division 7, indicating that regional climate influences radial growth. Annual growth of slash pine at NBP is primarily influenced by precipitation and available moisture during the growing season. RFA indicated that radial growth at NBP responded positively to current September precipitation and negatively to both previous November and current September temperature (Figure 2.5).

Correlation analysis between monthly mean temperature and the NBP chronology resulted in significant negative correlations between radial growth and current September and previous September and November temperature (Figure 2.5). We also found a significant negative correlation with current May precipitation and a significant positive correlation with current September precipitation. The comparison between the NBP chronology and the Niño 3.4 and AMO indices (not shown) showed a weak response of tree growth to North Atlantic conditions and no relationship with ENSO in slash pine. The NBP chronology is significantly and positively correlated with the AMO index only during current April, but the association is quite weak ($r = 0.17$, $p < 0.05$).

Table 2.2. Descriptive statistics from COFECHA for NBP (1871–2009).

Number of trees	32
Number of dated series [1]	53
Master series time span (yrs)	139
Total rings	2747
Interseries correlation [2]	0.520
Mean sensitivity [3]	0.399
Chronology start date [4]	1886
Percent flags [5]	12

[1] Dated series are individual radii that were crossdated

[2] Interseries correlation is a measure of the stand-level signal

[3] Mean sensitivity is a measure of the year-to-year ring-width variability in the master chronology

[4] Chronology year with 2 or more dated series

[5] Flags represent a segment of a dated series that contains possible problem

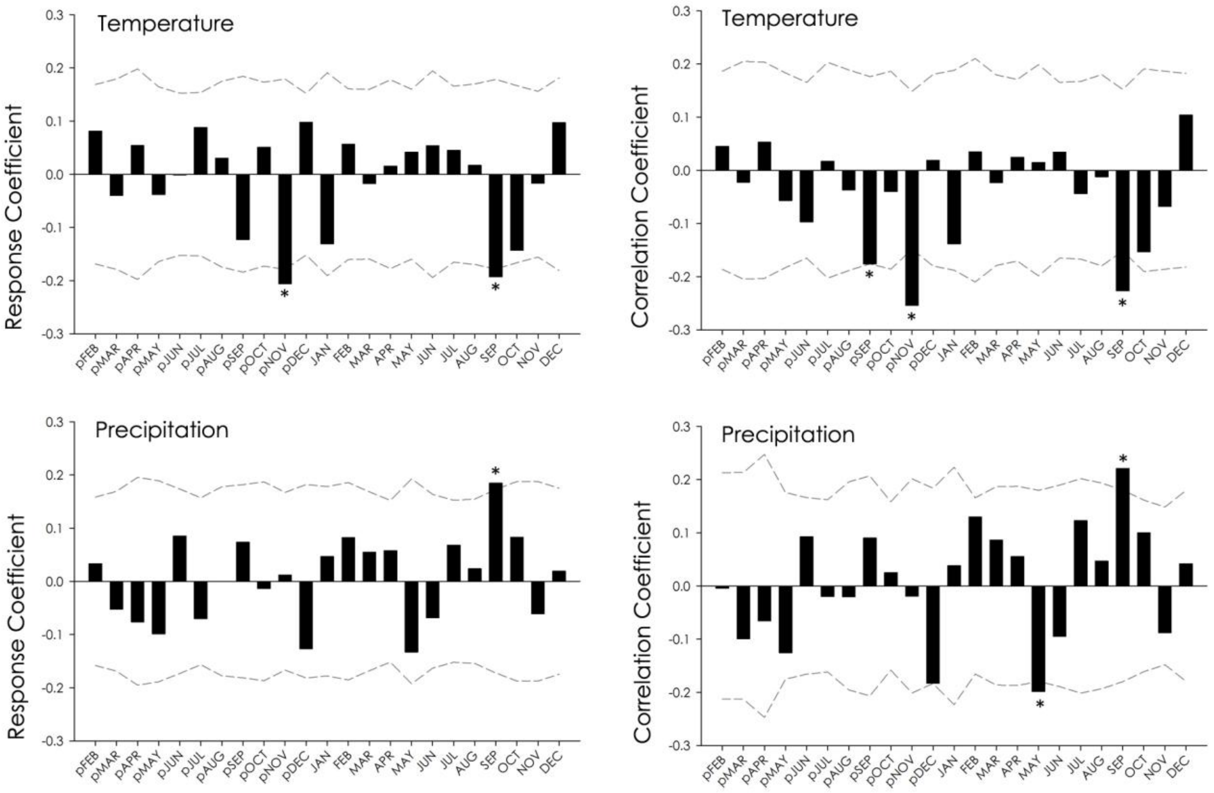

Figure 2.5. Annual growth response to monthly mean temperature and monthly total precipitation for the NBP chronology from previous February (pFEB) to current December (DEC) for the period 1895–2009. Response coefficients between NBP and climatic variables are shown in the left column and correlation coefficients are shown in the right column. Dashed lines indicate 95% confidence limits and asterisks indicate statistically significant months.

2.5 Discussion

The foundation species slash pine provides an opportunity to investigate the historical variation in regional climate and vegetation dynamics of pine rockland communities in the Lower Florida Keys. The presence of anatomically distinct and annual growth rings, high-quality crossdating (as shown by a high interseries correlation), and statistically significant correlations and RFA coefficients with climate makes slash pine a useful candidate for dendrochronological, ecological, and biogeographical studies in southern Florida. Langdon (1963) and Tomlinson and Craighead (1972) suggested that slash pine forms annual rings, but ours is the first study to confirm the annual nature of its growth rings, assess its crossdating potential, develop a chronology, and identify statistically significant relationships between radial growth and climate at its southern range limit.

Although slash pine produces annual rings, crossdating was challenging. False rings were problematic in many samples, as were a few locally absent growth rings. Five cross sections contained locally absent rings that occurred after the very narrow 1942 growth ring. This suggests that a long-term physiological growth decline in slash pine, ultimately resulting in an absence of xylogenesis during 1943, may have been initiated by adverse environmental conditions the previous year. False rings generally occurred just before the earlywood/latewood transition zone, suggesting that unusually low rainfall during earlywood growth might cause individuals to prematurely form tracheids with thicker cell walls, causing a false ring to appear before the formation of latewood cells.

Response function and correlation analysis revealed significant relationships between radial growth and precipitation and indicate that annual growth of slash pine at the NBP site is primarily influenced by water availability during the growing season. This corroborates the findings of Ford and Brooks (2003), who found slash pine at its northern range limit in central Florida to be sensitive to water availability during times of high demand. RFA indicated that previous November and current September temperature and current September precipitation are the most important predictors of radial growth at NBP. The response functions between tree growth and climatic variables suggests that warmer temperatures towards the end of the growing season result in less radial growth, likely due to increased moisture stress from higher temperatures. Additionally, increased late-season rainfall during September results in prolonged growth before dormancy occurs, thus producing a wider than average growth ring. Significant negative correlations between tree growth and late summer temperatures and May precipitation also support the argument that these relationships are likely a signal of moisture stress, as higher temperatures result in higher rates of evapotranspiration.

We did not find significant results between tree growth and the Palmer drought indices (Palmer Drought Severity Index (PDSI) and Palmer Hydrological Drought

Index (PHDI)). This was not a surprising result for several reasons. First, the closest PDSI grid point to the NBP chronology is located in central Florida (82.5° W, 27.5° N; Cook et al. 2004). The highly variable weather experienced from mainland Florida southward to the Lower Florida Keys might explain the lack of statistically significant response of slash pine to PDSI and PHDI (Winsberg 2003). Second, the Palmer drought indices are derived from measurements of precipitation, air temperature, and local soil moisture. The poor to non-existent soil development on Big Pine Key might also partly explain the lack of result.

The lack of a statistically significant response of slash pine to AMO was unexpected because the geographic proximity of our site to the influence of this oscillation suggested a significant climate response would be found. Our site is located on a small (25.8 km^2) island. Surrounded by vast expanses of ocean (tropical Atlantic to the east and Gulf of Mexico to the west), trees at the NBP site were strong candidates for picking up a signal from the North Atlantic ocean-atmospheric oscillations. Warm phases of the AMO correspond with increased precipitation and increased landfalling tropical storms in southern Florida. However, the response likely was instead manifest in the positive correlation and RFA coefficients found with September precipitation. On the other hand, ENSO SSTAs usually reach their peak and maximum aerial extent in the tropical Pacific during the winter months (Laing et al. 2008). Our RFA indicated that winter precipitation (December–February) is not an important component of annual tree growth, so the lack of an ENSO signal in the NBP pines is understandable.

Interpreting relationships between regional climate and tree growth at the NBP site, however, is limited by the lack of detailed information regarding the phenological properties of slash pine, such as when cambial reactivation, earlywood growth, latewood growth, and dormancy occur, and which environmental factors cause these changes in xylogenesis. These data are needed before more detailed interpretations of climate-tree growth relationships can be made. Consequently, we have initiated a long-term study on Big Pine Key aimed at providing detailed phenological data that will help further define the length of the growing season and determine which climate factors cause slash pine to form false and locally absent growth rings. This study will examine growth of six pines on a biweekly to monthly basis by extracting and preserving small punch cores and observing the amount and types of cells produced between intervals.

2.6 Conclusions

Tree-ring analysis in Florida has primarily been limited to species located in central–northern regions of the state (Foster and Brooks 2001; Ford and Brooks 2002, 2003; Henderson *et al*. 2009). The majority of tree species in South Florida fail to produce annual rings (Tomlinson and Craighead 1972), yet our research demonstrates that slash pine is a species of dendrochronological value. Multidecadal, and possibly multi-centennial, chronologies can be developed and used to provide more detailed information regarding the structure and dynamics of endangered pine rockland communities and how disturbance regimes (*e.g.* hurricanes and wildfires) have shaped the current distribution of slash pine in the Lower Florida Keys. Furthermore, slash pine is the southernmost pine species in the United States and the only pine to inhabit the lower third of peninsular Florida (Little and Dorman 1954). Because slash pine in the Lower Florida Keys exists at its southern range limit, the species could prove vital for understanding the possible effects of future climate change on range distributions of species in habitats that could be especially vulnerable to increasing global temperatures. The expected higher temperatures could reduce growth rates of these pines as indicated by the correlation and RFA results, leading to moisture stress that could lead to increased mortality of pines that survived the effects of Hurricane Wilma. Warmer temperatures, rising seas levels, and increased incidence of salt-water intrusion may render other studies of slash pine in the Lower Florida Keys impossible, creating the need for a better understanding of pine rockland dynamics while they still exist.

2.7 Acknowledgements

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Chapter 3

Cambial Activity of *Pinus elliottii* var. *densa* Reveals Influence of Seasonal Insolation on Growth Dynamics in the Florida Keys

Chapter 3

Cambial Activity of *Pinus elliottii* var. *densa* Reveals Influence of Seasonal Insolation on Growth Dynamics in the Florida Keys

This chapter represents a slightly revised version of a manuscript that was accepted for publication by a peer-reviewed journal as: Grant L. Harley, Henri D. Grissino-Mayer, Jennifer A. Franklin, Chad Anderson, and Nesibe Köse (2012). Cambial activity of *Pinus elliottii* var. *densa* reveals influence of seasonal insolation on growth dynamics in the Florida Keys. *Trees–Structure and Function,* In Press. The final publication is available at springerlink.com. The revisions follow suggestions made by members of my dissertation committee. The use of "we" in this chapter refers to my co-authors and myself. As the first author, I was lead on designing the study, obtaining the data, performing analyses, and writing the manuscript.

3.1 Abstract

We determined the temporal and seasonal dynamics of intra-annual cell formation of south Florida slash pine (*Pinus elliottii* Engelm. var. *densa* Little & Dor.), the southernmost native pine in the United States and the foundation species of globally endangered pine rockland ecosystems. To assess intra-annual cambial activity and identify possible relationships between cell production and climatic factors, wood micro-cores were extracted monthly from six trees during the period March 2010 to March 2011. The results confirmed annual growth ring formation in *P. elliottii* var. *densa* and indicated that its growing season extends from February to December, with a short period of dormancy that varied little between individuals. Within the growing season, earlywood cells were produced from February to July and latewood cells were produced from July to December. Intra-annual density fluctuations (IADFs) occurred in

the growth rings of four of six trees between July and August. A principal component analysis indicated a homogeneous response of cambial activity among trees to site-specific climatic factors. The first principal component axis explained 71% of the total variance in cell production during the study period. Our results indicated that the dynamics of seasonal cambial activity of *P. elliottii* var. *densa* are controlled by solar radiation ($r = 0.51$, $p < 0.10$) in the Florida Keys. The nature of our data allow us to only speculate on the ecophysiological processes responsible for IADFs in *P. elliottii* var. *densa*, and additional research is needed to better understand the relationship between their formation and the environment in the Lower Florida Keys.

3.2 Introduction

The science of dendrochronology has traditionally been restricted to temperate regions, where the majority of tree species produce a single and explicit growth ring each year in response to seasonal changes in temperature or precipitation (Speer et al. 2004, Speer 2010). However, a recent surge of dendrochronology into the tropics and subtropics continues to reveal the occurrence of annual growth rings in areas previously thought unsuitable for the science (Speer et al. 2004; Brienen and Zuidema 2006; Buckley et al. 2007; Baker et al. 2008). Tree-ring records from these areas are important because the tropics are the center of action for many broad-scale climate phenomena (*e.g.* El Niño-Southern Oscillation; D’Arrigo et al. 2006) and these data provide rare opportunities for understanding the ecological dynamics of tropical and subtropical communities (Brienen et al. 2009). Because dendrochronology relies on precise tree-ring dating procedures to ensure that each growth ring is correctly assigned to the exact calendar year in which it formed, new dendrochronological studies in the tropics and subtropics should first verify the annual nature of cambial activity and investigate climatic triggers responsible for this phenomenon. Intra-annual cambial activity data provide a greater confidence in the growth ring chronologies that are developed for these areas (Stahle 1999; Worbes 1995, 2002).

South Florida slash pine (*Pinus elliottii* Engelm. var. *densa* Little & Dor.; hereafter slash pine) is the southernmost native and the only subtropical pine in the United States (Little and Dorman 1954). The native range of slash pine is limited to the southern half of peninsular Florida, with a few small disjunct populations located in the Lower Florida Keys (LFK). We recently discovered that slash pine produces consistently annual growth rings in the LFK and can be a useful species for various dendrochronological applications (Harley et al. 2011). However, little is known about the seasonal wood formation dynamics of the species (*e.g.* timing of cambial reactivation, dormancy, earlywood formation, and latewood formation) or what climatic factors are responsible for variations in intra-annual radial growth. A better understanding of the intra-annual radial growth of slash pine not only contributes to a deeper knowledge of its growth dynamics, but also has ecological and climatic implications. As the foundation species for globally-endangered pine rockland communities, the ecological status of slash pine is important for the long-term persistence of these communities. Furthermore, slash pines in the LFK are uniquely positioned between the Gulf of Mexico and Atlantic Ocean, and could possibly reveal long-term ocean-climate interactions as well as hurricane activity.

In the LFK, slash pine forms anatomically distinct growth rings with boundaries marked by tracheid cells that have thicker cell walls and small cell lumens, similar to the latewood cells of the other southern yellow pines (*e.g. Pinus elliottii* Engelm. var. *elliottii*, *Pinus palustris* Mill., *Pinus echinata* Mill., *Pinus taeda* L.) (Harley et al. 2011). Previous investigations provided evidence in support for the formation of annual growth rings in slash pine located in south Florida. By measuring the incremental radial growth of 10 mature trees near Naples, Florida (26° 24′ N, 81° 36′ W) during the period 1956–1959, Langdon (1963) found that the first spring flush of growth occurred in early February, and 37% of the annual growth occurred from February to April, 35% from May to August, 25% from September to November, and 3% from December to January (no dormancy period). Diameter growth had two peaks; one in spring, centered on March, and another in the fall, centered on September. Langdon found that the 10-month period during which most radial growth occurred (February to November) contributed to a high percentage of latewood and therefore high wood density. The specific gravity of slash pine is 0.845 (Olson 1952), the highest of all pine species in the United States (Forest Products Laboratory 1974). He further discovered that the lack of moisture during drought conditions in 1956 did not affect radial growth considerably, which he attributed to the fact that the wilting point was not reached in the lower soil depths, where he postulated moisture was still available to trees. Although his study was not conducted at the cellular scale and did not specifically correlate radial growth with climate factors, Langdon was the first to present a basic understanding of the slash pine growing season in south Florida. Because changes in diameter can also be due to shrinking and swelling of the stem as water content changes (Klepper et al. 1971), measures of diameter growth may provide an accurate estimate of cambial activity over seasons or years, but may not have a high level of precision over shorter intervals such as weeks or months.

Recently, Harley et al. (2011) described the growth ring anatomy of slash pine and provided evidence that the species forms consistently annual growth rings at its southernmost range limit in the LFK. We were able to crossdate living trees and remnant wood and developed a tree-ring chronology for the period 1871–2009. Comparisons of our tree-ring chronology to divisional climate data suggested a weak, albeit statistically significant ($p < 0.05$), relationship between annual radial growth (total ring width) and water availability during the later months of the growing season. Correlation analysis produced significant negative correlations between radial growth and current September and previous September and November temperature, and a significant positive correlation with current September precipitation. The weak inter-annual climate signal found in slash pine indicated the need to better understand the influences of climate on intra-annual radial growth.

Despite several indications of seasonal cambial activity in slash pine (Langdon 1963; Harley et al. 2011), the timing and climatic factors responsible for the occurrence of anatomically distinct growth rings are unclear. In this study, we use anatomical evidence to examine the timing of growth ring formation in slash pine, and investigate relationships between climatic variables and intra-annual xylem differentiation at the southernmost distribution limit of this species during the period March 2010–March 2011.

3.3 Methods

3.3.1 Ecological setting

The island of Big Pine Key (24° 42′ N, 81° 22′ W) contains the largest contiguous area (920 ha) of pine rockland habitat that remains at the southernmost extent of its range in the United States (Figure 3.1). Slash pine stands are characterized by a monospecific overstory, a diverse subcanopy of West Indian shrubs and palms, and a variety of endemic herbs (Sah et al. 2004). The pine rocklands on Big Pine Key are located within the National Key Deer Refuge (NKDR), which is managed by the United States Fish and Wildlife Service (USFWS).

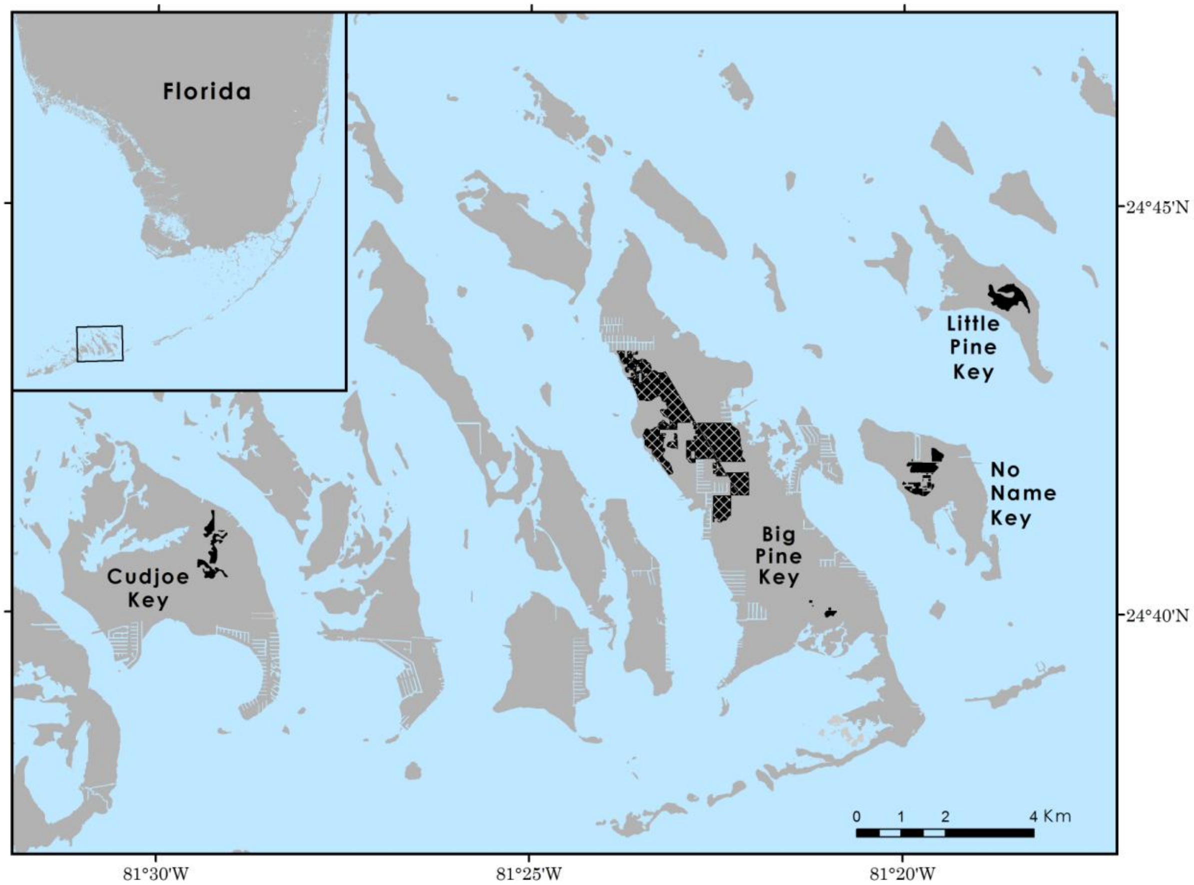

Figure 3.1. Map of current pine rockland distribution (black) and study site location (hatched area) in the National Key Deer Refuge, Lower Florida Keys, USA.

During the period 1895–2011, the tropical savanna climate of the LFK was characterized by hot summers (average maximum August temperature < 32 °C), cool winters (average minimum January temperature > 19 °C), and summer-wet, winter-dry seasons. The average annual precipitation was 980 mm, with *ca.* 70% occurring from May to November (NCDC 2011; Figure 3.2). On the rocklands, soil is thin to non-existent and Pleistocene-aged Miami limestone is exposed at the surface (Snyder et al. 1990).

3.3.2 Micro-core sampling and preparation

To better understand the annual growth patterns of slash pine in the LFK, seasonal cambial activity of slash pine was monitored for 13 months (March 2010–March 2011). Within the pine rocklands of the NKDR, six mature trees were selected and tissue samples extracted by taking shallow micro-cores (4 mm diameter and 10 mm length) containing phloem, cambium, and outer xylem with an increment hammer (Haglöf Inc., Madison, MS, USA). Monthly samples were extracted starting 15 March 2010 and occurred on day 15±2 of each subsequent month during the study period. Selected trees were approximately the same age (80 years) and were first assessed for presence of compression wood/symmetrical growth. To minimize effects of wounding and subsequent effects on our analyses, micro-cores were taken in a zigzag pattern from an area 30 cm above and below breast height (Rossi et al. 2007; Gruber et al. 2009; Begum et al. 2010), and at least 5 cm apart to avoid the interference of resin ducts on adjacent cores, which is a common reaction to disturbance in conifers (Deslauriers et al. 2003).

Samples were immediately placed in vials containing a preservative solution and stored at 5° C overnight to avoid any tissue deterioration (Rossi et al. 2007). The preservative solution contained a mixture of 1.6–2% paraformaldehyde and 2–2.5% glutaraldehyde in a 0.05 M phosphate buffer at pH 6.8 (Yeung 1999). After being fixed in preservative solution, samples were dehydrated in a graded ethanol series (70%, 80%, 90%, 100%), embedded in glycolmethacrylate (Technovit 7100), and polymerized by adding an accelerator. Transverse sections of *c.* 6 μm thickness were cut with a rotary microtome using a tungsten-carbide blade and placed on glass slides. Slides were dried at 40 °C overnight, stained with safranin (0.5% in 95% ethanol), and permanently fixed with Permount®.

3.2.3 Cell analysis

A Nikon Eclipse 800 light microscope (bright field and polarized light) and the NIS Elements image analysis system were used for observations of cells at various stages of development. On each sample, we counted the number of cells in the radial enlargement (R_e), wall thickening (W_t), and mature (M_t) phase along three radial files (Figure 3.3). The location of the cambium at the end of the previous growing season was easily identified by two to three radially flattened fusiform cells (Riding and Little 1984). Cells from both the cambial zone and in the radial enlargement phase (xylem)

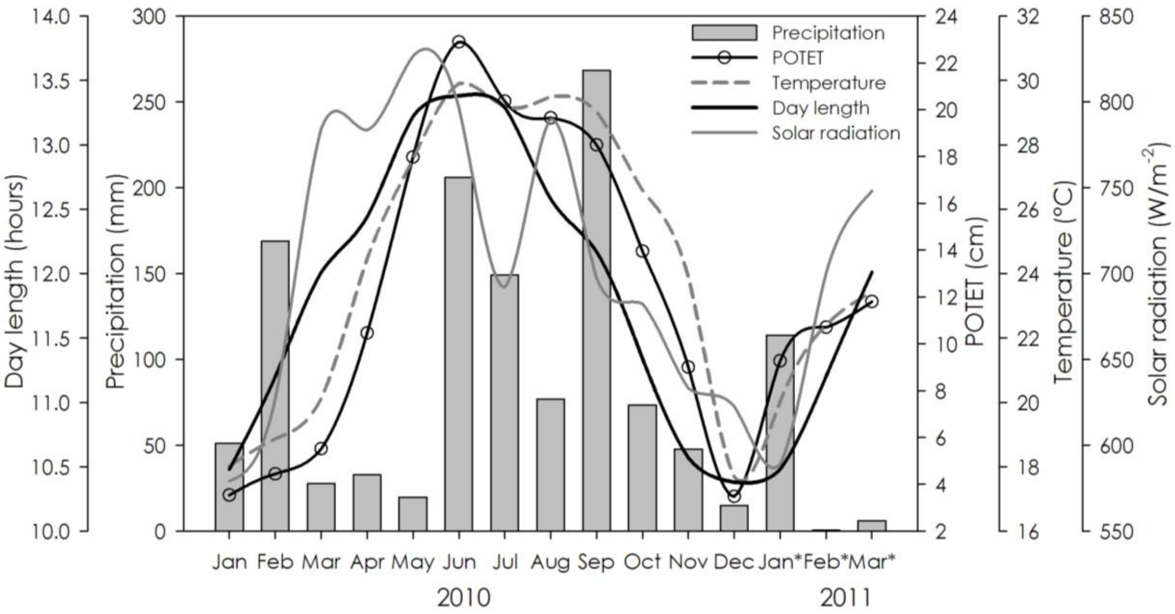

Figure 3.2. Climograph showing the average monthly day length (hours), precipitation (mm), potential evapotranspiration (POTET; cm), temperature (°C), and solar radiation (W/m^{-2}) recorded by the USFWS weather station on Big Pine Key from January 2010 to March 2011.

had thin primary walls that were light pink in color. Cells in the cambial zone and radial enlargement phase were easily identifiable and characterized by only primary walls, while tracheids in the wall thickening phase had secondary walls that displayed strong bi-refringence in polarized light (Zimmermann 1964; Riding and Little 1984). These cells changed from light pink in the beginning of the process to dark red near the mature cell state. Xylem cells were considered mature or entirely lignified when they were completely dark red (Figure 3.3). The number of cells along each of the radial files was averaged for each sample.

3.2.4 Cell standardization

Cell number varies within tree circumference and height along the stem, and thus requires standardization between samples (Creber and Chaloner 1984; Rossi et al. 2003). For each sample, the total cell number of the previous growth ring (2009) was recorded and used to correct the cell number for each month. The cell number in each *j*-sample (*i.e.* monthly throughout 2010 growing season) and by each *i*-phase (*i.e.* R_e, W_t, M_t) was corrected as follows:

$$\mathrm{nc}_{ij} = n_{ij} \times n_m / n_s$$

Here nc_{ij} is corrected cell number, n_{ij} is the counted cell number, n_m is mean cell number of the previous growth ring of all *j*-samples, and n_s is the cell number of the previous growth ring for each *j*-sample.

3.2.5 Cell production-climate relationships

Exploratory methods were used to investigate potential climatic controls on seasonal wood formation dynamics. Climatic factors influencing growth were described as monthly (from March 2010 to March 2011) series of mean day length (hours), total potential evapotranspiration (cm; calculated using Thornthwaite's method), mean solar radiation (W/m^{-2}), total precipitation (mm), and mean air temperature (°C). Day length was calculated for the study site, while microclimate data for the remaining variables were gathered from the USFWS weather station on Big Pine Key. The weather station included a sensor that recorded solar radiation (*i.e.* insolation), which was measured as the instantaneous solar energy flow received at the station. Based on initial correlations between climatic variables and individual trees, we used principal component analysis (PCA) to assess the homogeneity of intra-annual tracheid production between all six individuals. Monthly cell numbers were used to calculate principal components (PCs), such that PCs indicated the common variance in tracheid production between trees (*e.g.* Oliveira et al. 2009). To assess the possible relationships between tracheid production and climatic factors, Pearson product-moment correlation analysis (r) was used to identify relationships between PC axes and climatic variables.

3.3 Results

3.3.1 Intra-annual cambial activity

Cambial activity started prior to the first sampling on 15 March 2010 in all six trees. At that time, the average cambial zone was already six cell-layers wide and consisted of cells in the R_e and W_t phase (Figs. 4 and 5). This prevented a precise determination of cambial reactivation for the 2010 growing season. During the study period, the cambial zone consisted of 2–4 R_e cells and 1–3 W_t cells each month, and this was consistent among trees (Figure 3.4). Although the total number of tracheids produced from March 2010–March 2011 ranged from 12 to 40, the timing of radial growth was fairly consistent among trees during the study period; however, the monthly production of tracheids varied markedly during this time (i.e. high variation in cell production between months) (Figure 3.5). During 2010, the greatest variance in tracheid production occurred from June to August. As expected, when cambial activity started for the new growing season in February 2011, variance was the highest among trees.

Although the monthly and annual production of cells was highly variable between individuals, there was little variation in the timing of earlywood and latewood tracheid formation (Figure 3.5). For most trees, earlywood cells were produced from March to June. On average, we observed two rows of M_t latewood tracheids in June; therefore the earlywood/latewood transition occurred shortly before the June sampling

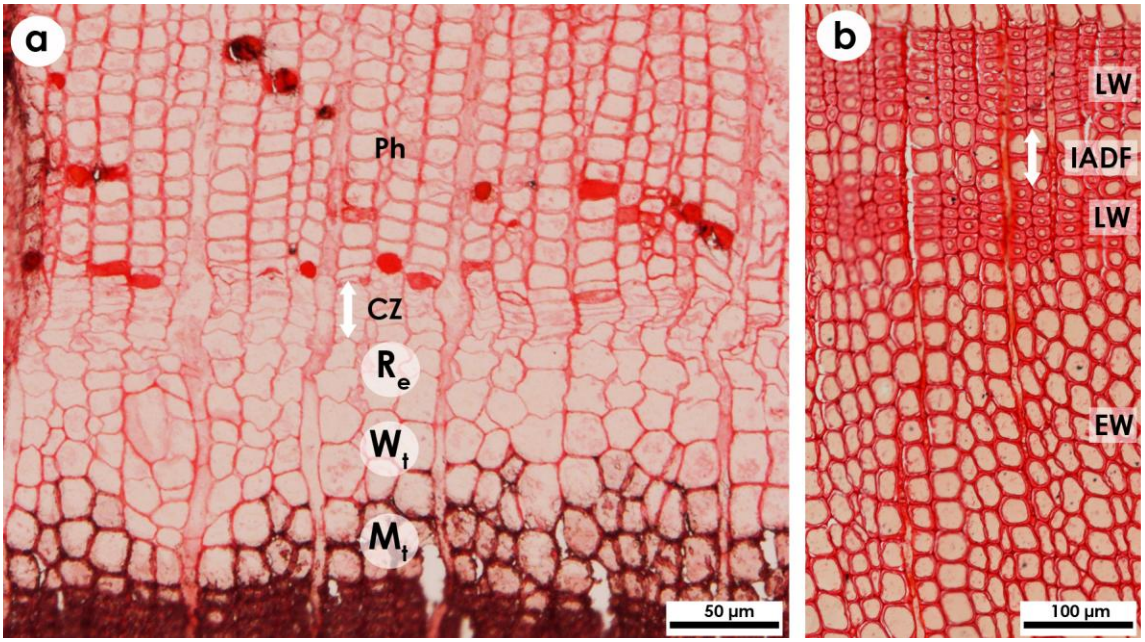

Figure 3.3. Transverse sections of samples under visible light microscopy; **a** cambial state during March 2010 showing tracheids in the mature (M_t), wall thickening (W_t), and radial enlarging (R_e) phase, cambial zone (CZ), and phloem (Ph); **b** section showing tracheid production that occurred during 2010 growing season with defined sections of earlywood (EW) and latewood (LW) tracheids and IADF that formed between July and August 2010.

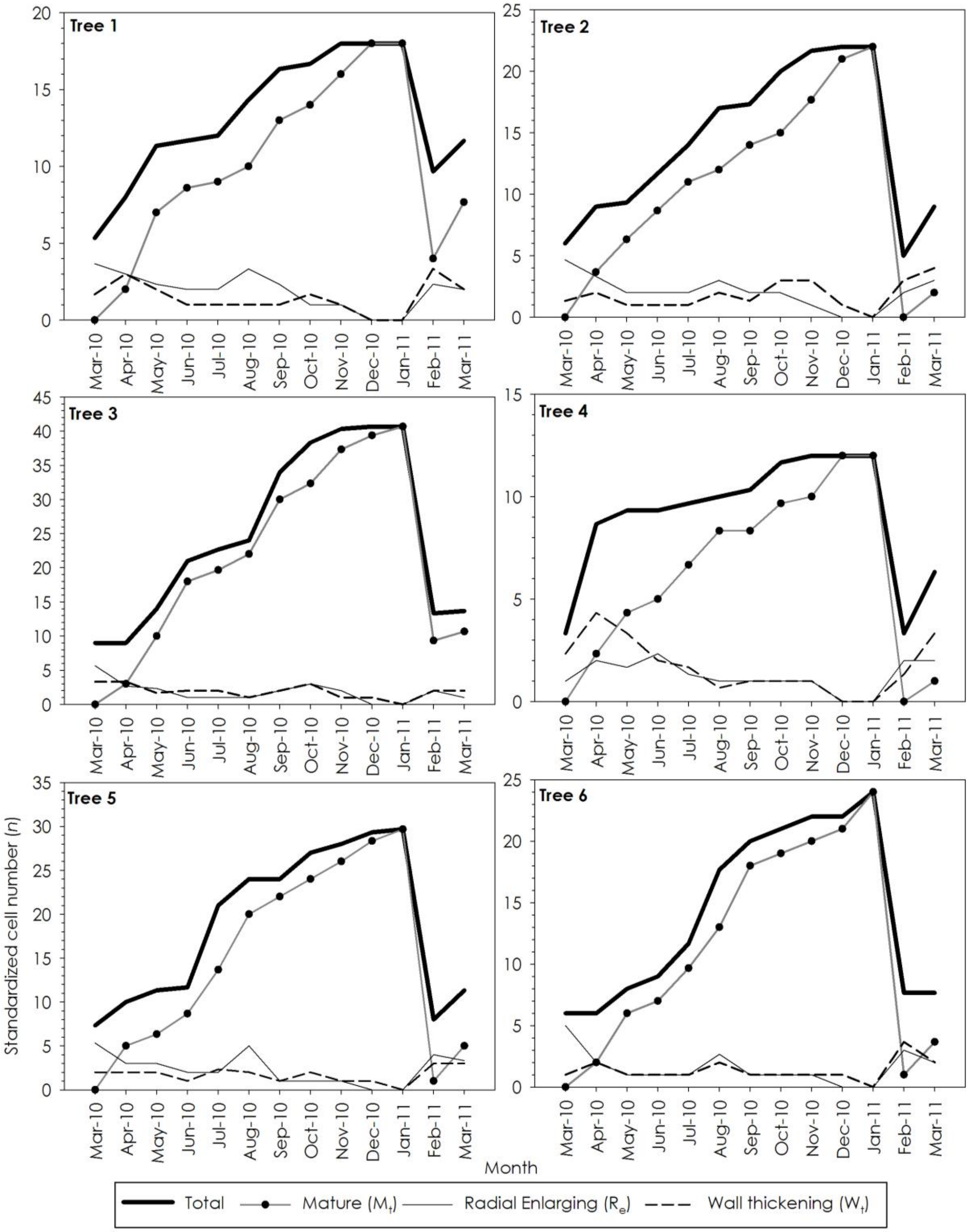

Figure 3.4. Number of cells (standardized) in radial enlargement phase, wall thickening phase, mature cells, and total number in the six sampled slash pine trees on Big Pine Key, Lower Florida Keys. Note that y-axes differ.

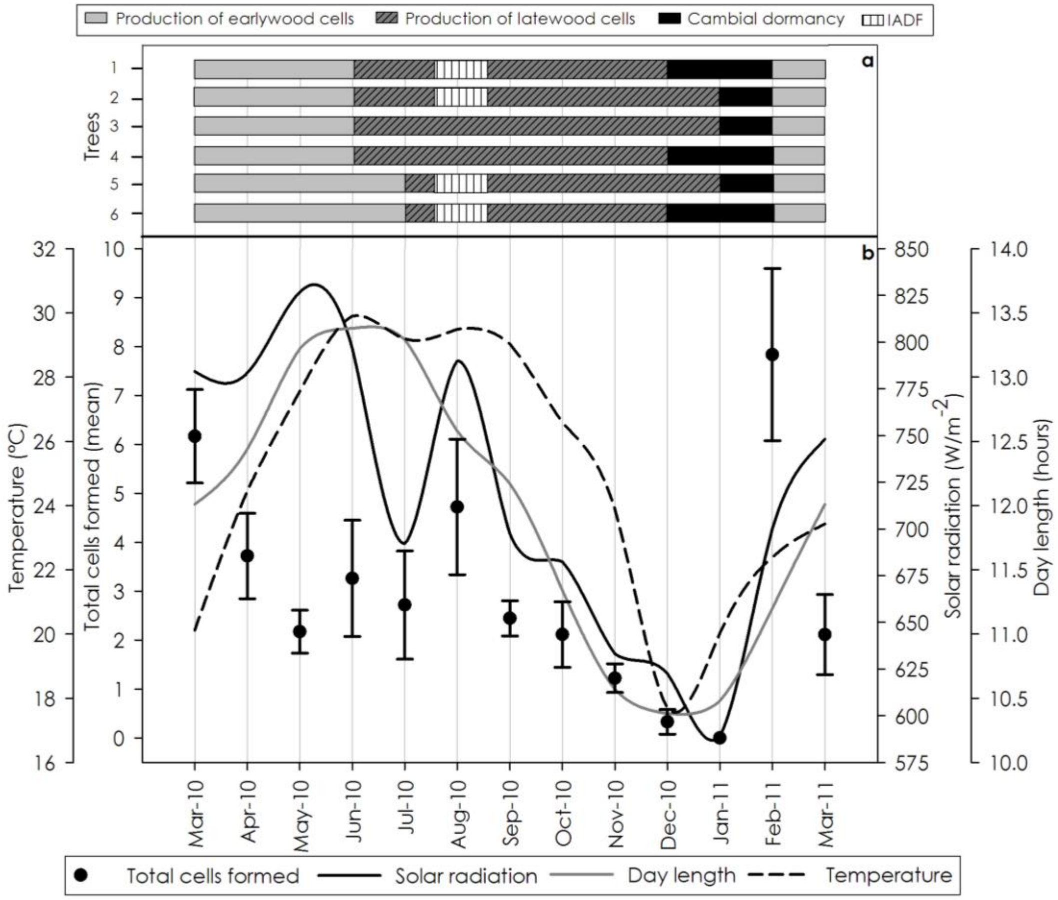

Figure 3.5. Temporal variations of cambial activity; **a** timing of earlywood-latewood production, cambial dormancy, and IADF (Intra-annual density fluctuation) formation in the six sampled trees; **b** monthly mean number of cells formed among all trees (black dots with bars) plotted with monthly mean values of temperature (°C; dashed black), solar radiation (W/m^{-2}; solid black), and day length (hours; solid gray). Bars represent variance.

effort in four trees. The earlywood/latewood transition was not observed for the remaining two trees until July. The timing of latewood tracheid production was slightly more variable among trees than earlywood production. We observed latewood cells from June/July to December for three trees, and from June/July to January for the remaining trees.

