To the Graduate Council:

I am submitting herewith a thesis written by Joshua W. Albritton entitled "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." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geography.

Sally P. Horn, Major Professor

We have read this thesis
and recommend its acceptance:

Kenneth H. Orvis

Henri D. Grissino-Mayer

Accepted for the Council:

Carolyn R. Hodges
Vice Provost and Dean of the Graduate School

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

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

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

Joshua Wright Albritton
December 2009

Copyright © by Joshua Wright Albritton
All rights Reserved

ACKNOWLEDGMENTS

The completion of this thesis would not have been possible without the help and support of a great number of people. Foremost of those I wish to thank is my advisor, Dr. Sally Horn. I am indebted to her for helping me to find my niche within the Department of Geography at the University of Tennessee, for allowing me to be directly involved in teaching at the University of Tennessee, and for including me in ongoing research in Costa Rica and in the lower Florida Keys. I am grateful for all of Dr. Horn's guidance, support, and insights through every stage of this thesis research, and through every stage of my undergraduate and graduate work. I also want to thank Dr. Ken Orvis for helping me understand and puzzle through issues of climate and charcoal and pollen deposition, and for his support, guidance, and patience, both on campus and in the field. I benefited immensely from having the opportunity to learn under the instruction of Dr. Orvis. I am also grateful to Dr. Henri Grissino-Mayer for his careful editing of an earlier version of this thesis, for his general enthusiasm for this project, and for his interest, support, and helpful insights during all stages of this research.

The sediment core from Key Deer Pond was recovered with the help of Sally Horn and Ken Orvis. The pond on Big Pine Key was selected by Sally Horn and Ken Orvis during an initial reconnaissance of potential coring sites. The reconnaissance field party also consisted of Chris Bergh of The Nature Conservancy, who suggested the pond as a good coring site, and Paige Schmidt of the U.S. Fish and Wildlife Service. Anne Morkill, the Director of National Key Deer Refuge, provided housing and logistical support for the reconnaissance visit, and Chris Bergh covered transportation costs. Anne

later arranged for additional support from the U.S. Fish and Wildlife Service for sediment coring and analysis. I wish to thank Anne Morkill and Chris Bergh for their generous support throughout this project.

I am indebted to Ian Slayton, Maria Caffrey, and Brian Watson for their friendship and cheerful conversation. They were constant with their encouragement, support, and energy. I am likewise indebted to Alisa Hass and Charles Batey for their laboratory assistance. I would especially like to thank Maria Caffrey for her valuable insights on issues of sedimentation, climate, pollen and charcoal production, among so many others during the laboratory phase of this research. I also benefited immensely from conversations with Chris Underwood, Ian Feathers, Grant Harley, Monica Rother, Zack Taylor, Mathew Valente, and others at the University of Tennessee, and Suzanne Koptur of Florida International University.

Finally, none of this could have been possible without the unwavering support of my parents, Larry and Debbie Albritton. They are a constant source of love, encouragement, and support, and for this I am thankful.

Sediment coring and analyses were funded by the U.S. Fish and Wildlife Service through Grant Agreement 40181-7-G045 (Sally Horn, PI). Additional support was provided by The Nature Conservancy and the University of Tennessee. During my graduate work at the University of Tennessee, I was supported by a teaching assistantship from the Department of Geography.

ABSTRACT

Key Deer Pond (24° 42′ 29.50″ N, 81° 22′ 36.12″ W; ca. 2 m elevation) is a small freshwater pond in a solution hole located within the pine rocklands of the National Key Deer Refuge on Big Pine Key, Florida. Overlapping sediment core sections and a surface grab sample from Key Deer Pond were subjected to pollen, microscopic charcoal, and loss-on-ignition analyses to investigate late-Holocene climate, fire occurrence, and vegetation-fire relationships in pine rockland ecosystems. Macroscopic charcoal from the uppermost meter of the profile was studied to provide a more detailed history of local fire occurrence.

The results from the microscopic charcoal analyses show that fire has long been a part of these pine rockland ecosystems. Generally higher values for all microscopic charcoal indices since ca. 1200 cal yr BP suggest increased fire in the region, and likely around Key Deer Pond. The high-resolution macroscopic charcoal, which spans the last ca. 400 years, provides compelling evidence for repeated fires surrounding the pond. This finding is consistent with the interpretation that lower Keys pine rocklands are a fire-dependent ecosystem characterized by frequent surface fires. The very late human colonization of Big Pine Key, perhaps occurring no more than 160 years ago, suggests that early fires were lightning-induced, and that changes in fire occurrence were the result of prehistoric climate shifts.

Pollen assemblages reveal that the vegetation at the site has changed only moderately since 1660 cal yr BP. Pine dominance over much of the record indicates that pine has long been abundant in the area. Increases in pollen of *Conocarpus erectus* since

ca. 357 cal yr BP, and decreases in the abundance of pine since ca. 83 cal yr BP, may signal the impacts of rising sea level.

TABLE OF CONTENTS

CHAPTER 1: INTRODUCTION …….. 1

CHAPTER 2: LITERATURE REVIEW ……... 5

Previous Paleoenvironmental Research in Florida ……... 5
Paleoenvironmental Research in Pine Forest Ecosystems of The Bahamas …….. 7
Previous Paleoecological Research in the Circum-Caribbean Region ……. 9
Charcoal as a Proxy for Past Fire Activity ……..... 11
Macroscopic Charcoal as a Proxy for Local Fires …….. 12
Microscopic Charcoal …….. 15
Comparisons of Microscopic and Macroscopic Charcoal in the Same Cores ……... 16
Sedimentary Charcoal as Evidence for Human Arrival on Islands ……. 17
Application of Paleoecological Research to Ecosystem Conservation …… 18
Hurricane and Tropical Storm Events and Their Representation in Sediment Records ……. 21
Sea Level Changes and Their Indication in Pollen Records …… 23

CHAPTER 3: ENVIRONMENTAL AND CULTURAL SETTING ……..25

Study Area …… 25
Geological and Physical Setting …….. 25
Climate ……. 31
Vegetation …… 32
Fire Ecology of Florida Pine Rocklands ……. 34
Pre-European Settlement ……. 36
European Settlement …… 39
Present Day Management of Pine Rockland Ecosystems of the Lower Florida Keys ……. 41

CHAPTER 4: METHODS …….. 46

Field Methods …….. 46
Laboratory Methods …… 48
Radiocarbon Dating and Core Chronology …… 48
Microfossil Preparation and Loss-on-Ignition …… 49
Pollen Analysis …… 50
Microscopic Charcoal Analysis ……... 51
Macroscopic Charcoal Analysis …….. 52

CHAPTER 5: RESULTS …… 53

Sediments and Stratigraphy ……. 53
Radiocarbon Analysis …….. 56
Loss-on-Ignition ……... 56
The Pollen Record …… 60
The Microscopic Charcoal Record …….. 64
The Macroscopic Charcoal Record ……. 66
Comparing Microscopic and Macroscopic Charcoal Records……. 69

CHAPTER 6: DISCUSSION …….. 71

What are the general trends in the fire history through time in the pine rockland ecosystem as shown by microscopic and macroscopic charcoal analysis of the Key Deer Pond sediments? …….. 71
How do the microscopic and macroscopic charcoal curves compare, and what does this reveal about the microscopic charcoal signal in the sediments? …… 78
Are there identifiable differences in fire activity between the modern, early historic, and prehistoric periods that would help identify differences between natural and anthropogenic (human-altered) fire regimes? ……. 79
Has the vegetation surrounding Key Deer Pond changed through time? ……... 81
Do changes in vegetation inferred from pollen analysis match evidence of changes in fire activity or climate from charcoal? ……... 83
Do stratigraphic layers exist in the sediment cores that indicate the impacts of hurricane or tropical storm events? ……... 84
Are changes in vegetation evident in the pollen record that indicate the impacts of sea level change? …… 85