The dormant cambium consisted of 2–3 cells positioned adjacent to M_t latewood tracheids when there was no cambial activity. A dormant cambium was observed for three trees during December indicating that the radial growth of those individuals ceased sometime between our November and December sampling efforts. However, a dormant cambium was observed for all trees in January. The cambial zone was active by February 2011 in all trees, indicating that cambial reactivation occurred between our January and February sampling efforts, and the production of tracheids was highly variable at this time (Figure 3.5).

Intra-annual density fluctuations (IADFs) are a common occurrence within the annual growth rings of slash pine in the LFK, and likewise we observed them in the majority of sampled trees during the study period. IADFs consisted of radially enlarged tracheids (larger cell lumen) that were 2–4 cell layers wide and positioned within the latewood zone of the annual growth ring (Figure 3.3). More specifically, IADFs were characterized by increased production of cells in the radial enlargement phase in Trees 1, 2, 5, and 6 (Figure 3.4). The timing of IADF formation in all four trees was consistent and occurred between the July 15th and August 15th sampling efforts (Figure 3.5). We did not notice any apparent differences in total cell number, earlywood/latewood timing, or climate response between the four individuals that contained IADFs and the two without.

3.3.2 Association between cambial activity and climatic factors

PCA indicated a homogeneous response of cambial activity among trees to site-specific climatic factors. Of the six PCs, most of the common variance in tracheid production during the 2010 growing season was explained by PC_1 and PC_2 with 71% (eigenvalue = 4.23) and 18% (eigenvalue = 1.03), respectively (Table 1). We found a statistically significant positive correlation between PC_1 and mean monthly solar radiation ($r = 0.51$; $p < 0.10$; $n = 13$; Figure 3.6). A visual assessment of monthly mean solar radiation values and cell production during the study period was convincing (Figure 3.5). Cambial dormancy in all six individuals occurred during the same time as the solar minimum, suggesting that dormancy was induced by decreased levels of insolation or short day length. Furthermore, the correlation between PC_1 and day length was noteworthy ($r = 0.28$, $p > 0.10$), but not surprising, given the close relationship between solar radiation and day length throughout the year. Although not statistically significant ($p > 0.10$), the highest correlation between PC_2 and our climate variables was with POTET ($r = 0.28$). We also found statistically significant correlations ($p < 0.10$) between PC_5 and day length, precipitation, temperature, and POTET; however this axis

Table 3.1. Parameters of principal component analysis (PCA) and Pearson correlations between PC axes and site-specific climatic variables.

	PCA Parameters		Correlations with climatic variables				
	Eigenvalue	Variance explained (%)	Solar radiation	Day length	Precipitation	Temperature	POTET
PC$_1$	4.23	71	0.51*	0.28	–0.20	0.13	0.10
PC$_2$	1.08	18	0.09	0.02	0.05	0.24	0.28
PC$_3$	0.32	5	0.16	–0.16	0.08	0.05	0.00
PC$_4$	0.18	3	–0.15	–0.20	–0.14	–0.21	–0.02
PC$_5$	0.12	2	–0.40*	–0.54*	–0.56*	–0.69*	–0.74*
PC$_6$	0.07	1	–0.20	–0.11	0.01	–0.01	–0.02

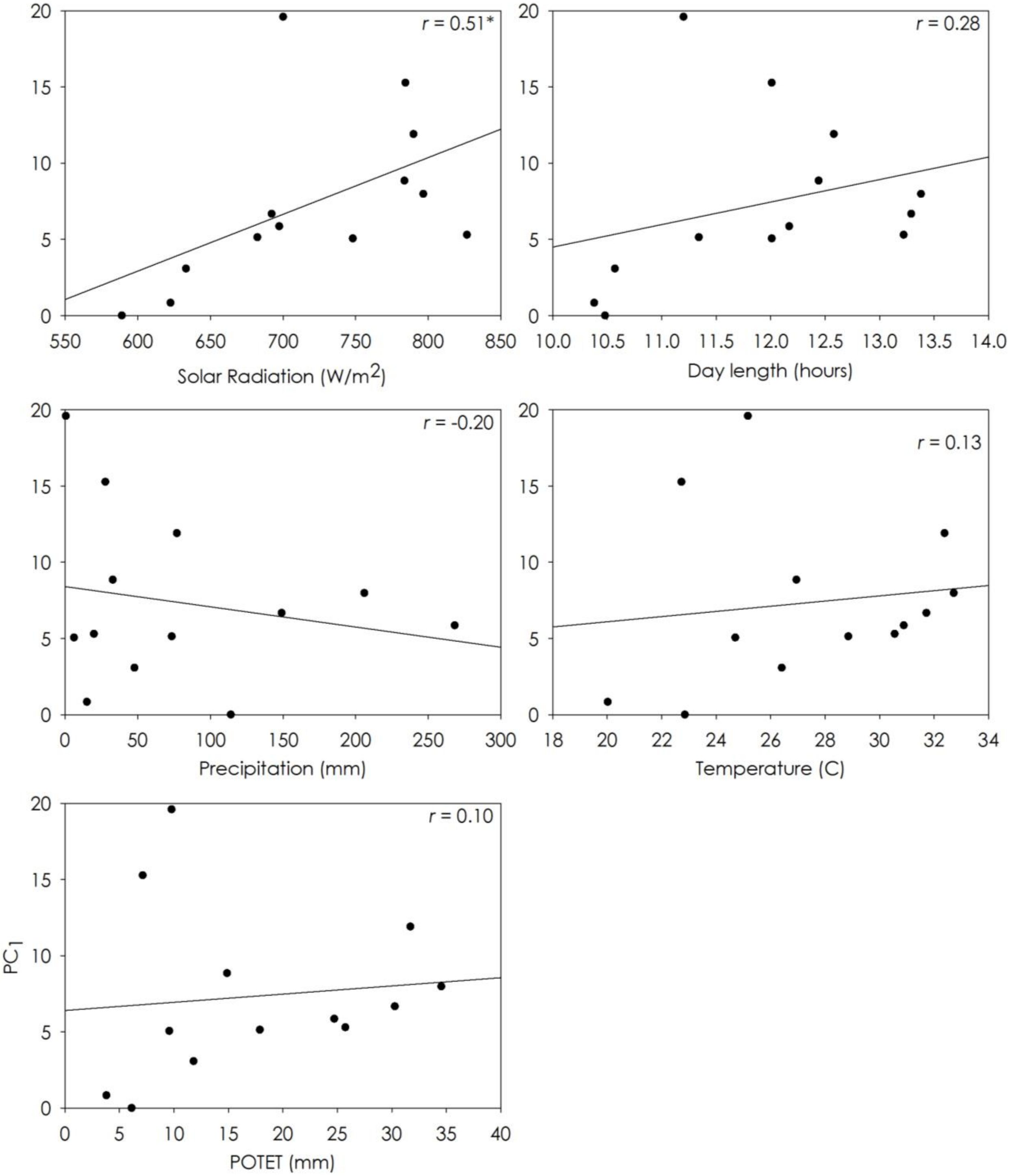

Figure 3.6. Pearson product-moment correlations between PC$_1$ (n = 6 trees) and climate parameters. *POTET* potential evapotranspiration.

explained little of the variance in tracheid production throughout the growing season (Table 1). Although our study design was not devised to specifically test the relationship between IADFs and climatic variables, there was a visual correspondence between the timing of IADFs and a period of increased solar radiation during August 2010 (Figure 3.7).

3.4 Discussion

Based on previous investigations by Langdon (1963) and Harley et al. (2011), we expected to find that slash pine forms earlywood tracheids from February to July, latewood tracheids from July to February, and the cambium has no period of rest (*e.g.* activity in the cambial zone during December and January slows considerably). Our data supported the assumption that most trees formed earlywood tracheids from March to June and then latewood tracheids until December. However, we did not expect to find that all trees experienced a period of cambial dormancy. Yet, this explains the anatomically distinct and clear boundaries, rather than diffuse boundaries, found between growth rings of slash pine at the study site.

The dendroclimatological analyses of Harley et al. (2011) revealed that inter-annual radial growth was positively correlated with current year September precipitation, indicating that increased late-season rainfall during September yields a longer growing season, thus producing a wider-than-average growth ring. We, however, found no evidence that precipitation was an important component of the

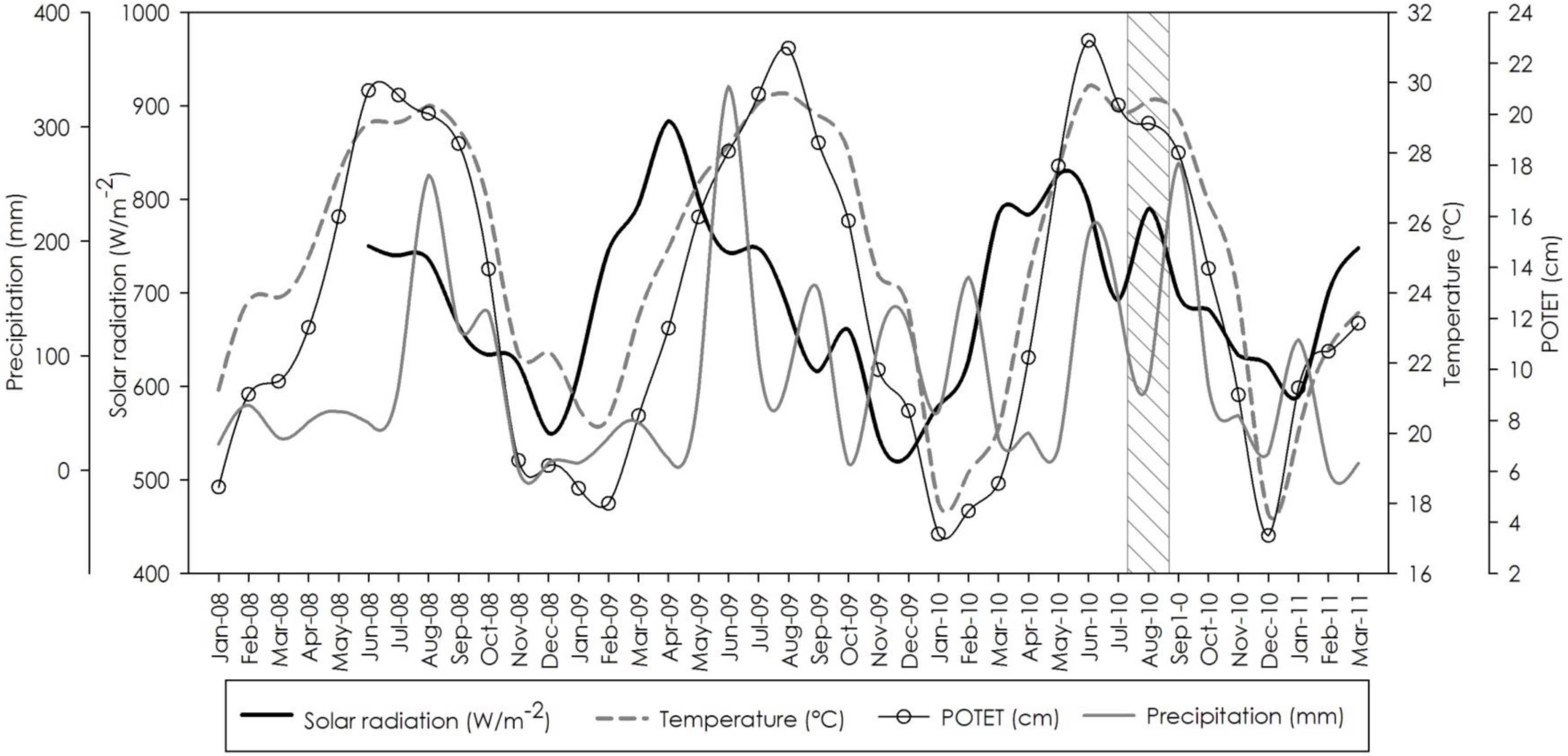

Figure 3.7. Visual correspondence between climate parameters of precipitation (mm), solar radiation (W/m^{-2}), temperature (C), and POTET (potential evapotranspiration; cm) from June 2008 to March 2011 and IADFs that occurred in four of six trees (grey hashed bar).

intra-annual growth dynamics of slash pine in the LFK. The difference in results might be explained by that fact that Harley et al. (2011) tested the relationships between tree growth and monthly climatic variables (temperature and precipitation) from 1895 to 2009, and our study, which had fewer replicates, produced climate-growth relationships at a much finer scale and for only the 2010 growing season.

We provided evidence that suggests the seasonal variation of solar radiation (*i.e.* insolation) is one of the primary controls of the intra-annual growth dynamics of slash pine in the LFK. Photoperiodism has long been recognized to control the seasonal growth dynamics of temperate plant species (Garner and Allard 1920; Downs and Borthwick 1956; Wareing 1956; Thomas and Vince-Prue 1997). However, the photoperiodic induction of phenological changes in temperate trees is generally masked by the low winter temperatures experienced at higher latitudes (*e.g.* rising temperatures in the spring induce cambial reactivation; Calle et al. 2010). Because all previous investigations were focused on plant species living in temperate and subpolar regions, only recently has the importance of seasonal insolation on tree phenology been revealed in subtropical/tropical environments (Borchert and Rivera 2001; Rivera and Borchert 2001).

Our results agree with several studies that recently recognized the seasonal variation of insolation, although too small to be identified by humans, controls tree growth dynamics in many tropical and subtropical locations (Yeang 2007; Calle et al.

2009, 2010). Between the winter and summer solstices, day length in the LFK ranges from 10.5 h to 13.25 h (*ca.* 165 min), which is much greater than any of the aforementioned studies. At *ca.* 24° N latitude, the geography of slash pines in the LFK and the associated climate regime (warm temperatures, adequate annual rainfall) possibly explain seasonal variations in daily insolation as one of the primary drivers of tracheid production. Although the LFK experiences distinct summer-wet, winter-dry seasons, correlation data between climate and tracheid production do not support the notion that precipitation has a major influence on seasonal slash pine radial growth dynamics. Given that Harley et al. (2011) found inter-annual climate-tree growth correlations with the month of September, Langdon (1963) found that drought conditions during 1956 did not affect radial growth considerably, and the compelling association between intra-annual tracheid production and climate found by this study, we propose that seasonal variations in tracheid production of slash pines are controlled primarily by insolation.

For the 2010 growing season, the majority of our sampled trees contained IADFs, which consisted of thin bands of radially enlarged tracheids positioned within the latewood zones of annual growth rings. In all four trees, which had similar growth dynamics, IADFs occurred between July and August. The relationship between IADFs and climate has been studied in various temperate species (*e.g.* Wimmer et al. 2000; Rigling et al. 2001, 2002; Masiokas and Villalba 2004;) and Mediterranean species (*e.g.*

Cherubini et al. 2003; De Micco and Arrone 2009; Copenheaver et al. 2010; Campelo et al. 2006, 2007; de Luis et al. 2011; Battipaglia et al. 2010), and the ecophysiological processes responsible for their formation can be difficult to interpret (De Micco et al. 2011). The majority of the aforementioned studies, which defined IADFs as being thin bands of radially flattened tracheids, found drought stress to cause IADFs during the growing season. However, the IADFs we observed in slash pine were characterized by thin bands of radially enlarged tracheids (larger cell lumen), which indicated a growth increase between our July 15th and August 15th sampling efforts. This growth increase was characterized by the increased production of cells in the radial enlarging (R_e) phase, as seen in the four individuals that contained IADFs (Trees 1, 2, 5, 6; Figure 3.4).

We noticed a visual correspondence between the timing of IADFs and a period of increased solar radiation during August 2010 (Figure 3.7). As in 2009, solar radiation during 2010 started to decrease in May. However, unlike 2009 solar radiation during August 2010 was marked by a rapid increase, with values similar to those recorded during the annual peak in May. A similar period of fluctuating solar radiation resembling that between June and August 2010 was not recorded in 2009. The solar radiation sensor was installed at the Big Pine Key weather station in June 2008, and this timing precluded a comparison of IADFs and solar radiation before 2009. Moreover, we were unable to determine whether the period of increased solar radiation from July through August was anomalous given our sample depth ($n = 2$). Nonetheless, although

IADFs are prevalent in slash pine at this location (Harley et al. 2011), the 2008 and 2009 growth rings did not contain them. Given the relationship between seasonal insolation and tracheid production shown by the PCA results, it is possible that amplified solar radiation from July through August augmented photosynthate production in trees and resulted in increased xylem production, as seen in the properties of the IADFs.

As De Micco et al. (2011) highlighted, specific and robust methodologies are necessary to avoid misleading interpretations of IADFs in tree rings. Hence, our data are not appropriate for making strong suggestions on the relationships between IADFs and climatic factors in slash pine given our study design. We here highlight the possibility that changes in solar radiation might be responsible for the occurrence of IADFs. Additional research that includes more trees and an appropriate study design (longer term with higher resolution) is needed to better understand the relationships between IADFs and the environment in the LFK.

3.5 Conclusions

We demonstrated that the growing season of slash pine, the southernmost native and only subtropical pine in the United States, was characterized by a short but consistent period of dormancy from December to January, the formation of earlywood tracheids from February to June, and the formation of latewood tracheids from June to December. Based on our present results, we propose that the initiation of cambial activity, production of tracheids throughout the growing season, and cambial dormancy are controlled primarily by seasonal insolation. We noticed a visual correspondence between the timing and occurrence of IADFs and increased solar radiation from July through August. Given the characteristics of the IADFs (radially enlarged tracheids, increased production of cells in the radial enlargement phase) and the coupled timing of their occurrence with a period of solar radiation increase, this visual comparison suggests that IADFs during the 2011 growing season were caused by increased solar radiation. However, because IADFs can be caused by various factors (*i.e.* drought, wind stress), more research is needed to better understand their occurrence in LFK slash pine environments.

3.6 Acknowledgments

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Chapter 4

Effects of Historical Fire on Structure of Globally Endangered Pine Rockland Ecosystems in the Florida Keys

Chapter 4

Effects of Historical Fire on Structure of Globally Endangered Pine Rockland Ecosystems in the Florida Keys

This chapter is a slightly revised version of a paper that was submitted to a peer-reviewed journal as: Grant L. Harley, Henri D. Grissino-Mayer, Sally P. Horn (2012). Effects of Historical Fire on Structure of Globally Endangered Pine Rockland Ecosystems in the Florida Keys. *International Journal of Wildland Fire.* The revisions follow suggestions made by members of my dissertation committee. The use of "we" in this chapter refers to my co-authors and myself. As the first author, I was lead on designing the study, obtaining the data, performing analyses, and writing the manuscript.

4.1 Abstract

Fire is believed to influence the structure and dynamics of nearly all plant communities in North America, but historical fire patterns and their consequences are unknown for many community types. Here, we focus on the influence of historical fire disturbance and varied fire management practices on structure and dynamics in globally-endangered pine rockland savannas on Big Pine Key and No Name Key in the Florida Keys. We reconstructed fire history in two stands from fire scars on South Florida slash pines (*Pinus elliottii* Engelm. var. *densa* Little & Dor.) that were accurately dated using dendrochronology, and quantified stand structure to infer successional trajectories. Fire regimes on Big Pine and No Name Keys over the past 150 years differed in fire return interval and relative spatial extent. Composite fire scar analysis indicated that fires burned at intervals of 6 and 9 years (Weibull median probability interval) on Big Pine Key and No Name Key, respectively, with the majority of fires occurring late in the growing season. On Big Pine Key, fires were significantly fewer after the National Key Deer Refuge was established in 1957, but pine recruitment was widespread, likely due to multiple, widespread prescribed burns conducted since 2000. No Name Key experienced fewer fires than Big Pine Key, but pines recruited at the site from at least the 1890s through the 1970s. Today, pine recruitment is nearly absent on No Name Key, where fire management practices since 1957 could inhibit the persistence of pine rockland. The re-introduction of fire could help prevent the loss of these endangered habitats by restoring and sustaining structural features (e.g. pine stand density, basal area, and fuel loads) resembling those of settlement-period rockland savannas. *Keywords: Pinus elliottii* var *densa*, dendrochronology, fire effects, National Key Deer Refuge, subtropical ecosystem, slash pine.

4.2 Introduction

Recurring fire has long been recognized as a key influence on the structure and dynamics of North American plant communities (Harper 1911; Chapman 1932; White 1979; Wright and Bailey 1982). Across the continent, fire regimes range between two extremes: low severity surface fires that occur every few years (e.g. Swetnam and others 1999; Grissino-Mayer and Swetnam 2000; Heyerdahl and others 2001) and high severity crown fires that occur on multi-decadal to century time scales (e.g. Romme 1982; Veblen and others 1991; Kipfmueller and Baker 2000; Weir and others 2000). In many boreal and western forest communities, infrequent high severity fires are stand-replacing events that initiate succession (Oliver 1981; Pickett and White 1985). Many plant communities in the southeastern United States, however, developed with frequent wildfire, and secondary succession occurs in the absence of this disturbance (Garren 1943; Wade and others 1980; Snyder 1991; Gilliam and Platt 1999).

Pine rocklands are globally endangered ecosystems unique to the Bahamas and South Florida, U.S.A. (Noss and others 1995). Within South Florida, they occur in three areas: Everglades National Park, Big Cypress National Preserve, and the Lower Florida Keys (LFK). These subtropical pine savannas, dominated by South Florida slash pine (*Pinus elliottii* Engelm. var. *densa* Little & Dorman.; hereafter slash pine), once covered a vast contiguous area of over 75,000 ha, but fire suppression and agricultural and residential development during the 20th century have fragmented and reduced the original range by 90 % (Snyder and others 1990). The southernmost extent of pine rockland is in the LFK, where the combined effects of sea-level rise (Ross and others 1994) and residential development over the last century have restricted its distribution to less than 1000 ha scattered over four islands.

In the LFK, most pine rocklands are located within the National Key Deer Refuge (NKDR), which is managed by the United States Fish and Wildlife Service (USFWS). Fire is an important component in these communities as it prevents the invasion of hardwoods, maintains the presence of endemic herbaceous flora, and maintains habitat for the endangered Key deer (*Odocoileus virginianus clavium* Barbour & Allen)

(Alexander 1967; Snyder and others 1990). The documented successional pattern in pine rocklands in the absence of fire is a transition from an open pine savanna to a closed canopy, tropical hardwood forest (Simpson 1920; Alexander 1967; Alexander and Dickson 1972). Recurring fires help maintain pine rockland habitat by creating conditions that favor establishment and persistence of slash pines over tropical hardwood species (Menges and Deyrup 2001; O'Brien and others 2008).

Dendroecological techniques can reveal the disturbance history of a forest stand, including the spatial and temporal variability of past fires (Abrams and others 1997; Drunkenbrod 2005). Extensive dendroecological and related research has shown that old-growth longleaf pine (*Pinus palustris* P. Miller) savannas of the southeastern U.S. developed under frequent, low-intensity surface fires (Frost 1993; Platt and others 1988; Platt and Rathburn 1993). However, the historical role of fire in the development of pine rocklands of South Florida has yet to be documented, in part because the suitability of slash pine as a viable species for dendroecological studies here has only recently been established (Harley and others 2011).

Since the establishment of the NKDR in 1957, management has included the suppression of all wildfires (Bergh and Wisby 1996), and the characteristics of the historical fire regimes in these communities are unclear. Taylor (1981) and Snyder (1986) suggested, based on observations and written fire reports, that pine rocklands experienced low-severity surface fires about once every decade, and Snyder and others

(1990) suggested the average interval between historical fires ranged from 2 to 15 years. Currently, fire regimes prior to the 1950s are undocumented (Bergh and Wisby 1996). Since the establishment of the NKDR, prescribed fire in the LFK was applied periodically, with fire sizes and return intervals that vary across islands (Bergh and Wisby 1996), resulting in a diversity of stand structures reflecting different stages of development (Sah and others 2004). Here, the effects of historical fire and varied fire management practices on the age structure and patterns of tree growth are uncertain.

We recently discovered that slash pine, the southernmost native pine in the United States and the foundation species of pine rockland communities, produces consistently annual growth rings in the LFK (Harley and others 2011), making possible a detailed dendroecological study of stand age structures and disturbance history. While several endogenous and exogenous disturbances potentially affect pine stand age structure in rocklands, including tropical cyclones (Platt and others 2000; 2002; Beckage and others 2006) and sea-level rise (Ross and others 1994; 2009), our focus in this paper is fire. Our goal was to determine how historical fire disturbance and varied fire management practices influenced stand structure and dynamics in pine rockland communities on two islands in the LFK: Big Pine Key and No Name Key. We addressed four primary questions: (1) What were the characteristics of the historical fire regimes in the LFK, and did they differ across islands? We were specifically interested in analyzing differences in fire return interval, fire season, and relative spatial extent between study sites on Big Pine Key and No Name Key and, because Big Pine Key is the larger of the two islands, we expected to find a higher frequency of fires. (2) Were fire regimes interrupted during the 20th century after the establishment of the NKDR? We expected to find that fires occurred more frequently and were more widespread prior to the establishment of the NKDR in 1957. (3) How have the historical fire regimes and varied fire management practices since establishment of the NKDR affected the stand structure of the two islands? We expected to find that tree age structures show evidence that recruitment is periodic and related to fire-prone and fire-free periods. (4) Finally, how might information from these stands assist in the development of management practices?

4.3. Methods

4.3.1 Study Sites

The islands of Big Pine Key (24.70° N, 81.37° W) and No Name Key (24.69° N, 81.32° W) contain the largest areas of pine rockland habitat in the Florida Keys (Figure 4.1). On Big Pine Key, the Boneyard Ridge (BYR) site is a 75 ha tract of land that last burned in a prescribed fire in 2009 and the No Name Key (NNK) site is a 75 ha area that last burned in a small wildfire in 2003 (Dana Cohen 2011, *personal communication*). Earlier prescribed burns since the establishment of the NKDR were conducted at BYR in 1977, 1990, 2000, 2004, and 2009, and at NNK in 1992 (Bergh and Wisby 1996).

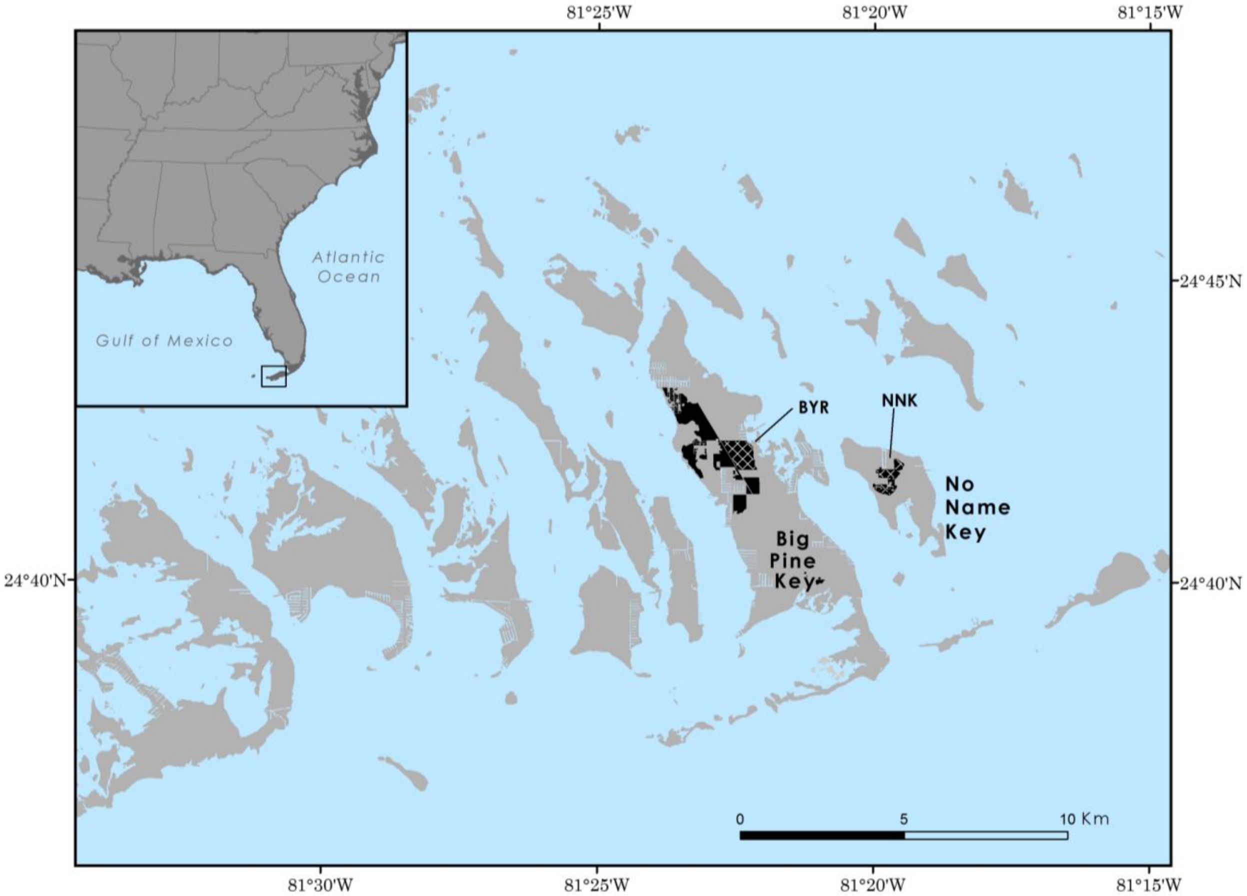

Figure 4.1. Map of study site locations (hatched areas) and current distribution of pine rocklands (black) in the National Key Deer Refuge, Lower Florida Keys, USA. *BYR* Boneyard Ridge and *NNK* No Name Key.

Slash pine stands in LFK rocklands are characterized by a monospecific pine overstory, a diverse subcanopy of West Indian shrubs and palms, and a variety of endemic herbs (Sah and others 2004). Pine rocklands provide an important habitat for several federal and state listed endangered species such as the Key deer, the Lower Keys marsh rabbit (*Sylvilagus palustris hefneri* Lazell), Kirtland's warbler (*Dendroica kirtlandii* Baird), and the Florida leafwing butterfly (*Anaea troglodyta floridalis* Johnson & Comstock) (Snyder and others 1990).

The LFK region experiences a tropical savanna climate with hot summers (mean maximum August temperature < 32 °C), cool winters (mean minimum January temperature > 19 °C), and consistent summer-wet, winter-dry seasons. Mean annual precipitation of the LFK is 980 mm, with 80% occurring from May to November (NCDC 2010). On the rocklands, Pleistocene-aged Miami limestone is exposed at the surface and soil is thin to non-existent. The topography of Big Pine Key and No Name Key is relatively uniform and flat, and the elevation at both sites is approximately 2.4 m above sea-level. Old-growth slash pine stands still exist in the LFK because land development and logging were minimal in the early 20th century, due to the rugged terrain of the rocklands and the difficulty of transporting timber from the islands to the mainland. Protection of pine rocklands began in the 1957 with the establishment of the NKDR.

4.3.2 Fire history

Crossdated fire scars identified in living trees and remnant woody material (snags and logs) were used to reconstruct fire history (return interval, fire season, relative spatial extent) in slash pine stands at the BYR and NNK sites. We used a targeted sampling design to sample trees that contained the greatest number of well-preserved fire scars distributed as broadly as possible over each site (Guyette and Stambaugh 2004). This sampling technique is intended to establish the most comprehensive record of fire dates over the longest possible period, and has been shown to produce a valid representation of local fire regimes (Van Horne and Fulé 2006). We used a chainsaw to remove partial cross-sections from living trees and full cross-sections from remnant material (Arno and Sneck 1977).

In the laboratory, standard dendrochronological methods were used to sand each fire-scarred sample to a high polish (Orvis and Grissino-Mayer 2002), then crossdate the annual growth rings of each fire-scarred sample against reference chronologies developed at each site (Stokes and Smiley 1968). Accuracy of crossdating was verified using the computer program COFECHA (Holmes 1983; Grissino-Mayer 2001*a*). The calendar year of each ring that contained a fire scar was recorded as the fire date and the season of each fire occurrence was estimated by examining the intra-ring position of each scar. The seasonal intra-annual growth dynamics of slash pine in the LFK is different than defined for the pine species first used to classify fire scar seasonality in the southwestern United States (e.g. Baisan and Swetnam 1990). Therefore, fire scar positions were classified as: (1) early (earlywood); (2) transition (earlywood/latewood transition zone); (3) latewood (in latewood); and (4) dormant (ring boundary). We based this classification on results from Langdon (1963) and a recent study of cambial phenology that suggests slash pine forms earlywood from February through June, latewood from July through November, and is dormant during December and January (Harley and others *in press*).

Estimates of relative fire extent were based on the percentage of samples that recorded a fire. Composite fire scar chronologies were used to calculate fire return intervals for fire years recorded by any sample, ≥ 25% of samples, and ≥ 50% of samples. We used FHX2 software to generate Weibull median probability intervals (WMPI) and mean fire interval (MFI) statistics (Grissino-Mayer 2001*b*), and Student's *t*-tests to compare the MFI statistics for the settlement and fire-management periods at each site. We considered the settlement period to extend from European-American settlement of the Florida Keys until the establishment of the NKDR (*ca.* 1840–1956) (Williams 1991). The fire-management period, characterized by wildfire suppression and prescribed burning by NKDR personnel, extended from 1957 to 2010.

4.3.3 Stand structure

We randomly established 20 0.04 ha circular plots (radius = 11.25 m) at each site to document stand structure. In each plot, we recorded diameter at breast height (dbh;

ca. 1.4 m above the surface) for all stems ≥ 5 cm dbh, and tallied all slash pine seedlings (< 1 m ht) and saplings (> 1 m ht and < 5 cm dbh) to quantify stand size structure. All living slash pines in the plots were cored at a height of 30 cm to evaluate stand age, recruitment, and radial growth patterns. The cores were taken with a 5.15 mm diameter Haglöf increment borer, with two radii extracted from each tree. In each plot, we also recorded dbh and decay class for all snags and logs to quantify the abundance of coarse woody debris and decay dynamics. Snags and logs were placed into one of four decay classes (1–4, with 4 being the most decayed) based on categories adapted from Maser and others (1979).

In the pine rockland savannas of the LFK, tree canopies are low in height and have simple vertical structure. Therefore, it was difficult to distinguish the canopy class of each pine tree. To characterize the density and openness of the overstory tree canopy and understory vegetation layer at each site, we used a spherical densitometer (Lemmon 1956), a concave spherical mirror engraved with a grid of squares. At each plot center, we determined the number of squares not occupied by vegetation, which resulted in the percentage of overhead area not occupied by canopy (which included both overstory pines and understory shrubs and palms). To further describe the understory vegetation layer, which was dominated by thatch palm (*Thrinax morissii* H. Wendl.) and silver palm (*Coccothrinax argentata* (Jacq.) L.H. Bailey), we used a 10-factor wedge prism to estimate the basal area of palm stems (ht ≥ 1.4 m) at each site.

Tree cores were dried, mounted, and sanded to a high polish (Stokes and Smiley 1968; Orvis and Grissino-Mayer 2002), and tree age was assigned based on the innermost growth ring for cores that contained the pith. Because the annual growth rings of slash pine often contain intra-annual density fluctuations (false rings) (Harley and others 2011), we selected 30 random cores at each site to statistically crossdate against the reference site chronologies (Grissino-Mayer 2001*a*). We used these chronologies to assist in visually crossdating each core using the list method (Yamaguchi 1991). We applied an age correction to cores that missed the pith based on the curvature of the innermost rings with pith estimators that represented different growth rates (Applequist 1958). Slash pine seedlings undergo a tussock-like ("grass") stage for 2–5 years (Menges and Deyrup 2001); hence, these data should not be considered the absolute establishment year of trees. To control for the potential imprecision in establishment dates, we constructed age structure graphs using 10-year bins (Villalba and Veblen 1997, Wong and Lertzman 2000).

4.4 Results

4.4.1 Fire history at Boneyard Ridge

Our fire reconstruction at BYR spanned 1707–2010 (Figure 4.2). We were able to crossdate 36 of 50 fire-scarred samples collected, and identified 224 fire scars recorded in the growth rings of the samples that represented 45 unique fire events. During the

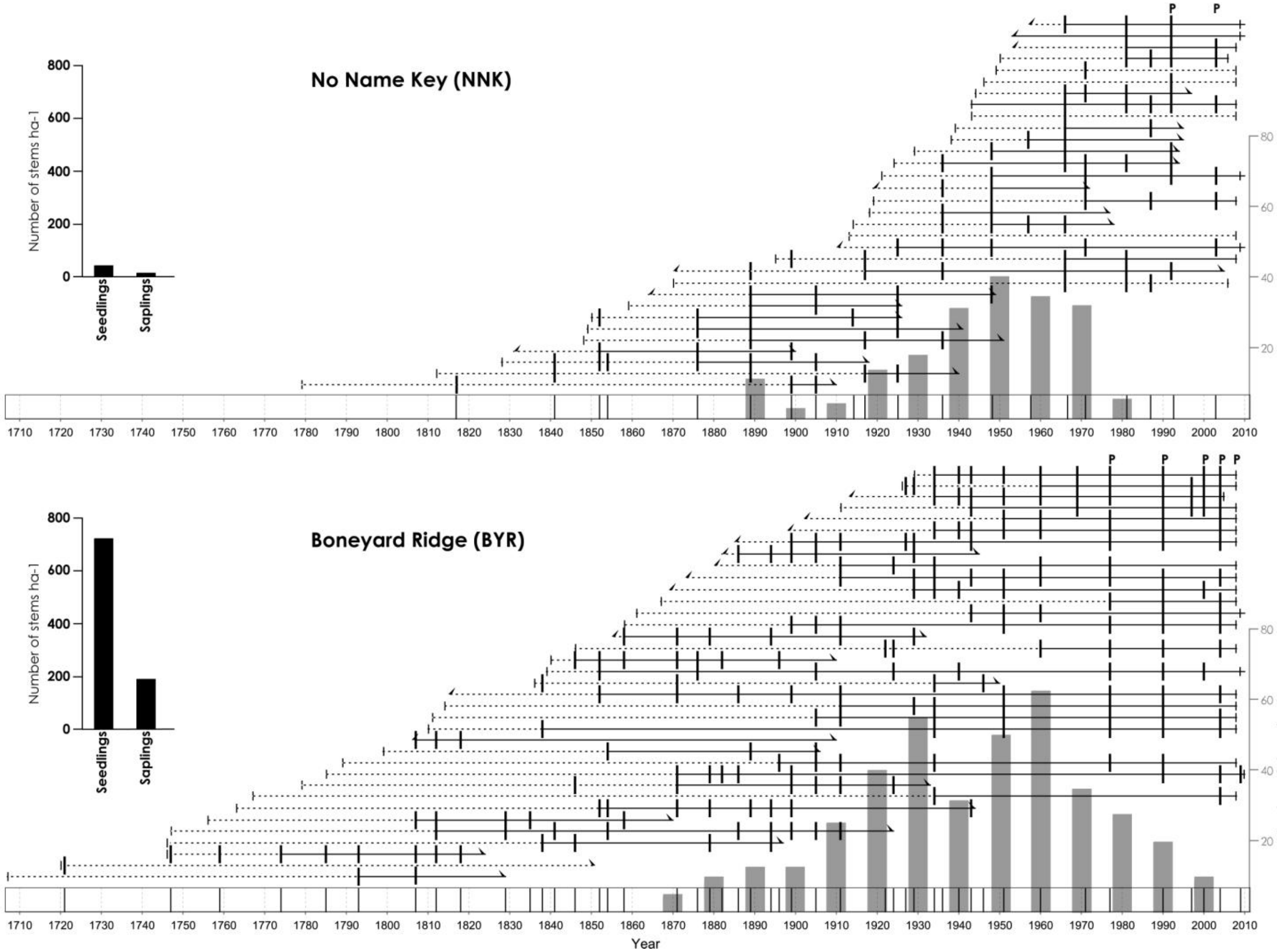

Figure 4.2. Fire history and age structure by decade for No Name Key (NNK; top) and Boneyard Ridge (BYR; bottom). Each horizontal line (solid line = recorder years; dotted line = non-recorder years) represents a fire-scarred sample; vertical bars denote fire events; P represents prescribed burns. Establishment per decade for all trees (stems ≥ 5 cm dbh) is plotted with total seedling (< 1 m ht) and sapling (> 1 m ht, < 5 cm dbh) density ha^{-1}.

period 1707–1851, 14 fires occurred at BYR, but the number of samples was low (< 10). Hence, the period of reliability for our fire reconstruction spanned *ca.* 1850 to 2010. During this period, our reconstruction revealed eight widespread fires (≥ 50 % scarred) at BYR, of which five occurred before the NKDR was established. After 1957, the three widespread fires that were recorded were prescribed burns conducted by fire management personnel.

The interval distributions for all fires at the site were positively skewed, with more short intervals (3–6 years) between fires, and the Weibull median probability interval (WMPI) was shorter than the MFI (Table 1). Although the MFIs during the settlement and fire-management periods were relatively similar, temporal differences between them were statistically significant ($P < 0.05$, *t*-test; Table 2). We were able to classify fire seasonality for 98% ($n = 219$) of the fire scars; 68% ($n = 149$) of fires occurred in the latewood, and 32% ($n = 70$) at the transition between earlywood and latewood.

4.4.2 Stand structure at Boneyard Ridge

We inventoried 158 trees in the 20 BYR plots. We applied an age correction to 27% of plot cores at BYR. The average age correction for cores that did not contain pith was 5–6 years, with a maximum correction of 9 years on three samples. Density of trees ≥ 5 cm dbh was 395 stems ha^{-1} and total basal area was 8 m^2 ha^{-1} (Table 3). The total basal area of palm stems at BYR was lower (459 m^2 ha^{-1}) compared to NNK (1836 m^2 ha^{-1}); hence, the understory vegetation was less dense than at NNK, and the

Table 4.1. Statistical Characteristics of Composite Fire Return Intervals (years) for Pine Rockland Communities in the LFK.

	MFI	WMPI	Range	SD
BYR (*n* = 36)				
All scarred	6.55	5.83	2–26	4.68
> 25%	8.47	7.91	2–26	4.88
> 50%	14.00	14.27	5–33	8.45
NNK (*n* = 32)				
All scarred	9.79	9.14	2–24	5.56
> 25%	10.94	10.32	2–24	5.91
> 50%	14.23	13.92	2–24	5.56

MFI = mean fire interval; WMPI = Weibull median probability interval; SD = standard deviation

Table 4.2. Composite Fire Return Interval Statistics for Settlement (*ca.* 1840–1956) and Fire-management (1957–2010) Periods in Pine Rockland Communities in the LFK.

Time period	*n*	Mean	SE	SD
BYR				
Interval (years)				
1840–1956	23	4.57*	0.57	2.74
1957–2010	8	7.25*	1.15	3.24
Percent Scarred				
1840–1956	24	32.56*	3.68	18.03
1957–2010	9	56.83*	10.71	32.14
NNK				
Interval (years)				
1840–1956	11	9.73	1.63	5.41
1957–2010	6	7.67	1.09	2.66
Percent Scarred				
1840–1956	12	66.85	7.97	27.60
1957–2010	7	50.61	7.49	19.83

Mean values with an asterisk are statistically different ($P < 0.05$, t-test); n = number of observations; SE = standard error; SD = standard deviation.

Table 4.3. Structural Measures of Slash Pine Trees, Seedlings, Saplings, and Understory Vegetation in Pine Rockland Communities in the LFK.

	BYR	**NNK**
Total density (ha^{-1})		
Live trees	395	195
Snags	280	79
Logs	213	136
Basal area (m^2 ha^{-1})		
Live trees	8	6
Snags	2	3
Logs	3	4
Palms	459	1836
Seedlings (ha^{-1})	710	46
Saplings (ha^{-1})	185	6
Understory Vegetation		
Mean/plot (%)	65	40
Range (%)	39–87	5–61

Understory vegetation data derive from spherical densiometer readings: mean percentage (per plot) of overhead area not occupied by vegetation, and site range.

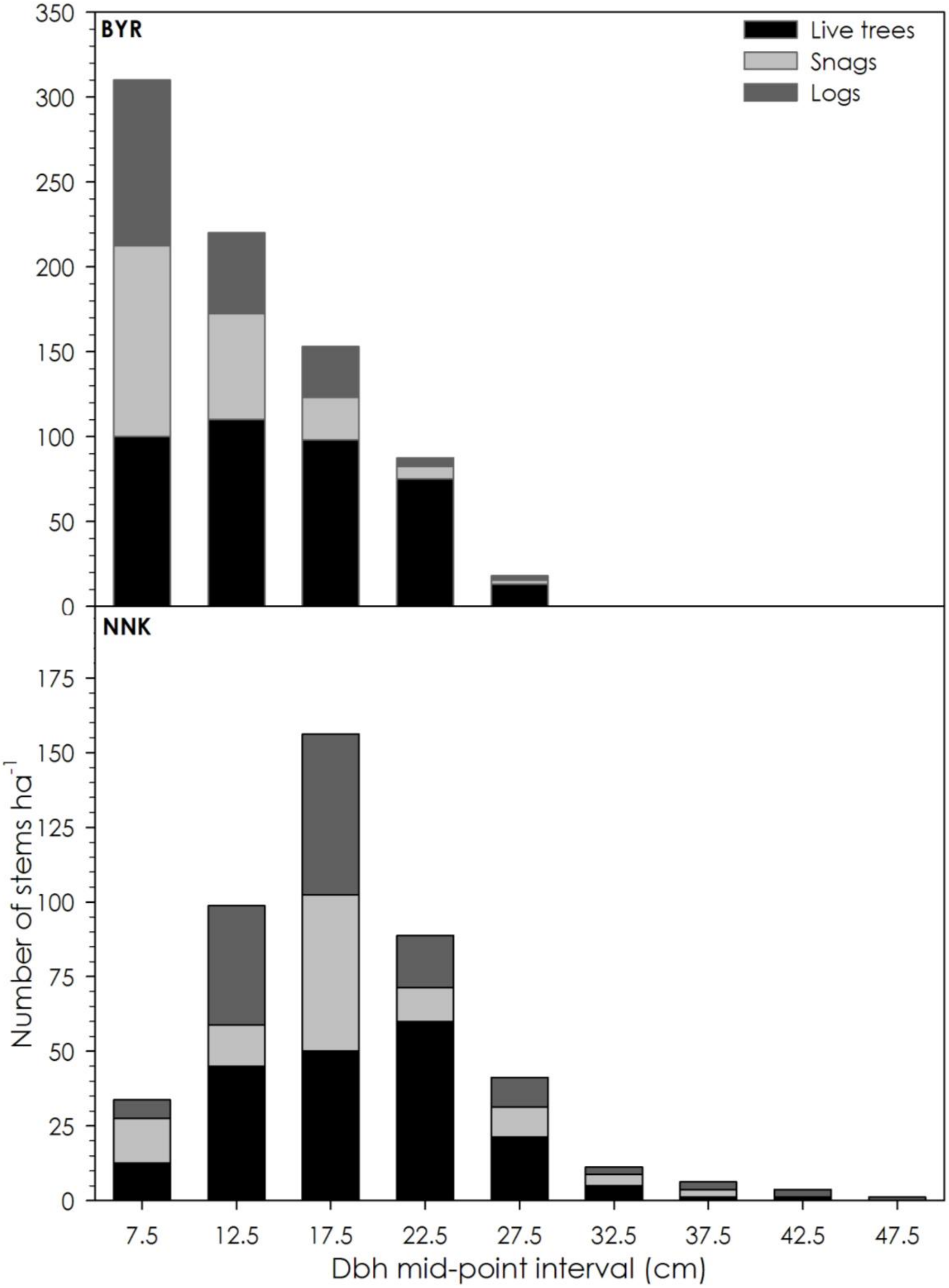

Figure 4.3. Size class distributions of live and dead (snags and logs) slash pine trees stems ≥ 5 cm dbh) in 40 plots (BYR, *n* = 20; NNK, *n* = 20) in pine rockland communities in the Lower Keys. Each dbh interval includes all stems ± 2.5 cm of the stated value. Note that the vertical axis is different for each site.

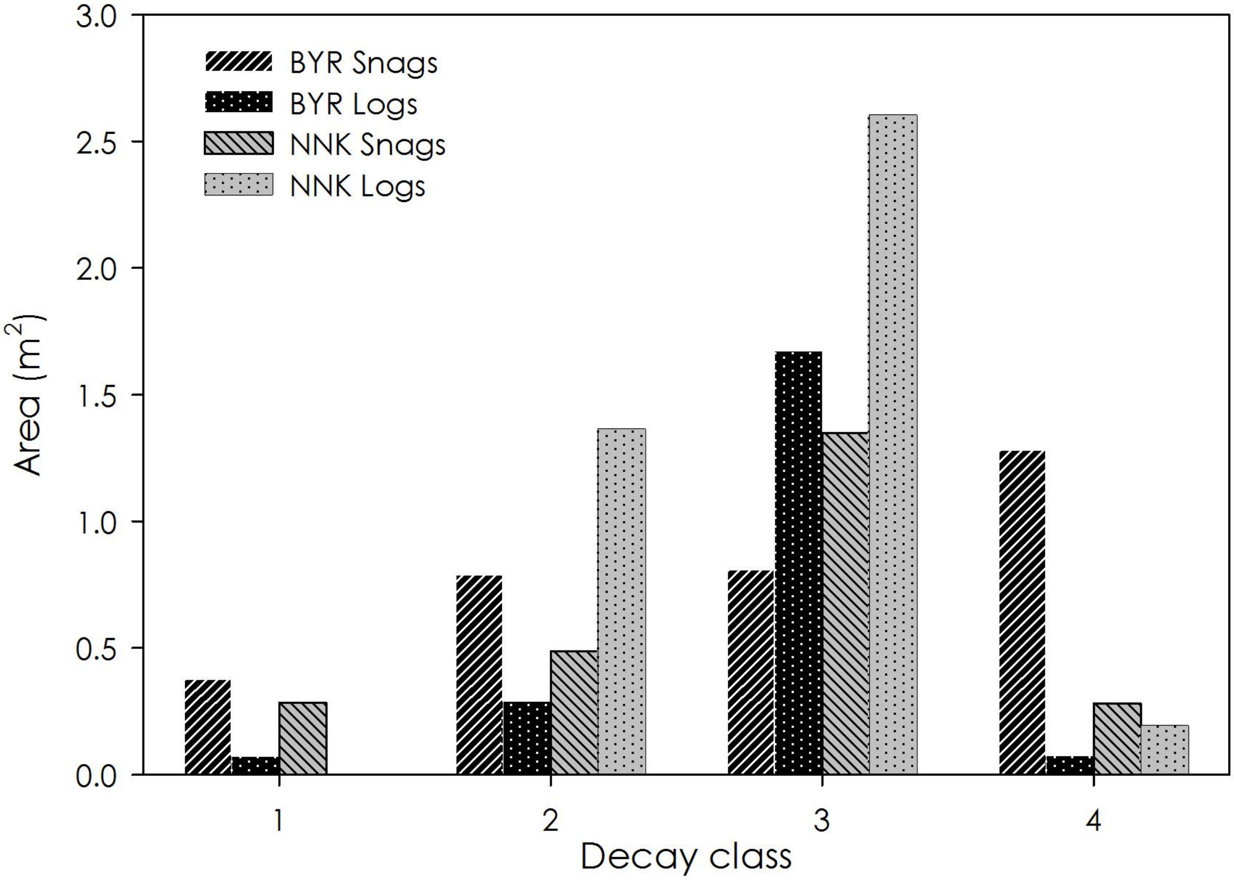

Figure 4.4. Decay class distributions for coarse wood debris in 40 plots (BYR, *n* = 20; NNK, *n* = 20) in pine rockland communities in the Lower Keys. Categories were adapted from Maser and others (1979). Decay class categories ranged from the least decayed (1) to the most decayed (4).

canopy was more open. Densities of snags and logs were similar, with 280 and 213 stems ha^{-1}, respectively. Snag and log densities were relatively similar to densities of live trees; however the total basal area of snags and logs was markedly lower (Figure 4.3; Table 3). Most coarse woody debris was in an advanced state of decay (Figure 4.4). The oldest trees established *ca.* 1870, and recruitment continued through the history of the stand with pulses *ca.* 1910–1930 and *ca.* 1950–1960 bracketing an interval of low recruitment during the 1940s. Although recruitment was low during the 1940s, it was higher than before 1910 and during the period 1980–2000. Seedlings and saplings were ubiquitous at BYR (Figure 4.2; Table 3).

We found a strong relationship between diameter and age ($R^2 = 0.77$, $P < 0.0001$; Figure 4.5) and a reverse J-shaped diameter structure (Figure 4.3) typical of a stand regenerating following disturbance. The two largest diameter individuals recorded were 28.0 cm and 28.4 cm dbh, and established in 1887 and 1891, respectively. The two oldest trees, which established in 1878, had diameters of 21.0 and 26.0 cm. We found many young trees (stems ≥ 5 cm dbh) that established since *ca.* 1990 (Figure 4.5).

4.4.3 Fire history at No Name Key

Our fire reconstruction at NNK spanned 1779–2010 (Figure 4.2). We were able to crossdate 32 of 52 fire-scarred samples collected from NNK, identifying 105 scars that represented 20 unique fire events. The NNK fire reconstruction period of reliability spanned *ca.* 1850 to 2010 due to low sample depth before this period. After the 1850s,

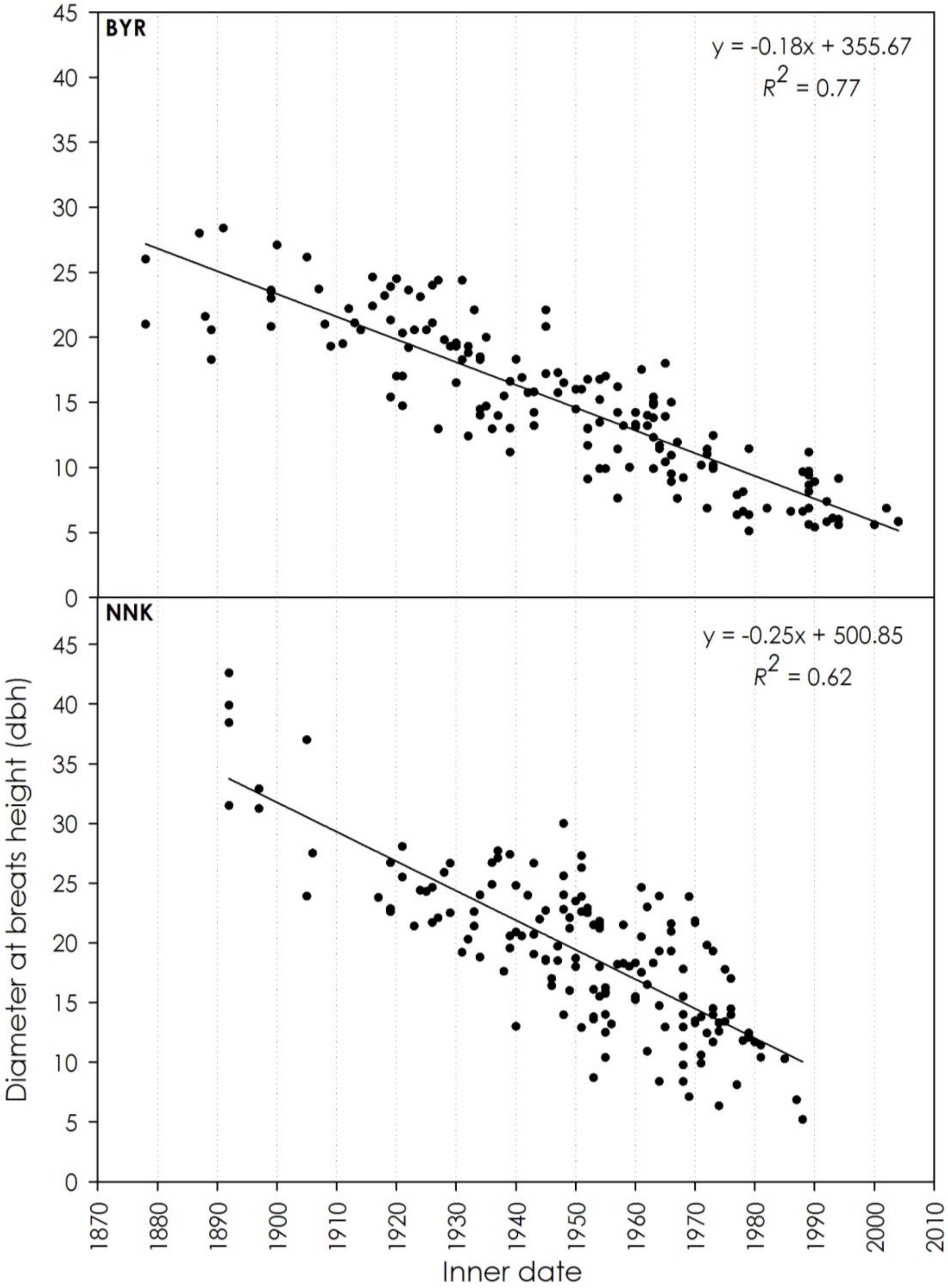

Figure 4.5. Diameter-age relationships for all trees (stems ≥ 5 cm dbh) cored in 40 plots (BYR, $n = 20$; NNK, $n = 20$) in pine rockland communities in the Lower Keys. Lines given are least-squares regressions of diameter on inner date and are both significant at $P < 0.001$.

the majority of fires included in our reconstruction scarred over 50% of trees. Since the NKDR was established, we documented the prescribed burn that was conducted at NNK in 1992 (Bergh and Wisby 1996).

The MFI for fires of different extents varied less at NNK than at BYR, indicating that fires were more consistently widespread. The interval distributions for all fires at NNK were less positively skewed than at BYR, with longer intervals (9–11 years) at NNK between fires. The MFI for small to intermediate-sized fires (9 years) was shorter than for widespread fires (11 years), and the WMPI was shorter than the MFI (Table 1). We found no significant difference in MFI between the settlement and fire-management periods ($P > 0.05$, *t*-test) for this site (Table 2). We classified seasonality for 90% (n = 94) of the fire scars; 75% ($n = 70$) occurred in the latewood and 25 % ($n = 24$) at the transition between earlywood and latewood.

4.4.4 Stand structure at No Name Key

At NNK, we inventoried 156 trees in 20 plots. We applied an age correction to 31% of plot cores at NNK. The average age correction for cores that did not contain pith was 5–6 years, with a maximum correction of eight years on one sample. Density of trees ≥ 5 cm dbh was 195 stems ha^{-1} and total basal area was 6 m^2 ha^{-1} (Table 3). The diameter structure at NNK was unimodal, and not indicative of a regenerating stand (Figure 4.3). The understory vegetation was more dense and the canopy was less open than at BYR. Palms occupied 1836 m^2 ha^{-1} and on average, only 40% of the overhead area was not occupied by understory shrubs and palms (Table 3). Density of snags was lower than density of logs, and densities of live trees and logs were similar. Total basal area of snags was markedly lower than that of live trees, but logs and live trees occupied relatively similar areas (Table 3). Compared to BYR, coarse woody debris was more abundant and less decayed (Figure 4.4).

The oldest trees established *ca.* 1890, with recruitment per decade that gradually increased from 1900 to the 1950s, then decreased markedly in the 1980s (Figure 4.5). Seedlings and saplings were nearly absent at NNK (Table 4). The relationship between diameter and age was less pronounced than at BYR, but still statistically significant (R^2 = 0.62, $P < 0.001$). Among the two sites, the largest diameter trees were found at NNK, with two individuals measured at ≥ 40.0 cm dbh. Although these trees were large, they were younger than individuals at BYR. The four oldest trees in the stand, all established by 1892, ranged in size from 32.0 to 42.6 cm dbh (Figure 4.5).

4.5 Discussion

4.5.1 Historical fire regimes of the LFK

Low sample depth and scarcity of fire scars precluded any conclusions regarding the fire regimes at the two sites before the 1850s. Our reconstructions indicated that the historical fire regimes in the LFK were characterized by relatively frequent surface fires that ranged between 6 and 9 years (MFI at BYR and NNK, respectively), which was within the speculations of previous studies (*i.e.* Taylor 1981; Snyder 1986; Snyder and others 1990). We also found a noticeable difference in fire regimes between islands. Although similar in season, fire frequency and spatial extent varied over time between BYR and NNK. During the settlement period, BYR burned more often and fire events had more spatial variability (*i.e.* fires that were mixed patchy, with low scarring percentage, and widespread, with high scarring percentage) compared to NNK. Fire history data from NNK revealed that, in general, fires burned less often and over larger areas, as indicated by the amount of fires that scarred ≥ 50% of sampled trees. Bergh and Wisby (1996) hypothesized that Big Pine Key was historically the most fire-prone island in the LFK because it has the largest land area; a similar island-size effect has been shown by several other studies (e.g. Bergeron 1991; Niklasson and others 2010). The larger land area of Big Pine Key might have resulted in a higher frequency of lightning strikes per thunderstorm during the summer wet season and lends a possible explanation to the varied fire frequency and spatial extent found between our study sites.

The intra-annual positions of fire scars in our reconstructions were most commonly in the latewood zones of annual growth rings, but some occurred at the transition between earlywood and latewood zones. A contemporary study of cambial phenology indicated that, on Big Pine Key, slash pines form earlywood from February through June, latewood from July through November, and are dormant during

December and January (Harley and others, *in press*). These data suggest that fires at both sites were most common later in the growing season. In South Florida, the majority of thunderstorms and lightning strikes occur from May to October, and previous studies from the Everglades found that the largest lightning-caused fires occur during this time (Taylor 1981; Duever and others 1994; Beckage and others 2003). The influence of humans on fire regimes is largely unknown because archaeological evidence from the Lower Florida Keys is limited, and the initial timing of human arrival and patterns of movement between and around islands is not well understood (Worth 1995). Based on the similarities between fire history data presented by previous studies and the abundance of mid- to late-season fires found at both sites, we propose that the majority of historical fires were most likely ignited by lightning.

Despite the increased use of prescribed fire over the past decade by NKDR personnel at BYR, we found a significant difference in the MFI and mean percentage of trees scarred between the settlement period and the fire-management period. Prior to the establishment of the NKDR, fires occurred more often and were more patchy at BYR, while the fire-management period was defined by less frequent fires that burned larger areas. Although the MFI of the settlement period (5 years) was similar to the fire-management period (7 years), the difference between means was statistically significant. More convincing, however, was the difference in percentage of trees scarred per fire between periods. We attribute the increase in scarring percentage to the prescribed burns that were conducted at BYR in 1977, 1990, 2000, 2004, and 2009, as these events account for nearly all the fire activity since 1957 at the site. The prescribed burns conducted at BYR during the fire-management period, especially within the last decade, resulted from NKDR efforts to increase fire activity at the site. The infrequency of prescribed fire at NNK, however, resulted in vastly different structural conditions compared to BYR.

4.5.2 Influence of fire on savanna structure

The frequency and spatial extent of fire at both BYR and NNK differed markedly over the past *ca*. 150 years, and the age structures of trees at both sites show periods of high and low recruitment that appear to be controlled by fire occurrence. At BYR, high fire frequency in the period 1870s–1920s likely explains the steady increase in recruitment through the 1930s. The decrease in recruitment during the 1940s was likely associated with the documented decrease in fire frequency during the 1930s, or with a prolonged drought that occurred from 1942 to 1946 (NCDC 2010). Palmer Drought Severity Index values for the Florida Keys climate division (Florida climate division 7) were consistently negative, indicating prolonged dryness during the period 1942–1946 (data not shown). During the 1970s and 1980s, wildfires were suppressed and only one prescribed burn was conducted at BYR (1977; Bergh and Wisby 1996), decreasing recruitment. The prescribed burns during the 2000s facilitated the ample recruitment seen today at the site, a structural component that was nearly absent at NNK. Different historic fire return intervals on the two islands produced distinct structural differences likely caused by inconsistence of fire management practices since the establishment of the NKDR. Since 1957, one prescribed burn was conducted at NNK, while five occurred at BYR, most of which took place since 2000. In comparison to NNK, the renewed prevalence of fire at BYR resulted in more regeneration and recruitment and less fuel (coarse woody debris).

The structural conditions found today at BYR might be similar to conditions that existed during the settlement period (1840–1956). Although we lack comparative structural data for this period, an historical photograph from Big Pine Key hints at structural conditions during the 1910s, when our data show recruitment at BYR began to increase and fires were patchy and frequent (Figure 4.6). The 1915 photograph from Big Pine Key is similar to a 2010 photograph of the island, with both showing lower and less dense vegetation than today found at NNK (2010 photograph). The absence of recurring fire at NNK has allowed the development of a dense layer of shrubs and palms that prevented pine recruitment, as pines in general are intolerant of shade. Our results agree with those of Gilliam and Platt (1999), who studied the effects of fire on the structure of old-growth longleaf pine savannas. They concluded that excluding fire altered structural conditions by allowing hardwoods to occupy the gaps between longleaf stems that are normally maintained by recurring fire. Because of the lack of frequent fire, the pine rockland habitat at NNK is similarly being taken over by tropical

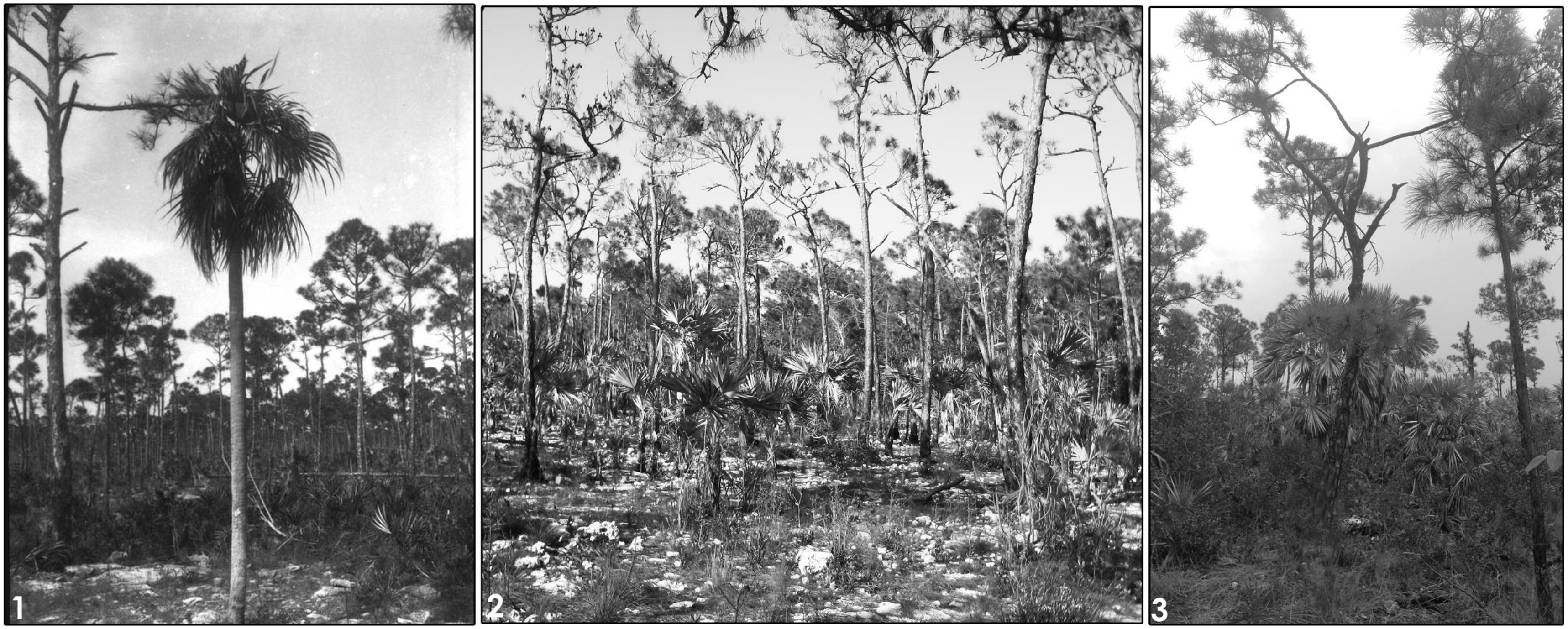

Figure 4.6. Photographs showing differences in understory density in pine rockland communities in the Lower Keys. Photograph 1 was taken on Big Pine Key in 1915 by John Kunkel Small (used with permission from Florida Photographic Collection, State Library and Archives of Florida). Photograph 2 was taken at BYR in 2010 and photograph 3 was taken at NNK in 2010 (photographs taken by the authors).

hardwood species, as indicated by our understory density data. The successional pathway of an open pine savanna to a closed canopy hardwood forest is a process estimated to take 50 years in the LFK (Alexander and Dickson 1972).

Snyder and others (1990) commented previously on the variation in understory density between Big Pine and No Name Keys. They reported that the majority of rocklands on Big Pine contained a sparse understory layer of shrubs and palms low in height, and a surface scantly covered with grasses. In contrast, the rockland areas of No Name Key were composed of a dense, nearly continuous hardwood understory 6 m or more high. Our data suggest that even though NNK has experienced historically less fire than BYR, pines were recruiting since at least the 1890s until the 1980s. However, since the comparison presented by Snyder and others (1990) 20 years ago, lack of recent fire at NNK has likely further increased the density of understory vegetation and prevented regeneration and recruitment. Given the successional trajectory presented by Alexander and Dickson (1972), the current density of understory vegetation, and the lack of recent recruitment, pine stands in rockland habitat at NNK are likely to succeed to hardwood hammock, if fire is not reintroduced. However, the amount of fuel amassed in the absence of fire might present a quandary for land managers.

4.6 Conclusions

We demonstrated that dendroecological analyses of slash pines can reveal both natural processes and management practices responsible for the documented successional pattern in pine rockland ecosystems in southern Florida, especially during the late 20th century. The goal of our study was to determine how historical fire disturbance and varied fire management practices influenced stand structure and dynamics in globally endangered, old-growth pine rockland communities in the LFK. We found that the fire regimes of two adjacent islands differed in return interval, frequency, and relative spatial extent, but were similar in fire season. At BYR, fire frequency dropped with the establishment of the NKDR, but recruitment was ubiquitous, likely due to multiple, widespread prescribed burns conducted in recent years. Although NNK experienced fewer fires altogether than BYR, pines recruited at the site from at least the 1890s until the 1980s. The near absence of recruitment at NNK currently suggests that the infrequency of fire since the 1990s might result in the loss of pine rockland habitat in the future. The structure of the BYR stand demonstrates that prescribed fire can be used to restore and sustain structural features (density, basal area, fuel loads) resembling those of the settlement period. However, re-introducing prescribed fire on NNK will be complicated by the density of understory vegetation and the amount of course woody debris. Implementing prescribed fires that do not become crown fires that kill overstory pines will be a daunting task for land managers, perhaps requiring initial manual clearing of understory fuels. The fire history and stand structure characterizations we produced for Big Pine and No Name Keys testify to both the past success of prescribed fire as a management tool and the difficulty of initiating this management tool in long-unburned pine rocklands stands of the Florida Keys.

4.7 Acknowledgements

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Chapter 5

Pacific Climate Forcing of Historical Fire Regimes in an Endangered Subtropical Ecosystem of the Florida Keys

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Pacific Climate Forcing of Historical Fire Regimes in an Endangered Subtropical Ecosystem of the Florida Keys

This chapter is a slightly revised version of a paper that was submitted to a peer-reviewed journal as: Grant L. Harley, Henri D. Grissino-Mayer, Sally P. Horn, and Chris Bergh (2012). Pacific Climate Forcing of Historical Fire Regimes in an Endangered Subtropical Ecosystem of the Florida Keys. *The Professional Geographer*, in review. The revisions follow suggestions made by members of my dissertation committee. The use of "we" in this chapter refers to my co-authors and myself. As the first author, I was lead on designing the study, obtaining the data, performing analyses, and writing the manuscript.

5.1 Abstract

We investigated the relationships between climatic variability and historical wildfires in globally endangered pine rockland communities in the Florida Keys, U.S.A, using tree-ring samples from the canopy dominant *Pinus elliottii* var. *densa* (South Florida slash pine), the southernmost native pine in the United States. We compared a new set of crossdated fire-scar chronologies spanning the period AD 1707–2010 from four sites on Big Pine Key to measured values of the El Niño-Southern Oscillation (NIÑO3.4), Pacific Decadal Oscillation (PDO), and divisional temperature and precipitation. Historical fires (scarring ≥ 50% of samples collected) occurred during years that were drier than average, and NIÑO3.4 values were significantly lower than average one year prior to these fires (La Niñas; $P < 0.01$). We found evidence that suggests linkages between the El Niño Decadal Modulation (ENDM) and wildfire, with antecedent years wetter than average combining with the effects of El Niño and PDO

(warm phase) to precondition widespread fires by increasing the amount and continuity of fine fuels. Our results agree with previous climate studies in Florida that demonstrated the influence of the ENDM on Florida’s climate. Here, we show the relationship between the ENDM, which is known to affect winter precipitation in Florida, and wildfire in the Florida Keys. This study adds to the network of fire history sites in the southeastern United States that can be used for analyzing fire-climate relationships. Our fire regime and fire-climate results might be applicable to other areas of pine rockland habitat. Additional fire-scar data could reveal broader, longer-term spatial relationships between climate and wildfire activity across neighboring islands in the Lower Florida Keys, southern mainland Florida, and The Bahamas.

5.2 Introduction

Fire is an important disturbance in many ecological communities. Plant communities from the tropics to the high latitudes are shaped by varied fire regimes (i.e. fire return interval, fire season, and relative spatial extent) operating at different temporal and spatial scales (Taylor and Skinner 1998, 2003; Kipfmueller and Baker 2000; Heyerdahl et al. 2001; Whitlock et al. 2003). Variations in fire regimes have often been linked with alternating patterns or cycles of global-scale climate-forcing mechanisms such as the El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO), as well as regional patterns of temperature and precipitation (Swetnam and Betancourt 1990, 1998; Kitzberger et al. 2001, 2007; Heyerdahl et al. 2002; Schoennagel et al. 2005;

Taylor and Beaty 2005). For example, ENSO is a complex, climate-forcing phenomenon that has been shown to affect global temperature and rainfall patterns (Ropelewski and Halpert 1986, 1987; Allan et al. 1996). Relationships between ENSO and fire occurrence have long been recognized in western North America at scales ranging from regional (Swetnam 1990; Heyerdahl and Alvarado 2003; Brown and Wu 2005; Fule et al. 2005; Skinner et al. 2008) to subcontinental (Swetnam and Betancourt 1990; Brenner 1991; Veblen and Kitzberger 2002; Kitzberger et al. 2007).

Previous investigations of fire-climate relationships in western North America revealed interactions between ENSO and PDO cycles (variations in sea surface temperatures between the northeastern and tropical Pacific Ocean; Mantua et al. 1997). Climate effects of PDO are often defined similarly to those of ENSO because the two mechanisms often operate in tandem (Kaplan et al. 1998). Respective climate conditions are intensified (constructive) when both mechanisms are in phase and weakened (destructive) when out of phase (Biondi et al. 2001; Mote et al. 2003). Amplified fire weather is often linked with interactions between phasing of ENSO and PDO in western North America (Norman and Taylor 2003; Taylor and Beaty 2005; Schoennagel et al. 2005).

Most studies of climate drivers of fire have been conducted in western North America and have focused on the influences of climate variability in the central and eastern Pacific region. In recent decades, this variability was shown to also influence wildfires on mainland Florida (*e.g.* Brenner 1991; Jones et al. 1999; Harrison and Meindl 2001; Beckage and Platt 2003; Beckage et al. 2003; Goodrick and Hanley 2009; Slocum et al. 2010). Studies based on instrumental records from the 1950s onward demonstrated that El Niño is associated with increased precipitation during the winter dry season, and results in lower wildfire activity. Conversely, decreased dry season precipitation during La Niña exacerbates the severity of winter droughts and is associated with lower surface water levels, more lightning strikes, heightened fire weather, and higher wildfire activity.

Recent investigations showed that combined effects of ENSO and PDO can modify winter precipitation in southern Florida. Kurtzman and Scanlon (2007) provided evidence that phase cycles of PDO can strengthen or weaken El Niño/La Niña effects, in processes termed El Niño Decadal Modulation (ENDM) and La Niña Decadal Modulation (LNDM). In South Florida, for example, positive anomalies of El Niño are strengthened during warm phases of PDO. Although relationships between ENSO, PDO, and winter precipitation are known, associations between the ENDM, LNDM, and wildfire are unknown. Here, we use new tree-ring records to improve understanding of the temporal and spatial relationships between ENSO, PDO, and wildfire at the centennial-scale. Such understanding is of critical importance in helping land managers better plan the application of fire management resources in plant communities on islands in the Florida Keys, especially during this time of uncertain climate change.