CHAPTER 7: CONCLUSIONS …….. 88

REFERENCES ……. 91

APPENDICES …… 104

Appendix A Pollen Processing Schedule ……. 105

Appendix B Charcoal Point Counting Calculations …….107

Appendix C Identified Pollen Taxa ……. 109

VITA ……... 110

LIST OF TABLES

Table 5.1 Sediment Stratigraphy of Hole 1A and 1C, Key Deer Pond …… 55

Table 5.2 Radiocarbon determinations and calibrated ages for material from Key Deer Pond sediment profile ……. 57

Table 5.3 Pollen concentrations exclusive of fern spores and indeterminate pollen grains for the Key Deer Pond sediment profile ……. 61

Table 5.4 Pollen diversity for the Key Deer Pond sediment profile …….62

LIST OF FIGURES

Figure 3.1 Recent satellite image of (1) south Florida and the Everglades; (2) Florida Keys; (3) Cuba; and (4) The Bahamas ……... 26

Figure 3.2 Recent satellite image of the lower Florida Keys numbered to indicate (1) Big Pine Key; (2) Little Torch Key; (3) Middle Torch Key; (4) No Name Key; and (5) Key West ……27

Figure 3.3 Location of Key Deer Pond and a second coring site, Blue Hole Wetland, on Big Pine Key in the lower Florida Keys …….. 28

Figure 4.1 Coring platform used at Key Deer Pond …….. 47

Figure 5.1 Sediment Stratigraphy of Hole 1A and 1C, Key Deer Pond …… 54

Figure 5.2 Age vs. depth relationship for Key Deer Pond, Big Pine Key, showing sedimentation rates …….58

Figure 5.3 Loss-on-ignition results for the Key Deer Pond sediment profile …… 59

Figure 5.4 Percentage pollen diagram for the Key Deer Pond sediment profile showing main pollen types, total fern spores, and charcoal to pollen ratios …… 63

Figure 5.5 Concentration of microscopic charcoal fragments (<125 µm) expressed as charcoal area per g dry sediment, charcoal area per cm^3 wet sediment, influx ($mm^2/cm^2/yr$), and charcoal to pollen ratios for the Key Deer Pond sediment profile …….. 65

Figure 5.6 Macroscopic charcoal in the upper ca. 1 m of the Key Deer Pond sediment profile (core section 0.11–1.11 m in Hole 1A) ……. 67

Figure 5.7 Macroscopic charcoal in the upper ca. 1 m of the Key Deer Pond Sediment profile (core section 0.11–1.11 m in Hole 1A), expressed as concentrations and influx for all particles >250 µm in size ……. 68

Figure 5.8 Comparison of microscopic and macroscopic charcoal concentrations in the upper ca. 1 m of the Key Deer Pond sediment profile (core section 0.11–1.11 m in Hole 1A) ……70

CHAPTER 1

Introduction

A great deal of research has focused on interactions between climate, vegetation, and ecological processes, and on how these interactions have shaped past and present landscapes. Paleoecological studies based on analyses of fossil pollen, charcoal, and other proxy indicators in sediment cores from lakes and wetlands can provide important evidence for reconstructing past climate, vegetation, and fire regimes (Sanford and Horn 2000). Reconstructions based on these proxy indicators can increase our understanding of the dynamic nature of landscapes and ecological processes (e.g., wildfire). Paleoecological data also can be used to assess the long-term interactions between climate, fire, and vegetation (Gavin *et al.* 2007). For example, parallel fire and vegetation histories can reveal changes in fire regimes in response to climate shifts, and how shifts in vegetation are tied to fire activity (Whitlock and Anderson 2003; Gavin *et al.* 2007). Such records can also yield information important for assessing human impacts on the environment, for example, the effects of altered fire regimes or land use changes on vegetation composition (Burney and Burney 2003, 2007; Willard *et al.* 2006).

Fossil pollen and charcoal records spanning tens to thousands of years can provide a unique, long-term perspective for biodiversity conservation efforts aimed at conserving processes, habitats, or species (Willis and Birks 2006; Gavin *et al.* 2007; Willard and Cronin 2007). Such studies are increasingly being used to inform natural resource management and conservation planning at local, regional, and global scales (Horn 1998; Swetnam *et al.* 1999; Willard *et al.* 2001; Willis and Birks 2006; Willard

and Cronin 2007). For example, long-term fire histories can provide important baseline information on the range of natural variability of fire activity prior to human disturbance, such as land use change or fire suppression (Gavin *et al.* 2007).

This thesis describes the first paleoecological research conducted in pine rockland habitats of the lower Florida Keys, although sediment records of vegetation, climate, and fire history have been developed for sites in pine rocklands on the islands of the Bahamas (Kjellmark 1995; 1996; Myers *et al.* 2004; Stork 2006; West 2007). Additional evidence on fire history in pine rocklands of the Bahamas was provided by Miller (2007), who conducted a dendrochronological study on *Pinus caribaea* var. *bahamensis* (Bahamian pine) on Abaco Island. Paleoecological studies relevant to my research have been conducted in the Florida Everglades, at mainland sites in central and northern Florida, and at other sites in the broader circum-Caribbean region, as reviewed in Chapter 2 of this thesis.

My thesis adds to knowledge of pine rockland habitats and circum-Caribbean paleoenvironments through a paleoecological study of pollen and charcoal in a ca. 1700-year sediment record from a solution hole in the National Key Deer Refuge (NKDR) on Big Pine Key, Florida. My primary objective is to provide charcoal and pollen evidence of past fire, vegetation, and climate near Key Deer Pond (unofficial name), where the surroundings currently are dominated by pine rockland vegetation. Prescribed fire is one of the most important considerations in pine rockland management; however, NKDR has not launched a comprehensive fire management program involving prescribed burning, in part because the proper fire frequency to maintain pine rocklands is not yet known (Snyder *et al*. 1990; Carlson *et al*. 1993; Bergh and Wisby 1996; USFWS 1999*b*; Liu and

Menges 2005; Snyder *et al*. 2005). The results of my investigation will hopefully assist NKDR officials with the development of fire management policy and plans for the pine rocklands of Big Pine Key and other Keys in the lower Florida Keys. A secondary objective of my work is to provide NKDR officials with environmental data that will assist with public education efforts both inside and outside of the refuge. To undertake these tasks, I used a multiple proxy approach. I analyzed the Key Deer Pond sediments for pollen, microscopic charcoal, and macroscopic charcoal, and asked the following questions:

- What are the general trends in the fire history through time in the pine rockland ecosystem as shown by microscopic and macroscopic charcoal analysis of the Key Deer Pond sediments?
- How do the microscopic and macroscopic charcoal curves compare, and what does this reveal about the microscopic charcoal signal in the sediments?
- Are there identifiable differences in fire activity between the modern, early historic, and prehistoric periods that would help identify differences between natural and anthropogenic (human-altered) fire regimes?
- Has the vegetation surrounding Key Deer Pond changed through time?
- Do changes in vegetation inferred from pollen analysis match evidence of changes in fire activity or climate from charcoal?
- Do stratigraphic layers exist in the sediment cores that indicate the impacts of hurricane or tropical storm events?
- Are changes in vegetation evident in the pollen record that indicate the impacts of sea level change?

This thesis consists of seven chapters. In the chapter that follows, I review literature on fire, vegetation, and climate history in Florida and the circum-Caribbean region, and on methods and applications of paleoecological studies. Chapter Three describes the environmental and cultural setting of the lower Florida Keys, with specific details about Big Pine Key and adjacent Keys. In Chapter Four, I describe the field and laboratory methods used to conduct this multiple proxy analysis of the Key Deer Pond sediment profile. In Chapter Five, I present pollen and charcoal records from the sediments of Key Deer Pond. I discuss the implications of my results in Chapter Six, and how they fit with other research conducted in the region with respect to fire, vegetation, and climate history, and human impacts on the environment. In Chapter Seven, I conclude this thesis by summarizing my results and offering some suggestions for future research on Big Pine Key.

CHAPTER 2

Literature Review

Previous Paleoenvironmental Research in Florida

Several paleoenvironmental investigations have been undertaken in peninsular Florida. Published sediment records from lakes and other wetlands in mainland Florida document distinct climate shifts and a generally wetter climate in the middle to late Holocene, along with changes in vegetation and fire activity. As yet, comprehensive studies of sedimentary charcoal have not been carried out outside of the Florida Everglades.