Pine rocklands are globally endangered, pyrogenic plant communities restricted in the United States to small areas in mainland South Florida and the Lower Florida Keys (Noss et al. 1995). Fire is an important disturbance in these communities as it encourages persistence of the foundation pine species (South Florida slash pine, *Pinus elliottii* Engelm. var. *densa* Little & Dorman, hereafter slash pine), and discourages invasion by tropical hardwood species. In the absence of fire, open-canopy pine savannas with diverse herbaceous and graminoid floral assemblages succeed to dense tropical hardwood hammock with depauperate herbaceous and graminoid assemblages. We selected pine rocklands on Big Pine Key (BPK) in the Lower Florida Keys to quantify the potential influence of climate on the fire regime for several reasons. The island of BPK contains the largest contiguous areas of pine rockland habitat in the Florida Keys. While previous investigations of the effects of climate on fires in Florida focused on the past *ca.* 60 years, the abundance of old-growth, fire-scarred slash pines with demonstrated annual ring formation (Harley et al. 2011) on Big Pine Key offered the opportunity to characterize the fire regime on the island over a longer interval of time. Slash pine reaches the southern limit of its natural distribution in this area, and historical fire information from the species would add a much needed data point for analyzing fire-climate relationships within the network of fire history sites in the southeastern United States. Finally, the geographic location of BPK, situated along the Florida Straits between the Gulf of Mexico and Atlantic Ocean, suggested potential for identifying the effects of multiple oceanic-atmospheric climate-forcing mechanisms on fire occurrence in pine rockland communities.

The objectives of this study were (1) to characterize the historical fire regime in slash pine savannas on BPK, including return interval, fire season, and relative spatial extent, and (2) to determine whether fire years were associated with ENSO and PDO. Specific questions included: What were the characteristics of the fire regime on BPK? Did the historical fire regime change in the 20th century, when study sites came under management with the establishment of the National Key Deer Refuge? What are the effects of ENSO and PDO on fires in the Florida Keys?

5.3 Methods

5.3.1 Study Area

Big Pine Key (24.70° N, 81.37° W) is the largest of the islands that make up the Lower Florida Keys (Figure 5.1). On BPK, pine rocklands are characterized by a monospecific pine overstory, a diverse subcanopy of West Indian shrubs and palms, and a diverse assemblage of herbaceous and graminoid species including a variety of endemic herbs (Sah et al. 2004). Pine rocklands provide an important habitat for several state and federally listed endangered species such as the Key deer (*Odocoileus* *virginianus clavium*), the Lower Keys marsh rabbit (*Sylvilagus palustris hefneri* Lazell), Kirtland's warbler (*Dendroica kirtlandii* Baird), and the Florida leafwing butterfly (*Anaea troglodyta floridalis* Johnson & Comstock) (Snyder et al. 1990).

Climate on BPK is defined as tropical savanna, with hot summers (mean maximum August temperature < 32 °C), cool winters (mean minimum January temperature > 19 °C), and a consistent summer-wet, winter-dry season. Mean annual precipitation in the region is 980 mm, with 80% occurring from May to November (NCDC 2011; Figure 5.2). On the rocklands, Pleistocene-aged Miami limestone is exposed at the surface and soil is thin to non-existent. Elevation on BPK ranges from sea-level to *ca.* 2.4 m, with old-growth slash pine savannas inhabiting the highest elevations. Old-growth pines remain on the island because land development and logging were minimal in the early 20th century. Logging was minimal in the region because of the rugged terrain of the rocklands, low commercial value of the timber, and difficulty of transporting timber from the islands to the mainland. Protection of pine rockland habitat began in 1957 with the establishment of the National Key Deer Refuge (NKDR).

5.3.2 Fire history

Crossdated fire scars identified in living trees and remnant woody material (snags and logs) were used to reconstruct the fire regime in slash pine stands at sites on BPK. Samples were collected from four sites: Boneyard Ridge (BYR), North Big Pine

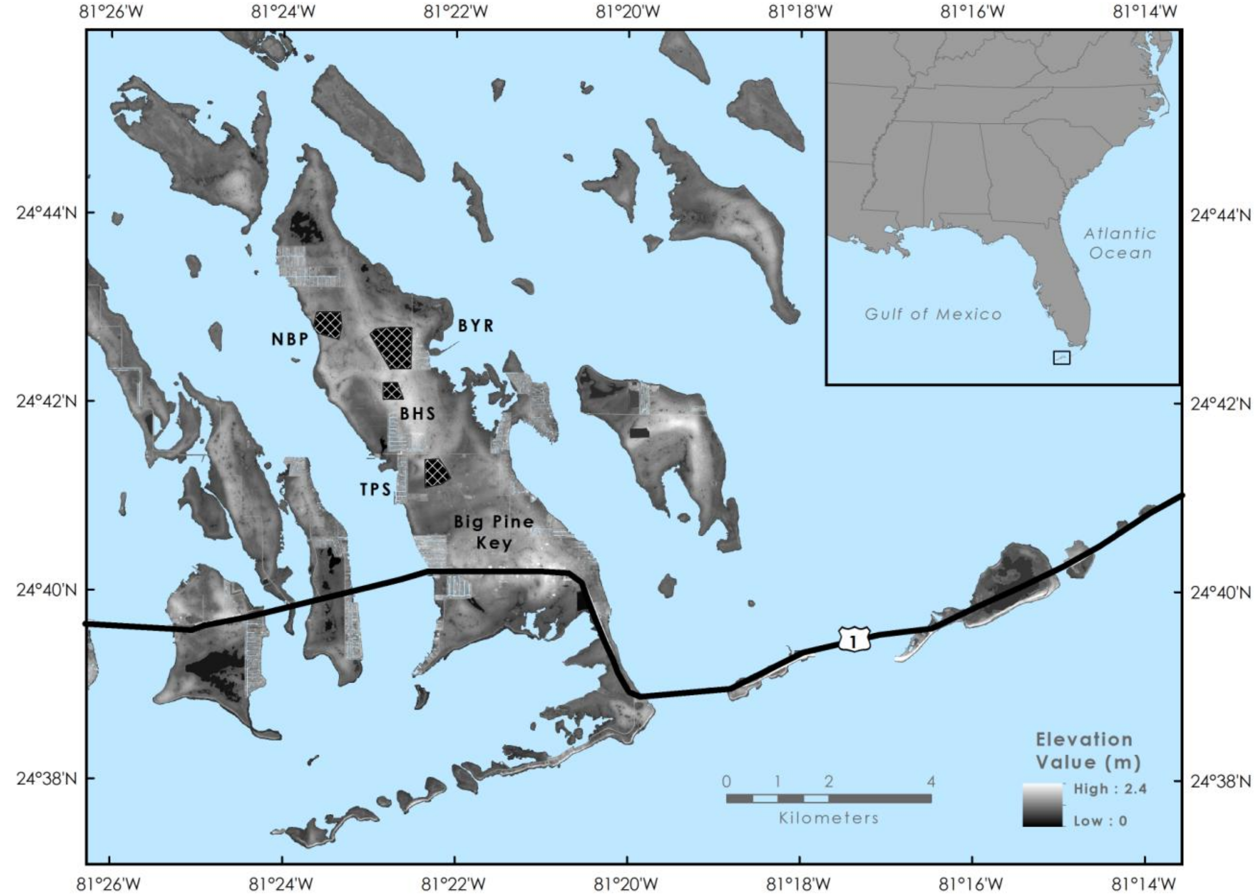

Figure 5.1. Map of study site locations (hatched areas) in the National Key Deer Refuge, Big Pine Key, Florida Keys, USA. Site codes are given in Table 1.

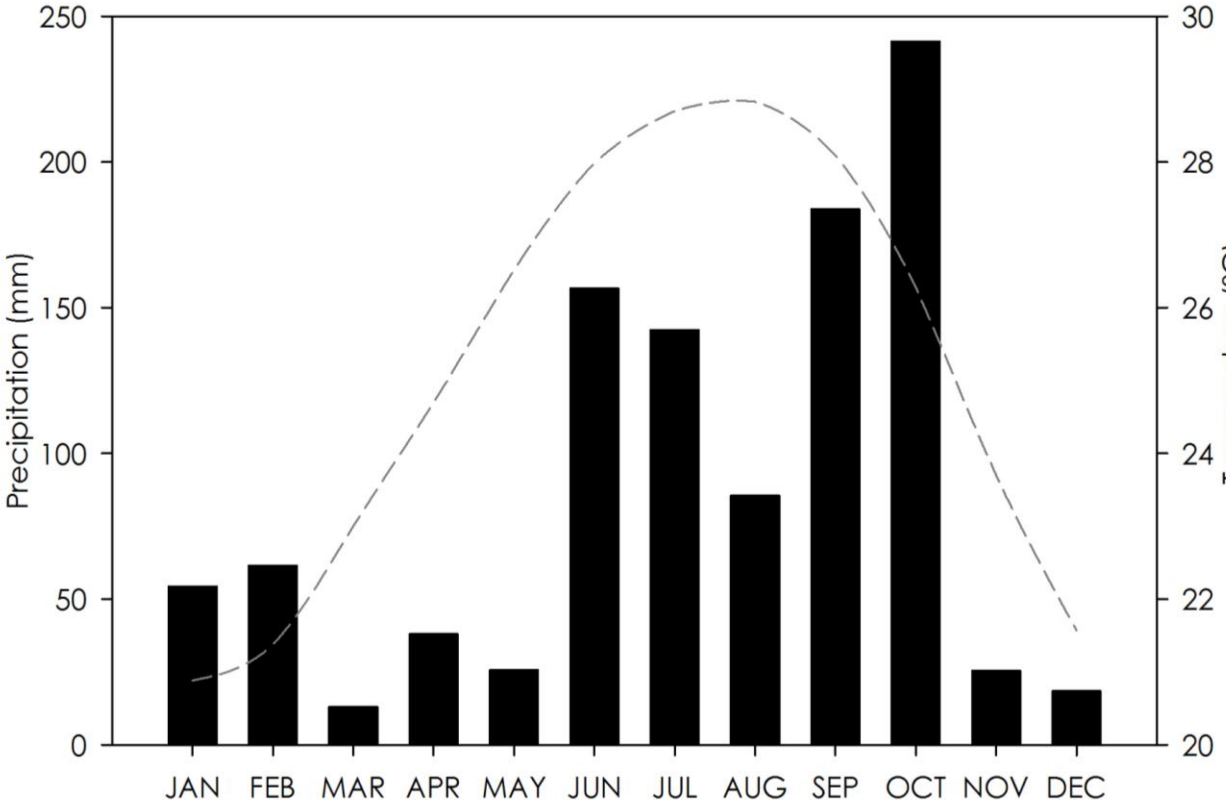

Figure 5.2. Climograph showing the average monthly precipitation (bars) and average monthly temperature (dashed line) for Big Pine Key from 1895 to 2010 (NCDC 2011).

(NBP), Blue Hole South (BHS), and Terrestris Preserve (TPS) (Table 1). At each site, we used a targeted sampling design to sample trees that contained the greatest number of well-preserved fire scars distributed as broadly as possible over the site (Guyette and Stambaugh 2004; Van Horne and Fulé 2006). We used a chainsaw to remove partial cross-sections from living trees and full cross-sections from remnant material (Arno and Sneck 1977). At BYR and NBP, we recorded the location of each sampled tree, stump, or log with a GPS.

In the laboratory, standard dendrochronological methods were used to sand each fire-scarred sample to a high polish (Orvis and Grissino-Mayer 2002), then crossdate the annual growth rings of each fire-scarred sample against reference chronologies developed at each site (Stokes and Smiley 1968). Accuracy of crossdating was verified using the computer program COFECHA (Holmes 1983, Grissino-Mayer 2001*a*). The calendar year of each ring that contained a fire scar was recorded as the fire date and the season of each fire event was estimated by examining the intra-ring position of each scar. The seasonal intra-annual growth dynamics of slash pine in the study area are different than defined for the pine species first used to classify fire scar seasonality in the southwestern United States (*e.g.* Baisan and Swetnam 1990). Therefore, fire scar positions were classified as: (1) early (earlywood); (2) transition (earlywood/latewood transition zone); (3) latewood (in latewood); and (4) dormant (ring boundary). We based this classification on research that indicates that slash pines form earlywood from

February through June, latewood from July through November, and are dormant during December and January (Langdon 1963, Harley et al. *in press*).

The relative extent of each fire was estimated using an index based on the percentage of samples that recorded the fire. Composite fire scar chronologies were used to calculate fire return intervals for fire years recorded by: (1) any sample, (2) ≥ 25%, and (3) ≥ 50% of samples. We used FHX2 software to generate Weibull median probability intervals (WMPI) and mean fire interval (MFI) statistics (Grissino-Mayer 2001*b*), and Student's *t*-tests to compare the MFI statistics for the settlement and fire-management periods. We considered the settlement period to extend from European-American settlement of the Lower Keys until the establishment of the NKDR (*ca.* 1840–1956) (Williams 1991). The fire-management period, characterized by prescribed burning by NKDR personnel and wildfire suppression by Florida Division of Forestry and Monroe County (Florida Keys) Fire Department, extended from 1957 to 2010.

5.3.3 Fire-climate relationships

To evaluate climate conditions related to historical (pre-management period) fire occurrence in our study area, we used superposed epoch analysis (SEA) to compare indices of ENSO and PDO with fire years with the computer program FHX2 (Baisan and Swetnam 1990; Swetnam 1993; Grissino-Mayer 2001*b*). SEA is a technique that identifies statistical, non-linear relationships between climate indices and fire dates by superimposing windows of concurrent and lagged climate conditions on each fire event

Table 5.1. Site characteristics on Big Pine Key, Florida Keys, USA.

	Study Sites				
Site Characteristics	North Big Pine (NBP)	Boneyard Ridge (BYR)	Blue Hole South (BHS)	Terrestris Preserve (TPS)	Big Pine Key* (BPK)
Years of analysis	1860–2010	1707–2010	1854–2002	1842–2009	1707–2010
Samples collected (*n*)	37	50	10	13	110
Area (*ha*)	20	40	8	20	88

*BPK represents the composite of all four sites on the island: NBP, BYR, BHS, and TPS.

(year). To test for possible preconditioning affects of climate on fire activity we chose a 3:1 window (3 years before, 1 year after fire events) in our SEA, and Monte Carlo simulations were used (n = 1000) to develop bootstrapped confidence intervals to determine whether climate was significantly different from average in years before, during, and after fire events (Swetnam and Baison 2003). To represent years of more extensive and widespread fire activity, we conducted SEA using years in which ≥ 50% of sampled trees were scarred.

To assess potential climate forcing of wildfires, we compared our fire chronologies with global- and regional-scale climate variables: (1) sea surface temperature (SST) anomalies monitored in the equatorial Pacific Ocean from the Niño3.4 region (1856–2010; 5°N to 5°S, 120°W to 170°W); (2) PDO values in the form of SST anomalies in the North Pacific Ocean (1900–2010 ; poleward of 20°N; Mantua et al. 1997; Mantua and Hare 2002); (3) divisional precipitation and (4) temperature data from Florida Climatic Division 7 (1895–2010; NCDC 2011). We chose to use SST data from the Niño3.4 region, rather than other regions, as recent studies found this region to provide a more discerning index for examining ENSO impacts (Hanley et al. 2003; Larkin and Harrison 2005).

5.4 Results

5.4.1 Fire history

We collected 110 fire-scarred samples from the four study sites on BPK, of which 71 were successfully crossdated. We identified 373 fire scars recorded in the annual growth rings of the samples that represented 57 unique fire events during the period 1707–2010 (Figure 5.3). The interval distributions for all fires were positively skewed, with more short intervals (2–6 years) between fires. Although similar, the Weibull median probability interval (4 years; WMPI) was shorter than the mean fire interval (5 years; MFI; Table 2). We were able to classify fire seasonality for 95% ($n = 355$) of the fire scars; 30% of fires occurred at the transition between earlywood and latewood, and 70% were positioned in the latewood. Although the MFI during the settlement and fire-management periods were relatively similar, differences between them were significant ($P < 0.05$; *t*-test; Table 3). The mean percentages of trees scarred per fire during the two periods were markedly different, however. The percentage of scarred trees during the settlement period was significantly higher than during the fire-management period ($P < 0.05$, *t*-test).

Ten widespread (≥ 50% scarred) fires occurred during the period 1707–1851, but sample depth was low during this period. The period of reliability (at least 10 recorder trees) for our fire reconstruction spanned 1852–2010. During this period, our reconstruction revealed 13 widespread fires on BPK. Of these 13 fires, 10 occurred

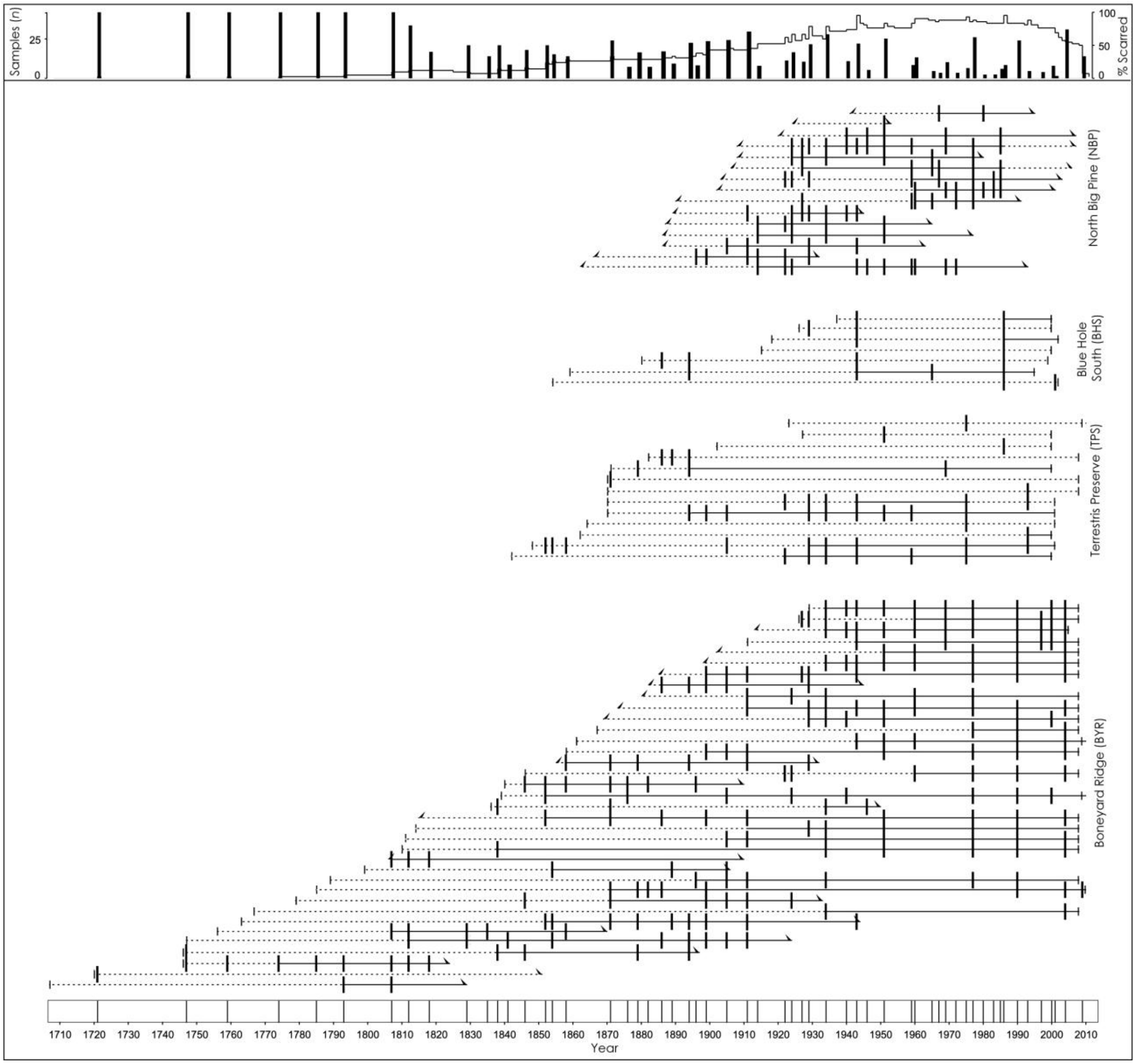

Figure 5.3. Fire history chart (1707–2010) for the four study sites in the National Key Deer Refuge, Big Pine Key, Florida Keys, USA. Top: Solid black line is the number of samples (n) plotted with the percentage of trees that recorded each fire, represented by black bars. Bottom: Each horizontal line represents a sample and vertical tick marks represent fires. The composite record below the chart includes all fires.

before the establishment of the NKDR in 1957. After the establishment of the NKDR, the three widespread fires that were recorded were prescribed burns conducted by fire management personnel (Bergh and Wisby 1996).

5.4.2 Fire-climate relationships

Given our objective of testing historical fire-climate relationships, we included widespread fires that burned between 1852 and 1956 in our climate analyses (pre-management period). SEA indicated that widespread fires before the establishment of the NKDR were likely to occur during years of low precipitation, and one year following strong La Niña events (precipitation and Niño3.4 values significantly below average; Figure 5.4). Antecedent climate conditions forced by both ENSO and PDO were also important for widespread fire years. Three years prior to fire events, Niño3.4 and PDO values were significantly above average (wet conditions). Although temperature was above average during fire years, results were not statistically significant ($P > 0.05$).

5.5 Discussion

5.5.1 What were the characteristics of the fire regime on BPK?

Low sample depth and scarcity of fire scars and recorder years precluded characterization of the fire regime before 1852. Our fire history reconstruction indicated that the fire regime on BPK was defined by relatively frequent surface fires from the

Table 5.2. Composite fire interval statistics (years) for Big Pine Key, Florida Keys, USA.

Characteristics	Composite Fire Record
Samples (*n*)	71
Total fires	57
MFI	
All fires	5.14
≥25% scarred	8.23
≥50 % scarred	12.52
WMPI	
All fires	4.39
≥25% scarred	7.54
≥50% scarred	11.92
Range	1–26
SD	4.33

MFI = mean fire interval; WMPI = Weibull median probability interval; SD = standard deviation

Table 5.3. Composite fire statistics (years) for settlement (ca. 1840–1956) and fire-management (1957–2010) periods on Big Pine Key, Florida Keys, USA.

Period	*n*	Mean	SE	SD
MFI				
1840–1956	25	4.40*	0.48	2.40
1957–2010	18	2.78*	0.29	1.22
Percent Scarred				
1840–1956	26	38.74*	3.41	17.37
1957–2010	19	26.58*	6.22	27.10

Mean values with an asterisk are statistically different ($P < 0.05$, t-test); n = number of observations; SE = standard error; SD = standard deviation; MFI = mean fire interval

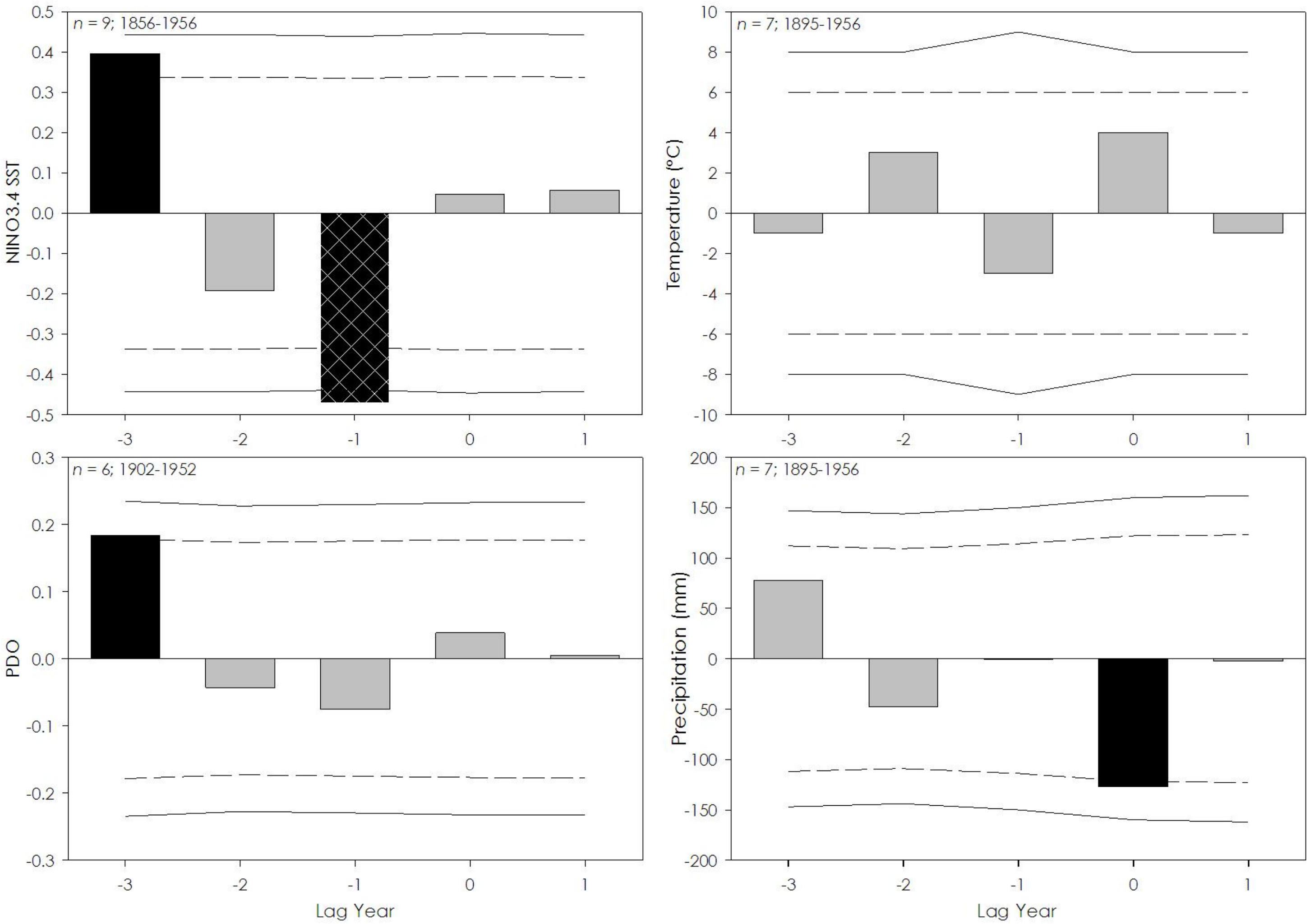

Figure 5.4. Superposed epoch analysis showing departures from mean annual NIÑO3.4, PDO, temperature (°C), and precipitation (mm) during years containing a widespread fire that scarred ≥ 50% of recorder trees from all four sites. The horizontal lines are the 95% (dashed) and 99% (solid) confidence intervals derived from 1000 Monte Carlo simulations performed on the entire data sets. Solid black and crosshatched bars represent departures that exceeded confidence limits.

1850s to the 1950s. The number of well-preserved fire scars found on individual trees demonstrated the prevalence of historical fire in these communities. On average, individual trees contained five scars, and several trees experienced and survived up to 12 fires. The intra-annual positions of fire scars were most commonly in the latewood zones of annual growth rings (70%), or at the transition between earlywood and latewood zones (30%). A contemporary study of cambial phenology indicated that on BPK, slash pines form earlywood from February through June, latewood from July through November, and are dormant during December and January (Harley et al. *in press*). These data indicate that fires on BPK may be more common, of greater intensity, or resulting in greater tree injury later in the growing season. In South Florida, the majority of thunderstorms and lightning strikes occur from May to October, and previous studies found that the largest lightning-caused fires on the mainland occur during this period (Taylor 1981, Beckage et al. 2003).

Archaeological evidence from the Lower Florida Keys is limited, and the initial timing of human arrival and patterns of movement between and around islands remains largely unknown (Worth 1995). Given the relationship between wildfire and La Niña on BPK and the abundance of mid- to late-season scars, we propose that the majority of historical fires were likely ignited by lightning strikes. Bergh and Wisby (1996) used written fire records to document fires that occurred across the entire island of BPK during 1961–1996, a period covering most of the fire-management period.

During this time, they documented 58 fires, of which 27 were wildfires, and 31 were prescribed burns. Of the documented wildfire, 6 were known to be caused by lightning and occurred between April and September.

5.5.2 Did the historical fire regime change in the 20th century?

The frequency and spatial extent of fire events were significantly different between the settlement period (*ca.* 1840–1956) and the fire-management period (1957–2010). Although the MFI values during settlement and fire-management periods were relatively similar, the difference between them was statistically significant ($P < 0.05$; *t*-test). During the settlement period, fires on BPK burned about every four years and were spatially extensive, possibly burning large areas of the island. As the human population on BPK slowly increased from the early to middle 1900s, fires became more frequent and less widespread. After the establishment of the NKDR in 1957, fires occurred nearly twice as often as during the settlement period and were spatially restricted, likely due to an increase in roads, active fire management policies, and more incendiary fires due to increased population.

The locations of the four study sites on BPK made possible an analysis of the spatial extent of fires across much of the island. The periods of reliability for the fire records from BHS and TPS were not similar to those from NBP and BYR. Nonetheless, an analysis of the spatial extent of fires across BPK suggests that before the 1950s, wildfires burned large areas of the island. Beginning in the 1960s, however, fires at each site became less frequent and more patchy, scarring fewer trees. Several widespread fires within sites did occur during the fire-management period, but these were prescribed burns conducted by NKDR personnel in 1977, 1990, and 2004. Habitat fragmentation and active fire management were likely causes of the change in spatial extent of fire between the settlement and fire-management periods documented by the difference between percentages of trees scarred during these two intervals.

5.5.3 What are the effects of ENSO and PDO on fires in the Florida Keys?

Our analyses of fire and climate revealed that the historical fire regime on BPK was influenced by years of low precipitation in combination with cycles of ENSO and PDO. Beckage et al. (2003) discovered that El Niño/La Niña phase cycles influenced fire regimes in the Everglades from 1948 to 1999. They proposed that increased winter (dry-season) rainfall associated with El Niño increased plant growth and preconditioned fire activity. In contrast, the decreased winter rainfall associated with La Niña resulted in lowered surface water levels in the Everglades, increased the spatial continuity of fine fuels, and allowed fires to spread over larger areas. The ENSO portion of our results agrees with the findings of Beckage et al. (2003), and we suggest that the same interacting effects of El Niño/La Niña, in part, influence fire occurrence on BPK. In addition to the interacting effects of ENSO on fires, we suggest that modulation of El Niño/La Niña phases by PDO may influence fires on BPK.

Although weakly significant, we found that El Niño conditions (wet) occur three years prior to fire events and could produce increased growth of fine fuels (grasses, shrubs, palms), just as Beckage et al. (2003) proposed in the Everglades of southern Florida. In addition to El Niño conditions, we found evidence that suggests the ENDM, which is known to intensify winter precipitation anomalies in southern Florida (Kurtzman and Scanlon 2007), was responsible for increased fire activity on BPK. Our results suggest that positive anomalies of El Niño were strengthened by PDO warm phases, which could cause increased growth of fine fuels. In congruence with dry years, strong La Niña conditions one year before fire years seem to be responsible for escalating the probability of fire weather that supports the frequent and widespread wildfires on which the pyrogenic pine rocklands depended prior to the advent of intentional human ignitions.

We did not find convincing evidence for an association between the LNDM and wildfires. Although PDO values one year prior to fire events were generally negative, departures from mean were not significant. This result was not surprising given that Kurtzman and Scanlon (2007) found that the PDO modulation was more related to El Niño than La Niña in southern Florida. They found the effect of PDO on La Niña winter precipitation to be negligible, in keeping with our results relative to climate drivers of wildfire activity in the Lower Florida Keys.

Because we hypothesized that a relationship exists between the ENDM and fire, we expected to find significant departures (higher) from mean precipitation three years prior to fire events. Although values were not statistically significant, precipitation was generally above normal during this time. An explanation of this result could be the unknown error associated with using precipitation data averaged over Florida Climate Division 7, which can vary drastically between the southern portion of peninsular Florida and the Lower Florida Keys; rainfall totals may not be representative of what was actually experienced on BPK. Regardless, we have shown that antecedent phase patterns of ENSO and PDO, combined with drier than normal years, might result in widespread fire on BPK. In the past, these fires likely burned large areas and contributed to the long-term persistence of pine rockland communities in the Lower Florida Keys.

5.5 Conclusions

Pine rocklands are globally endangered, pyrogenic plant communities restricted to The Bahamas and small areas in southern Florida. On BPK, we suggest linkages between climatic variability in the equatorial Pacific and historical wildfire occurrence, and given the co-development of pine rocklands with fire, these processes have likely operated for thousands of years across the Lower Florida Keys region (Tudhope et al. 2001). Our results are applicable to other areas of pine rockland habitat. Additional fire-scar data (including increased sample depth during the 18th and 19th centuries) from neighboring islands in the Lower Florida Keys, southern mainland Florida, and The Bahamas could reveal broader, longer-term spatial relationships between climate and wildfire activity.

5.6 Acknowledgements

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Chapter 6

Summary and Conclusions

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Summary and Conclusions

The purpose of this dissertation research was to identify the ecological and climatic processes responsible for the long-term persistence of pine rocklands in the Florida Keys and investigate how human-induced changes during the past several centuries contributed to the decline of these endangered communities. Additionally, this research fills a void in our knowledge of how global-scale climate dynamics and natural and human-induced disturbances shape the distribution of pine rocklands. This chapter summarizes the major findings of my research.

Tree-ring analysis in Florida has primarily been limited to species located in central and northern regions of the state. Although the majority of tree species in South Florida fail to produce annual rings, my research demonstrated that South Florida slash pine is a species of dendrochronological value. Multi-centennial chronologies can be developed and used to provide more detailed information regarding the structure and dynamics of endangered pine rockland communities and how fire disturbance has shaped the current distribution of slash pine in the Lower Florida Keys. Slash pine is the southernmost pine species in the United States and the only pine to inhabit the lower third of peninsular Florida. Hence, because slash pine in the Lower Florida Keys exists at its southern range limit, the species could prove vital for understanding the possible effects of future climate change on range distributions of species in habitats that could be especially vulnerable to increasing global temperatures. The expected higher temperatures could reduce growth rates of these pines as indicated by the correlation and response function analysis results, leading to moisture stress that could lead to increased mortality of pines that survived the effects of Hurricane Wilma. Warmer temperatures, rising sea levels, and increased incidence of salt-water intrusion may hence render future studies of slash pine in the Lower Florida Keys impossible, creating the need for a better understanding of pine rockland dynamics while they still exist.

After establishing the annual nature of growth rings in slash pine, I demonstrated that the growing season of slash pine is characterized by a short period of dormancy from December to January, the formation of earlywood tracheids from February to June, and the formation of latewood tracheids from June to December. Based on these results, I propose that the initiation of cambial activity, production of tracheids throughout the growing season, and cambial dormancy are controlled by threshold levels of solar radiation and/or day length. However, I was unable to identify the ecophysiological processes behind the formation of intra-annual density fluctuations (IADFs) in slash pine given our study design. Because IADFs can be caused by various factors (*i.e.* drought, wind stress), more research is needed to fully understand their occurrence in LFK slash pine environments.

I established that dendroecological analyses of slash pines can reveal both natural processes and management practices responsible for the documented successional pattern in pine rockland ecosystems in southern Florida, especially during the late 20th century. I found that the fire regimes of two adjacent islands differed in return interval, frequency, and relative spatial extent, but were similar in fire season. At the Boneyard Ridge site (BYR), fire activity decreased with the establishment of the NKDR, but recruitment was ubiquitous, likely due to multiple, widespread prescribed burns conducted in recent years. Although the No Name Key site (NNK) experienced fewer fires altogether than BYR, pines recruited at the site from at least the 1890s until the 1980s. The near absence of recruitment at NNK currently suggests that the lack of fire since the 1990s might result in the loss of pine rockland habitat in the future.

The structure of the BYR stand demonstrates that prescribed fire can be used to restore and sustain structural features (density, basal area, fuel loads) resembling those that existed before the 1950s (fire-management period). However, re-introducing prescribed fire on NNK will be complicated by the density of understory vegetation and the amount of course woody debris. Implementing prescribed fires that do not become crown fires that kill overstory pines will be a daunting task for land managers, perhaps requiring initial manual clearing of understory fuels. The fire history and stand structure characterizations we produced for Big Pine and No Name Keys testify to both the past success of prescribed fire as a management tool and the difficulty of initiating this management tool in long-unburned pine rocklands stands of the Florida Keys.

Fire is a primary disturbance that shapes the distribution of slash pine on islands in the Lower Florida Keys. Microscopic and macroscopic charcoal in sediment cores from small ponds on Big Pine and No Name Keys demonstrate repeated fire through the late Holocene (Albritton 2009, Kocis 2012, Horn *unpublished data*). However, archaeological evidence on the timing and movement of people in the Florida Keys is scarce, resulting in some uncertainty over ignition sources (e.g. anthropogenic versus climate) of historic and prehistoric wildfires recorded by tree rings and sedimentary charcoal. Based on my tree-ring chronologies, I suggest linkages between climatic variability in the equatorial Pacific and historical wildfire occurrence on BPK, the largest island in the Lower Florida Keys. The fire-climate relationship data suggest that antecedent phase patterns of ENSO and PDO, combined with drier than normal years, might result in widespread fire on BPK. In the past, these fires likely burned large areas and contributed to the long-term persistence of pine rockland communities in the Lower Florida Keys. Given the co-development of pine rocklands with fire, these processes have likely operated for thousands of years across the Lower Florida Keys region. The fire regime and fire-climate results are applicable to other areas of pine rockland habitat. Additional fire-scar data from neighboring islands, as well as increased sample depth during the 18th and 19th centuries, could reveal broader, longer-term spatial relationships between climate and wildfire occurrence in the Lower Florida Keys.

6.1 Recommendations for future research

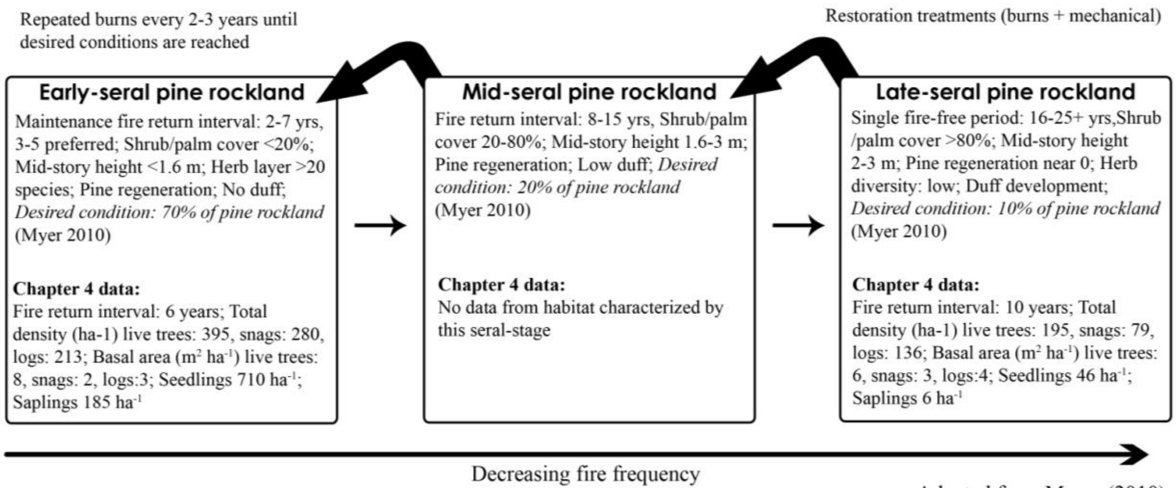
This research demonstrated that the southernmost native distributed conifer in the United States forms consistently annual growth rings and is a useful species for ecological and climatic studies. Although I was able to show that late season moisture availability is an important climatic variable for annual slash pine radial growth, the overall climate signal found using total annual ring width was weak. In addition to considering total ring-width chronologies, future dendroclimatological research in this area should investigate a slash pine climate signal using earlywood/latewood tree-ring chronologies and stable oxygen isotopic ratios within annual growth rings. Analysis of stable oxygen isotopic ratios within annual growth rings also provides the opportunity to potentially reconstruct drought and tropical cyclone occurrence for the Lower Florida Keys region.

The research outlined in this dissertation was conducted on two of the five islands that contain pine rockland savanna habitat in the Florida Keys. To test whether the relationships between historical wildfires and ocean/atmosphere oscillations found in pine rocklands of the Lower Florida Keys exist at broader spatial scales, future research projects should investigate these potential relationships in other pine rockland areas. To broaden the fire history network in the Southeast United States and the Caribbean Basin, fire history chronologies should be developed from habitat areas on other islands in the Lower Florida Keys, mainland southern Florida, and The Bahamas.

6.2 Conceptual ecological model and desired future conditions

On February 12, 2010, the Pine Rocklands Working Group held a workshop in Coral Gables, Florida. One of the primary results from this workshop was a customized conceptual ecological model for pine rockland in the National Key Deer Refuge (NKDR), Lower Florida Keys (Myers 2010; Figure 1.1). The ecological model for the NKDR pine rocklands incorporates the desired future condition preferences of land managers and agencies. Current and future management decisions in the NKDR will be made based on the desire to have 70% of pine rockland habitat characterized at the early-seral stage, 20% at the mid-seral stage, and 10% at the late-seral stage.

I incorporated data from Chapter 4 into the original model and these data agree with some of the model parameters, but revise others. The fire history reconstruction from the Boneyard Ridge site (BYR; early-seral stage) revealed a fire return interval of 6 years, which is within the 2–7 year maintenance fire interval range, but greater than the upper end of the preferred interval (5 years). Structural data from BYR revealed the stand to be at the early-seral stage (as defined by Myers 2010), which is the most desired successional stage for habitat in the NKDR (70%). The fire history reconstruction from the No Name Key site (NNK; late-seral stage) revealed a fire return interval of 10 years, which is more frequent than the later-seral stage fire return interval range proposed in the model (16–25+). Rather, the 10-year fire return interval found in the late-seral habitat at NNK was within the fire return interval range for the mid-seral stage (8–15 years).



Early-seral pine rockland

Maintenance fire return interval: 2-7 yrs, 3-5 preferred; Shrub/palm cover <20%; Mid-story height <1.6 m; Herb layer >20 species; Pine regeneration; No duff; *Desired condition: 70% of pine rockland* (Myer 2010)

Chapter 4 data:
Fire return interval: 6 years; Total density (ha-1) live trees: 395, snags: 280, logs: 213; Basal area (m^2 ha^{-1}) live trees: 8, snags: 2, logs:3; Seedlings 710 ha^{-1}; Saplings 185 ha^{-1}

Mid-seral pine rockland

Fire return interval: 8-15 yrs, Shrub/palm cover 20-80%; Mid-story height 1.6-3 m; Pine regeneration; Low duff; *Desired condition: 20% of pine rockland* (Myer 2010)

Chapter 4 data:
No data from habitat characterized by this seral-stage

Late-seral pine rockland

Single fire-free period: 16-25+ yrs,Shrub /palm cover >80%; Mid-story height 2-3 m; Pine regeneration near 0; Herb diversity: low; Duff development; *Desired condition: 10% of pine rockland* (Myer 2010)

Chapter 4 data:
Fire return interval: 10 years; Total density (ha-1) live trees: 195, snags: 79, logs: 136; Basal area (m^2 ha^{-1}) live trees: 6, snags: 3, logs:4; Seedlings 46 ha^{-1}; Saplings 6 ha^{-1}

Adapted from Myers (2010)

Figure 6.1. Revised conceptual ecological model for pine rockland ecosystems in the National Key Deer Refuge, Lower Florida Keys including data from Myers (2010) and this dissertation.

Fire history and stand structure data from NNK demonstrate that pine rockland habitat can progress to the late-seral stage with a fire return interval of 10 years.

The inclusion of tree-ring based fire history and stand structure data from early- and late-seral habitat areas in the NKDR suggests the need to revise the current conceptual ecological model proposed by Myers (2010). More data on the historical fire frequency, vegetation structure, and fire effects on vegetation, especially from mid-seral pine rockland, are needed to better refine model parameters in the NKDR. A revised ecological model will aid land managers in implementing the desired future conditions of NKDR pine rocklands.

References

Albritton, J.W. 2009. A 1700-year history of fire and vegetation in Pine Rocklands of National Key Deer Refuge, Big Pine Key, Florida: Charcoal and pollen evidence from Key Deer Pond. M.S. Thesis, Department of Geography, University of Tennessee, Knoxville.

Kocis, D.L. 2012. Reconstruction of fire history in the National Key Deer Refuge, Monroe County, Florida: The Palmetto Pond macroscopic charcoal record. M.S. Thesis, Department of Geography, University of Tennessee, Knoxville.

Myers, R.L. 2010. Pine rockland fire management decision-making workshop: a synopsis. Pine Rockland Working Group. http://fl.biology.usgs.gov/pineland/pdf/Pine_Rocklands_Fire_Workshop_Synopsis.pdf

Appendices

Appendix 1. COFECHA program output for Boneyard Ridge site chronology, Big Pine Key, Lower Florida Keys.

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P R O G R A M     C O F E C H A                                                                                        Version 6.06P    27843
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 QUALITY CONTROL AND DATING CHECK OF TREE-RING MEASUREMENTS

 File of DATED series:   BYR.TXT

 Time span of Master dating series is  1707 to  2009   303 years
 Continuous time span is               1707 to  2009   303 years
 Portion with two or more series is    1721 to  2009   289 years

                                                        ****************************************
                                                        *C* Number of dated series        63 *C*
                                                        *O* Master series 1707 2009  303 yrs *O*
                                                        *F* Total rings in all series   7367 *F*
                                                        *E* Total dated rings checked   7353 *E*
                                                        *C* Series intercorrelation     .576 *C*
                                                        *H* Average mean sensitivity    .461 *H*
                                                        *A* Segments, possible problems    5 *A*
                                                        *** Mean length of series      116.9 ***
                                                        ****************************************

ABSENT RINGS listed by SERIES:            (See Master Dating Series for absent rings listed by year)

BYR31x A    1 absent rings:   1992
BYR31axA    2 absent rings:   1853  1930
BYR35x A    1 absent rings:   1766
BYR42x A    1 absent rings:   1882
BYR48x A    1 absent rings:   1942
BYR112xA    1 absent rings:   1845
BYR505xA    1 absent rings:   1838

8 absent rings    .109%
```

```
PART 2:  TIME PLOT OF TREE-RING SERIES
1050 1100 1150 1200 1250 1300 1350 1400 1450 1500 1550 1600 1650 1700 1750 1800 1850 1900 1950 2000 2050 Ident   Seq Time-span  Yrs
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   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <====>    . BYR602 B   5 1954 2009   56
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <======>    . BYR603 D   6 1933 2009   77
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   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<===>    . BYR607 D  10 1969 2009   41
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<========>    . BYR608 C  11 1916 2009   94
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <=========>    . BYR609 C  12 1908 2009  102
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   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <====>    . BYR616 E  17 1958 2009   52
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   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<==================>    . BYR40x A  32 1810 2008  199
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                           1750   .823   6          1800   .271  13          1850  -.699  21          1900 -1.373  32          1950  -.221  43
                           1751  -.201   6          1801  -.419  13          1851  1.142  21          1901   .685  32          1951 -2.302  42
                           1752 -2.673   6          1802  -.208  13          1852  -.145  20          1902   .689  33          1952   .222  42
                           1753  -.351   6          1803   .592  13          1853 -2.606  20  1       1903   .219  33          1953   .749  42
                           1754   .871   6          1804   .202  13          1854   .486  20          1904 -2.285  34          1954   .355  44
                           1755   .745   6          1805  -.102  13          1855   .029  21          1905   .463  33          1955   .352  44
                           1756  -.253   7          1806 -1.423  13          1856   .973  21          1906   .523  33          1956   .492  44
  1707  -.682   1          1757  -.444   7          1807  1.285  13          1857  -.316  21          1907   .190  34          1957   .960  44
  1708   .221   1          1758  -.489   7          1808  -.689  13          1858   .407  22          1908   .143  35          1958   .135  45
  1709   .811   1          1759  -.767   7          1809   .089  13          1859 -1.705  22          1909   .350  35          1959 -2.601  45

  1710 -2.678   1          1760   .188   7          1810  1.348  14          1860 -1.102  22          1910   .894  35          1960  -.990  45
  1711  1.027   1          1761   .696   7          1811  -.135  15          1861  -.656  23          1911   .862  34          1961  -.064  45
  1712 -2.115   1          1762   .871   7          1812  1.689  15          1862   .310  23          1912  -.577  34          1962   .376  45
  1713  2.486   1          1763   .973   8          1813  -.624  15          1863   .723  23          1913   .875  35          1963   .600  45
  1714  -.718   1          1764  1.090   8          1814   .324  16          1864   .979  23          1914   .112  35          1964  -.301  45
  1715   .174   1          1765  -.404   8          1815   .183  17          1865   .956  23          1915   .297  35          1965   .757  45
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  1717  -.190   1          1767   .670   9          1817 -1.551  17          1867   .308  26          1917  -.691  36          1967   .544  45
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  1720  1.555   1          1770  -.397   9          1820   .645  17          1870   .202  27          1920   .420  37          1970   .419  46
  1721  2.077   2          1771   .474   9          1821 -1.034  17          1871 -1.709  26          1921   .214  38          1971   .294  46
  1722  1.028   2          1772   .422   9          1822 -1.554  18          1872   .348  26          1922   .762  39          1972   .464  46
  1723  -.048   2          1773  -.620   9          1823  -.829  18          1873   .734  27          1923   .857  39          1973   .302  46
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  1733   .030   2          1783   .599  10          1833   .178  16          1883   .223  29          1933   .538  42          1983   .530  47
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  1736   .016   2          1786 -2.475  11          1836  1.437  17          1886   .831  32          1936   .361  43          1986   .750  47
  1737   .868   2          1787  -.007  11          1837   .601  17          1887   .012  32          1937   .435  43          1987   .513  47
  1738   .801   2          1788   .708  11          1838 -1.571  18  1       1888 -1.636  32          1938   .721  43          1988  -.255  47
  1739   .055   2          1789  -.327  12          1839   .284  19          1889   .395  32          1939   .433  43          1989  -.454  47

  1740  -.593   2          1790 -1.655  12          1840  -.817  20          1890  1.128  32          1940   .682  43          1990  -.322  47
  1741  1.124   2          1791   .857  12          1841   .160  20          1891   .548  32          1941  -.178  43          1991  -.133  47
  1742  1.467   2          1792  1.085  12          1842  1.139  20          1892 -2.783  32          1942 -2.938  43  1       1992 -2.999  47  1
  1743 -2.227   2          1793  1.158  12          1843   .733  20          1893  -.036  32          1943  -.009  43          1993   .241  47
  1744 -2.264   2          1794   .890  12          1844 -1.225  20          1894   .658  32          1944  -.406  43          1994   .252  47
  1745   .490   2          1795  -.645  12          1845 -2.061  20  1       1895   .572  32          1945   .315  42          1995   .098  47
  1746 -1.197   2          1796   .574  12          1846   .233  21          1896  -.185  32          1946   .675  42          1996   .281  47
  1747  1.250   5          1797   .501  12          1847  1.196  21          1897   .416  32          1947  -.242  42          1997   .842  47
  1748   .817   5          1798  -.952  12          1848  1.058  21          1898   .424  32          1948   .732  43          1998   .313  46
  1749   .610   5          1799 -2.172  13          1849   .392  21          1899  -.165  32          1949  -.303  43          1999  -.142  46
```

```
PART 3:  Master Dating Series (CONT)
2000   .293  46
2001   .593  46
2002  -.028  46
2003  -.775  46
2004  -.060  46
2005   .468  46
2006   .632  46
2007  -.505  46
2008   .543  46
2009  -.961  24
```

```
PART 4:  Master Bar Plot:
------------------------------------------------------------------------------------------------------------------------------------
   Year Rel value  Year Rel value  Year Rel value  Year Rel value  Year Rel value  Year Rel value  Year Rel value  Year Rel value
                   1750---------C  1800-----A      1850--c         1900-e          1950---a        2000-----A
                   1751---a        1801--b         1851----------E 1901--------C   1951i           2001-------B
                   1752k           1802---a        1852---a        1902--------C   1952-----A      2002----@
                   1753---a        1803-------B    1853j           1903-----A      1953--------C   2003--c
                   1754---------C  1804-----A      1854------B     1904i           1954------A     2004----@
                   1755--------C   1805---@        1855----@       1905------B     1955------A     2005------B
                   1756---a        1806-f          1856---------D  1906-------B    1956-------B    2006-------C
   1707--c         1757--b         1807----------E 1857---a        1907-----A      1957---------D  2007--b
   1708-----A      1758--b         1808--c         1858------B     1908----A       1958----A       2008-------B
   1709---------C  1759--c         1809----@       1859g           1909------A     1959j           2009-d
   1710k           1760-----A      1810----------E 1860-d          1910---------D  1960-d
   1711----------D 1761--------C   1811---a        1861--c         1911---------C  1961----@
   1712h           1762---------C  1812----------G 1862-----A      1912--b         1962------B
   1713----------J 1763---------D  1813--b         1863--------C   1913---------D  1963-------B
   1714--c         1764----------D 1814-----A      1864---------D  1914----@       1964---a
   1715-----A      1765--b         1815-----A      1865---------D  1915-----A      1965--------C
   1716---------C  1766j           1816--------C   1866---------C  1916i           1966--------C
   1717---a        1767--------C   1817-f          1867-----A      1917--c         1967-------B
   1718--c         1768----A       1818---a        1868-f          1918--c         1968-------B
   1719--b         1769---a        1819------B     1869--------C   1919--b         1969---------C
   1720----------F 1770--b         1820--------C   1870-----A      1920------B     1970------B
   1721----------H 1771------B     1821-d          1871g           1921-----A      1971-----A
   1722----------D 1772------B     1822-f          1872------A     1922--------C   1972------B
   1723----@       1773--b         1823-c          1873--------C   1923---------C  1973-----A
   1724---a        1774----------G 1824------B     1874-----A      1924-------B    1974-c
   1725m           1775-----A      1825---a        1875g           1925-e          1975m
   1726-c          1776i           1826---------D  1876-----A      1926--------C   1976---@
   1727----------D 1777--c         1827----------D 1877-------B    1927------A     1977--b
   1728------B     1778---a        1828--c         1878---------D  1928-------B    1978--b
   1729----@       1779-----A      1829---------C  1879----------F 1929---@        1979---a
   1730h           1780---------C  1830----------D 1880-------B    1930i           1980-----A
   1731---------D  1781-e          1831--b         1881----@       1931-----A      1981----@
   1732-e          1782---------D  1832-f          1882g           1932-d          1982-------B
   1733----@       1783-------B    1833-----A      1883-----A      1933-------B    1983-------B
   1734----@       1784--------C   1834----------D 1884----@       1934-------B    1984-------C
   1735---------C  1785--------C   1835-----A      1885---a        1935---------D  1985-------C
   1736----@       1786j           1836----------F 1886---------C  1936------A     1986--------C
   1737---------C  1787----@       1837-------B    1887----@       1937------B     1987-------B
   1738---------C  1788--------C   1838-f          1888-g          1938--------C   1988---a
   1739----@       1789---a        1839-----A      1889------B     1939------B     1989--b
   1740--b         1790-g          1840-c          1890----------E 1940--------C   1990---a
   1741----------D 1791---------C  1841-----A      1891-------B    1941---a        1991---a
   1742----------F 1792----------D 1842----------E 1892k           1942l           1992l
   1743i           1793----------E 1843--------C   1893----@       1943----@       1993-----A
   1744i           1794---------D  1844-e          1894--------C   1944--b         1994-----A
   1745-------B    1795--c         1845h           1895-------B    1945-----A      1995----@
   1746-e          1796-------B    1846-----A      1896---a        1946--------C   1996-----A
   1747----------E 1797-------B    1847----------E 1897------B     1947---a        1997---------C
   1748---------C  1798-d          1848----------D 1898------B     1948--------C   1998-----A
   1749-------B    1799i           1849------B     1899---a        1949---a        1999---a
```

```
PART 5:  CORRELATION OF SERIES BY SEGMENTS
-----------------------------------------------------------------------------------------------------------------------------------
 Correlations of  50-year dated segments, lagged  25 years
 Flags:  A = correlation under   .3281 but highest as dated;  B = correlation higher at other than dated position

 Seq Series  Time_span   1700 1725 1750 1775 1800 1825 1850 1875 1900 1925 1950 1975
                         1749 1774 1799 1824 1849 1874 1899 1924 1949 1974 1999 2024
 --- -------- ---------  ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ----
   1 BYR60  B 1886 2009                                       .71  .64  .41  .47  .53
   2 BYR61  A 1933 2009                                                 .63  .54  .50
   3 BYR62  B 1924 2009                                            .78  .76  .62  .45
   4 BYR601 B 1935 2008                                                 .64  .68  .64
   5 BYR602 B 1954 2009                                                      .52  .41
   6 BYR603 D 1933 2009                                                 .48  .50  .45
   7 BYR604 D 1943 2009                                                 .66  .64  .58
   8 BYR605 D 1935 2009                                                 .50  .50  .50
   9 BYR606 D 1946 2009                                                 .52  .55  .56
  10 BYR607 D 1969 2009                                                      .67
  11 BYR608 C 1916 2009                                            .75  .69  .65  .59
  12 BYR609 C 1908 2009                                            .40  .52  .60  .54
  13 BYR610 D 1907 2009                                            .61  .62  .66  .58
  14 BYR612 D 1867 2009                                  .63  .65  .55  .67  .66  .54
  15 BYR614 D 1904 2008                                            .59  .65  .57  .57
  16 BYR615 C 1867 2009                                  .72  .66  .48  .43  .31A .19B
  17 BYR616 E 1958 2009                                                      .67  .58
  18 BYR617 A 1954 2009                                                      .65  .60
  19 BYR620 B 1919 2009                                            .66  .65  .64  .61
  20 BYR621 C 1948 2009                                                 .55  .55  .54
  21 BYR622 D 1921 2009                                            .76  .75  .64  .54
  22 BYR623 B 1922 2009                                            .49  .49  .36  .24A
  23 BYR625 C 1977 2009                                                           .43
  24 BYR626 A 1977 2009                                                           .47
  25 BYR627 B 1884 2008                                       .61  .54  .64  .57  .48
  26 BYR001 A 1835 1944                             .63  .59  .41  .50
  27 BYR30x A 1869 2008                                  .63  .56  .45  .49  .61  .60
  28 BYR31x A 1839 2009                             .71  .72  .72  .63  .51  .50  .41
  29 BYR31axA 1763 1942              .73  .69  .68  .59  .60  .66  .63
  30 BYR35x A 1721 1851    .53  .54  .61  .63  .50  .56
  31 BYR36x C 1785 2008                   .57  .66  .62  .59  .64  .61  .58  .61  .50
  32 BYR40x A 1810 2008                        .72  .71  .65  .67  .68  .60  .42  .36
  33 BYR42x A 1822 1979                        .65  .68  .63  .63  .72  .74  .76
  34 BYR43x B 1750 1910              .63  .70  .69  .68  .53  .51
  35 BYR44x A 1747 1897         .35  .41  .42  .41  .54  .56
  36 BYR45x A 1858 2008                                  .62  .51  .25B .41  .62  .56
  37 BYR46x A 1779 1933                   .68  .65  .69  .68  .55  .56
  38 BYR48x A 1767 2008              .59  .52  .65  .72  .42  .37  .59  .56  .61  .59
  39 BYR49x A 1846 2008                             .81  .82  .71  .50  .45  .56  .60
  40 BYR50x C 1789 2008                   .45  .47  .41  .51  .47  .55  .58  .45  .32A
  41 BYR112xA 1747 1924         .60  .63  .71  .62  .61  .67  .62
  42 BYR501xA 1880 2008                                       .69  .78  .76  .63  .58
  43 BYR502xB 1898 2008                                       .67  .65  .71  .61  .57
  44 BYR503xA 1929 2008                                                 .56  .43  .41
  45 BYR504xA 1747 1824         .45  .46  .53
  46 BYR505xA 1756 1870              .48  .57  .65  .69
  47 BYR507xA 1913 1997                                            .63  .62  .68
  48 BYR510xB 1902 2008                                            .54  .52  .48  .42
  49 BYR511xC 1867 2008                                  .54  .64  .64  .49  .51  .51
  50 BYR512xA 1873 2008                                  .63  .61  .61  .53  .65  .50
  51 BYR513xA 1911 2008                                            .52  .43  .61  .54
```

```
  PART 5:  CORRELATION OF SERIES BY SEGMENTS (CONT)
  52 BYR514xB 1932 2008                                                .62  .64  .58
  53 BYR515xB 1885 2008                                      .70  .69  .67  .66  .70
  54 BYR516xB 1815 2008                       .68  .69  .59  .65  .74  .65  .52  .37
  55 BYR518xA 1811 2008                       .61  .63  .53  .53  .57  .44  .44  .36
  56 BYR519xA 1814 2008                       .67  .68  .80  .68  .61  .70  .61  .56
  57 BYR520xA 1838 1950                            .74  .78  .66  .57  .55
  58 BYR521xB 1799 1904                  .53  .60  .52  .36  .42
  59 BYR600xA 1855 1932                                 .48  .38  .49
  60 BYR700AA 1707 1829   .60  .62  .69  .64  .60
  61 BYR701xB 1882 1945                                      .34  .39
  62 BYR702xD 1861 2009                                 .40  .48  .46  .55  .63  .60
  63 BYR703xB 1840 1910                            .61  .65  .67
 Av segment correlation   .56  .51  .58  .59  .62  .64  .60  .59  .58  .58  .58  .51

PART 6:  POTENTIAL PROBLEMS:
------------------------------------------------------------------------------------------------------------------------------------

 For each series with potential problems the following diagnostics may appear:

 [A] Correlations with master dating series of flagged  50-year segments of series filtered with  32-year spline,
     at every point from ten years earlier (-10) to ten years later (+10) than dated

 [B] Effect of those data values which most lower or raise correlation with master series
     Symbol following year indicates value in series is greater (>) or lesser (<) than master series value

 [C] Year-to-year changes very different from the mean change in other series

 [D] Absent rings (zero values)

 [E] Values which are statistical outliers from mean for the year
====================================================================================================================================

 BYR60  B  1886 to  2009     124 years                                                                                    Series   1

 [B] Entire series, effect on correlation (  .556) is:
       Lower   1969< -.018   1952< -.016   1942> -.015   1955< -.012   1978> -.012   1896> -.011  Higher   1992  .063   1892  .014

====================================================================================================================================

 BYR61  A  1933 to  2009      77 years                                                                                    Series   2

 [B] Entire series, effect on correlation (  .572) is:
       Lower   1954< -.036   1941< -.024   1985< -.014   1996< -.014   1975> -.013   1992> -.011  Higher   1942  .053   1959  .018

====================================================================================================================================

 BYR62  B  1924 to  2009      86 years                                                                                    Series   3

 [B] Entire series, effect on correlation (  .654) is:
       Lower   1974> -.015   1984< -.012   2005< -.011   1986< -.010   1989> -.009   1999> -.009  Higher   1942  .049   1959  .029

====================================================================================================================================

 BYR601 B  1935 to  2008      74 years                                                                                    Series   4

 [B] Entire series, effect on correlation (  .620) is:
       Lower   1936< -.028   1947> -.021   1988< -.019   2005< -.015   1986< -.014   1965< -.010  Higher   1992  .069   1959  .024
```

```
===================================================================================================================

 BYR602 B  1954 to  2009      56 years                                                                    Series   5

 [B] Entire series, effect on correlation (  .460) is:
       Lower   1997< -.048   2005< -.022   1978> -.020   1963< -.016   1983< -.016   1958< -.015  Higher   1992  .159   1959  .049

===================================================================================================================

 BYR603 D  1933 to  2009      77 years                                                                    Series   6

 [B] Entire series, effect on correlation (  .453) is:
       Lower   2009> -.026   1983< -.021   2001< -.018   1998< -.017   1959> -.017   1933< -.013  Higher   1992  .109   1975  .025

===================================================================================================================

 BYR604 D  1943 to  2009      67 years                                                                    Series   7

 [B] Entire series, effect on correlation (  .635) is:
       Lower   1951> -.027   2007> -.024   1999< -.023   1977> -.011   1991< -.010   1987< -.009  Higher   1959  .082   1975  .024

===================================================================================================================

 BYR605 D  1935 to  2009      75 years                                                                    Series   8

 [B] Entire series, effect on correlation (  .550) is:
       Lower   1994< -.019   1974> -.016   1973> -.016   1997< -.014   1985< -.014   1995< -.012  Higher   1992  .116   1942  .042

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1973 +3.3 SD
===================================================================================================================

 BYR606 D  1946 to  2009      64 years                                                                    Series   9

 [B] Entire series, effect on correlation (  .538) is:
       Lower   1957< -.032   1983< -.028   1971< -.027   2001< -.025   1977> -.020   1988> -.016  Higher   1992  .064   1975  .040

===================================================================================================================

 BYR607 D  1969 to  2009      41 years                                                                    Series  10

 [B] Entire series, effect on correlation (  .673) is:
       Lower   1992> -.063   2000< -.025   1971< -.019   1986< -.019   1999> -.012   1978> -.010  Higher   1975  .159   2009  .017

===================================================================================================================

 BYR608 C  1916 to  2009      94 years                                                                    Series  11

 [B] Entire series, effect on correlation (  .685) is:
       Lower   1991< -.010   1938< -.009   1973< -.009   1941> -.009   1993< -.008   1939< -.008  Higher   1942  .034   1951  .025

===================================================================================================================

 BYR609 C  1908 to  2009     102 years                                                                    Series  12

 [B] Entire series, effect on correlation (  .488) is:
       Lower   1924< -.061   1913< -.036   1939< -.015   1969< -.014   1934< -.010   1937< -.010  Higher   1959  .041   1916  .040

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
```

```
===================================================================================================================================

 BYR610 D  1907 to  2009     103 years                                                                                Series  13

 [B] Entire series, effect on correlation (  .609) is:
       Lower   2002< -.018   2009> -.014   1912> -.012   1923< -.008   1952< -.008   1940< -.008  Higher   1916  .033   1992  .029

===================================================================================================================================

 BYR612 D  1867 to  2009     143 years                                                                                Series  14

 [B] Entire series, effect on correlation (  .636) is:
       Lower   1925> -.010   1986< -.010   1877< -.008   1940< -.007   1989> -.007   1873< -.007  Higher   1892  .031   1959  .024

===================================================================================================================================

 BYR614 D  1904 to  2008     105 years                                                                                Series  15

 [B] Entire series, effect on correlation (  .574) is:
       Lower   1940< -.017   1953< -.017   1971> -.012   1975> -.010   1994> -.009   1909< -.009  Higher   1959  .055   1951  .021

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1971 +3.0 SD
===================================================================================================================================

 BYR615 C  1867 to  2009     143 years                                                                                Series  16

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
     1950 1999    0    .22  .18  .18 -.17 -.09 -.04  .05 -.20  .02 -.08  .31*-.35 -.29 -.08  .17  .08  .01  .25  .11  .19 -.14
     1960 2009  -10    .33*-.09  .13 -.08 -.02 -.04  .03 -.21 -.03 -.10  .19|   -    -    -    -    -    -    -    -    -    -

 [B] Entire series, effect on correlation (  .466) is:
       Lower   1985< -.034   1983< -.022   1935< -.016   1970< -.014   1978> -.012   1940< -.011  Higher   1942  .021   1904  .020
     1950 to 1999 segment:
       Lower   1985< -.081   1983< -.051   1970< -.032   1978> -.028   1958> -.021   1974> -.013  Higher   1951  .058   1959  .054
     1960 to 2009 segment:
       Lower   1985< -.072   1983< -.046   1978> -.031   1970< -.027   2007> -.018   1974> -.016  Higher   1992  .066   1975  .063

 [E] Outliers     3   3.0 SD above or -4.5 SD below mean for year
       1958 +3.3 SD;    1978 +3.0 SD;    1985 -5.3 SD
===================================================================================================================================

 BYR616 E  1958 to  2009      52 years                                                                                Series  17

 [B] Entire series, effect on correlation (  .654) is:
       Lower   1973< -.022   2001< -.021   1980< -.018   1997< -.017   2008< -.016   1989> -.008  Higher   1992  .119   1959  .079

===================================================================================================================================

 BYR617 A  1954 to  2009      56 years                                                                                Series  18

 [B] Entire series, effect on correlation (  .645) is:
       Lower   1998< -.022   1986< -.020   1993< -.014   1973< -.014   1975> -.013   1962< -.012  Higher   1992  .119   1959  .045

===================================================================================================================================

 BYR620 B  1919 to  2009      91 years                                                                                Series  19
```

```
 [B] Entire series, effect on correlation (  .643) is:
       Lower   1974> -.023   1920< -.018   1992> -.011   1993< -.009   1995> -.008   1941> -.008  Higher   1975  .044   1942  .024

====================================================================================================================================

 BYR621 C  1948 to  2009      62 years                                                                                    Series  20

 [B] Entire series, effect on correlation (  .564) is:
       Lower   1965< -.026   1992> -.023   1961< -.020   1953< -.015   2000< -.015   1974> -.015  Higher   1975  .056   1951  .030

====================================================================================================================================

 BYR622 D  1921 to  2009      89 years                                                                                    Series  21

 [B] Entire series, effect on correlation (  .660) is:
       Lower   1988< -.014   1982< -.014   1926< -.012   1936< -.011   1999> -.009   1928< -.009  Higher   1942  .051   1959  .026

====================================================================================================================================

 BYR623 B  1922 to  2009      88 years                                                                                    Series  22

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1960 2009    0   -.14  .11 -.09 -.09  .00  .12  .07 -.09 -.29 -.20  .24*   -    -    -    -    -    -    -    -    -    -

 [B] Entire series, effect on correlation (  .408) is:
       Lower   1997< -.035   1978> -.019   1952< -.017   1963< -.014   1984< -.013   2008< -.012  Higher   1951  .052   1975  .026
     1960 to 2009 segment:
       Lower   1997< -.060   1978> -.034   1963< -.024   1984< -.023   2008< -.021   1960> -.019  Higher   1975  .080   1992  .057

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
       1978 +3.3 SD;    2004 +3.1 SD
====================================================================================================================================

 BYR625 C  1977 to  2009      33 years                                                                                    Series  23

 [B] Entire series, effect on correlation (  .433) is:
       Lower   1977> -.067   1985< -.038   1988> -.030   1997< -.024   1987< -.023   2003> -.022  Higher   1992  .249   2007  .021

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1977 +3.1 SD
====================================================================================================================================

 BYR626 A  1977 to  2009      33 years                                                                                    Series  24

 [B] Entire series, effect on correlation (  .471) is:
       Lower   2009> -.069   1980< -.057   1978> -.039   1987< -.032   2000< -.026   2003> -.019  Higher   1992  .498   2007  .016

====================================================================================================================================

 BYR627 B  1884 to  2008     125 years                                                                                    Series  25

 [B] Entire series, effect on correlation (  .573) is:
       Lower   1984< -.011   1990> -.011   1905< -.009   1926< -.008   2002> -.008   1902< -.008  Higher   1892  .024   1992  .019

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1888 -5.3 SD
====================================================================================================================================
```

```
 BYR001 A  1835 to  1944     110 years                                                                                   Series  26

 [B] Entire series, effect on correlation (  .549) is:
       Lower   1907< -.056   1889< -.026   1918> -.011   1861> -.011   1876< -.010   1843< -.007  Higher   1942  .028   1892  .017

 [C] Year-to-year changes diverging by over 4.0 std deviations:
       1906 1907  -4.1 SD

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1907 -6.4 SD
===================================================================================================================================

 BYR30x A  1869 to  2008     140 years                                                                                   Series  27

 [B] Entire series, effect on correlation (  .558) is:
       Lower   1930> -.030   1957< -.014   1901< -.013   1919> -.009   1926< -.009   1981< -.008  Higher   1975  .038   1904  .021

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1930 +3.2 SD
===================================================================================================================================

 BYR31x A  1839 to  2009     171 years                                                                                   Series  28

 [B] Entire series, effect on correlation (  .645) is:
       Lower   2005< -.009   2003> -.008   1994< -.008   1951> -.007   1972< -.007   1957< -.007  Higher   1992  .032   1975  .019

 [D]    1 Absent rings:  Year   Master  N series Absent
                         1992   -2.999      47       1

===================================================================================================================================

 BYR31axA  1763 to  1942     180 years                                                                                   Series  29

 [B] Entire series, effect on correlation (  .677) is:
       Lower   1776> -.009   1816< -.007   1834< -.007   1859> -.006   1797< -.006   1867< -.004  Higher   1853  .015   1786  .011

 [D]    2 Absent rings:  Year   Master  N series Absent
                         1853   -2.606      20       1
                         1930   -2.283      40       1

===================================================================================================================================

 BYR35x A  1721 to  1851     131 years                                                                                   Series  30

 [B] Entire series, effect on correlation (  .561) is:
       Lower   1736< -.017   1846< -.016   1845> -.016   1734> -.013   1801> -.013   1757> -.012  Higher   1752  .016   1725  .013

 [D]    1 Absent rings:  Year   Master  N series Absent
                         1766   -2.405       8       1

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
       1766 -5.9 SD;    1845 +3.0 SD
===================================================================================================================================

 BYR36x C  1785 to  2008     224 years                                                                                   Series  31

 [B] Entire series, effect on correlation (  .591) is:
       Lower   1860> -.010   2008< -.010   1794< -.009   1855< -.007   1986< -.007   1824< -.006  Higher   1951  .014   1992  .013
```

```
====================================================================================================================================

 BYR40x A  1810 to  2008     199 years                                                                                    Series  32

 [B] Entire series, effect on correlation (  .599) is:
       Lower   1992> -.037   1832> -.008   2006< -.007   1826< -.007   1896< -.007   1824< -.007  Higher   1959  .014   1904  .011

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1992 +4.2 SD
====================================================================================================================================

 BYR42x A  1822 to  1979     158 years                                                                                    Series  33

 [B] Entire series, effect on correlation (  .693) is:
       Lower   1961< -.008   1859> -.008   1917> -.007   1910< -.006   1856< -.006   1857> -.005  Higher   1975  .019   1853  .013

 [D]    1 Absent rings:  Year   Master  N series Absent
                         1882   -1.789      29      1

====================================================================================================================================

 BYR43x B  1750 to  1910     161 years                                                                                    Series  34

 [B] Entire series, effect on correlation (  .622) is:
       Lower   1768> -.020   1890< -.018   1758< -.010   1811> -.008   1870> -.008   1850> -.007  Higher   1853  .019   1859  .012

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1768 +3.6 SD
====================================================================================================================================

 BYR44x A  1747 to  1897     151 years                                                                                    Series  35

 [B] Entire series, effect on correlation (  .445) is:
       Lower   1834< -.020   1888> -.015   1808< -.014   1788< -.014   1767< -.013   1803< -.012  Higher   1799  .013   1892  .012

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1808 -4.7 SD
====================================================================================================================================

 BYR45x A  1858 to  2008     151 years                                                                                    Series  36

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1900 1949   -4   -.07 -.02  .02 -.14 -.24  .06  .31* .06 -.06 -.18  .25|-.10  .15 -.17 -.04  .03 -.03  .08 -.03  .15 -.31

 [B] Entire series, effect on correlation (  .506) is:
       Lower   1942> -.023   1932> -.016   1918> -.014   1946< -.011   1972< -.011   1923< -.009  Higher   1892  .038   1959  .015
     1900 to 1949 segment:
       Lower   1932> -.043   1942> -.042   1918> -.036   1946< -.032   1923< -.027   1940< -.024  Higher   1930  .072   1904  .041

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1942 +3.6 SD
====================================================================================================================================

 BYR46x A  1779 to  1933     155 years                                                                                    Series  37

 [B] Entire series, effect on correlation (  .636) is:
       Lower   1918< -.022   1900> -.015   1844> -.011   1883< -.010   1838> -.007   1913< -.007  Higher   1916  .015   1853  .012
```

```
=================================================================================================================================

 BYR48x A  1767 to  2008     242 years                                                                                Series  38

 [B] Entire series, effect on correlation (  .590) is:
       Lower   1916> -.013   1882> -.011   1895< -.008   1864< -.008   1799> -.007   1959> -.006  Higher   1942  .023   1975  .015

 [D]    1 Absent rings:  Year   Master  N series Absent
                         1942   -2.938      43       1

=================================================================================================================================

 BYR49x A  1846 to  2008     163 years                                                                                Series  39

 [B] Entire series, effect on correlation (  .607) is:
       Lower   1946< -.020   1934< -.012   1993< -.011   1952< -.011   1951> -.010   2004< -.009  Higher   1892  .026   1975  .018

=================================================================================================================================

 BYR50x C  1789 to  2008     220 years                                                                                Series  40

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1959 2008    0    .01  .08  .03  .10 -.03 -.15 -.25 -.22 -.16  .02  .32* .04    -    -    -    -    -    -    -    -    -

 [B] Entire series, effect on correlation (  .465) is:
       Lower   1790> -.015   1859> -.015   1854< -.012   1836< -.010   1840> -.009   1957< -.008  Higher   1942  .025   1930  .015
     1959 to 2008 segment:
       Lower   1965< -.039   2001< -.036   2008< -.030   2000< -.022   1969< -.021   1966< -.019  Higher   1992  .077   1975  .073

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1790 +3.0 SD
=================================================================================================================================

 BYR112xA  1747 to  1924     178 years                                                                                Series  41

 [B] Entire series, effect on correlation (  .632) is:
       Lower   1757> -.012   1811> -.009   1870> -.007   1775> -.007   1764< -.006   1748< -.006  Higher   1786  .013   1752  .010

 [D]    1 Absent rings:  Year   Master  N series Absent
                         1845   -2.061      20       1

=================================================================================================================================

 BYR501xA  1880 to  2008     129 years                                                                                Series  42

 [B] Entire series, effect on correlation (  .700) is:
       Lower   1921< -.015   1992> -.012   1893< -.008   1991> -.007   1959> -.007   1885> -.005  Higher   1942  .029   1892  .023

=================================================================================================================================

 BYR502xB  1898 to  2008     111 years                                                                                Series  43

 [B] Entire series, effect on correlation (  .591) is:
       Lower   1949> -.017   1951> -.015   1901< -.011   2004< -.009   1902< -.009   2008< -.009  Higher   1959  .039   1942  .038

=================================================================================================================================

 BYR503xA  1929 to  2008      80 years                                                                                Series  44
```

```
 [B] Entire series, effect on correlation (  .502) is:
       Lower   1952< -.026   1941< -.019   1992> -.017   1979> -.015   1987< -.011   1959> -.010  Higher   1951  .036   1930  .027

===================================================================================================================================

 BYR504xA  1747 to  1824      78 years                                                                                   Series  45

 [B] Entire series, effect on correlation (  .412) is:
       Lower   1750< -.054   1761< -.021   1769> -.020   1803< -.015   1770< -.012   1823> -.012  Higher   1776  .043   1786  .028