Watts and Stuiver (1980) obtained a sediment core from Sheeler Lake in north Florida. The pollen diagram showed that after ca. 14,000 ^{14}C yr BP[1], herbs and dry forest taxa were replaced by pollen of mesic trees, an indication of increased precipitation. After 13,000 ^{14}C yr BP, mesic trees steadily declined while a variety of herbaceous taxa (*Ambrosia, Selaginella,* Poaceae) and pine (*Pinus*) expanded. The authors attributed this transition to a drier climate and increased fire frequency. In the later Holocene (ca. 7200 ^{14}C yr BP), the modern vegetation and climate became established. *Pinus* became much more abundant than *Quercus*, and cypress swamps and bayhead communities developed, all indicative of a return to wetter conditions.

Pollen diagrams from a sediment core recovered from Camel Lake (Watts *et al.* 1992) revealed the vegetation history of northwest Florida since the late Pleistocene. After 29,000 ^{14}C yr BP, pine became the dominant pollen type. In sediments deposited

[1] All dates and ages in this chapter are presented as originally reported, in either radiocarbon years (^{14}C yr BP) or calibrated years (cal yr BP).

between 14,000–12,000 ^{14}C yr BP, *Pinus* percentages dramatically declined, and pollen of deciduous hardwood trees such as *Quercus*, *Carya*, and *Fagus* increased. Consistent with the findings from Sheeler Lake, at 7500 ^{14}C yr BP, *Pinus* increases and pollen of hardwood deciduous trees decreases.

Pollen records from Lake Tulane in south-central Florida (Grimm *et al.* 1993, Watts and Hansen 1994) revealed alternating periods of dominance of the pollen spectra by *Pinus* and *Quercus* with *Ambrosia*-type, and Poaceae. Grimm *et al*. (1993) associated peaks in *Pinus* pollen with the North Atlantic Heinrich events. During such events, large, periodic flows of icebergs broke off from the eastern margin of the Laurentide Ice Sheet and traversed the North Atlantic. Development of modern pine forests and wetland communities occurred at ca. 4600 ^{14}C yr BP, indicating wetter conditions in the later Holocene. The Lake Tulane records indicate that modern-day pine forests developed later in south Florida than at more northern sites, suggesting that the southern portion of the Florida peninsula was drier than sites farther north during the early to middle Holocene.

Willard *et al.* (2006) analyzed pollen from sediment cores from tree islands in the greater Everglades ecosystem to reconstruct timing and patterns of tree island development and responses to environmental stressors. Pollen assemblages revealed initial community establishment between 3500 and 500 cal yr BP, well before substantial human alteration to the ecosystem. The authors suggested that tree islands developed in response to intervals of sustained regional drought, including near the onset of the Little Ice Age (AD 1450–1900). These drought episodes generally correspond with periods of dry conditions identified in sediments from lakes of the Yucatan Peninsula of Mexico

(AD 800–1000; AD 1400–1500) (Hodell *et al.* 1995, 2005*b*), Haiti (2400–1500 ^{14}C yr BP; 900 ^{14}C yr BP to present) (Hodell *et al*. 1991, Higuera-Gundy *et al*. 1999), and elsewhere in the circum-Caribbean (Willard *et al.* 2006).

Paleoenvironmental Research in Pine Forest Ecosystems of The Bahamas

Analysis of fossil pollen and charcoal from a sediment core from Church's Blue Hole on Andros Island, The Bahamas (Kjellmark 1996) provided the first evidence of long-term vegetation and fire history from The Bahamas. Sediments deposited prior to 1500 ^{14}C yr BP showed inconsistent ^{14}C dates due to possible mixing, making this part of the record difficult to interpret. The record from 1500 ^{14}C yr BP to present, however, appears to have a normal stratigraphic sequence, and paleoenvironmental interpretations are consistent with other research in the region. The pollen spectra indicated a relatively dry period from 2400 to 1500 ^{14}C yr BP, followed by a period of wetter climate. Around 1500 ^{14}C yr BP, pollen of plants such as *Metopium* (poisonwood), *Myrsine* (myrsine), and other hardwood taxa became more abundant. This mesic hardwood plant community persisted until about 740 ^{14}C yr BP, when it was displaced by *Pinus*, *Trema* (West Indian Trema), and other species characteristic of pine rockland communities.

Kjellmark (1996) also studied microscopic charcoal in the Church's Blue Hole core. Charcoal concentrations were generally low throughout the sediment profile until 900 ^{14}C yr BP, at which point concentrations increase significantly. The peak value occurred at ca. 750 ^{14}C yr BP, followed by a gradual decline through the rest of the record. The initial decline of pollen of hardwoods and increase in pine and other taxa characteristic of pine rocklands occurred when charcoal concentrations in the sediments

began to increase. Kjellmark attributed this change to an increase in fire frequency, possibly caused by an increase in human-set fires.

Stork (2006) studied pollen and charcoal in a sediment profile from West Pond on Great Abaco Island, The Bahamas. Similar to the findings of Kjellmark (1996), the pollen record indicated a major shift from tropical hardwoods to a pine-dominated community at about 770 cal yr BP (Stork 2006). At 550 cal yr BP, sediments changed from peat to marl, a trend that is consistent with an interval of sustained regional drought identified in other studies (e.g., Hodell *et al.* 2005; Willard *et al.* 2006). Stork (2006) expected higher overall charcoal values, as recent estimates suggest pine rockland forests such as those surrounding West Pond experience fire every 7 to 10 years (Stork 2006). She speculated that generally low charcoal concentrations (ca. 4–170 mm^2/cm^3 wet sediment) could have been caused by the low-intensity nature of fire in these ecosystems, which may not produce an abundance of charcoal, or to the lack of overland water flow, which would have reduced the effect of secondary charcoal deposition.

West (2007) examined microscopic and macroscopic charcoal in sediments from Split Pond, Great Abaco Island, The Bahamas. He also conducted air-fall charcoal experiments to examine charcoal transport and deposition in pine rocklands in Abaco National Park. A microscopic charcoal peak at 1500 ^{14}C yr BP concurrent with peaks in macroscopic charcoal suggested a period of higher fire activity adjacent to Split Pond (West 2007). West suggested that several smaller peaks in microscopic charcoal concentrations at 1200 ^{14}C yr BP may indicate increased burning associated with initial human arrival on the island (Burney *et al.* 1994; Burney and Burney 2003). This

interpretation is generally consistent with the results obtained by Stork (2006) at West Pond.

Previous Paleoecological Research in the Circum-Caribbean Region

Oxygen isotopes in biogenic carbonates, pollen, and microfossil assemblages in lake sediment cores from the Yucatan Peninsula (Hodell *et al.* 1995, 2005*b*; Gabriel *et al.* 2009) indicate that wet conditions, high lake levels, and a slow rate of sea level rise persisted through the mid-Holocene. Records show the onset of drier conditions at 3100 ^{14}C yr BP (Hodell *et al.* 1995). An exceptionally dry period occurred from 2200–1100 ^{14}C yr BP, with peak aridity occurring at 1300–1100 ^{14}C yr BP. Hodell *et al*. (1995) associated the former interval with the collapse of the Maya civilization at AD 750–900. The δ^{18}O data also documented drying conditions beginning in the middle 15th century near the onset of the Little Ice Age (Hodell *et al.* 2005*b*). Coincident with these changes, a pollen profile from a nearby sinkhole in northwestern Yucatan showed vegetation changes indicative of increasing salinity (Hodell *et al.* 2005*b*). Hodell *et al.* (2005*b*) suggested that climatic drying and cooler temperatures in the circum-Caribbean from AD 1450–1900 were part of a larger pattern of change in oceanic and atmospheric conditions.