===================================================================================================================================

 BYR505xA  1756 to  1870     115 years                                                                                   Series  46

 [B] Entire series, effect on correlation (  .616) is:
       Lower   1757< -.030   1848< -.012   1844> -.012   1794< -.011   1787> -.007   1854< -.006  Higher   1766  .014   1859  .014

 [D]    1 Absent rings:  Year   Master  N series Absent
                         1838   -1.571      18       1

===================================================================================================================================

 BYR507xA  1913 to  1997      85 years                                                                                   Series  47

 [B] Entire series, effect on correlation (  .626) is:
       Lower   1935< -.019   1932> -.016   1940< -.014   1988< -.011   1956< -.010   1928< -.010  Higher   1959  .035   1930  .030

===================================================================================================================================

 BYR510xB  1902 to  2008     107 years                                                                                   Series  48

 [B] Entire series, effect on correlation (  .455) is:
       Lower   1955< -.030   1910< -.027   2006< -.025   1998< -.022   1973< -.019   1927< -.011  Higher   1959  .036   1975  .028

===================================================================================================================================

 BYR511xC  1867 to  2008     142 years                                                                                   Series  49

 [B] Entire series, effect on correlation (  .521) is:
       Lower   1949> -.013   1974> -.012   1931< -.011   1871> -.010   1962< -.009   1872< -.009  Higher   1975  .041   1942  .039

===================================================================================================================================

 BYR512xA  1873 to  2008     136 years                                                                                   Series  50

 [B] Entire series, effect on correlation (  .555) is:
       Lower   2000< -.042   1888> -.015   1973< -.015   1879< -.013   1900> -.010   2003> -.010  Higher   1892  .044   1992  .027

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       2000 -4.9 SD
===================================================================================================================================

 BYR513xA  1911 to  2008      98 years                                                                                   Series  51

 [B] Entire series, effect on correlation (  .497) is:
       Lower   1925> -.051   1926< -.032   2003> -.019   1970< -.012   1972< -.012   1997< -.012  Higher   1992  .057   1959  .041

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
```

```
       1925 +4.0 SD
===================================================================================================================================

 BYR514xB  1932 to  2008      77 years                                                                                  Series  52

 [B] Entire series, effect on correlation (  .579) is:
       Lower   1941< -.014   1947> -.013   2006< -.011   1937< -.011   1952< -.011   1994< -.010  Higher   1951  .047   1975  .046

===================================================================================================================================

 BYR515xB  1885 to  2008     124 years                                                                                  Series  53

 [B] Entire series, effect on correlation (  .659) is:
       Lower   1906< -.019   1949> -.017   1894< -.011   1952< -.010   1976< -.008   1981> -.006  Higher   1975  .034   1959  .025

===================================================================================================================================

 BYR516xB  1815 to  2008     194 years                                                                                  Series  54

 [B] Entire series, effect on correlation (  .615) is:
       Lower   2003> -.008   2005< -.008   1975> -.007   1949< -.006   1967< -.005   1884> -.005  Higher   1942  .024   1951  .013

===================================================================================================================================

 BYR518xA  1811 to  2008     198 years                                                                                  Series  55

 [B] Entire series, effect on correlation (  .533) is:
       Lower   1859> -.033   1978< -.018   1974> -.012   1968< -.009   1960> -.008   1932> -.008  Higher   1992  .029   1951  .014

 [E] Outliers     4   3.0 SD above or -4.5 SD below mean for year
       1859 +4.2 SD;    1960 +3.2 SD;    1974 +3.0 SD;    1978 -5.6 SD
===================================================================================================================================

 BYR519xA  1814 to  2008     195 years                                                                                  Series  56

 [B] Entire series, effect on correlation (  .644) is:
       Lower   1910< -.007   1937< -.007   1936< -.006   1912> -.006   1820< -.006   1834< -.006  Higher   1942  .023   1959  .013

===================================================================================================================================

 BYR520xA  1838 to  1950     113 years                                                                                  Series  57

 [B] Entire series, effect on correlation (  .686) is:
       Lower   1946< -.023   1918> -.022   1948< -.010   1913< -.009   1838> -.007   1924< -.007  Higher   1942  .023   1892  .020

===================================================================================================================================

 BYR521xB  1799 to  1904     106 years                                                                                  Series  58

 [B] Entire series, effect on correlation (  .478) is:
       Lower   1888> -.029   1799> -.028   1894< -.022   1801> -.015   1842< -.013   1813> -.012  Higher   1904  .021   1859  .021

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
       1799 +3.5 SD;    1888 +3.5 SD
===================================================================================================================================

 BYR600xA  1855 to  1932      78 years                                                                                  Series  59

 [B] Entire series, effect on correlation (  .489) is:
```

```
      Lower   1875> -.037   1892> -.030   1932> -.027   1866< -.027   1918> -.024   1878< -.013  Higher   1930  .050   1859  .038

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1892 +3.1 SD
==================================================================================================================================

 BYR700AA  1707 to  1829     123 years                                                                                    Series  60

 [*] Early part of series cannot be checked from 1707 to 1720 -- not matched by another series

 [B] Entire series, effect on correlation (  .610) is:
      Lower   1736> -.021   1734< -.017   1791< -.016   1729> -.013   1808> -.013   1824< -.010  Higher   1725  .023   1786  .022

==================================================================================================================================

 BYR701xB  1882 to  1945      64 years                                                                                    Series  61

 [B] Entire series, effect on correlation (  .406) is:
      Lower   1882> -.043   1900> -.036   1901< -.035   1911< -.033   1933< -.018   1941> -.013  Higher   1942  .072   1888  .036

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
      1882 +3.0 SD;    1888 -4.7 SD
==================================================================================================================================

 BYR702xD  1861 to  2009     149 years                                                                                    Series  62

 [B] Entire series, effect on correlation (  .494) is:
      Lower   1900> -.020   1872< -.019   1861> -.014   1865< -.012   2009> -.012   1926< -.011  Higher   1992  .053   1904  .027

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1900 +3.1 SD
==================================================================================================================================

 BYR703xB  1840 to  1910      71 years                                                                                    Series  63

 [B] Entire series, effect on correlation (  .631) is:
      Lower   1840> -.027   1854< -.021   1898< -.021   1847< -.021   1886< -.014   1887> -.010  Higher   1853  .046   1892  .028

==================================================================================================================================

PART 7:  DESCRIPTIVE STATISTICS:

                                                Corr   //-------- Unfiltered --------\\  //---- Filtered -----\\
                          No.    No.    No.     with   Mean   Max     Std   Auto   Mean   Max     Std   Auto  AR
 Seq Series   Interval   Years  Segmt  Flags   Master  msmt   msmt    dev   corr   sens  value    dev   corr  ()
 --- -------- ---------  -----  -----  -----   ------ -----  -----  -----  -----  -----  -----  -----  -----  --
   1 BYR60  B 1886 2009    124      5      0     .556  1.04   3.28   .579   .543   .353   2.54   .346  -.023   1
   2 BYR61  A 1933 2009     77      3      0     .572  1.25   4.51   .977   .708   .417   2.81   .588   .028   1
   3 BYR62  B 1924 2009     86      4      0     .654  1.18   6.67  1.386   .772   .458   2.77   .554  -.012   1
   4 BYR601 B 1935 2008     74      3      0     .620   .64   1.90   .354   .464   .438   2.94   .572  -.045   1
   5 BYR602 B 1954 2009     56      2      0     .460  1.27   3.66   .753   .593   .390   2.61   .539   .025   1
   6 BYR603 D 1933 2009     77      3      0     .453   .69   5.56   .857   .713   .458   2.96   .511  -.034   1
   7 BYR604 D 1943 2009     67      3      0     .635  1.05   2.53   .592   .668   .424   2.61   .467   .027   1
   8 BYR605 D 1935 2009     75      3      0     .550   .70   3.91   .756   .723   .502   2.86   .414  -.077   1
   9 BYR606 D 1946 2009     64      3      0     .538  1.15   2.91   .580   .491   .430   2.76   .639  -.023   1
  10 BYR607 D 1969 2009     41      1      0     .673  1.51   4.54  1.072   .719   .426   2.50   .448   .032   1
  11 BYR608 C 1916 2009     94      4      0     .685   .60   1.97   .355   .205   .539   2.85   .622   .030   1
  12 BYR609 C 1908 2009    102      4      0     .488   .86   3.89   .720   .671   .432   2.85   .524  -.060   1
  13 BYR610 D 1907 2009    103      4      0     .609   .62   2.61   .509   .729   .467   2.74   .506  -.052   1
```

```
 PART 7:  DESCRIPTIVE STATISTICS: (CONT)
 14 BYR612 D 1867 2009    143      6      0    .636    .78   2.73   .419   .431   .365   2.82   .452  -.070   2
 15 BYR614 D 1904 2008    105      4      0    .574    .67   2.82   .459   .332   .493   2.82   .406   .026   1
 16 BYR615 C 1867 2009    143      6      2    .466    .75   2.48   .494   .390   .493   3.10   .576  -.035   1
 17 BYR616 E 1958 2009     52      2      0    .654    .56   1.24   .284   .526   .394   2.72   .511   .007   1
 18 BYR617 A 1954 2009     56      2      0    .645   1.00   3.86   .613   .361   .436   2.74   .495   .044   1
 19 BYR620 B 1919 2009     91      4      0    .643    .85   3.07   .551   .453   .485   2.73   .569  -.004   1
 20 BYR621 C 1948 2009     62      3      0    .564    .64   1.69   .349   .422   .456   2.76   .562  -.033   1
 21 BYR622 D 1921 2009     89      4      0    .660    .69   2.73   .440   .374   .498   2.87   .506   .005   1
 22 BYR623 B 1922 2009     88      4      1    .408    .43   1.33   .228   .318   .461   2.94   .641   .066   1
 23 BYR625 C 1977 2009     33      1      0    .433    .83   2.79   .479   .488   .387   3.02   .713  -.109   1
 24 BYR626 A 1977 2009     33      1      0    .471   1.08   2.60   .506   .186   .454   2.48   .498   .017   1
 25 BYR627 B 1884 2008    125      5      0    .573   1.00   3.61   .815   .563   .503   2.58   .405   .020   1
 26 BYR001 A 1835 1944    110      4      0    .549    .70   2.45   .469   .436   .486   2.84   .472  -.048   3
 27 BYR30x A 1869 2008    140      6      0    .558    .62   1.97   .324   .339   .468   2.83   .489  -.007   2
 28 BYR31x A 1839 2009    171      7      0    .645    .75   2.59   .452   .422   .466   2.65   .414   .027   1
 29 BYR31axA 1763 1942    180      7      0    .677    .77   3.25   .556   .440   .552   2.72   .367  -.052   2
 30 BYR35x A 1721 1851    131      6      0    .561    .66   2.07   .388   .361   .548   2.43   .334   .008   1
 31 BYR36x C 1785 2008    224      9      0    .591    .97   5.19   .725   .419   .475   2.92   .533  -.020   2
 32 BYR40x A 1810 2008    199      8      0    .599    .76   3.11   .480   .298   .533   3.12   .657  -.008   1
 33 BYR42x A 1822 1979    158      7      0    .693    .63   2.59   .403   .292   .501   3.03   .554  -.023   3
 34 BYR43x B 1750 1910    161      6      0    .622    .69   2.07   .396   .311   .492   3.07   .576   .030   1
 35 BYR44x A 1747 1897    151      6      0    .445    .74   2.79   .418   .384   .441   2.61   .397  -.004   3
 36 BYR45x A 1858 2008    151      6      1    .506    .92   3.18   .522   .449   .447   2.84   .446  -.038   2
 37 BYR46x A 1779 1933    155      6      0    .636    .77   4.72   .671   .249   .585   2.99   .447  -.041   2
 38 BYR48x A 1767 2008    242     10      0    .590    .78   2.76   .418   .348   .474   2.59   .365  -.009   1
 39 BYR49x A 1846 2008    163      7      0    .607    .77   2.67   .463   .500   .453   3.16   .546   .044   1
 40 BYR50x C 1789 2008    220      9      1    .465    .99   3.82   .638   .579   .448   2.74   .462  -.003   1
 41 BYR112xA 1747 1924    178      7      0    .632    .44   1.12   .231   .210   .510   2.84   .495  -.036   2
 42 BYR501xA 1880 2008    129      5      0    .700    .86   2.88   .479   .537   .418   2.77   .506  -.006   1
 43 BYR502xB 1898 2008    111      5      0    .591    .61   3.79   .453   .576   .403   2.85   .569   .048   1
 44 BYR503xA 1929 2008     80      3      0    .502   1.16   4.21   .843   .606   .418   2.82   .589   .068   1
 45 BYR504xA 1747 1824     78      3      0    .412    .72   2.75   .558   .679   .475   2.76   .532  -.054   1
 46 BYR505xA 1756 1870    115      4      0    .616    .86   4.00   .786   .740   .510   2.72   .497  -.097   2
 47 BYR507xA 1913 1997     85      3      0    .626    .33    .84   .177   .480   .401   2.84   .629   .003   1
 48 BYR510xB 1902 2008    107      4      0    .455    .92   3.28   .622   .528   .430   3.12   .645  -.073   2
 49 BYR511xC 1867 2008    142      6      0    .521    .62   3.13   .469   .550   .419   2.75   .481  -.056   2
 50 BYR512xA 1873 2008    136      6      0    .555   1.26   3.28   .561   .443   .355   2.60   .409  -.020   1
 51 BYR513xA 1911 2008     98      4      0    .497    .70   1.83   .370   .448   .386   2.83   .619   .022   1
 52 BYR514xB 1932 2008     77      3      0    .579    .79   3.24   .619   .675   .473   2.69   .625   .097   1
 53 BYR515xB 1885 2008    124      5      0    .659   1.08   2.82   .504   .381   .416   2.64   .469  -.022   2
 54 BYR516xB 1815 2008    194      8      0    .615   1.11   6.05   .719   .474   .439   2.84   .471  -.003   2
 55 BYR518xA 1811 2008    198      8      0    .533    .77   2.14   .384   .359   .466   2.73   .438  -.015   1
 56 BYR519xA 1814 2008    195      8      0    .644    .78   2.38   .424   .330   .478   2.71   .456  -.044   2
 57 BYR520xA 1838 1950    113      5      0    .686   1.07   2.76   .622   .484   .477   2.60   .465   .031   1
 58 BYR521xB 1799 1904    106      5      0    .478    .90   2.40   .505   .372   .467   2.77   .642  -.002   1
 59 BYR600xA 1855 1932     78      3      0    .489   1.31   3.71   .762   .419   .502   2.64   .540  -.074   1
 60 BYR700AA 1707 1829    123      5      0    .610    .74   1.63   .332   .170   .504   2.65   .484   .002   1
 61 BYR701xB 1882 1945     64      2      0    .406    .52   1.59   .333   .782   .326   2.71   .546   .040   1
 62 BYR702xD 1861 2009    149      6      0    .494    .87   2.85   .476   .584   .384   2.56   .438  -.024   1
 63 BYR703xB 1840 1910     71      3      0    .631   1.68   6.35  1.326   .724   .434   2.65   .468  -.007   1
--- -------- ---------  -----  -----  -----   ------ -----  -----  -----  -----  -----  -----  -----  -----   --
Total or mean:           7367    299      5    .576    .83   6.67   .535   .455   .461   3.16   .497  -.012
```

Appendix 2. COFECHA program output for No Name Key site chronology, No Name Key, lower Florida Keys.

```
P R O G R A M     C O F E C H A                                                            Version 6.06P    27843
------------------------------------------------------------------------------------------------------------------------------------

 QUALITY CONTROL AND DATING CHECK OF TREE-RING MEASUREMENTS

 File of DATED series:   NNK.TXT

 Time span of Master dating series is  1779 to  2009   231 years
 Continuous time span is               1779 to  2009   231 years
 Portion with two or more series is    1812 to  2009   198 years


                                       ****************************************
                                       *C* Number of dated series        34 *C*
                                       *O* Master series 1779 2009  231 yrs *O*
                                       *F* Total rings in all series   2719 *F*
                                       *E* Total dated rings checked   2686 *E*
                                       *C* Series intercorrelation     .539 *C*
                                       *H* Average mean sensitivity    .472 *H*
                                       *A* Segments, possible problems    5 *A*
                                       *** Mean length of series       80.0 ***
                                       ****************************************

 ABSENT RINGS listed by SERIES:            (See Master Dating Series for absent rings listed by year)

 NNK02x A    3 absent rings:   1916  1930  1951
 NNK26x A    3 absent rings:   1838  1871  1925
 NNK42x A    1 absent rings:   1975
 NNK74x B    1 absent rings:   1904
 NNK82x      1 absent rings:   1951
 NNK84x A    1 absent rings:   1951

            10 absent rings    .368%
```

```
PART 2:  TIME PLOT OF TREE-RING SERIES:
------------------------------------------------------------------------------------------------------------------------------------
 1050 1100 1150 1200 1250 1300 1350 1400 1450 1500 1550 1600 1650 1700 1750 1800 1850 1900 1950 2000 2050 Ident   Seq Time-span  Yrs
   :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    : -------- --- ---- ---- ----
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   <==========>    . NNK02x A   1 1895 2008  114
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <======>.    . NNK03x B   2 1924 1994   71
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   <==========>    .    . NNK05x B   3 1848 1951  104
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <======>  .    .    . NNK07x A   4 1850 1924   75
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <========>   .    .    . NNK08x A   5 1828 1918   91
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <====>    . NNK11x A   6 1953 2008   56
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<========>    . NNK12x B   7 1919 2008   90
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<============>.    .    . NNK13x A   8 1812 1940  129
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <============>    . NNK14x A   9 1870 2005  136
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <=====>.    . NNK16x B  10 1939 1995   57
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   <=====>    . NNK17x A  11 1943 2008   66
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   <=====>    . NNK18x B  12 1949 2008   60
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   <=====>    . NNK19x A  13 1943 2008   66
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   <=====>    . NNK20x A  14 1946 2008   63
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<========>    . NNK21x B  15 1913 2008   96
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <=============>   .    .    . NNK22x A  16 1779 1910  132
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <==========>.    .    . NNK26x A  17 1833 1943  111
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<=======>.    .    . NNK30x A  18 1864 1946   83
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <====>    . NNK34x A  19 1950 2006   57
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <====>    . NNK35x A  20 1957 2009   53
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<=====>  .    . NNK36x A  21 1918 1977   60
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   <====>.    . NNK38x B  22 1944 1997   54
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <=====>.    .    .    . NNK41x A  23 1831 1894   64
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <======>.    . NNK42x A  24 1929 1994   66
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<========>    . NNK50x A  25 1910 2009  100
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <====>    . NNK61x B  26 1953 2009   57
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<=====>  .    . NNK71x A  27 1914 1978   65
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <=====>.    . NNK72x A  28 1938 1995   58
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <======>  .    .    . NNK74x B  29 1859 1921   63
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   <=========>.    .    . NNK76x A  30 1849 1941   93
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <=======>    . NNK80x A  31 1921 2009   89
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<=====>  .    . NNK82x    32 1919 1970   52
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <============>    . NNK84x A  33 1870 2006  137
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <====>    .    . NNK85x A  34 1903 1953   51
   :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :
 1050 1100 1150 1200 1250 1300 1350 1400 1450 1500 1550 1600 1650 1700 1750 1800 1850 1900 1950 2000 2050
```

```
PART 3:  Master Dating Series:
------------------------------------------------------------------------------------------------------------------------------------
  Year  Value  No Ab    Year  Value  No Ab    Year  Value  No Ab    Year  Value  No Ab    Year  Value  No Ab    Year  Value  No Ab
  ------------------    ------------------    ------------------    ------------------    ------------------    ------------------
                        1800   .411   1       1850  -.151   8       1900 -1.567  12       1950  -.436  22       2000   .143  15
                        1801   .031   1       1851   .571   8       1901   .463  12       1951 -1.850  22  3    2001   .237  15
                        1802   .361   1       1852  -.103   8       1902   .810  12       1952   .775  21       2002  -.109  15
                        1803   .732   1       1853 -1.566   8       1903  -.138  13       1953   .860  23       2003 -1.796  15
                        1804  1.402   1       1854  -.101   8       1904 -2.045  13  1    1954   .567  22       2004   .114  15
                        1805 -1.718   1       1855   .392   8       1905   .224  13       1955   .661  22       2005   .067  15
                        1806 -1.685   1       1856   .611   8       1906   .819  13       1956   .419  22       2006   .824  14
                        1807  1.836   1       1857  -.143   8       1907   .850  13       1957   .935  23       2007  -.061  12
                        1808  1.543   1       1858   .790   8       1908   .057  13       1958  -.755  23       2008   .879  12
                        1809   .951   1       1859 -1.464   9       1909   .275  13       1959 -2.377  23       2009  -.421   4

                        1810  1.314   1       1860  -.062   9       1910   .479  14       1960  -.970  23
                        1811 -1.084   1       1861  -.136   9       1911   .642  13       1961  -.028  23
                        1812  1.278   2       1862   .428   9       1912  -.873  13       1962   .222  23
                        1813   .816   2       1863  -.169   9       1913  -.022  14       1963  -.030  23
                        1814   .703   2       1864   .415  10       1914   .161  15       1964  -.768  23
                        1815   .552   2       1865   .582  10       1915   .157  15       1965   .425  23
                        1816   .223   2       1866   .870  10       1916 -2.196  15  1    1966   .601  23
                        1817 -1.698   2       1867   .400  10       1917  -.512  15       1967  1.170  23
                        1818  -.234   2       1868 -1.005  10       1918  -.302  16       1968   .947  23
                        1819  -.043   2       1869  1.090  10       1919  -.036  17       1969   .856  23

                        1820  -.314   2       1870  -.203  12       1920   .561  17       1970   .510  23
                        1821 -2.275   2       1871 -1.966  12  1    1921   .810  18       1971   .018  22
                        1822 -2.756   2       1872   .770  12       1922   .839  17       1972  -.015  22
                        1823  -.712   2       1873   .533  12       1923  1.108  17       1973   .068  22
                        1824  1.474   2       1874  -.392  12       1924   .618  18       1974  -.426  22
                        1825   .401   2       1875 -2.149  12       1925 -1.408  17  1    1975 -2.694  22  1
                        1826   .517   2       1876  -.168  12       1926   .848  17       1976  -.004  22
                        1827   .836   2       1877   .815  12       1927   .372  17       1977  -.009  22
                        1828   .458   3       1878  1.467  12       1928   .366  17       1978  -.544  21
  1779   .038   1       1829   .878   3       1879  1.284  12       1929  -.274  18       1979   .106  20

  1780   .816   1       1830   .752   3       1880   .195  12       1930 -2.086  18  1    1980   .116  20
  1781   .550   1       1831  -.468   4       1881  -.530  12       1931  -.540  18       1981   .168  20
  1782  1.087   1       1832 -1.043   4       1882 -1.440  12       1932 -1.144  18       1982   .573  20
  1783 -1.120   1       1833   .754   5       1883   .087  12       1933   .717  18       1983  1.105  20
  1784   .614   1       1834   .762   5       1884   .491  12       1934   .413  18       1984   .523  20
  1785   .682   1       1835   .495   5       1885  -.150  12       1935   .757  18       1985   .143  20
  1786 -4.013   1       1836   .468   5       1886   .467  12       1936   .477  18       1986   .317  20
  1787  2.113   1       1837  -.415   5       1887  -.290  12       1937   .165  18       1987   .323  20
  1788  1.894   1       1838 -1.610   5  1    1888 -2.287  12       1938   .296  19       1988  -.406  20
  1789  -.264   1       1839  -.315   5       1889   .211  12       1939   .551  20       1989  -.170  20

  1790 -3.852   1       1840   .073   5       1890   .934  12       1940   .463  20       1990   .089  20
  1791  -.131   1       1841  -.044   5       1891   .745  12       1941  -.696  19       1991   .049  20
  1792  -.533   1       1842  1.190   5       1892 -1.360  12       1942 -2.408  18       1992 -2.736  20
  1793   .036   1       1843  -.554   5       1893   .454  12       1943  -.314  20       1993  -.355  20
  1794   .614   1       1844 -1.326   5       1894   .894  12       1944   .050  20       1994   .110  20
  1795 -1.408   1       1845 -1.016   5       1895   .458  12       1945   .412  20       1995   .207  18
  1796  1.278   1       1846  -.092   5       1896   .150  12       1946  1.000  21       1996   .616  16
  1797   .286   1       1847   .959   5       1897   .940  12       1947   .209  20       1997  1.099  16
  1798  -.884   1       1848  1.224   6       1898  -.103  12       1948   .702  20       1998   .211  15
  1799 -2.830   1       1849   .589   7       1899  -.501  12       1949  -.423  21       1999   .066  15
------------------------------------------------------------------------------------------------------------------------------------
```

```
PART 4:  Master Bar Plot:
------------------------------------------------------------------------------------------------------------------------------------
   Year Rel value  Year Rel value  Year Rel value  Year Rel value  Year Rel value  Year Rel value  Year Rel value  Year Rel value
                   1800------B     1850---a        1900-f          1950--b         2000-----A
                   1801----@       1851-------B    1901------B     1951g           2001-----A
                   1802------A     1852---@        1902---------C  1952--------C   2002---@
                   1803--------C   1853-f          1903---a        1953---------C  2003g
                   1804----------F 1854---@        1904h           1954-------B    2004-----@
                   1805g           1855------B     1905-----A      1955--------C   2005----@
                   1806g           1856-------B    1906---------C  1956------B     2006---------C
                   1807----------G 1857---a        1907---------C  1957---------D  2007---@
                   1808----------F 1858---------C  1908----@       1958-c          2008---------D
                   1809---------D  1859-f          1909-----A      1959j           2009--b
                   1810----------E 1860---@        1910-------B    1960-d
                   1811-d          1861---a        1911--------C   1961----@
                   1812----------E 1862------B     1912-c          1962-----A
                   1813---------C  1863---a        1913----@       1963----@
                   1814--------C   1864------B     1914-----A      1964-c
                   1815-------B    1865-------B    1915-----A      1965------B
                   1816-----A      1866---------C  1916i           1966-------B
                   1817g           1867------B     1917--b         1967----------E
                   1818---a        1868-d          1918--a         1968---------D
                   1819----@       1869----------D 1919----@       1969---------C
                   1820--a         1870---a        1920-------B    1970-------B
                   1821i           1871h           1921---------C  1971----@
                   1822k           1872--------C   1922---------C  1972----@
                   1823--c         1873-------B    1923----------D 1973----@
                   1824----------F 1874--b         1924-------B    1974--b
                   1825------B     1875i           1925-f          1975k
                   1826-------B    1876---a        1926---------C  1976----@
                   1827---------C  1877---------C  1927------A     1977----@
                   1828------B     1878----------F 1928------A     1978--b
   1779----@       1829---------D  1879----------E 1929---a        1979-----@
   1780---------C  1830--------C   1880-----A      1930h           1980-----@
   1781-------B    1831--b         1881--b         1931--b         1981-----A
   1782----------D 1832-d          1882-f          1932-e          1982-------B
   1783-d          1833--------C   1883----@       1933--------C   1983----------D
   1784-------B    1834--------C   1884-------B    1934------B     1984-------B
   1785--------C   1835-------B    1885---a        1935--------C   1985-----A
   1786p           1836------B     1886------B     1936-------B    1986------A
   1787----------H 1837--b         1887--a         1937-----A      1987------A
   1788----------H 1838-f          1888i           1938------A     1988--b
   1789---a        1839--a         1889-----A      1939-------B    1989---a
   1790o           1840----@       1890---------D  1940------B     1990----@
   1791---a        1841----@       1891--------C   1941--c         1991----@
   1792--b         1842----------E 1892-e          1942j           1992k
   1793----@       1843--b         1893------B     1943--a         1993--a
   1794-------B    1844-e          1894---------D  1944----@       1994-----@
   1795-f          1845-d          1895------B     1945------B     1995-----A
   1796----------E 1846---@        1896-----A      1946---------D  1996-------B
   1797-----A      1847---------D  1897---------D  1947-----A      1997----------D
   1798-d          1848----------E 1898---@        1948--------C   1998-----A
   1799k           1849-------B    1899--b         1949--b         1999----@
```

```
PART 5:  CORRELATION OF SERIES BY SEGMENTS:
------------------------------------------------------------------------------------------------------------------------------------
 Correlations of  50-year dated segments, lagged  25 years
 Flags:  A = correlation under   .3281 but highest as dated;  B = correlation higher at other than dated position

 Seq Series  Time_span   1800 1825 1850 1875 1900 1925 1950 1975
                         1849 1874 1899 1924 1949 1974 1999 2024
 --- -------- ---------  ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ----
   1 NNK02x A 1895 2008                  .61  .58  .36  .28A .21A
   2 NNK03x B 1924 1994                       .58  .54  .46
   3 NNK05x B 1848 1951        .48  .45  .47  .49  .45
   4 NNK07x A 1850 1924             .45  .53
   5 NNK08x A 1828 1918        .47  .56  .54
   6 NNK11x A 1953 2008                                 .68  .74
   7 NNK12x B 1919 2008                       .61  .63  .65  .65
   8 NNK13x A 1812 1940   .36  .40  .59  .68  .55
   9 NNK14x A 1870 2005             .62  .65  .61  .55  .56  .52
  10 NNK16x B 1939 1995                            .45  .58
  11 NNK17x A 1943 2008                            .61  .57  .52
  12 NNK18x B 1949 2008                            .50  .50  .51
  13 NNK19x A 1943 2008                            .57  .59  .56
  14 NNK20x A 1946 2008                            .58  .56  .49
  15 NNK21x B 1913 2008                       .59  .56  .51  .50
  16 NNK22x A 1779 1910   .22B .21A .50  .58
  17 NNK26x A 1833 1943        .56  .65  .66  .62
  18 NNK30x A 1864 1946             .57  .58  .51
  19 NNK34x A 1950 2006                                 .47  .54
  20 NNK35x A 1957 2009                                 .49  .47
  21 NNK36x A 1918 1977                       .64  .64  .61
  22 NNK38x B 1944 1997                            .57  .59
  23 NNK41x A 1831 1894        .41  .45
  24 NNK42x A 1929 1994                            .69  .69
  25 NNK50x A 1910 2009                       .63  .53  .53  .57
  26 NNK61x B 1953 2009                                 .36  .30B
  27 NNK71x A 1914 1978                       .61  .61  .63
  28 NNK72x A 1938 1995                            .58  .63
  29 NNK74x B 1859 1921             .40  .59
  30 NNK76x A 1849 1941        .56  .55  .59  .52
  31 NNK80x A 1921 2009                       .66  .67  .67  .60
  32 NNK82x   1919 1970                       .59  .56
  33 NNK84x A 1870 2006             .61  .77  .65  .54  .52  .51
  34 NNK85x A 1903 1953                       .60  .61
 Av segment correlation   .29  .44  .53  .60  .59  .56  .55  .51
```

```
PART 6:  POTENTIAL PROBLEMS:
-------------------------------------------------------------------------------------------------------------------------------------

 For each series with potential problems the following diagnostics may appear:

 [A] Correlations with master dating series of flagged  50-year segments of series filtered with  32-year spline,
     at every point from ten years earlier (-10) to ten years later (+10) than dated

 [B] Effect of those data values which most lower or raise correlation with master series
     Symbol following year indicates value in series is greater (>) or lesser (<) than master series value

 [C] Year-to-year changes very different from the mean change in other series

 [D] Absent rings (zero values)

 [E] Values which are statistical outliers from mean for the year
=====================================================================================================================================

 NNK02x A  1895 to  2008     114 years                                                                                     Series   1

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1950 1999    0   -.11  .00  .04  .05  .00 -.10  .17  .25  .08 -.03  .28*-.31 -.13 -.14 -.05  .05 -.20  .15  .02  .00  .17
    1959 2008    0   -.08 -.01  .13  .01  .12 -.18  .17  .18  .10  .02  .21*-.27    -    -    -    -    -    -    -    -    -

 [B] Entire series, effect on correlation (  .476) is:
       Lower   1967< -.026   2003> -.023   1982< -.014   1974> -.013   1971> -.011   1996< -.011  Higher   1951  .027   1916  .026
     1950 to 1999 segment:
       Lower   1967< -.049   1982< -.026   1974> -.026   1996< -.021   1971> -.021   1999> -.016  Higher   1951  .105   1992  .039
     1959 to 2008 segment:
       Lower   1967< -.065   2003> -.044   1982< -.036   1974> -.030   1996< -.028   1971> -.023  Higher   1992  .127   1959  .072

 [D]    3 Absent rings:  Year   Master  N series Absent
                         1916   -2.196      15       1
                         1930   -2.086      18       1
                         1951   -1.850      22       3

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
       1951 -6.0 SD;    1999 +3.3 SD
=====================================================================================================================================

 NNK03x B  1924 to  1994      71 years                                                                                     Series   2

 [B] Entire series, effect on correlation (  .481) is:
       Lower   1974< -.028   1975> -.021   1927< -.018   1942> -.014   1979< -.013   1952< -.012  Higher   1959  .027   1925  .025

=====================================================================================================================================

 NNK05x B  1848 to  1951     104 years                                                                                     Series   3

 [B] Entire series, effect on correlation (  .467) is:
       Lower   1893< -.016   1863> -.015   1886< -.015   1874> -.012   1858< -.010   1904> -.009  Higher   1892  .027   1925  .017

=====================================================================================================================================

 NNK07x A  1850 to  1924      75 years                                                                                     Series   4

 [B] Entire series, effect on correlation (  .487) is:
       Lower   1870< -.043   1875> -.026   1855< -.022   1909< -.012   1880< -.011   1877< -.010  Higher   1916  .043   1892  .022
```

```
 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1875 +3.1 SD
===================================================================================================================================

 NNK08x A  1828 to  1918      91 years                                                                                    Series   5

 [B] Entire series, effect on correlation (  .478) is:
       Lower   1879< -.022   1843> -.019   1835< -.017   1901< -.013   1855< -.012   1840> -.011  Higher   1888  .034   1871  .028

===================================================================================================================================

 NNK11x A  1953 to  2008      56 years                                                                                    Series   6

 [B] Entire series, effect on correlation (  .698) is:
       Lower   1958> -.025   2002> -.023   1961< -.018   1977< -.016   1953< -.016   2006< -.008  Higher   1992  .061   1959  .035

===================================================================================================================================

 NNK12x B  1919 to  2008      90 years                                                                                    Series   7

 [B] Entire series, effect on correlation (  .610) is:
       Lower   1941> -.026   1927> -.018   1934< -.015   1978> -.009   1982< -.009   1981> -.008  Higher   1942  .040   1992  .031

===================================================================================================================================

 NNK13x A  1812 to  1940     129 years                                                                                    Series   8

 [B] Entire series, effect on correlation (  .488) is:
       Lower   1823< -.033   1861< -.021   1850< -.017   1841< -.013   1843> -.009   1940< -.009  Higher   1888  .025   1859  .018

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1823 -5.7 SD
===================================================================================================================================

 NNK14x A  1870 to  2005     136 years                                                                                    Series   9

 [B] Entire series, effect on correlation (  .567) is:
       Lower   1977< -.019   1886< -.018   1871> -.018   1937< -.010   1923< -.007   1925> -.006  Higher   1992  .035   1916  .025

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1871 +3.1 SD
===================================================================================================================================

 NNK16x B  1939 to  1995      57 years                                                                                    Series  10

 [B] Entire series, effect on correlation (  .516) is:
       Lower   1940< -.052   1941> -.024   1947< -.023   1957< -.019   1954< -.015   1986< -.014  Higher   1992  .075   1975  .040

===================================================================================================================================

 NNK17x A  1943 to  2008      66 years                                                                                    Series  11

 [B] Entire series, effect on correlation (  .568) is:
       Lower   1996< -.019   1971> -.018   1972< -.017   1988> -.017   1997< -.016   1963< -.014  Higher   1992  .109   1951  .016

===================================================================================================================================

 NNK18x B  1949 to  2008      60 years                                                                                    Series  12
```

```
 [B] Entire series, effect on correlation (  .513) is:
       Lower   1994< -.022   1952< -.022   1974> -.022   1967< -.022   1998> -.021   1984< -.016  Higher   1992  .172   1951  .030

====================================================================================================================================

 NNK19x A  1943 to  2008      66 years                                                                                    Series  13

 [B] Entire series, effect on correlation (  .552) is:
       Lower   1992> -.032   1968< -.025   1948< -.021   2005< -.015   1999< -.013   1983< -.008  Higher   1975  .086   1959  .020

====================================================================================================================================

 NNK20x A  1946 to  2008      63 years                                                                                    Series  14

 [B] Entire series, effect on correlation (  .540) is:
       Lower   1988> -.017   2006< -.016   1962< -.016   1954< -.015   1978> -.014   1967< -.014  Higher   1975  .090   1951  .039

====================================================================================================================================

 NNK21x B  1913 to  2008      96 years                                                                                    Series  15

 [B] Entire series, effect on correlation (  .523) is:
       Lower   1995< -.017   1945< -.017   2008< -.015   1976< -.009   1958> -.009   1967< -.009  Higher   1992  .040   1942  .019

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       2003 -5.2 SD
====================================================================================================================================

 NNK22x A  1779 to  1910     132 years                                                                                    Series  16

 [*] Early part of series cannot be checked from 1779 to 1811 -- not matched by another series

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
     1812 1861    1   -.10 -.06 -.11 -.14 -.05  .02 -.17 -.04 -.17 -.11  .22| .24* .06  .23  .14  .03  .07 -.08 -.35 -.04  .10
     1825 1874    0   -.12  .07 -.14  .05 -.06  .03 -.26  .17 -.23 -.07  .21*-.07 -.16  .17  .08  .00  .05  .12 -.27  .05  .08

 [B] Entire series, effect on correlation (  .364) is:
       Lower   1834< -.045   1823> -.042   1845> -.037   1837> -.021   1840< -.018   1898> -.013  Higher   1821  .028   1904  .026
     1812 to 1861 segment:
       Lower   1823> -.067   1834< -.067   1845> -.058   1837> -.033   1840< -.024   1828< -.018  Higher   1821  .060   1822  .038
     1825 to 1874 segment:
       Lower   1834< -.077   1845> -.074   1837> -.043   1840< -.026   1864< -.021   1828< -.021  Higher   1871  .062   1838  .041

 [E] Outliers     3   3.0 SD above or -4.5 SD below mean for year
       1823 +5.7 SD;    1837 +3.1 SD;    1845 +4.5 SD
====================================================================================================================================

 NNK26x A  1833 to  1943     111 years                                                                                    Series  17

 [B] Entire series, effect on correlation (  .640) is:
       Lower   1843> -.021   1841> -.010   1872< -.010   1896< -.008   1913< -.007   1848< -.006  Higher   1871  .016   1875  .014

 [D]    3 Absent rings:  Year   Master  N series Absent
                         1838   -1.610       5      1
                                                        Present in series    5  NNK08x A time span  1828 to  1918
                                                        Present in series    8  NNK13x A time span  1812 to  1940
                                                        Present in series   16  NNK22x A time span  1779 to  1910
```

```
                                                          Present in series   23  NNK41x A time span  1831 to  1894
                      1871   -1.966      12       1
                      1925   -1.408      17       1

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1925 -5.3 SD
==================================================================================================================================

 NNK30x A  1864 to  1946      83 years                                                                                  Series  18