Pollen, charcoal, and oxygen isotope ratios in a long sediment core from Lake Miragôane, Haiti (Hodell *et al*. 1991, Higuera-Gundy *et al*. 1999) reflect climate and vegetation changes in Hispaniola since 10,300 ^{14}C yr BP. The δ^{18}O data indicate the climate became gradually wetter from 10,000 to 6000 ^{14}C yr BP, followed by generally drier conditions (Higuera-Gundy *et al*. 1999). Pollen data show that vegetation changes tracked the climate changes identified in the isotope record, shifting from a xeric

community in the early Holocene to a moist forest in the middle Holocene. Microscopic charcoal concentrations increased at ca. 6000 ^{14}C yr BP, indicating increased fire frequency under wetter conditions. Higuera-Gundy *et al*. (1999) suggested this may have been caused by forest expansion and subsequent increases in fuel production for ignition, or by initial human disturbance. After ca. 3000 ^{14}C yr BP, generally drier conditions returned, and *Pinus* and other dry forest taxa expanded. This interpretation is consistent with other records from the circum-Caribbean region (e.g., Hodell *et al.* 1991, 1995; Kjellmark 1996) that show the onset of generally drier conditions at around the same time. The most recent part of the Miragôane record shows the decline of forest taxa and an increase in successional taxa, most likely associated with increased human disturbance and land clearance (Higuera-Gundy *et al*. 1999).

Peros *et al.* (2007) studied pollen and other palynological proxies in ten sediment cores extracted from and near Laguna de la Leche, a natural lake located on the north coast of the Province of Ciego de Avila, Cuba. The basin of Laguna de la Leche began to fill by 6200 cal yr BP, a process the authors attributed to rising sea level. Water levels fluctuated, but the lake maintained a frequent connection with the sea until about 2000 cal yr BP, when pollen of *Rhizophora mangle* (red mangrove) increased and the lake changed to a closed, brackish lake. The initiation of Laguna de la Leche at 6200 cal yr BP corresponds with the development of modern day pine forests and extensive swamps in peninsular Florida. Peros *et al*. (2007) suggested that sea level rise, increased precipitation, and a shift in seasonality may have driven late Holocene environmental changes in south Florida and northern Cuba.

Charcoal as a Proxy for Past Fire Activity

Analysis of particulate charcoal preserved in sediments from lakes or wetlands can be used to develop records of local and regional fire occurrence (Sanford and Horn 2000; Whitlock and Larsen 2001; Whitlock and Anderson 2003). Together with radiocarbon dating, such records reveal changes in fire activity over time (Sanford and Horn 2000). In many cases, the study of fossil charcoal includes pollen analysis from the same core(s) (e.g., Horn 1993). Such analyses provide the opportunity to examine long-term relationships between vegetation, fire, and climate. Charcoal records can be used in combination with dendrochronological records to provide longer fire histories at different temporal and spatial scales (Sanford and Horn 2000; Whitlock 2004).

Charcoal production occurs when organic matter, such as plant tissue, is incompletely combusted during a fire (Patterson *et al.* 1987). Due to its composition, charcoal is not chemically destroyed during the preparation of sediment samples for pollen analysis (MacDonald *et al.* 1991). The rate of charcoal production and delivery to sediments depends on the characteristics of a fire (e.g., size, intensity, duration, and severity), vegetation characteristics, and the processes that transport the charcoal to and deposit it in the sediment (e.g., wind, surface runoff) (Clark *et al.* 1998; Gardner and Whitlock 2001; Whitlock and Larsen 2001; Whitlock and Anderson 2003). Charcoal introduced to the sediment record during or immediately after a fire event is referred to as *primary charcoal*. Secondary deposition occurs when charcoal is introduced to the sediment record during non-fire years, and is referred to as *secondary charcoal* (Whitlock and Larsen 2001).

Fire reconstruction based on sedimentary records of charcoal involves two main approaches: the analysis of microscopic charcoal fragments (fragments < 125 µm) and the analysis of macroscopic charcoal fragment (fragments > 125 µm) (Sanford and Horn; Whitlock and Larsen 2001; Whitlock and Anderson 2003). In this study, I focused on the analysis of both microscopic and macroscopic charcoal in the sediments of Key Deer Pond. Macroscopic charcoal analysis, in particular, was chosen in order to better understand the local fire record (Sanford and Horn 2000; League and Horn 2000).

The cut-off value of 125µm for the largest dimension of a charcoal fragment is commonly used for distinguishing between microscopic and macroscopic charcoal, but is not a universal value. Rather, microscopic versus macroscopic charcoal is more often defined by how it is prepared and examined. Microscopic charcoal particles are prepared and examined on microscope slides (also referred to as pollen slides) using compound microscopes, often together with pollen. The microscopic charcoal and pollen residues are prepared using standard pollen processing procedures. Macroscopic charcoal, in contrast, is generally separated from sediments by sieving, using more basic processing procedures (Schlachter and Horn, in press), and is examined using a dissecting scope.

Macroscopic Charcoal as a Proxy for Local Fires

Many paleoecological studies have used macroscopic charcoal in lake and wetland sediment as a proxy for past fire (Whitlock and Millspaugh 1996; League and Horn 2000; Gardner and Whitlock 2001; Gavin 2003; Anchukaitis and Horn 2005; Schlachter 2005), with some studies involving the sieving of contiguous, narrow core intervals (often 1 cm) to produce high resolution records. Charcoal in soils has also been

used to develop coarse resolution fire histories (Horn and Sanford 1992; Horn *et al.* 2000; Albritton 2006; Titiz and Sanford 2007; Hart *et al.* 2008). Macroscopic charcoal in soils or sediments is usually considered to be primary charcoal. Fragments of charcoal over 125 μm in size are not easily transported long distances by wind during or after a fire (Patterson *et al.* 1987; Clark 1988; MacDonald *et al.* 1991; Whitlock and Larsen 2001; Peters and Higuera 2007). With this in mind, the presence of large charcoal particles in sediments should indicate a fire at or very near the sampled location, thus allowing for a more detailed reconstruction of local fire activity. Several studies of macroscopic charcoal deposition in sediments or traps provide empirical support for this suggestion.

Macroscopic charcoal in a sediment core from a lake in central Yellowstone National Park documents fire history over the past ca. 750 years (Millspaugh and Whitlock 1995). The study revealed that the site has experienced repeated burning since AD 1220, and that the fire regime has changed through time. Evident in the charcoal record was the near-absence of fires during the ca. 40–50 years preceding the large fire of 1988 that burned significant portions of the park. The charcoal record is in close agreement with a dendrochronological record for the last 450 years (Millspaugh and Whitlock 1995).

Gardner and Whitlock (2001) studied macroscopic charcoal deposition in sediments from 36 lakes after a 1996 fire in the Oregon Cascade Range. Nineteen lakes were located within a burned area and 17 were in unburned watersheds. The researchers examined how the proximity of each lake to the burn area affected the presence of charcoal in the sediments, and if fire events were recorded as charcoal peaks in the sediment records. Their findings indicate that all lakes received charcoal during the 1996

fire, but that the abundance of charcoal particles >125μm in diameter was greatest in lakes within the burned perimeter. They also noted that although burned and unburned sites had peaks in charcoal abundance, peaks in burned sites were much better defined than in unburned sites. The authors concluded that a relationship exists between the occurrence of local fires and peaks in sedimentary macroscopic charcoal.

Several studies have investigated atmospheric transport of macroscopic charcoal to assess its reliability as a proxy for local fire. Clark *et al.* (1998) calculated charred particle area of macroscopic charcoal (180, 250, and 500 μm particle sizes) in a series of 21 traps during a 1993 high-intensity prescribed fire in Siberia. Traps were located at approximately 10 m intervals along 3 transects extending away from the edge of the burn perimeter. They calculated settling velocities for the difference particle size ranges. Results showed that charcoal abundance dropped off sharply with distance from the edge of the fire. The authors concluded these larger charcoal particles are not suspended in the atmosphere longer than a few minutes, and thus are an indication of a nearby fire. They also suggested that burns of relatively lower intensity would show a more marked decline in charcoal accumulation with distance from fire, thus allowing for better resolution of local fires.