 [B] Entire series, effect on correlation (  .567) is:
       Lower   1941> -.016   1870> -.016   1933< -.014   1873< -.012   1914< -.012   1897< -.011  Higher   1942  .034   1875  .021

==================================================================================================================================

 NNK34x A  1950 to  2006      57 years                                                                                  Series  19

 [B] Entire series, effect on correlation (  .481) is:
       Lower   1966< -.029   1950> -.028   1958< -.022   1974> -.020   1971> -.020   1951> -.015  Higher   1975  .052   1959  .022

 [E] Outliers     3   3.0 SD above or -4.5 SD below mean for year
       1950 +3.1 SD;    1951 +3.4 SD;    1958 -5.0 SD
==================================================================================================================================

 NNK35x A  1957 to  2009      53 years                                                                                  Series  20

 [B] Entire series, effect on correlation (  .462) is:
       Lower   2009> -.042   1971< -.037   1958> -.018   1972> -.012   1977> -.011   2004< -.010  Higher   1975  .099   2003  .032

==================================================================================================================================

 NNK36x A  1918 to  1977      60 years                                                                                  Series  21

 [B] Entire series, effect on correlation (  .578) is:
       Lower   1924< -.046   1971< -.035   1975> -.014   1928< -.012   1970< -.012   1941> -.011  Higher   1959  .041   1930  .024

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1971 -4.7 SD
==================================================================================================================================

 NNK38x B  1944 to  1997      54 years                                                                                  Series  22

 [B] Entire series, effect on correlation (  .559) is:
       Lower   1956< -.029   1988> -.026   1978> -.016   1957< -.016   1981< -.013   1960> -.011  Higher   1992  .207   1975  .026

==================================================================================================================================

 NNK41x A  1831 to  1894      64 years                                                                                  Series  23

 [B] Entire series, effect on correlation (  .383) is:
       Lower   1892> -.054   1832> -.045   1856< -.021   1831> -.016   1890< -.015   1833< -.015  Higher   1888  .056   1878  .023

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
       1832 +4.0 SD;    1892 +3.3 SD
==================================================================================================================================

 NNK42x A  1929 to  1994      66 years                                                                                  Series  24

 [B] Entire series, effect on correlation (  .730) is:
```

```
      Lower   1936< -.026   1986< -.019   1952< -.015   1929> -.014   1950< -.012   1931> -.010  Higher   1975  .041   1942  .028

 [D]    1 Absent rings:  Year   Master  N series Absent
                         1975   -2.694      22       1

==================================================================================================================================

 NNK50x A  1910 to  2009     100 years                                                                                Series  25

 [B] Entire series, effect on correlation (  .582) is:
      Lower   1968< -.030   1959> -.012   1911< -.010   1918> -.009   1965< -.009   1994< -.008  Higher   1992  .078   1925  .017

==================================================================================================================================

 NNK61x B  1953 to  2009      57 years                                                                                Series  26

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1960 2009   -6   -.03 -.15 -.13 -.11  .40*-.29  .07 -.02 -.10  .00  .30|   -    -    -    -    -    -    -    -    -    -

 [B] Entire series, effect on correlation (  .342) is:
      Lower   1992> -.042   1998< -.038   1970< -.025   2007> -.019   1957< -.018   2005> -.016  Higher   1958  .036   1997  .028
    1960 to 2009 segment:
      Lower   1992> -.042   1998< -.042   1970< -.030   2007> -.022   2005> -.019   2006< -.010  Higher   1997  .036   1975  .033

==================================================================================================================================

 NNK71x A  1914 to  1978      65 years                                                                                Series  27

 [B] Entire series, effect on correlation (  .610) is:
      Lower   1933< -.030   1973> -.021   1939< -.010   1962< -.010   1946< -.009   1922< -.008  Higher   1930  .019   1975  .019

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1973 +3.1 SD
==================================================================================================================================

 NNK72x A  1938 to  1995      58 years                                                                                Series  28

 [B] Entire series, effect on correlation (  .659) is:
      Lower   1948< -.036   1967< -.022   1964> -.015   1973< -.014   1987< -.011   1941> -.008  Higher   1992  .093   1942  .047

==================================================================================================================================

 NNK74x B  1859 to  1921      63 years                                                                                Series  29

 [B] Entire series, effect on correlation (  .511) is:
      Lower   1866< -.074   1888> -.061   1859> -.025   1861> -.018   1881> -.012   1910< -.010  Higher   1916  .059   1904  .044

 [D]    1 Absent rings:  Year   Master  N series Absent
                         1904   -2.045      13       1

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1888 +3.6 SD
==================================================================================================================================

 NNK76x A  1849 to  1941      93 years                                                                                Series  30

 [B] Entire series, effect on correlation (  .555) is:
      Lower   1898< -.028   1907< -.021   1891< -.017   1862< -.016   1902< -.016   1925> -.011  Higher   1888  .032   1871  .021
```

```
====================================================================================================================================

 NNK80x A  1921 to  2009      89 years                                                                                   Series  31

 [B] Entire series, effect on correlation (  .629) is:
       Lower   1954< -.015   1949> -.012   2007< -.012   2003> -.011   1922< -.010   1927> -.009  Higher   1975  .023   1930  .020

====================================================================================================================================

 NNK82x    1919 to  1970      52 years                                                                                   Series  32

 [B] Entire series, effect on correlation (  .604) is:
       Lower   1942> -.050   1969< -.026   1925> -.023   1933< -.023   1921< -.019   1947> -.015  Higher   1930  .059   1951  .049

 [D]    1 Absent rings:  Year   Master  N series Absent
                         1951   -1.850      22       3

====================================================================================================================================

 NNK84x A  1870 to  2006     137 years                                                                                   Series  33

 [B] Entire series, effect on correlation (  .571) is:
       Lower   1871> -.029   1874< -.028   1932> -.012   1992> -.011   1981< -.009   1982< -.008  Higher   1916  .027   1930  .017

 [D]    1 Absent rings:  Year   Master  N series Absent
                         1951   -1.850      22       3

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1871 +3.7 SD
====================================================================================================================================

 NNK85x A  1903 to  1953      51 years                                                                                   Series  34

 [B] Entire series, effect on correlation (  .606) is:
       Lower   1941< -.026   1944< -.022   1930> -.018   1937< -.016   1908< -.016   1931> -.012  Higher   1916  .048   1925  .015

====================================================================================================================================

PART 7:  DESCRIPTIVE STATISTICS:
                                                Corr   //-------- Unfiltered --------\\  //---- Filtered -----\\
                         No.    No.    No.    with   Mean   Max     Std   Auto   Mean   Max     Std   Auto  AR
 Seq Series   Interval  Years  Segmt  Flags   Master  msmt   msmt    dev   corr   sens  value    dev   corr  ()
 --- -------- ---------  -----  -----  -----   ------ -----  -----  -----  -----  -----  -----  -----  -----  --
   1 NNK02x A 1895 2008    114      5      2    .476    .77   2.44   .483   .348   .517   2.56   .378  -.017   8
   2 NNK03x B 1924 1994     71      3      0    .481   1.16   3.70   .783   .523   .467   2.69   .529  -.091   2
   3 NNK05x B 1848 1951    104      5      0    .467   1.27   4.03   .842   .562   .502   2.70   .475   .002   1
   4 NNK07x A 1850 1924     75      2      0    .487   1.43   4.92   .971   .472   .536   2.74   .483  -.046   2
   5 NNK08x A 1828 1918     91      3      0    .478   1.06   4.11   .767   .513   .469   2.72   .443  -.064   1
   6 NNK11x A 1953 2008     56      2      0    .698    .62   1.68   .318   .304   .495   2.96   .583  -.042   1
   7 NNK12x B 1919 2008     90      4      0    .610   1.45   5.24   .910   .516   .410   2.81   .501  -.054   1
   8 NNK13x A 1812 1940    129      5      0    .488    .79   2.10   .451   .603   .456   2.70   .566  -.005   1
   9 NNK14x A 1870 2005    136      6      0    .567   1.24   5.66   .937   .699   .457   2.86   .519  -.011   3
  10 NNK16x B 1939 1995     57      2      0    .516   2.38   6.63  1.571   .530   .472   2.91   .711  -.104   1
  11 NNK17x A 1943 2008     66      3      0    .568   2.80   6.97  1.669   .651   .445   2.61   .544  -.066   2
  12 NNK18x B 1949 2008     60      3      0    .513   1.69   6.18  1.363   .532   .451   2.77   .446   .054   1
  13 NNK19x A 1943 2008     66      3      0    .552   2.20   7.91  1.925   .690   .453   2.74   .453   .000   1
  14 NNK20x A 1946 2008     63      3      0    .540   1.30   3.71   .869   .606   .415   2.66   .444  -.036   2
  15 NNK21x B 1913 2008     96      4      0    .523   1.48   4.03   .911   .637   .413   2.38   .371  -.069   2
```

```
 PART 7:  DESCRIPTIVE STATISTICS: (CONT)
 16 NNK22x A 1779 1910    132      4      2    .364   1.17   3.52   .699   .395   .510   2.80   .549  -.068   2
 17 NNK26x A 1833 1943    111      4      0    .640    .76   2.60   .496   .273   .581   2.58   .391  -.024   1
 18 NNK30x A 1864 1946     83      3      0    .567    .80   2.06   .460   .388   .484   2.80   .504  -.059   1
 19 NNK34x A 1950 2006     57      2      0    .481    .95   3.13   .580   .674   .433   2.59   .409   .006   1
 20 NNK35x A 1957 2009     53      2      0    .462   1.34   3.93   .904   .464   .516   2.68   .587  -.055   2
 21 NNK36x A 1918 1977     60      3      0    .578   1.87   7.95  1.423   .459   .411   3.24   .608   .106   1
 22 NNK38x B 1944 1997     54      2      0    .559   1.32   3.52   .834   .683   .357   2.52   .403   .036   1
 23 NNK41x A 1831 1894     64      2      0    .383   1.08   3.09   .711   .629   .446   2.84   .611  -.073   2
 24 NNK42x A 1929 1994     66      2      0    .730   1.11   2.71   .633   .464   .523   2.64   .538  -.031   1
 25 NNK50x A 1910 2009    100      4      0    .582   1.61   7.26  1.562   .731   .426   2.73   .397  -.007   2
 26 NNK61x B 1953 2009     57      2      1    .342   1.32   6.25  1.361   .782   .447   2.86   .463   .049   1
 27 NNK71x A 1914 1978     65      3      0    .610   1.53   5.72  1.142   .569   .478   2.73   .427  -.022   1
 28 NNK72x A 1938 1995     58      2      0    .659   1.26   3.85   .748   .600   .395   2.58   .454   .022   1
 29 NNK74x B 1859 1921     63      2      0    .511   1.59   3.83   .822   .446   .452   2.64   .534  -.084   3
 30 NNK76x A 1849 1941     93      4      0    .555    .80   2.65   .705   .586   .557   3.00   .583  -.086   3
 31 NNK80x A 1921 2009     89      4      0    .629   1.44   3.77   .891   .490   .503   2.76   .508  -.032   1
 32 NNK82x   1919 1970     52      2      0    .604    .74   1.77   .366   .407   .478   2.61   .551  -.029   1
 33 NNK84x A 1870 2006    137      6      0    .571    .95   3.61   .791   .720   .445   2.63   .457  -.009   1
 34 NNK85x A 1903 1953     51      2      0    .606   1.35   3.83   .789   .363   .525   2.89   .552   .042   1
--- -------- ---------  -----  -----  -----   ------ -----  -----  -----  -----  -----  -----  -----  -----  --
Total or mean:           2719    108      5    .539   1.26   7.95   .874   .541   .472   3.24   .494  -.028
```

Appendix 3. COFECHA program output for North Big Pine Key site chronology, Big Pine Key, lower Florida Keys.

```
P R O G R A M     C O F E C H A                                                                     Version 6.06P    27843
-------------------------------------------------------------------------------------------------------------------------------------

 QUALITY CONTROL AND DATING CHECK OF TREE-RING MEASUREMENTS

 File of DATED series:   NBP.TXT

 Time span of Master dating series is  1848 to  2009   162 years
 Continuous time span is               1848 to  2009   162 years
 Portion with two or more series is    1871 to  2009   139 years


                                       ****************************************
                                       *C* Number of dated series        49 *C*
                                       *O* Master series 1848 2009  162 yrs *O*
                                       *F* Total rings in all series   2942 *F*
                                       *E* Total dated rings checked   2919 *E*
                                       *C* Series intercorrelation     .535 *C*
                                       *H* Average mean sensitivity    .414 *H*
                                       *A* Segments, possible problems    9 *A*
                                       *** Mean length of series       60.0 ***
                                       ****************************************

 ABSENT RINGS listed by SERIES:            (See Master Dating Series for absent rings listed by year)

 NWH500xB    2 absent rings:   1951  1959

             2 absent rings    .068%
```

```
PART 2:  TIME PLOT OF TREE-RING SERIES:
------------------------------------------------------------------------------------------------------------------------------------
 1050 1100 1150 1200 1250 1300 1350 1400 1450 1500 1550 1600 1650 1700 1750 1800 1850 1900 1950 2000 2050 Ident    Seq Time-span  Yrs
   :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    : -------- --- ---- ---- ----
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <====>    . NWH624 A   1 1952 2008   57
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <==>    . NWH622 A   2 1977 2009   33
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <====>    . NWH616 A   3 1955 2009   55
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <=>    . NWH617 B   4 1986 2009   24
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <=>    . NWH618 A   5 1988 2009   22
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   <>    . NWH618 B   6 1990 2009   20
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <=>    . NWH605 A   7 1985 2009   25
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <=>    . NWH605 B   8 1985 2009   25
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   <>    . NWH610 B   9 1992 2007   16
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <=>    . NWH626 A  10 1986 2009   24
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <=>    . NWH626 B  11 1987 2009   23
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   <>    . NWH620 C  12 1991 2009   19
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <=>    . NWH620 D  13 1983 2009   27
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <====>    . NWH624 A  14 1952 2008   57
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <=>    . NWH614 C  15 1983 2009   27
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <==>    . NWH612 C  16 1979 2008   30
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <==>    . NWH612 B  17 1979 2008   30
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   <=====>    . NWH604 B  18 1944 2008   65
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<===>    . NWH602 A  19 1960 2009   50
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <=======>   .    . NWH530xB  20 1885 1963   79
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <==========>.    . NWH500xB  21 1888 1997  110
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <===========>    . NWH501xA  22 1888 2006  119
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <=========>    . NWH503xB  23 1908 2007  100
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <=========>    . NWH503xA  24 1908 2007  100
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <=========>    . NWH506xA  25 1900 2009  110
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <=========>    . NWH506xB  26 1900 2009  110
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <=====> .    .    . NWH509xB  27 1871 1932   62
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <=====> .    .    . NWH509xC  28 1871 1932   62
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <====> .    .    . NWH510xB  29 1889 1932   44
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <====> .    .    . NWH510xC  30 1889 1932   44
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <==>    .    . NWH512xA  31 1924 1953   30
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <==>    .    . NWH512xB  32 1924 1953   30
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <========>  .    . NWH513xA  33 1886 1977   92
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<=======>.    . NWH520xB  34 1910 1991   82
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   <=====>    . NWH531xA  35 1948 2007   60
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   <=====>    . NWH531xB  36 1948 2007   60
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <======>    .    . NWH533xA  37 1887 1955   69
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <======>    .    . NWH533xC  38 1887 1955   69
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <=========>    . NWH534xD  39 1903 2003  101
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <=========>    . NWH534xC  40 1903 2003  101
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <=======> .    . NWH535xA  41 1908 1980   73
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <=======> .    . NWH535xB  42 1908 1980   73
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <=====>   .    . NWH538xA  43 1902 1965   64
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <=====>   .    . NWH538xC  44 1902 1965   64
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   <==============>.    . NWH539xA  45 1848 1993  146
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <===>   .    . NWH540xA  46 1929 1965   37
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <===>   .    . NWH540xB  47 1929 1965   37
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <====>  .    . NWH540xC  48 1929 1977   49
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <============>    . NWH600xA  49 1873 2008  136
   :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :
 1050 1100 1150 1200 1250 1300 1350 1400 1450 1500 1550 1600 1650 1700 1750 1800 1850 1900 1950 2000 2050
```

```
PART 3:  Master Dating Series:
------------------------------------------------------------------------------------------------------------------------------------
  Year  Value  No Ab    Year  Value  No Ab    Year  Value  No Ab    Year  Value  No Ab    Year  Value  No Ab    Year  Value  No Ab
  ------------------    ------------------    ------------------    ------------------    ------------------    ------------------
                        1850  -.652   1       1900 -1.240  14       1950   .018  27       2000   .564  29
                        1851 -1.314   1       1901   .789  14       1951 -1.462  27  1    2001  1.210  29
                        1852 -1.407   1       1902   .461  16       1952   .255  29       2002   .042  29
                        1853  -.660   1       1903   .227  18       1953   .768  29       2003 -1.113  29
                        1854  1.306   1       1904 -1.039  18       1954  -.080  27       2004  -.489  27
                        1855  1.845   1       1905  -.093  18       1955   .219  28       2005  -.289  27
                        1856  1.015   1       1906   .403  18       1956   .692  26       2006   .646  27
                        1857   .666   1       1907   .624  18       1957   .950  26       2007   .563  26
                        1858  -.732   1       1908   .269  22       1958   .082  26       2008  1.241  21
                        1859 -2.869   1       1909   .459  22       1959 -1.437  26  1    2009 -2.800  15

                        1860 -1.594   1       1910   .166  23       1960  -.868  27
                        1861   .356   1       1911  1.011  23       1961   .192  27
                        1862  1.983   1       1912 -1.021  23       1962   .743  27
                        1863   .717   1       1913  -.213  23       1963   .577  27
                        1864   .030   1       1914  -.144  23       1964  -.188  26
                        1865  2.153   1       1915   .456  23       1965  -.126  26
                        1866  -.181   1       1916 -1.920  23       1966   .080  22
                        1867 -1.129   1       1917 -1.051  23       1967   .414  22
                        1868 -2.478   1       1918  -.331  23       1968   .111  22
                        1869  -.471   1       1919   .371  23       1969   .434  22

                        1870  -.319   1       1920   .079  23       1970   .579  22
                        1871 -1.081   3       1921   .677  23       1971   .355  22
                        1872   .088   3       1922   .266  23       1972   .350  22
                        1873   .594   4       1923   .374  23       1973   .383  22
                        1874   .331   4       1924   .942  25       1974 -1.201  22
                        1875 -1.419   4       1925  -.555  25       1975 -1.684  22
                        1876  1.583   4       1926   .982  25       1976  -.148  22
                        1877  1.747   4       1927   .014  25       1977  -.139  23
                        1878  1.696   4       1928   .402  25       1978 -1.046  21
                        1879  1.476   4       1929   .103  28       1979  -.501  23

                        1880   .096   4       1930 -1.997  28       1980   .014  23
                        1881  -.157   4       1931  -.273  28       1981   .713  21
                        1882 -3.582   4       1932 -1.464  28       1982  1.046  21
                        1883  -.408   4       1933   .375  24       1983  1.165  23
                        1884  -.648   4       1934   .827  24       1984  1.148  23
                        1885  -.344   5       1935  1.244  24       1985   .891  25
                        1886   .534   6       1936   .859  24       1986   .608  27
                        1887  -.168   8       1937   .242  24       1987   .161  28
                        1888 -1.842  10       1938   .507  24       1988  -.678  29
                        1889   .740  12       1939   .246  24       1989  -.420  29

                        1890   .724  12       1940   .776  24       1990  -.471  30
                        1891  1.038  12       1941   .728  24       1991  -.206  31
                        1892 -2.842  12       1942 -1.930  24       1992 -2.903  31
                        1893   .294  12       1943   .106  24       1993  -.047  31
                        1894   .951  12       1944  -.067  25       1994   .009  30
                        1895   .998  12       1945  -.183  25       1995   .162  30
                        1896  -.607  12       1946   .135  25       1996   .496  30
                        1897   .382  12       1947  -.547  25       1997   .686  30
  1848  1.392   1       1898   .426  12       1948   .056  27       1998   .479  29
  1849  1.143   1       1899  -.836  12       1949  -.637  27       1999   .215  29
------------------------------------------------------------------------------------------------------------------------------------
```

```
PART 4:  Master Bar Plot:
-----------------------------------------------------------------------------------------------------------------------------------
   Year Rel value  Year Rel value  Year Rel value  Year Rel value  Year Rel value  Year Rel value  Year Rel value  Year Rel value
                   1850--c         1900-e          1950----@       2000-------B
                   1851-e          1901--------C   1951-f          2001---------E
                   1852-f          1902-------B    1952-----A      2002----@
                   1853--c         1903-----A      1953--------C   2003-d
                   1854----------E 1904-d          1954----@       2004--b
                   1855----------G 1905---@        1955-----A      2005---a
                   1856---------D  1906------B     1956--------C   2006--------C
                   1857--------C   1907--------B   1957---------D  2007-------B
                   1858--c         1908------A     1958----@       2008----------E
                   1859k           1909-------B    1959-f          2009k
                   1860f           1910-----A      1960-c
                   1861------A     1911---------D  1961-----A
                   1862----------H 1912-d          1962--------C
                   1863--------C   1913---a        1963-------B
                   1864----@       1914---a        1964---a
                   1865----------I 1915-------B    1965---a
                   1866---a        1916h           1966----@
                   1867-e          1917-d          1967------B
                   1868j           1918---a        1968-----@
                   1869--b         1919------A     1969-------B
                   1870---a        1920----@       1970-------B
                   1871-d          1921--------C   1971------A
                   1872----@       1922------A     1972------A
                   1873--------B   1923------A     1973------B
                   1874------A     1924---------D  1974-e
                   1875-f          1925--b         1975g
                   1876----------F 1926---------D  1976---a
                   1877----------G 1927----@       1977---a
                   1878----------G 1928------B     1978-d
                   1879----------F 1929-----@      1979--b
                   1880-----@      1930h           1980----@
                   1881---a        1931---a        1981--------C
                   1882n           1932-f          1982---------D
                   1883--b         1933------A     1983---------E
                   1884--c         1934---------C  1984---------E
                   1885---a        1935----------E 1985---------D
                   1886-------B    1936---------C  1986--------B
                   1887---a        1937-----A      1987-----A
                   1888g           1938-------B    1988--c
                   1889--------C   1939-----A      1989--b
                   1890--------C   1940--------C   1990--b
                   1891---------D  1941--------C   1991---a
                   1892k           1942h           1992l
                   1893------A     1943-----@      1993----@
                   1894---------D  1944----@       1994----@
                   1895---------D  1945---a        1995-----A
                   1896--b         1946-----A      1996-------B
                   1897------B     1947--b         1997--------C
   1848----------F 1898-------B    1948----@       1998-------B
   1849---------E  1899-c          1949--c         1999-----A
```

```
PART 5:  CORRELATION OF SERIES BY SEGMENTS:
------------------------------------------------------------------------------------------------------------------------------------
 Correlations of  50-year dated segments, lagged  25 years
 Flags:  A = correlation under   .3281 but highest as dated;  B = correlation higher at other than dated position

 Seq Series  Time_span   1850 1875 1900 1925 1950 1975
                         1899 1924 1949 1974 1999 2024
 --- -------- ---------  ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ----
   1 NWH624 A 1952 2008                       .68  .69
   2 NWH622 A 1977 2009                            .67
   3 NWH616 A 1955 2009                       .50  .53
   4 NWH617 B 1986 2009                            .77
   5 NWH618 A 1988 2009                            .59
   6 NWH618 B 1990 2009                            .82
   7 NWH605 A 1985 2009                            .28A
   8 NWH605 B 1985 2009                            .68
   9 NWH610 B 1992 2007                            .81
  10 NWH626 A 1986 2009                            .62
  11 NWH626 B 1987 2009                            .53
  12 NWH620 C 1991 2009                            .85
  13 NWH620 D 1983 2009                            .71
  14 NWH624 A 1952 2008                       .68  .69
  15 NWH614 C 1983 2009                            .30A
  16 NWH612 C 1979 2008                            .71
  17 NWH612 B 1979 2008                            .74
  18 NWH604 B 1944 2008                  .39  .41  .47
  19 NWH602 A 1960 2009                       .39
  20 NWH530xB 1885 1963        .20B .34  .48
  21 NWH500xB 1888 1997        .42  .46  .22B .39
  22 NWH501xA 1888 2006        .69  .70  .46  .45  .44
  23 NWH503xB 1908 2007             .53  .58  .63  .58
  24 NWH503xA 1908 2007             .42  .60  .61  .54
  25 NWH506xA 1900 2009             .66  .66  .49  .65
  26 NWH506xB 1900 2009             .45  .46  .49  .62
  27 NWH509xB 1871 1932   .71  .71  .57
  28 NWH509xC 1871 1932   .74  .75  .58
  29 NWH510xB 1889 1932        .73
  30 NWH510xC 1889 1932        .55
  31 NWH512xA 1924 1953             .57
  32 NWH512xB 1924 1953             .53
  33 NWH513xA 1886 1977        .59  .53  .33  .30A
  34 NWH520xB 1910 1991             .41  .38  .38
  35 NWH531xA 1948 2007                  .45  .37  .46
  36 NWH531xB 1948 2007                  .38  .30A .42
  37 NWH533xA 1887 1955        .65  .30B .36
  38 NWH533xC 1887 1955        .62  .23B .32A
  39 NWH534xD 1903 2003             .34  .70  .63  .61
  40 NWH534xC 1903 2003             .55  .73  .64  .65
  41 NWH535xA 1908 1980             .57  .55  .51
  42 NWH535xB 1908 1980             .61  .62  .61
  43 NWH538xA 1902 1965             .58  .56
  44 NWH538xC 1902 1965             .59  .57
  45 NWH539xA 1848 1993   .59  .58  .51  .55  .59
  46 NWH540xA 1929 1965                  .60
  47 NWH540xB 1929 1965                  .73
  48 NWH540xC 1929 1977                  .47
  49 NWH600xA 1873 2008   .59  .58  .58  .49  .33  .41
 Av segment correlation   .66  .59  .50  .51  .49  .60
```

```
PART 6:  POTENTIAL PROBLEMS:
------------------------------------------------------------------------------------------------------------------------------------

 For each series with potential problems the following diagnostics may appear:

 [A] Correlations with master dating series of flagged  50-year segments of series filtered with  32-year spline,
     at every point from ten years earlier (-10) to ten years later (+10) than dated

 [B] Effect of those data values which most lower or raise correlation with master series
     Symbol following year indicates value in series is greater (>) or lesser (<) than master series value

 [C] Year-to-year changes very different from the mean change in other series

 [D] Absent rings (zero values)

 [E] Values which are statistical outliers from mean for the year
====================================================================================================================================

 NWH624 A  1952 to  2008      57 years                                                                                    Series   1

 [B] Entire series, effect on correlation (  .681) is:
       Lower   1985< -.020   1988> -.016   1960> -.015   1961< -.014   2005< -.012   1962< -.012  Higher   1992  .150   1959  .022

====================================================================================================================================

 NWH622 A  1977 to  2009      33 years                                                                                    Series   2

 [B] Entire series, effect on correlation (  .671) is:
       Lower   1983< -.056   1986< -.053   1979> -.017   1991> -.014   1989< -.013   1996> -.011  Higher   2009  .170   2003  .018

====================================================================================================================================

 NWH616 A  1955 to  2009      55 years                                                                                    Series   3

 [B] Entire series, effect on correlation (  .556) is:
       Lower   1968< -.054   1962< -.036   1971< -.020   1956< -.014   1985< -.012   2004< -.009  Higher   2009  .032   1959  .027

====================================================================================================================================

 NWH617 B  1986 to  2009      24 years                                                                                    Series   4

 [B] Entire series, effect on correlation (  .767) is:
       Lower   2005< -.038   1992> -.028   1994< -.022   2003< -.016   1986> -.008   2004> -.006  Higher   2009  .104   2001  .013

====================================================================================================================================

 NWH618 A  1988 to  2009      22 years                                                                                    Series   5

 [B] Entire series, effect on correlation (  .591) is:
       Lower   1992> -.099   2006< -.038   1994< -.026   2002> -.020   2000< -.019   1995> -.011  Higher   2009  .167   2008  .030

====================================================================================================================================

 NWH618 B  1990 to  2009      20 years                                                                                    Series   6

 [B] Entire series, effect on correlation (  .825) is:
       Lower   1992> -.059   2006< -.025   2004> -.018   1990< -.007   2005< -.003   1993< -.003  Higher   2009  .169   2008  .006

====================================================================================================================================
```

```
 NWH605 A  1985 to  2009      25 years                                                                                    Series   7

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1985 2009    0    .02 -.24 -.31 -.22 -.09 -.32 -.02  .06  .09 -.03  .28*   -    -    -    -    -    -    -    -    -    -

 [B] Entire series, effect on correlation (  .280) is:
       Lower   1990< -.247   1992> -.075   1998< -.011   1991< -.008   2004> -.003   1989> -.002  Higher   2009  .052   2008  .040
     1985 to 2009 segment:
       Lower   1990< -.247   1992> -.075   1998< -.011   1991< -.008   2004> -.003   1989> -.002  Higher   2009  .052   2008  .040

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
       1990 -5.8 SD;    1992 +3.3 SD
====================================================================================================================================

 NWH605 B  1985 to  2009      25 years                                                                                    Series   8

 [B] Entire series, effect on correlation (  .680) is:
       Lower   1990< -.097   1997< -.021   2000< -.020   2002> -.019   1988> -.013   1996< -.013  Higher   2009  .180   2008  .017

====================================================================================================================================

 NWH610 B  1992 to  2007      16 years                                                                                    Series   9

 [B] Entire series, effect on correlation (  .810) is:
       Lower   2003> -.071   2001< -.024   2002> -.023   1998< -.015   1997< -.009   2007> -.006  Higher   1992  .600   1993  .005

====================================================================================================================================

 NWH626 A  1986 to  2009      24 years                                                                                    Series  10

 [B] Entire series, effect on correlation (  .624) is:
       Lower   1996< -.052   1992> -.034   1990> -.030   1995< -.030   2003> -.027   1988> -.026  Higher   2009  .403   2001  .016

====================================================================================================================================

 NWH626 B  1987 to  2009      23 years                                                                                    Series  11

 [B] Entire series, effect on correlation (  .528) is:
       Lower   1993< -.074   2001< -.043   1996< -.031   1995< -.030   1994< -.022   1991> -.019  Higher   2009  .336   2008  .023

====================================================================================================================================

 NWH620 C  1991 to  2009      19 years                                                                                    Series  12

 [B] Entire series, effect on correlation (  .847) is:
       Lower   2002> -.030   1993< -.023   2004> -.022   2000< -.015   1999> -.010   1991< -.007  Higher   2009  .133   1992  .056

====================================================================================================================================

 NWH620 D  1983 to  2009      27 years                                                                                    Series  13

 [B] Entire series, effect on correlation (  .710) is:
       Lower   1992> -.092   1988> -.022   1984< -.017   1989< -.014   2003> -.012   2001< -.012  Higher   2009  .272   2008  .013

====================================================================================================================================

 NWH624 A  1952 to  2008      57 years                                                                                    Series  14
```

```
 [B] Entire series, effect on correlation (  .681) is:
       Lower   1985< -.020   1988> -.016   1960> -.015   1961< -.014   2005< -.012   1962< -.012  Higher   1992  .150   1959  .022

=================================================================================================================================

 NWH614 C  1983 to  2009      27 years                                                                                    Series  15

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1983 2009    0   -.22  .02 -.09 -.44 -.26 -.20  .00 -.13 -.04  .02  .30*   -    -    -    -    -    -    -    -    -    -

 [B] Entire series, effect on correlation (  .304) is:
       Lower   2007< -.064   1987< -.058   2002> -.039   2008< -.037   2001< -.030   2000< -.017  Higher   1992  .082   2009  .058
     1983 to 2009 segment:
       Lower   2007< -.064   1987< -.058   2002> -.039   2008< -.037   2001< -.030   2000< -.017  Higher   1992  .082   2009  .058

=================================================================================================================================

 NWH612 C  1979 to  2008      30 years                                                                                    Series  16

 [B] Entire series, effect on correlation (  .706) is:
       Lower   1989> -.048   1979< -.036   2003> -.034   1993< -.023   1998< -.015   1991> -.013  Higher   1992  .345   2008  .017

=================================================================================================================================

 NWH612 B  1979 to  2008      30 years                                                                                    Series  17

 [B] Entire series, effect on correlation (  .735) is:
       Lower   1990> -.058   2003> -.054   2002< -.023   1994< -.013   1993< -.011   1979< -.010  Higher   1992  .226   2008  .018

=================================================================================================================================

 NWH604 B  1944 to  2008      65 years                                                                                    Series  18

 [B] Entire series, effect on correlation (  .354) is:
       Lower   1959> -.034   1950< -.030   1975> -.025   2001< -.021   2007< -.021   1951> -.018  Higher   1992  .240   1983  .020

=================================================================================================================================

 NWH602 A  1960 to  2009      50 years                                                                                    Series  19

 [B] Entire series, effect on correlation (  .389) is:
       Lower   1964< -.043   1975> -.042   1972< -.028   1974> -.021   1960> -.020   1979> -.016  Higher   2009  .089   2003  .028

=================================================================================================================================

 NWH530xB  1885 to  1963      79 years                                                                                    Series  20

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1885 1934    4   -.32  .08 -.10 -.02  .09  .07 -.13  .00 -.06  .18  .20|-.05 -.08 -.22  .26*-.09 -.12 -.12 -.06 -.18  .07

 [B] Entire series, effect on correlation (  .220) is:
       Lower   1892> -.119   1901< -.064   1886< -.025   1896> -.022   1906< -.011   1905< -.011  Higher   1888  .053   1930  .052
     1885 to 1934 segment:
       Lower   1892> -.166   1901< -.082   1886< -.032   1896> -.029   1906< -.014   1905< -.013  Higher   1888  .071   1930  .067

 [C] Year-to-year changes diverging by over 4.0 std deviations:
```

```
       1891 1892   4.2 SD

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
       1892 +4.1 SD;    1901 -4.5 SD
====================================================================================================================================

 NWH500xB  1888 to  1997     110 years                                                                                    Series  21

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1925 1974   -9    .00  .22* .20  .05  .07  .02 -.05 -.17 -.17 -.19  .22| .08  .07  .08 -.16  .02 -.10  .10 -.06  .10 -.05

 [B] Entire series, effect on correlation (  .422) is:
       Lower   1888> -.045   1957< -.027   1974> -.015   1899> -.010   1982< -.008   1944> -.008  Higher   1992  .049   1959  .026
     1925 to 1974 segment:
       Lower   1957< -.061   1974> -.040   1964> -.018   1960> -.017   1944> -.016   1938< -.015  Higher   1959  .091   1951  .055

 [D]    2 Absent rings:  Year   Master  N series Absent
                         1951   -1.462      27       1
                         1959   -1.437      26       1

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
       1888 +4.1 SD;    1959 -5.7 SD
====================================================================================================================================

 NWH501xA  1888 to  2006     119 years                                                                                    Series  22

 [B] Entire series, effect on correlation (  .575) is:
       Lower   1963< -.018   1964> -.013   1943< -.011   1984< -.011   1954> -.009   1892> -.009  Higher   1916  .024   1992  .017

====================================================================================================================================

 NWH503xB  1908 to  2007     100 years                                                                                    Series  23

 [B] Entire series, effect on correlation (  .551) is:
       Lower   1947> -.015   1912> -.011   1996< -.010   1963< -.009   2004< -.009   1919< -.008  Higher   1951  .022   1959  .017

====================================================================================================================================

 NWH503xA  1908 to  2007     100 years                                                                                    Series  24

 [B] Entire series, effect on correlation (  .478) is:
       Lower   1992> -.025   1912> -.020   1923< -.013   1947> -.013   1996< -.011   1916> -.010  Higher   1951  .027   1974  .026

====================================================================================================================================

 NWH506xA  1900 to  2009     110 years                                                                                    Series  25

 [B] Entire series, effect on correlation (  .619) is:
       Lower   1904> -.023   1921< -.013   1990> -.011   1936< -.010   1959> -.009   1915< -.009  Higher   1942  .034   2009  .023

====================================================================================================================================

 NWH506xB  1900 to  2009     110 years                                                                                    Series  26

 [B] Entire series, effect on correlation (  .503) is:
       Lower   1921< -.024   1904> -.020   1936< -.013   1990> -.009   1924< -.009   1930> -.007  Higher   1916  .023   2009  .021

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
```

```
      1916 -6.1 SD
==================================================================================================================================

 NWH509xB  1871 to  1932      62 years                                                                                    Series  27

 [B] Entire series, effect on correlation (  .600) is:
      Lower   1932> -.056   1911< -.028   1930> -.021   1926< -.018   1918> -.012   1906< -.008  Higher   1892  .115   1888  .019

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1932 +3.9 SD
==================================================================================================================================

 NWH509xC  1871 to  1932      62 years                                                                                    Series  28

 [B] Entire series, effect on correlation (  .644) is:
      Lower   1932> -.048   1911< -.028   1930> -.023   1926< -.016   1893< -.009   1917> -.008  Higher   1892  .102   1882  .044

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1932 +3.6 SD
==================================================================================================================================

 NWH510xB  1889 to  1932      44 years                                                                                    Series  29

 [B] Entire series, effect on correlation (  .725) is:
      Lower   1930> -.062   1915< -.024   1909< -.017   1906< -.016   1928< -.012   1907> -.011  Higher   1892  .134   1916  .021

==================================================================================================================================

 NWH510xC  1889 to  1932      44 years                                                                                    Series  30

 [B] Entire series, effect on correlation (  .551) is:
      Lower   1930> -.066   1909< -.022   1900> -.020   1913< -.018   1898< -.012   1896< -.009  Higher   1892  .087   1916  .042

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1930 +3.1 SD
==================================================================================================================================

 NWH512xA  1924 to  1953      30 years                                                                                    Series  31

 [B] Entire series, effect on correlation (  .570) is:
      Lower   1932> -.077   1947< -.065   1941< -.021   1951> -.015   1939< -.013   1945> -.012  Higher   1942  .146   1930  .034

==================================================================================================================================

 NWH512xB  1924 to  1953      30 years                                                                                    Series  32

 [B] Entire series, effect on correlation (  .530) is:
      Lower   1932> -.108   1927< -.074   1939< -.018   1951> -.018   1935< -.012   1925> -.012  Higher   1942  .145   1930  .023

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1932 +3.2 SD
==================================================================================================================================

 NWH513xA  1886 to  1977      92 years                                                                                    Series  33

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1928 1977    0    .16 -.03 -.04  .17 -.12 -.01 -.31 -.18 -.08  .04  .30*-.05  .13 -.04 -.15  .12  .14  .23 -.05 -.14 -.13
```

```
 [B] Entire series, effect on correlation (  .437) is:
       Lower   1888> -.039   1924< -.023   1947> -.021   1889< -.016   1964> -.013   1907< -.012  Higher   1892  .075   1930  .046
     1928 to 1977 segment:
       Lower   1947> -.046   1964> -.028   1960> -.022   1943< -.017   1977> -.016   1973< -.015  Higher   1930  .164   1942  .027

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
       1888 +3.1 SD;    1947 +3.1 SD
=====================================================================================================================================

 NWH520xB  1910 to  1991      82 years                                                                                   Series  34

 [B] Entire series, effect on correlation (  .344) is:
       Lower   1967< -.039   1916> -.038   1959> -.029   1929< -.029   1969< -.024   1975> -.018  Higher   1930  .047   1942  .034