Ohlson and Tryterud (2000) studied the transport of macroscopic charcoal (>500 μm) from three experimental burns in Scandinavia. A series of 704 traps were arranged both inside (280) and outside (424) of the burn areas at different distances from the fire edge. They counted and compared the number of charcoal particles and charcoal masses in traps inside and outside of the burn area. They found a marked discrepancy in the amount of charcoal between traps inside and outside of burn areas. The number of

charcoal particles and charcoal mass dropped off sharply with distance from the burn edge. In all, they found almost no charcoal particles >500 µm in traps outside of the burn area, while charcoal was present in close to 90% of the traps inside the burn area. They concluded that the occurrence of charcoal particles >500 µm is a reliable indicator of local fire occurrence, and that the presence of such particles can be used to distinguish between fire-prone and fire-free areas.

Microscopic Charcoal

Microscopic charcoal is also referred to as pollen-slide charcoal. Many fire history studies in the circum-Caribbean have been based on the analysis of charcoal particles on pollen slides (*e.g.*, Horn 1993; Burney *et al.* 1994; Kjellmark 1995, 1996; Clement and Horn 2001; Kennedy *et al.* 2006; Lane *et al.*, in press). Many such studies have combined the study of microscopic charcoal with pollen analysis from the same core(s) to infer climate history and long-term interactions between fire and vegetation. Microscopic charcoal may at some sites reflect the regional importance of fire, as microscopic fragments can be transported long distances by wind or water (Clark 1988; Millspaugh and Whitlock 1995; Ohlson and Tryterud 2000; Sanford and Horn 2000; Whitlock and Anderson 2003; Patterson *et al.* 1987).

However, microscopic charcoal, even particles <50 µm, may signal local burning. Patterson *et al.* (1987) suggested that most microscopic charcoal in small ponds (<25 m in diameter) is derived from local area fires, within about 20–30 m of the sampling site. Although microscopic fragments may be carried long distances by wind, this does not mean that all microscopic charcoal that is deposited in a lake originates from a large

source area (Clement and Horn 2001; Kennedy and Horn 2008). Pitkänen *et al.* (1999) suggested that if winds and the convective column produced by low-intensity fires are low, much microscopic charcoal can de deposited locally, that is, within the immediate vicinity of the fire.

Comparisons of Microscopic and Macroscopic Charcoal in the Same Cores

Most charcoal studies are based on either microscopic or macroscopic charcoal, but a few studies have compared macroscopic and microscopic charcoal records from the same sediment core. Horn (1993) studied microscopic charcoal from a sediment core from Lago de las Morrenas 1, a glacial lake in the high elevation, treeless páramo of Chirripó National Park, Costa Rica. Her findings show that fires set by people or lightning have been a part of the páramo environment since the massif was deglaciated ca. 10,000 ^{14}C yr BP. To improve upon this record of fire history, League and Horn (2000) resampled the same core for macroscopic charcoal fragments >500 µm at contiguous 1-cm intervals. The Lago de las Morrenas high-resolution macroscopic charcoal record corresponds well with the microscopic charcoal record, confirming that fire is a natural part of the páramo environment (League and Horn 2000). Charcoal curves from both records revealed higher charcoal values during the later Holocene (since ca. 4200 ^{14}C yr BP). The macroscopic record shows that the fire frequency has varied throughout the Holocene (League and Horn 2000).

Graham (2008) developed a high-resolution macroscopic charcoal record from a 5.8 m long sediment core from Laguna Martínez, Costa Rica. He sampled the core at contiguous 1 cm intervals for two size classes of charcoal (fragments 250–499 µm and

fragments >500 μm in size). He compared this record to a microscopic charcoal record from the same core that had been developed previously (Arford 2007). Trends in charcoal concentrations and influx from both the macroscopic and microscopic charcoal records were similar. Graham (2008) found several sediment intervals in the core where distinct charcoal peaks occur in both records, which he suggested indicated times of greater fire activity around the lake. He found other intervals where microscopic charcoal values were low, but macroscopic charcoal values were high. Graham (2008) suggested that this may indicate that regional fire activity was low, but that the area around the lake was still burning frequently. Alternatively, he suggested that the wide sampling interval used for microscopic charcoal may have missed intervals with abundant microscopic charcoal, whereas the contiguous sampling procedure used for macroscopic charcoal sampling revealed previously unrecognized patterns in the fire regime around the lake.

Schlachter (2005) also compared a high-resolution macroscopic charcoal record to a microscopic charcoal record from the same core. His study used a sediment core from Laguna Estero Blanco, also previously analyzed by Arford (2007). Curves of macroscopic and microscopic charcoal influx matched well. Schlachter (2005) suggested that peaks in macroscopic charcoal (particles >500 μm) indicated burning at or very near the lake.

Sedimentary Charcoal as Evidence for Human Arrival on Islands

Burney *et al.* (1994) and Burney and Burney (2003) postulated that initial human modification of the environment, especially on oceanic islands, may be indicated by

peaks in charcoal in sediment cores, and that these charcoal peaks may provide a means for determining the timing of human arrival on remote islands. Burney *et al.* (1994) studied the charcoal stratigraphy of a sediment core from Laguna Tortuguero, Puerto Rico that spanned the last ca. 7000 cal yr BP. They found a sudden and sustained increase in charcoal concentrations and influx between 5300 and 3200 cal yr BP that they interpretated as evidence of human arrival to the island and their continued use of fire (Burney *et al.* 1994). Burney and Burney (2003) studied charcoal in sediments from nine sites on Kaua'i in the Hawaiian Islands. Microscopic charcoal records from eight different sites show good agreement. One record was discounted due to poor resolution resulting from tsunami disturbance and possible sediment mixing. Burney and Burney (2003) suggested that increased charcoal concentrations in several of the records at ca. AD 1100 (830 ^{14}C yr BP) indicated human arrival to the island.

Higuera-Gundy *et al.* (1999) also observed a sustained increase in charcoal concentrations in sediments from Lake Miragôane, Haiti that began at 5400 ^{14}C yr BP. The authors suggested that this may indicate drier climate conditions, but could also be attributed to early human disturbance on the island. Stork (2006) and West (2007) considered the possibility that charcoal peaks at ca. 1190 cal yr BP and 1200 ^{14}C yr BP may indicate early human arrival on Abaco Island, The Bahamas and modification of the landscape through the use of fire.

Application of Paleoecological Research to Ecosystem Conservation

A number of recent paleoecological studies have provided information important for biodiversity conservation, including recommendations on wildfire, climate change,

and management within thresholds of natural variability (e.g., Chambers *et al*. 1999; Willard *et al*. 2001; Willard *et al.* 2006; Burney and Burney 2007; Gavin *et al.* 2007; Willard and Cronin 2007). Horn (1998) examined issues relating to fire management in Chirripó National Park, Costa Rica. The park's management plan raises a number of issues related to fire, with the prevailing objective to prevent fire, especially in the high-elevation treeless páramo. Results of her research, however, have revealed that fire has long been a component of the Chirripó páramo, and that some plants that typify páramo vegetation thrive under frequent burning (Horn 1989, 1993, 1997, 1998; League and Horn 2000). Her findings highlight the need for park authorities to reevaluate fire management goals (Horn 1998). Horn (1998) suggested that in order to conserve the Chirripó páramo, park managers, rather than preventing fire, may want to focus efforts on maintaining some target fire frequency and controlling fire size.

Lindbladh *et al.* (2003) studied pollen and macroscopic charcoal in three size classes (fragments >500, 1000–2000, and >2000 μm) from a 2500-year sediment record from a forested wetland site in the Hornsö-Allgunnen region of southeast Sweden. The 200 ha forest site is of concern to local conservation authorities due to its exceptionally large number of endangered species of beetle, many of which depend on open forest conditions (Lindbladh *et al.* 2003). The different size classes of charcoal show large conformity throughout the record. Charcoal analysis indicates frequent and continuous burning until AD 1850, when charcoal abundance significantly decreases. The pollen data indicated that the site is more closed today than at any time in the past 2500 ^{14}C yr. The authors concluded that openness of the forest site in the past was a consequence of the long-term occurrence of frequent fires. Lindbladh *et al.* (2003) suggested that open

forests conditions would need to be restored in order to conserve beetle assemblages at this site.

In the Florida Everglades, human alteration of the natural hydrologic regime, including a shift in the seasonality of freshwater flow, has rearranged and degraded native plant communities throughout the ecosystem (Bernhardt *et al.* 2004; Willard *et al.* 2006; Willard and Cronin 2007). This degradation has prompted efforts to rehabilitate the natural hydrology and plant communities of the Everglades. Willard and Holmes (1997) and Willard *et al.* (2001) analyzed pollen from surface samples and sediment cores from several sites throughout the Everglades and near Florida Bay. Results of these two studies are consistent. Pollen assemblages indicated that marsh and slough plants, primarily *Cladium* (sawgrass) and *Typha* (cattail), dominated plant communities for most of the last two millennia, until about AD 1950. By AD 1960, the abundance of *Cladium* pollen and other marsh and slough pollen types in core samples had dropped to their lowest levels, with tree pollen becoming more abundant (Willard and Holmes 1997; Willard *et al.* 2001). These records provided evidence of major vegetation changes in response to human-induced alterations to the Everglades hydrologic regime, and suggest that water depths were greater and hydroperiods were longer before the onset of water management practices. This evidence plays an important role in determining hydrologic targets for the whole ecosystem (Willard and Cronin 2007). These data also provide important information on how vegetation will respond to planned changes in water management (Bernhardt *et al.* 2004).

Hurricane and Tropical Storm Events and Their Representation in Sediment Records

Tropical cyclone activity in the North Atlantic Basin (including the North Atlantic Ocean, the Caribbean sea, and the Gulf of Mexico) exhibits significant interannual and interdecadal variability (Goldenberg *et al* 2001). This variability is especially pronounced for cyclonic storms that develop into hurricanes. Such variability can be attributed to changes in sea surface temperatures (SSTs), and to regional and global-scale climate phenomenon such as El-Niño Southern Oscillation (ENSO) (Liu and Fearn 2000; Goldenberg *et al.* 2001; Trenberth 2005).

Overwash sand layers preserved in sediments of coastal lakes and other wetlands can provide a proxy record of hurricane strikes that extends beyond the historic period (Liu and Fearn 1993; 2000). According to Liu and Fearn (2000), overwash occurs when the storm surge caused by a landfalling hurricane exceeds the height of the sand barrier (e.g., barrier beach or dune ridges). Wave activity erodes sand from the overwashed beach into the lake, forming a fan that spreads out in the form of a sand layer on top of the organic material that generally accumulates in the lake. This sand layer is thickest at the lake margin, and thinnest near the center. Stronger hurricanes produce stronger storm surges, which produce thicker and more widespread sand layers in coastal lakes (Liu and Fearn 2000).

A sediment core from Western Lake revealed a 7000-yr record of environmental change and hurricane landfalls along the Gulf Coast of the Florida Panhandle (Liu and Fearn 2000). Water and organic content of the sediments and pollen data suggest that the modern lake environment was established at ca. 5000 ^{14}C yr BP and has remained relatively unchanged since. Prior to 5000 ^{14}C yr BP, the lake may have had a frequent

connection with the Gulf, such that sand layers deposited before 5000 ^{14}C yr BP cannot be directly attributed to hurricane events. Stratigraphic data show that 11 distinct sand layers occur between 1.6 and 0.4 m depth in the core, suggesting that 11 hurricanes struck the Panhandle of Florida between 3400 and 1000 ^{14}C yr BP. Evidence for hurricane activity from 5000–3400 ^{14}C yr BP was all but absent, as only one distinct sand layer occurred in the past 1000 yr. The authors suggested that continental-scale shifts in atmospheric circulation patterns may cause shifts in hurricane frequency in the Florida Panhandle during the late Holocene.

Tropical storm events might also leave other evidence in lake sediments. S. Horn (*pers. communication*, Oct 19, 2009) suggested that defoliation of trees in hurricanes could lead to layers of leaves in sediment cores following hurricanes. Hurricanes can have damaging effects on vegetation. Hurricane Andrew in 1992 left a 50 km wide band of defoliated vegetation across southern peninsular Florida (Platt *et al.* 2000). In 2005, researchers from the National Park Service South Florida/Caribbean Monitoring Network and the U.S. Geological Survey sampled storm deposits from Hurricane Wilma in the Everglades region. At a soil surface monitoring site, the researchers found that Hurricane Wilma had deposited a 30–60 cm thick storm-deposit layer, consisting of very fine material on top underlain by mangrove leaf matter (Whelan and Smith 2006). At site Shark River 3 on the southwest Florida coast, researchers found layers of mangrove leaves that had been covered by sediment deposited by the storm surge (Smith *et al.* 2005).

Sea level Changes and Their Indication in Pollen Records

Since the last glacial maximum ca. 18,000 yr BP, global sea level has risen about 120 m (Maul and Martin 1993). This change in sea level has affected south Florida and the low-lying islands of the Florida Keys. Lidz and Shinn (1991) extrapolated a sea level curve to 8000 ^{14}C yr BP that shows sea level had risen to 0.5 m below present-day levels by 2000 ^{14}C yr BP.

Sea level changes have strong effects on coastal vegetation. Mangrove communities are the dominant coastal vegetation type throughout the tropics, south Florida, and the Florida Keys (Blasco *et al.* 1996; USFWS 1999*a*; Peros *et al.* 2007). Common mangrove species include *Rhizophora mangle* (red mangrove), *Avicennia germinans* (black mangrove), *Laguncularia racemosa* (white mangrove), and *Conocarpus erectus* (buttonwood mangrove), all of which are adapted to brackish environments (USFWS 1999*a*; Peros 2005). These taxa form a markedly uniform pattern of zonation along coastlines (Blasco *et al.* 1996). *Rhizophora* occupies the most outward (seaward) portion of the littoral zone, followed by *Avicennia* then *Laguncularia*, with *Conocarpus* forming the landward most fringe in the upper portion of the intertidal zone (Blasco *et al.* 1996; Peros 2005). Changes in relative sea level are one important factor that changes mangrove distributions (Blasco *et al.* 1996; Peros 2005). Each species of mangrove lives in specific ecological conditions that approach the limits of their tolerance levels with respect to soil and water salinity and inundation regime (Blasco *et al.* 1996). If those conditions change, for example due to changes in sea level, mangrove species either readjust or succumb to unsuitable conditions (Blasco *et al.* 1996). For this

reason, pollen of mangroves can be an indicator of past sea level (Blasco *et al.* 1996; Peros 2005; Gabriel *et al.* 2009)

In the Rio Hondo region near the Belize border, Torrescano and Islebe (2006) investigated a sediment core that revealed mangrove and tropical forest change since ca. 5000 ^{14}C yr BP. The early part of the record was dominated by mesic forest taxa, with Moraceae and Fabaceae pollen most abundant. A clear change in forest composition occurred between ca. 4600 and 4000 ^{14}C yr BP, when pollen of *Rhizophora mangle* and *Conocarpus erectus* significantly increased, and forest taxa decreased. After ca. 4000 ^{14}C yr BP, pollen of *C. erectus* dominated the record. The authors suggested that changes in forest composition and increased abundance of *C. erectus* in the pollen record was due to a rise in relative sea level and a shift to a higher salinity, drier environment.

Kjellmark (1995) studied pollen in a sediment core from Stalactite Blue Hole on Andros Island, The Bahamas. The core is estimated to span the last 2390 ^{14}C yr BP. The percentage of *Pinus* pollen is high over much of the record, but it declines significantly above the 30 cm level. This change occurred when pollen of *Conocarpus erectus* became a dominant pollen type in the profile. Kjellmark (1995) suggested that this change was due to rising sea level, which raised the water table enough to convert many hectares of pine forest into wet shrublands dominated by buttonwood mangrove.