=====================================================================================================================================

 NWH531xA  1948 to  2007      60 years                                                                                   Series  35

 [B] Entire series, effect on correlation (  .365) is:
       Lower   1951> -.074   2003> -.039   1999< -.038   1998< -.020   1964> -.018   1953< -.018  Higher   1992  .111   1974  .063

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
       1951 +3.6 SD;    1999 -5.9 SD
=====================================================================================================================================

 NWH531xB  1948 to  2007      60 years                                                                                   Series  36

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1950 1999    0    .07 -.08 -.20  .18 -.07 -.21 -.06 -.06 -.02  .01  .30* .03  .04 -.03  .23  .18 -.09 -.19 -.30 -.37  .17

 [B] Entire series, effect on correlation (  .321) is:
       Lower   1951> -.078   1999< -.049   2003> -.026   1953< -.023   1964> -.017   1989> -.016  Higher   1992  .052   1975  .034
     1950 to 1999 segment:
       Lower   1951> -.094   1999< -.055   1953< -.025   1964> -.021   1989> -.020   1998< -.012  Higher   1992  .065   1975  .041

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
       1951 +3.6 SD;    1999 -5.7 SD
=====================================================================================================================================

 NWH533xA  1887 to  1955      69 years                                                                                   Series  37

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1900 1949   -2   -.10 -.13  .02 -.11 -.15 -.06 -.10  .05  .33* .12  .30|-.07  .03  .05 -.04 -.25 -.21 -.11 -.16  .05  .13

 [B] Entire series, effect on correlation (  .589) is:
       Lower   1925> -.027   1910> -.018   1946> -.014   1937> -.013   1944< -.010   1890< -.010  Higher   1892  .147   1951  .015
     1900 to 1949 segment:
       Lower   1925> -.046   1910> -.024   1946> -.020   1937> -.018   1919< -.017   1944< -.016  Higher   1942  .038   1916  .036

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1910 +3.1 SD
=====================================================================================================================================

 NWH533xC  1887 to  1955      69 years                                                                                   Series  38

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
```

```
   1900 1949   -2   -.09 -.10 -.02 -.05 -.20 -.06 -.12  .07  .35* .13  .23|-.07  .07  .04 -.11 -.20 -.17 -.14 -.13  .06  .13
   1906 1955    0   -.07  .01 -.12  .00 -.21 -.06 -.13  .15  .29  .07  .32*-.09  .05  .04 -.11 -.18 -.21 -.11 -.07  .08  .14

 [B] Entire series, effect on correlation (  .562) is:
      Lower   1925> -.026   1940< -.018   1910> -.017   1919< -.016   1937> -.012   1921< -.011  Higher   1892  .159   1951  .019
    1900 to 1949 segment:
      Lower   1925> -.044   1940< -.033   1919< -.029   1910> -.020   1921< -.018   1937> -.015  Higher   1942  .036   1916  .028
    1906 to 1955 segment:
      Lower   1925> -.043   1940< -.031   1919< -.027   1910> -.023   1921< -.018   1937> -.017  Higher   1951  .065   1942  .020

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1910 +3.2 SD
==================================================================================================================================

 NWH534xD  1903 to  2003     101 years                                                                                    Series  39

 [B] Entire series, effect on correlation (  .485) is:
      Lower   1916> -.036   1912> -.029   1909< -.023   1978> -.020   1904> -.018   1917> -.017  Higher   1992  .119   1930  .035

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1992 -5.0 SD
==================================================================================================================================

 NWH534xC  1903 to  2003     101 years                                                                                    Series  40

 [B] Entire series, effect on correlation (  .593) is:
      Lower   1912> -.026   1978> -.022   1924< -.015   1909< -.014   2002> -.011   1918> -.011  Higher   1992  .089   1916  .028

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1992 -4.7 SD
==================================================================================================================================

 NWH535xA  1908 to  1980      73 years                                                                                    Series  41

 [B] Entire series, effect on correlation (  .512) is:
      Lower   1973< -.028   1978> -.023   1964> -.018   1916> -.014   1941< -.013   1917> -.011  Higher   1974  .034   1932  .032

==================================================================================================================================

 NWH535xB  1908 to  1980      73 years                                                                                    Series  42

 [B] Entire series, effect on correlation (  .544) is:
      Lower   1978> -.030   1930> -.027   1973< -.024   1933< -.016   1917> -.015   1954> -.014  Higher   1942  .078   1932  .029

==================================================================================================================================

 NWH538xA  1902 to  1965      64 years                                                                                    Series  43

 [B] Entire series, effect on correlation (  .561) is:
      Lower   1942> -.027   1938< -.022   1917< -.020   1957< -.019   1939< -.014   1959> -.014  Higher   1930  .049   1951  .032

==================================================================================================================================

 NWH538xC  1902 to  1965      64 years                                                                                    Series  44

 [B] Entire series, effect on correlation (  .569) is:
      Lower   1938< -.025   1959> -.020   1957< -.019   1903< -.014   1925> -.010   1917< -.009  Higher   1930  .021   1951  .019

==================================================================================================================================
```

```
 NWH539xA  1848 to  1993     146 years                                                                                    Series  45

 [*] Early part of series cannot be checked from 1848 to 1870 -- not matched by another series

 [B] Entire series, effect on correlation (  .588) is:
       Lower   1901< -.021   1877< -.013   1896> -.012   1955< -.012   1899> -.009   1900> -.008  Higher   1892  .048   1942  .025

====================================================================================================================================

 NWH540xA  1929 to  1965      37 years                                                                                    Series  46

 [B] Entire series, effect on correlation (  .595) is:
       Lower   1942> -.049   1963< -.036   1960> -.022   1965> -.018   1946< -.012   1950< -.012  Higher   1930  .106   1932  .044

====================================================================================================================================

 NWH540xB  1929 to  1965      37 years                                                                                    Series  47

 [B] Entire series, effect on correlation (  .732) is:
       Lower   1962< -.028   1950< -.022   1960> -.014   1951> -.014   1946< -.012   1931> -.011  Higher   1930  .061   1959  .029

====================================================================================================================================

 NWH540xC  1929 to  1977      49 years                                                                                    Series  48

 [B] Entire series, effect on correlation (  .472) is:
       Lower   1959> -.027   1952< -.023   1962< -.023   1975> -.023   1971< -.018   1974> -.018  Higher   1930  .110   1932  .043

====================================================================================================================================

 NWH600xA  1873 to  2008     136 years                                                                                    Series  49

 [B] Entire series, effect on correlation (  .535) is:
       Lower   1892> -.018   1915< -.018   1974> -.013   1951> -.009   1949> -.009   1956< -.007  Higher   1882  .039   1930  .019

====================================================================================================================================
```

```
PART 7:  DESCRIPTIVE STATISTICS:
------------------------------------------------------------------------------------------------------------------------------------

                                                Corr   //-------- Unfiltered --------\\  //---- Filtered -----\\
                           No.    No.    No.    with   Mean   Max     Std   Auto   Mean   Max     Std   Auto  AR
 Seq Series   Interval   Years  Segmt  Flags   Master  msmt   msmt    dev   corr   sens  value    dev   corr  ()
 --- -------- ---------  -----  -----  -----   ------ -----  -----  -----  -----  -----  -----  -----  -----  --
   1 NWH624 A 1952 2008     57      2      0    .681   1.05   3.90   .726   .681   .429   2.57   .430  -.054   1
   2 NWH622 A 1977 2009     33      1      0    .671   2.42   6.49  1.721   .243   .619   2.94   .592  -.079   1
   3 NWH616 A 1955 2009     55      2      0    .556    .63   1.52   .356   .539   .448   2.88   .620  -.073   1
   4 NWH617 B 1986 2009     24      1      0    .767   1.97   4.37   .873   .614   .328   2.73   .721  -.111   1
   5 NWH618 A 1988 2009     22      1      0    .591   2.89   5.53  1.573   .525   .399   2.73   .683  -.180   2
   6 NWH618 B 1990 2009     20      1      0    .825   2.15   3.92  1.008   .663   .366   2.38   .525  -.067   2
   7 NWH605 A 1985 2009     25      1      1    .280   2.11   3.33   .614  -.186   .334   2.37   .467   .085   1
   8 NWH605 B 1985 2009     25      1      0    .680   1.85   2.83   .583   .111   .317   2.57   .667   .025   1
   9 NWH610 B 1992 2007     16      1      0    .810   1.80   4.34  1.414   .838   .349   2.26   .521  -.204   1
  10 NWH626 A 1986 2009     24      1      0    .624   2.65   6.61  1.578   .562   .453   2.44   .486  -.025   1
  11 NWH626 B 1987 2009     23      1      0    .528   1.83   3.96  1.091   .755   .288   2.57   .618   .094   1
  12 NWH620 C 1991 2009     19      1      0    .847   2.71   4.13   .908   .129   .320   2.52   .637  -.020   1
  13 NWH620 D 1983 2009     27      1      0    .710   1.87   4.15  1.061   .555   .392   2.53   .477  -.075   1
  14 NWH624 A 1952 2008     57      2      0    .681   1.05   3.90   .726   .681   .429   2.57   .430  -.054   1
  15 NWH614 C 1983 2009     27      1      1    .304   2.24   3.81   .910   .658   .291   2.72   .710  -.001   1
  16 NWH612 C 1979 2008     30      1      0    .706   2.28   5.86  1.606   .845   .269   2.43   .470   .084   1
  17 NWH612 B 1979 2008     30      1      0    .735   1.98   5.45  1.705   .876   .358   2.61   .540   .035   1
  18 NWH604 B 1944 2008     65      3      0    .354   1.42   4.54  1.163   .717   .453   2.76   .432  -.121   2
  19 NWH602 A 1960 2009     50      1      0    .389   2.00   5.83  1.596   .842   .361   2.70   .499   .034   1
  20 NWH530xB 1885 1963     79      3      1    .220   1.50   6.96  1.316   .657   .499   2.66   .478  -.022   2
  21 NWH500xB 1888 1997    110      4      1    .422   1.07   4.47   .748   .554   .491   2.70   .445  -.038   2
  22 NWH501xA 1888 2006    119      5      0    .575   1.38   5.67   .927   .630   .394   2.69   .487   .050   1
  23 NWH503xB 1908 2007    100      4      0    .551   1.77   4.52   .861   .316   .434   2.81   .573   .046   1
  24 NWH503xA 1908 2007    100      4      0    .478   1.97   6.18   .996   .249   .421   2.89   .552   .057   1
  25 NWH506xA 1900 2009    110      4      0    .619   1.24   6.99  1.307   .799   .453   2.76   .443   .008   1
  26 NWH506xB 1900 2009    110      4      0    .503   1.25   8.04  1.395   .788   .444   2.65   .348   .022   1
  27 NWH509xB 1871 1932     62      3      0    .600   1.38   3.55   .770   .673   .364   2.80   .453  -.021   1
  28 NWH509xC 1871 1932     62      3      0    .644   1.39   3.48   .765   .693   .334   2.84   .468  -.005   1
  29 NWH510xB 1889 1932     44      1      0    .725   2.46   6.09  1.180   .656   .310   2.69   .510  -.025   1
  30 NWH510xC 1889 1932     44      1      0    .551   2.35   6.34  1.373   .662   .371   2.99   .717  -.057   1
  31 NWH512xA 1924 1953     30      1      0    .570   2.08   5.98  1.117   .406   .509   2.54   .591  -.017   1
  32 NWH512xB 1924 1953     30      1      0    .530   2.09   5.84  1.161   .467   .446   2.57   .689  -.076   1
  33 NWH513xA 1886 1977     92      4      1    .437   1.48   7.09  1.134   .610   .404   2.72   .544   .005   1
  34 NWH520xB 1910 1991     82      3      0    .344   1.47   3.50   .740   .510   .404   2.74   .609   .062   1
  35 NWH531xA 1948 2007     60      3      0    .365   1.53   5.43  1.154   .547   .464   2.91   .651  -.077   2
  36 NWH531xB 1948 2007     60      3      1    .321   1.57   5.43  1.160   .544   .474   2.91   .575   .047   1
  37 NWH533xA 1887 1955     69      3      1    .589   1.79   5.75  1.132   .635   .352   2.68   .415  -.099   1
  38 NWH533xC 1887 1955     69      3      2    .562   1.79   5.82  1.130   .633   .360   2.68   .406  -.107   1
  39 NWH534xD 1903 2003    101      4      0    .485   1.16   2.79   .526   .402   .438   2.41   .346  -.040   1
  40 NWH534xC 1903 2003    101      4      0    .593   1.14   2.75   .536   .436   .440   2.44   .355  -.036   1
  41 NWH535xA 1908 1980     73      3      0    .512   2.19   7.28  1.342   .533   .414   2.71   .538   .072   1
  42 NWH535xB 1908 1980     73      3      0    .544   1.98   6.46  1.276   .578   .394   2.64   .505   .005   1
  43 NWH538xA 1902 1965     64      2      0    .561   1.50   4.04   .905   .779   .319   2.73   .533  -.012   1
  44 NWH538xC 1902 1965     64      2      0    .569   1.50   4.18   .901   .770   .342   2.62   .442  -.027   1
  45 NWH539xA 1848 1993    146      5      0    .588   1.22   3.13   .593   .532   .390   2.65   .432  -.021   1
  46 NWH540xA 1929 1965     37      1      0    .595   1.94   4.69  1.430   .800   .416   2.49   .504  -.189   1
  47 NWH540xB 1929 1965     37      1      0    .732   1.92   4.38  1.316   .681   .479   2.77   .536  -.094   2
  48 NWH540xC 1929 1977     49      1      0    .472   1.77   4.79  1.278   .653   .491   2.78   .513  -.088   1
```

```
PART 7:  DESCRIPTIVE STATISTICS:
--------------------------------------------------------------------------------------------------------------------------------------

                                                Corr   //-------- Unfiltered --------\\  //---- Filtered -----\\
                          No.    No.    No.    with   Mean   Max     Std   Auto   Mean   Max     Std   Auto  AR
 Seq Series   Interval   Years  Segmt  Flags   Master msmt   msmt    dev   corr   sens  value    dev   corr  ()
 --- -------- ---------  -----  -----  -----   ------ -----  -----  -----  -----  -----  -----  -----  -----  --
  49 NWH600xA 1873 2008    136      6      0    .535  1.24   7.78  1.334   .788   .460   2.79   .445   .004   1
 --- -------- ---------  -----  -----  -----   ------ -----  -----  -----  -----  -----  -----  -----  -----  --
 Total or mean:           2942    113      9    .535  1.58   8.04  1.032   .594   .414   2.99   .495  -.017
```

Appendix 4. COFECHA program output for Terrestris Preserve site chronology, Big Pine Key, lower Florida Keys.

```
P R O G R A M     C O F E C H A                                                                Version 6.06P    27843
-----------------------------------------------------------------------------------------------------------------------------------

 QUALITY CONTROL AND DATING CHECK OF TREE-RING MEASUREMENTS

 File of DATED series:   TPC.TXT

 Time span of Master dating series is  1842 to  2009   168 years
 Continuous time span is               1842 to  2009   168 years
 Portion with two or more series is    1848 to  2008   161 years


                                       ****************************************
                                       *C* Number of dated series        20 *C*
                                       *O* Master series 1842 2009  168 yrs *O*
                                       *F* Total rings in all series   2352 *F*
                                       *E* Total dated rings checked   2345 *E*
                                       *C* Series intercorrelation     .561 *C*
                                       *H* Average mean sensitivity    .451 *H*
                                       *A* Segments, possible problems    2 *A*
                                       *** Mean length of series      117.6 ***
                                       ****************************************

 ABSENT RINGS listed by SERIES:            (See Master Dating Series for absent rings listed by year)

 TPC01x A    2 absent rings:   1992  2003
 TPC04BxA    1 absent rings:   1992
 B3x    A    1 absent rings:   1930
 B7x    A    2 absent rings:   1868  1871
 T8x    A    1 absent rings:   1992
 T9x    A    1 absent rings:   1904

             8 absent rings    .340%
```

```
PART 2:  TIME PLOT OF TREE-RING SERIES:
------------------------------------------------------------------------------------------------------------------------------------
 1050 1100 1150 1200 1250 1300 1350 1400 1450 1500 1550 1600 1650 1700 1750 1800 1850 1900 1950 2000 2050 Ident   Seq Time-span  Yrs
   :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    : -------- --- ---- ---- ----
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <===========>    . TPC01x A   1 1886 2008  123
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <============>    . TPC04AxA   2 1870 2008  139
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <===========>    . TPC04BxA   3 1887 2008  122
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <=======>    . TPC02x A   4 1923 2009   87
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <=======>    . B3x    A   5 1927 2000   74
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <============>    . B6x    B   6 1870 2001  132
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   <===============>    . B7x    A   7 1842 2000  159
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   <===============>    . B8x    A   8 1848 2001  154
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<=============>    . B9x    A   9 1864 2001  138
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<=============>    . B10x   A  10 1860 2001  142
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <==============>    . N4x    A  11 1854 2001  148
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <==========>.    . N5x    A  12 1880 1999  120
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <=======>    . N6x    A  13 1926 2000   75
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <=============>.    . N7x    A  14 1859 1995  137
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<========>    . N8x    A  15 1915 2000   86
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <=====>.    . N9x    A  16 1937 1999   63
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<========>    . N10x   A  17 1918 2002   85
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <============>    . T5x    A  18 1871 2000  130
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<=============>    . T8x    A  19 1862 2000  139
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <=========>    . T9x    A  20 1902 2000   99
   :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :
 1050 1100 1150 1200 1250 1300 1350 1400 1450 1500 1550 1600 1650 1700 1750 1800 1850 1900 1950 2000 2050
```

```
PART 3:  Master Dating Series:
------------------------------------------------------------------------------------------------------------------------------------
  Year  Value  No Ab    Year  Value  No Ab    Year  Value  No Ab    Year  Value  No Ab    Year  Value  No Ab    Year  Value  No Ab
  ------------------    ------------------    ------------------    ------------------    ------------------    ------------------
                        1850   .409   2       1900 -1.327  13       1950  -.192  20       2000   .177  17
                        1851   .092   2       1901   .487  13       1951 -2.310  20       2001   .144  10
                        1852 -1.570   2       1902   .105  14       1952   .366  20       2002   .319   5
                        1853 -1.714   2       1903   .189  14       1953   .902  20       2003 -2.435   4  1
                        1854   .396   3       1904 -2.097  14  1    1954   .807  20       2004   .782   4
                        1855   .295   3       1905   .128  14       1955   .739  20       2005   .723   4
                        1856   .857   3       1906   .327  14       1956   .581  20       2006   .803   4
                        1857  -.257   3       1907   .475  14       1957   .867  20       2007  -.813   4
                        1858   .859   3       1908  -.063  14       1958  -.809  20       2008   .739   4
                        1859 -1.778   4       1909   .824  14       1959 -2.220  20       2009 -1.028   1

                        1860 -1.353   5       1910   .612  14       1960  -.103  20
                        1861  -.918   5       1911   .805  14       1961   .701  20
                        1862  1.429   6       1912  -.547  14       1962  1.047  20
                        1863   .308   6       1913   .840  14       1963   .222  20
                        1864   .986   7       1914   .122  14       1964  -.932  20
                        1865   .259   7       1915  -.110  15       1965   .768  20
                        1866  1.116   7       1916 -2.668  15       1966   .358  20
                        1867   .774   7       1917  -.690  15       1967   .442  20
                        1868 -2.484   7  1    1918   .004  16       1968   .487  20
                        1869  1.349   7       1919   .200  16       1969   .886  20

                        1870  -.243   9       1920   .649  16       1970   .134  20
                        1871 -1.256  10  1    1921   .475  16       1971  -.010  20
                        1872   .331  10       1922   .607  16       1972   .100  20
                        1873   .295  10       1923  -.112  17       1973   .566  20
                        1874   .037  10       1924   .652  17       1974  -.197  20
                        1875 -2.054  10       1925 -1.654  17       1975 -3.389  20
                        1876  -.294  10       1926  1.005  18       1976  -.012  20
                        1877   .523  10       1927   .314  19       1977  -.305  20
                        1878  1.377  10       1928   .618  19       1978  -.569  20
                        1879  1.690  10       1929   .181  19       1979  -.384  20

                        1880  1.442  11       1930 -2.069  19  1    1980  -.230  20
                        1881  -.327  11       1931   .130  19       1981   .170  20
                        1882 -1.866  11       1932 -1.425  19       1982   .732  20
                        1883   .482  11       1933   .844  19       1983   .197  20
                        1884   .106  11       1934   .501  19       1984  -.246  20
                        1885  -.554  11       1935   .573  19       1985  -.269  20
                        1886   .224  12       1936   .122  19       1986   .581  20
                        1887  -.534  13       1937   .691  20       1987   .382  20
                        1888 -2.158  13       1938  1.072  20       1988  -.767  20
                        1889   .916  13       1939   .432  20       1989  -.098  20

                        1890  1.200  13       1940   .527  20       1990  -.452  20
                        1891   .716  13       1941   .167  20       1991   .719  20
  1842  1.092   1       1892 -1.539  13       1942 -3.140  20       1992 -2.653  20  3
  1843  1.518   1       1893   .543  13       1943  -.453  20       1993   .803  20
  1844 -1.771   1       1894  1.059  13       1944  -.316  20       1994   .261  20
  1845 -1.337   1       1895  -.049  13       1945   .034  20       1995   .213  20
  1846   .392   1       1896  -.371  13       1946   .464  20       1996   .525  19
  1847  -.908   1       1897  1.049  13       1947  -.169  20       1997  1.136  19
  1848  1.570   2       1898   .481  13       1948   .675  20       1998  -.369  19
  1849  1.608   2       1899  -.078  13       1949  -.239  20       1999   .271  19
------------------------------------------------------------------------------------------------------------------------------------
```

```
PART 4:  Master Bar Plot:
-----------------------------------------------------------------------------------------------------------------------------------
   Year Rel value  Year Rel value  Year Rel value  Year Rel value  Year Rel value  Year Rel value  Year Rel value  Year Rel value
                   1850------B     1900-e          1950---a        2000-----A
                   1851----@       1901-------B    1951i           2001----A
                   1852-f          1902----@       1952------A     2002------A
                   1853g           1903-----A      1953---------D  2003j
                   1854------B     1904h           1954---------C  2004--------C
                   1855-----A      1905----A       1955--------C   2005--------C
                   1856---------C  1906------A     1956-------B    2006---------C
                   1857---a        1907-------B    1957---------C  2007--c
                   1858---------C  1908---@        1958--c         2008--------C
                   1859g           1909---------C  1959i           2009-d
                   1860-e          1910-------B    1960---@
                   1861-d          1911---------C  1961--------C
                   1862----------F 1912--b         1962---------D
                   1863------A     1913---------C  1963-----A
                   1864---------D  1914----@       1964-d
                   1865-----A      1915---@        1965--------C
                   1866----------D 1916k           1966------A
                   1867--------C   1917--c         1967------B
                   1868j           1918----@       1968-------B
                   1869----------E 1919-----A      1969---------D
                   1870---a        1920--------C   1970----A
                   1871-e          1921-------B    1971----@
                   1872------A     1922-------B    1972----@
                   1873-----A      1923---@        1973-------B
                   1874----@       1924--------C   1974---a
                   1875h           1925-g          1975n
                   1876--a         1926---------D  1976----@
                   1877-------B    1927------A     1977--a
                   1878----------F 1928-------B    1978--b
                   1879----------G 1929-----A      1979--b
                   1880----------F 1930h           1980---a
                   1881--a         1931----A       1981-----A
                   1882g           1932-f          1982--------C
                   1883-------B    1933---------C  1983-----A
                   1884----@       1934-------B    1984---a
                   1885--b         1935-------B    1985---a
                   1886-----A      1936----@       1986-------B
                   1887--b         1937--------C   1987------B
                   1888i           1938---------D  1988--c
                   1889---------D  1939------B     1989---@
                   1890----------E 1940-------B    1990--b
                   1891--------C   1941-----A      1991--------C
   1842---------D  1892-f          1942m           1992k
   1843----------F 1893-------B    1943--b         1993---------C
   1844g           1894---------D  1944--a         1994-----A
   1845-e          1895---@        1945----@       1995-----A
   1846------B     1896--a         1946------B     1996-------B
   1847-d          1897---------D  1947---a        1997----------E
   1848----------F 1898-------B    1948--------C   1998--a
   1849----------F 1899---@        1949---a        1999-----A
```

```
PART 5:  CORRELATION OF SERIES BY SEGMENTS:
------------------------------------------------------------------------------------------------------------------------------------
 Correlations of  50-year dated segments, lagged  25 years
 Flags:  A = correlation under   .3281 but highest as dated;  B = correlation higher at other than dated position

 Seq Series  Time_span   1825 1850 1875 1900 1925 1950 1975
                         1874 1899 1924 1949 1974 1999 2024
 --- -------- ---------  ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ----
   1 TPC01x A 1886 2008             .53  .49  .52  .47  .40
   2 TPC04AxA 1870 2008        .60  .66  .56  .53  .56  .61
   3 TPC04BxA 1887 2008             .69  .68  .64  .55  .49
   4 TPC02x A 1923 2009                  .74  .73  .58  .57
   5 B3x    A 1927 2000                       .49  .50  .50
   6 B6x    B 1870 2001        .61  .64  .59  .63  .54  .52
   7 B7x    A 1842 2000   .58  .53  .39  .60  .77  .65  .64
   8 B8x    A 1848 2001   .68  .66  .64  .52  .42  .50  .49
   9 B9x    A 1864 2001        .64  .67  .63  .58  .35  .28A
  10 B10x   A 1860 2001        .63  .67  .54  .50  .62  .62
  11 N4x    A 1854 2001        .64  .52  .50  .52  .51  .50
  12 N5x    A 1880 1999             .64  .65  .65  .59
  13 N6x    A 1926 2000                       .68  .55  .55
  14 N7x    A 1859 1995        .49  .53  .60  .45  .43
  15 N8x    A 1915 2000                  .66  .62  .62  .62
  16 N9x    A 1937 1999                       .28B .38
  17 N10x   A 1918 2002                  .44  .45  .42  .43
  18 T5x    A 1871 2000        .41  .40  .49  .63  .67  .67
  19 T8x    A 1862 2000        .63  .64  .63  .63  .43  .43
  20 T9x    A 1902 2000                  .49  .43  .44  .43
 Av segment correlation   .63  .58  .59  .58  .56  .52  .52

PART 6:  POTENTIAL PROBLEMS:
------------------------------------------------------------------------------------------------------------------------------------

 For each series with potential problems the following diagnostics may appear:

 [A] Correlations with master dating series of flagged  50-year segments of series filtered with  32-year spline,
     at every point from ten years earlier (-10) to ten years later (+10) than dated

 [B] Effect of those data values which most lower or raise correlation with master series
     Symbol following year indicates value in series is greater (>) or lesser (<) than master series value

 [C] Year-to-year changes very different from the mean change in other series

 [D] Absent rings (zero values)

 [E] Values which are statistical outliers from mean for the year
====================================================================================================================================

 TPC01x A  1886 to  2008     123 years                                                                                    Series   1

 [B] Entire series, effect on correlation (  .584) is:
       Lower   1959> -.015   1937< -.015   2007> -.012   1890< -.011   1932> -.011   1991< -.009  Higher   2003  .058   1992  .025

 [D]    2 Absent rings:  Year   Master  N series Absent
                         1992   -2.653      20       3
                         2003   -2.435       4       1
                                                        Present in series    2  TPC04AxA time span  1870 to  2008
                                                        Present in series    3  TPC04BxA time span  1887 to  2008
                                                        Present in series    4  TPC02x A time span  1923 to  2009
```

```
 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
       1905 +3.1 SD;    2003 -5.3 SD
====================================================================================================================================

 TPC04AxA  1870 to  2008     139 years                                                                                    Series   2

 [B] Entire series, effect on correlation (  .582) is:
       Lower   1870> -.014   1965< -.012   1912< -.012   1989< -.012   1953< -.007   2001> -.007  Higher   2003  .019   1975  .016

====================================================================================================================================

 TPC04BxA  1887 to  2008     122 years                                                                                    Series   3

 [B] Entire series, effect on correlation (  .629) is:
       Lower   1958> -.017   2006< -.016   2003> -.013   1988> -.011   1897< -.011   1954< -.010  Higher   1992  .040   1916  .021

 [D]    1 Absent rings:  Year   Master  N series Absent
                         1992   -2.653      20       3

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1992 -4.6 SD
====================================================================================================================================

 TPC02x A  1923 to  2009      87 years                                                                                    Series   4

 [*] Later part of series cannot be checked from 2009 to 2009 -- not matched by another series

 [B] Entire series, effect on correlation (  .637) is:
       Lower   1976< -.027   1977< -.013   2004< -.013   1985> -.009   1989> -.008   2006> -.008  Higher   1942  .049   1975  .038

====================================================================================================================================

 B3x    A  1927 to  2000      74 years                                                                                    Series   5

 [B] Entire series, effect on correlation (  .531) is:
       Lower   1935< -.019   1958> -.016   1949> -.016   1964> -.016   1968< -.015   1987< -.013  Higher   1975  .077   1930  .051

 [D]    1 Absent rings:  Year   Master  N series Absent
                         1930   -2.069      19       1

====================================================================================================================================

 B6x    B  1870 to  2001     132 years                                                                                    Series   6

 [B] Entire series, effect on correlation (  .607) is:
       Lower   1989< -.017   1917> -.012   1977> -.009   1930> -.009   1910< -.009   1964> -.009  Higher   1992  .033   1942  .021

====================================================================================================================================

 B7x    A  1842 to  2000     159 years                                                                                    Series   7

 [*] Early part of series cannot be checked from 1842 to 1847 -- not matched by another series

 [B] Entire series, effect on correlation (  .607) is:
       Lower   1906> -.013   1900> -.012   1985> -.010   1857< -.009   1897< -.008   1891< -.007  Higher   1942  .031   1975  .021

 [D]    2 Absent rings:  Year   Master  N series Absent
                         1868   -2.484       7       1
```

```
                         1871   -1.256      10       1

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
       1906 +3.4 SD;    1959 -5.3 SD
====================================================================================================================================

 B8x    A  1848 to  2001     154 years                                                                                    Series   8

 [B] Entire series, effect on correlation (  .555) is:
       Lower   1925> -.027   1964> -.010   1903< -.010   1919< -.009   1912> -.008   1854< -.007  Higher   1942  .034   1992  .033

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
       1925 +3.2 SD;    1931 +3.2 SD
====================================================================================================================================

 B9x    A  1864 to  2001     138 years                                                                                    Series   9

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1952 2001    0   -.09  .18  .23 -.31  .10 -.19 -.09 -.20 -.06  .15  .28* .06  .00  .04  .02  .28 -.07 -.08 -.09    -    -

 [B] Entire series, effect on correlation (  .514) is:
       Lower   1992> -.065   1869< -.015   1945< -.011   1998< -.010   1976< -.007   1972< -.007  Higher   1975  .038   1916  .027
     1952 to 2001 segment:
       Lower   1992> -.189   1976< -.018   1979> -.015   1985> -.014   1972< -.014   1965< -.014  Higher   1975  .210   1959  .049

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1992 +4.5 SD
====================================================================================================================================

 B10x   A  1860 to  2001     142 years                                                                                    Series  10

 [B] Entire series, effect on correlation (  .593) is:
       Lower   1940< -.011   1985> -.010   1930> -.010   1994< -.009   1868> -.008   1980< -.007  Higher   1992  .033   1916  .019

====================================================================================================================================

 N4x    A  1854 to  2001     148 years                                                                                    Series  11

 [B] Entire series, effect on correlation (  .552) is:
       Lower   1959> -.021   1916> -.010   1921< -.008   1901< -.008   1889< -.007   1870< -.006  Higher   1992  .040   1942  .021

====================================================================================================================================

 N5x    A  1880 to  1999     120 years                                                                                    Series  12

 [B] Entire series, effect on correlation (  .613) is:
       Lower   1985< -.022   1890< -.012   1992> -.012   1885> -.009   1947< -.007   1938< -.007  Higher   1975  .041   1916  .029

====================================================================================================================================

 N6x    A  1926 to  2000      75 years                                                                                    Series  13

 [B] Entire series, effect on correlation (  .631) is:
       Lower   1935< -.021   1975> -.011   1978> -.011   1955< -.009   1989> -.009   1947> -.009  Higher   1942  .064   1930  .033

====================================================================================================================================

 N7x    A  1859 to  1995     137 years                                                                                    Series  14
```

```
 [B] Entire series, effect on correlation (  .485) is:
       Lower   1959> -.026   1952< -.019   1879< -.018   1932> -.014   1860> -.013   1861> -.012  Higher   1942  .024   1992  .024

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1959 +3.5 SD
====================================================================================================================================

 N8x    A  1915 to  2000      86 years                                                                                    Series  15

 [B] Entire series, effect on correlation (  .628) is:
       Lower   1985< -.021   1973< -.011   1977> -.011   1988< -.010   1954< -.009   1995> -.008  Higher   1975  .051   1916  .019

====================================================================================================================================

 N9x    A  1937 to  1999      63 years                                                                                    Series  16

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1937 1986    2    .07  .22 -.10  .20 -.08  .06 -.14 -.02  .08 -.09  .28|-.07  .30* .20 -.18 -.09 -.10  .05 -.10 -.14 -.03

 [B] Entire series, effect on correlation (  .290) is:
       Lower   1939< -.065   1942> -.027   1973< -.022   1956< -.018   1957< -.017   1996< -.013  Higher   1951  .051   1959  .038
     1937 to 1986 segment:
       Lower   1939< -.079   1942> -.043   1973< -.026   1956< -.022   1957< -.020   1969< -.011  Higher   1951  .066   1959  .048

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1942 +3.2 SD
====================================================================================================================================

 N10x   A  1918 to  2002      85 years                                                                                    Series  17

 [B] Entire series, effect on correlation (  .426) is:
       Lower   1992> -.027   1962< -.021   1922< -.017   1979> -.014   1971> -.013   1958> -.012  Higher   1975  .051   1959  .042

====================================================================================================================================

 T5x    A  1871 to  2000     130 years                                                                                    Series  18

 [B] Entire series, effect on correlation (  .538) is:
       Lower   1871> -.019   1921< -.013   1994< -.012   1958> -.012   1927< -.012   1894< -.010  Higher   1992  .043   1975  .029

====================================================================================================================================

 T8x    A  1862 to  2000     139 years                                                                                    Series  19

 [B] Entire series, effect on correlation (  .587) is:
       Lower   1978> -.017   1880< -.014   1865< -.010   1895> -.010   1969< -.007   1922> -.007  Higher   1992  .015   1875  .012

 [D]    1 Absent rings:  Year   Master  N series Absent
                         1992   -2.653      20       3

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1868 -5.5 SD
====================================================================================================================================

 T9x    A  1902 to  2000      99 years                                                                                    Series  20

 [B] Entire series, effect on correlation (  .501) is:
```

```
      Lower   1978> -.015   1932> -.012   1957< -.010   1946< -.010   1982< -.010   1967< -.009  Higher   1992  .053   1904  .042

 [D]    1 Absent rings:  Year   Master  N series Absent
                         1904   -2.097      14       1

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1904 -5.1 SD
===================================================================================================================================

PART 7:  DESCRIPTIVE STATISTICS:
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                                                Corr   //-------- Unfiltered --------\\  //---- Filtered -----\\
                         No.    No.    No.    with   Mean   Max     Std   Auto   Mean   Max     Std   Auto  AR
 Seq Series   Interval   Years  Segmt  Flags   Master  msmt   msmt    dev   corr   sens  value    dev   corr  ()
 --- -------- ---------  -----  -----  -----   ------ -----  -----  -----  -----  -----  -----  -----  -----  --
   1 TPC01x A 1886 2008    123      5      0     .584   .61   2.03   .387   .359   .524   2.66   .350   .000   2
   2 TPC04AxA 1870 2008    139      6      0     .582   .83   4.22   .669   .702   .424   2.82   .489  -.037   1
   3 TPC04BxA 1887 2008    122      5      0     .629   .64   2.48   .374   .434   .407   2.74   .366  -.011   1
   4 TPC02x A 1923 2009     87      4      0     .637   .87   2.42   .538   .548   .450   2.73   .537   .140   3
   5 B3x    A 1927 2000     74      3      0     .531   .81   3.82   .861   .571   .465   2.80   .547  -.097   1
   6 B6x    B 1870 2001    132      6      0     .607   .82   4.08   .735   .642   .441   2.82   .570  -.099   1
   7 B7x    A 1842 2000    159      7      0     .607   .78   3.29   .597   .510   .475   2.86   .399   .006   1
   8 B8x    A 1848 2001    154      7      0     .555   .86   2.70   .439   .320   .420   2.99   .517   .021   1
   9 B9x    A 1864 2001    138      6      1     .514   .54   2.37   .412   .536   .481   2.86   .563   .013   1
  10 B10x   A 1860 2001    142      6      0     .593   .80   2.30   .473   .420   .448   2.79   .525   .048   1
  11 N4x    A 1854 2001    148      6      0     .552   .67   2.84   .512   .592   .444   2.63   .395  -.005   1
  12 N5x    A 1880 1999    120      4      0     .613   .72   2.78   .497   .533   .433   2.72   .507   .059   1
  13 N6x    A 1926 2000     75      3      0     .631   .86   2.93   .623   .595   .474   2.88   .547  -.031   1
  14 N7x    A 1859 1995    137      5      0     .485   .99   3.35   .653   .506   .408   2.66   .430   .038   2
  15 N8x    A 1915 2000     86      4      0     .628   .70   2.24   .485   .582   .458   2.67   .561  -.015   1
  16 N9x    A 1937 1999     63      2      1     .290   .64   2.16   .463   .684   .406   2.67   .512  -.085   2
  17 N10x   A 1918 2002     85      4      0     .426   .56   1.67   .317   .497   .455   2.71   .479  -.037   1
  18 T5x    A 1871 2000    130      6      0     .538   .82   3.08   .598   .513   .454   2.74   .507  -.046   2
  19 T8x    A 1862 2000    139      6      0     .587   .73   3.06   .543   .534   .479   2.81   .387  -.056   1
  20 T9x    A 1902 2000     99      4      0     .501   .74   2.23   .487   .526   .474   2.48   .367  -.058   1
 --- -------- ---------  -----  -----  -----   ------ -----  -----  -----  -----  -----  -----  -----  -----  --
 Total or mean:           2352     99      2     .561   .75   4.22   .532   .522   .451   2.99   .472  -.009
```

VITA

Grant L. Harley earned a Bachelor of Arts degree in geography with a concentration in physical/environmental geography from the University of South Florida in 2005. He received a Master of Arts degree from the Department of Geography at the University of South Florida in 2007. His thesis research involved the integration of GIS and environmental impact assessment techniques to develop a new approach to evaluating the sensitivity and disturbance of cave and karst environments in west-central Florida. In 2012, he was awarded the Doctorate of Philosophy degree in geography by the University of Tennessee. During his tenure as a doctoral student at the University of Tennessee, he served as a Graduate Fellow for the University of Tennessee GK–12 Earth Project funded by the National Science Foundation, and worked as a Graduate Teaching Associate in the Department of Geography. After graduation, Grant will relocate to Mississippi where he accepted a position as an assistant professor in the Department of Geography and Geology at The University of Southern Mississippi.