CHAPTER 3

Environmental and Cultural Setting

Study Area

The Florida Keys are a chain of limestone islands that extends some 210 km from Soldier Key southwest to Key West (Figure 3.1). The islands have traditionally been grouped into the Upper, Middle, and Lower Keys, a classification based on contrasting climate, geological, and geographical features (Lidz and Shinn 1991; Ross *et al.* 1992). The National Key Deer Refuge (NKDR) managed by the U.S. Fish and Wildlife Service is located on Big Pine Key and 25 nearby islands in the lower Florida Keys, approximately 85 km southwest of the southern tip of mainland Florida (Carlson *et al.* 1993; Barrett *et al.* 2006) (Figures 3.1 and 3.2). My study site, Key Deer Pond (24° 42′ 29.50″ N, 81° 22′ 36.12″ W; GPS data by K. Orvis), is a small, shallow, freshwater pond in a solution hole located within the boundaries of the NKDR on Big Pine Key (Figure 3.3). Key Deer Pond is located northeast of the Blue Hole quarry between Pine Avenue and Key Deer Boulevard.

Geological and Physiographic Setting

The lower Florida Keys extend from Little Duck Key about 60 km west to Key West (Ross *et al.* 1994). Surface geology consists mostly of inorganically produced oolitic limestone, a rock composed of small spherical pellets of calcium carbonate originally precipitated underwater in a shallow, low-energy marine environment (Lidz

Figure 3.1 Recent satellite image of (1) south Florida and the Everglades; (2) Florida Keys; (3) Cuba; and (4) The Bahamas. The darkness of the blue is proportional to water depth. The white colored objects are clouds. (NASA/courtesy of nasaimages.org).

Figure 3.2 Recent satellite image of the lower Florida Keys numbered to indicate (1) Big Pine Key; (2) Little Torch Key; (3) Middle Torch Key; (4) No Name Key; and (5) Key West. The National Key Deer Refuge is located on Big Pine Key and 25 nearby Keys between Big Pine Key and Key West. The darkness of the blue is proportional to water depth. The white colored haze is cloud cover. (NASA/courtesy of nasaimages.org).

Figure 3.3 Location of Key Deer Pond and a second coring site, Blue Hole Wetland, on Big Pine Key in the lower Florida Keys. This false-color visible infrared image is from the United States Geological Survey; core site locations from GPS data by K. Orvis. Main East-West road near bottom of the image is Big Pine Street. North-South road on the right (forming eastern border of forest patch) is Pine Avenue. Key Deer Boulevard trends Northwest-Southeast. Typical pine rockland vegetation in managed fire rotation in this infrared image is mottled pink and gray, except for stands recently burned or otherwise disturbed (darker gray patches at top of image, including wetland). Long-unburned tree stands near housing show deeper shades of red.

and Shinn 1991; Lidz *et al.* 2003). During times of low sea-level, these pellets, or ooids, became exposed to precipitation, and some of the lime was dissolved and reprecipitated around the ooids as cement, binding them together into hard rock (Snyder *et al.* 1990; Obeysekera 1999). Over many cycles of sea level change, this process gradually built up the rock formation known today as the Miami limestone formation. The lower Florida Keys represent elevated portions of the Miami oolitic limestone formation, which also forms the bedrock of the southern Everglades and adjacent Miami Rock Ridge.

Solution holes and uneven loose rock rubble characterize the karst surface. Solution holes are formed by the dissolution of rock below the surface followed by the collapse of the top, and can be several meters wide and deep (USFWS 1999*a*). Organic materials and humus accumulate within the collapsed portion (Snyder *et al.* 1990). Due to the high porosity of the Miami limestone substrate, surface drainage in the lower Keys is usually very rapid, and no rivers, streams, or other sources of overland flow exist (USFWS 1999*a*). The only exception may be during periods of intense rain during the wet season, which periodically result in short periods of inundation and slow-flowing surface water (USFWS 1999*a*). Although the Miami oolitic rock is highly porous, it has low permeability. This reduces salt and freshwater mixing, and maintains a nearly fresh groundwater lens (Ross *et al.* 1992). These groundwater lenses exhibit only minor seasonal changes in extent, depth, and salinity (Ross *et al.* 1994). In general, mean ground water is usually slightly higher (30 cm or less) than mean sea level (Ross *et al.* 1992).

Soils in lower Keys pine rocklands differ greatly from those found elsewhere in Florida. The oolitic rock is at or very near the surface, and soil development is minimal.

Soils are generally composed of small accumulations of nutrient-poor sand, marl, and clayey loam and organic debris in depressions and crevices in the rock surface (Snyder *et al.* 1990; USFWS 1999*a*).

The Florida Keys have been affected by changes in sea level throughout the Pleistocene and Holocene. The extent of these fluctuations can be seen in three Quaternary shorelines, ranging from the Wicomico shoreline when sea level was about 30 m higher than present during the early Pleistocene, through the late Pleistocene Wisconsinan shoreline of about 20,000 ^{14}C yr BP when sea level was roughly 100 m below present, to the present-day shoreline (Obeysekera 1999). Evidence for sea-level changes include fossil corals, laminated $CaCO_3$ crusts (caliche or soilstone), offshore peat deposits, bedrock contours, root casts, molds, and offshore dead snags and logs (Fairbanks 1989; Lidz and Shinn 1991; Ross *et al.* 1994; Toscano and Macintyre 2003). Since the middle Holocene, sea level has risen. By approximately 8000 ^{14}C yr BP, sea level had risen to at least 8.5 m below present level. The Florida Keys remained part of the Florida peninsula until about 4000 ^{14}C yr BP, when rising seas began to inundate low-lying areas, leading to the formation of islands. At 2000 ^{14}C yr BP, sea level was 0.5 m below present and shorelines were similar to those of today (Lidz and Shinn 1991). Sea level reconstructions for the past 8000 ^{14}C yr BP indicate that sea level has risen on average 1.1 m/1000 ^{14}C yr BP (Lidz and Shinn 1991). In the past 80 to 90 years, sea level at Key West has risen at a rate of about 0.22 cm/yr (Ross *et al.* 1994; Obeysekera 1999; Toscano and Macintyre 2003). At present sea levels, few places in the lower Keys reach elevations >2 m above sea level (Ross *et al.* 1994; USFWS 1999*a*).

Climate

Although the Florida Keys lie a few degrees north of the Tropic of Cancer (23.5° N), the climate can be considered tropical, with a warm winter and a hot tropical summer (Ross *et al.* 1992). The climate of the region is significantly moderated by the Gulf of Mexico, the Atlantic Ocean, and the Gulf Stream, which act to warm the air masses that cross them (Obeysekera 1999). Because of this maritime effect, temperature is generally uniform across the Keys, with only minor variation between summer and winter. In the lower Florida Keys, mean annual daily temperatures in July range between 27 ° (81 °F) and 29 °C (84 °F), and in January range between 18 ° (64 °F) and 21 °C (70 °F) (Snyder *et al*. 1990). The lower Keys do not experience freezes (Snyder *et al.* 1990; Obeysekera 1999).

The rainfall regime is highly seasonal, with a distinct wet-dry cycle. The wet season begins when rainfall increases in late May, and typically extends through September. The dry season extends roughly seven months from October through May (Snyder *et al*. 1990). Rainfall tends to be unevenly distributed, with the lower Florida Keys receiving 890 to 1015 mm/yr, of which 75% is concentrated in the wet season (Ross *et al.* 1994). Wet season rainfall is primarily a result of tropical storms, including hurricanes, tropical low pressures, and convection thunderstorms. These systems primarily occur between the months of August and October (Obeysekera *et al.* 1999). Dry season rainfall events are associated with the passage of cold fronts, which sweep down into south Florida during late fall, winter, and early spring.

Tropical storms, including hurricanes, play a significant role in the climate of the Florida Keys. Most tropical storms form from easterly (African) waves that propagate

westward from Africa across the tropical Atlantic and Caribbean Sea primarily between 10° and 20° N. Easterly waves account for ca. 60% of the Atlantic Basin tropical storms and non-major hurricanes and ca. 85% of major (category 3 or greater) hurricanes (Goldenberg *et al.* 2001). South Florida is affected by tropical storms at a frequency of about once per year, and hurricanes about two to three times per decade (Snyder *et al.* 1990; Obeysekera 1999; Blake *et al.* 2005). Hurricanes almost always occur in September or October (Peros 2005).

An important influence on regional tropical storm activity is the El Niño-Southern Oscillation (ENSO). ENSO cycles, characterized by alternating periods of warm or cool sea surface temperatures in the central and eastern Pacific, have occurred with a periodicity of once every 3 to 7 years for the last 130 years (Beckage *et al.* 2003). Warm-phase ENSO conditions (El Niño) have been linked to decreased tropical storm activity in the North Atlantic Basin, and conversely for cool-phase ENSO conditions (La Niña) (Goldenberg *et al.* 2001). Annual probability of a major hurricane making landfall in the United States is 23% during a (warm-phase) El Niño season, 58% during neutral conditions, and 63% during cold-phase (La Niña) conditions (Keim *et al*. 2004).

Vegetation

Modern vegetation of the Florida Keys varies from northeast to southwest away from the mainland, and from island to island. In general, the gradient is characterized by a decrease in forest stature and productivity from upper to lower Keys, as well as a change in species composition of upland forest types (Ross *et al.* 1994).

Vegetation communities of the lower Florida Keys are arranged along distinctive within-island gradients associated with elevation, soil development, and the frequency of inundation by tidal waters (Ross *et al.* 1994; USFWS 1999*a*; Snyder *et al.* 2005). Most plant species are adapted to dry conditions that result from rapid runoff of rainfall (Barrett *et al.* 2006). The flora is primarily of West Indian origin, with most species not occurring in North America outside of southern Florida and the Florida Keys (Ross *et al.* 1994; USFWS 1999*a*; Barrett *et al.* 2006).

Big Pine Key contains several vegetation communities including mangrove wetlands, buttonwood communities, freshwater marshes, tropical hardwood hammocks, and pine rocklands. In south Florida, pine rocklands are found in the southern Big Cypress National Preserve, on the Atlantic Coastal Ridge of southeastern Florida, and in the lower Florida Keys (Doren 1993 *et al*. 1993; USFWS 1999*a*, Snyder *et al*. 2005). Perhaps 99% of pine rockland habitat outside of Everglades National Park has been lost to human influence (Snyder *et al.* 1990; USFWS 1999*b*).

Lower Keys pine rocklands are found in high-elevation (1–2 m) environments in the interior of several islands large enough to support a significant fresh-water lens (Ross *et al.* 1992). Ground water salinity is generally low, averaging 2–3‰ (Ross *et al*. 1992). My core site of Key Deer Pond is presently surrounded by pine rockland vegetation, with an upper canopy composed of a single tree, South Florida slash pine (*Pinus elliottii* var. *densa*), and a diverse open understory (Snyder *et al*. 2005). The understory is dominated by a mixture of temperate and tropical hardwoods such as black-bead (*Pithocellobium keyense*), poisonwood (*Metopium toxiferum*), wax-myrtle (*Myrica cerifera*), buttonwood mangrove (*Conocarpus erectus* L.), locust berry (*Byrsonima lucida*), and myrsine

(*Myrsine floridana*), and a few species of palm including saw palmetto (*Serenoa repens*), silver palm (*Coccothrinax argentata*), and thatch palm (*Thrinax morissii*). The herbaceous layer is very diverse, with a combination of grasses, sedges, and other herbs. Common angiosperms include members of the Poaceae, Asteraceae, Fabaceae, Cyperaceae, Rubiaceae and Euphorbiaceae families (Snyder *et al.* 2005). Ferns include maidenhair pineland fern (*Anemia adiantifolia*) and lacy bracken (*Pteridium aquilinum* var. *cuadatum*), and are a common component of the herbaceous layer (USFWS 1999*a*).

Fire Ecology of Florida Pine Rocklands

The importance of fire in modern pine rockland ecosystems has long been recognized by ecologists and managers. Periodic fire is required to maintain the open understory and to sustain the mixed-age pine stands that support a diversity of flora and fauna (Alexander 1967; Snyder *et al*. 1990, 2005; Carlson *et al.* 1993; Doren *et al*. 1993; USFWS 1999*a*; Liu and Menges 2005). Fire controls, at least in part, whether pine rockland or hardwood hammock vegetation dominates uplands (Snyder *et al*. 1990). Where natural fire has been suppressed, fire-sensitive hardwood species have invaded pine rocklands, resulting in changes in forest composition and loss of vegetation characteristic of pine rocklands (Alexander 1967; Snyder et al. 1990, 2005; Carlson *et al*. 1993; Ross *et al.* 1994; USFWS 1999*a*; Liu and Menges 2005). Pine rocklands in which fire is excluded succeed to tropical hardwood hammocks with a relic overstory of pine within 20–30 years (Snyder *et al*. 1990, 2005). Where fire has been excluded for long periods, fuel buildup has increased the risk for catastrophic fires (USFWS 1999*b*).

Pine rockland fires are low-intensity surface fires that have minimal effect on the pine canopy (Snyder *et al.* 2005). The primary source of naturally occurring fire is lightning. Most lightning-induced fires occur between May and September when convective thunderstorms are most common (Doren *et al.* 1993; USFWS 1999*a*; Liu and Menges 2005). Larger fires most frequently occur during the early part of the wet season (Doren *et al.* 1993; USFWS 1999*a*). Human-induced wildfires, in contrast, generally occur during the winter dry season (Liu and Menges 2005).

Although long-term records of fire history are not available from lower Keys pine rocklands, plant species possess characteristics that increase survival in fire-prone areas, and that might indicate a long-term history of burning. These include adaptations that allow plant species to survive fire and respond favorably to fire. *Pinus elliottii* var. *densa* is considered fire dependent (Nelson 1994). It has thick bark that protects the living inner bark and cambium, and its cones open best when subjected to heat (Snyder *et al*. 1990; Nelson 1994). Many hardwood shrubs and herbaceous plants characteristic of pine rocklands resprout vigorously after fire (Snyder *et al*. 1990; Myers *et al.* 2004; Liu and Menges 2005; Snyder *et al.* 2005). Fire prepares the seed bed for pine regeneration and stimulates seed dispersal and flowering and regeneration by seeds of many species (Doren *et al.* 1993; Liu and Menges 2005; Snyder *et al.* 2005). Fires generally do not result in significant changes in species composition because almost all species are perennials that survive and recover in place (Snyder *et al.* 1990).

Pre-European Settlement

The timing of human arrival and patterns of movement of prehistoric people around the islands of the Florida Keys are in large part unknown due to the paucity of archeological or paleoecological evidence of early human presence (Carr and Beriault 1984; Worth 1995). There exists considerable debate as to which historic Indians are the descendents of the first inhabitants of south Florida. Wilkinson (2002*b*) suggested that the Calusa (Caloosa) are descendants of Paleo-Indians who inhabited southwest Florida, from the Gulf coast inland to Lake Okeechobee, approximately 12,000 years ago. Archeological materials from a site in Collier County in southwestern Florida have been dated to as early as 7000 yr BP (Carr and Beriault 1984). The earliest dated archeological materials in southeastern Florida are from the Late Archaic around 4000 yr BP (Carr and Beriault 1984). Some archeological evidence exists for the upper Florida Keys, but archeological sites are rare in the lower Florida Keys, and other evidence of past use of the area by aboriginal people is scant (Ross *et al.* 1994; Clark 2002; USFWS 2002). Dade County (Florida) archeologists uncovered fragmentary remains of a single temporary structure on Sugar Loaf Key, a nearby island. However, that structure may date to the late 19th or early 20th century (Ross *et al.* 1994). Remnants of what is thought to be a "native" rock wall exist on nearby Ramrod Key, but no attempts have been made to date the structure (Clark 2002).

The memoirs of a shipwrecked Spaniard provide information on human habitation in the Florida Keys in the middle 16th century. Hernando de Escalante Fontaneda was shipwrecked along Florida's southeast coast when 13 years old and spent 17 years as a captive of the Calusa tribe (Worth 2006). Fontaneda became an interpreter for the

principal Calusa chief and was privy to information that lead historians to regard his memoirs as extremely reliable (Worth 1995, 2006).

According to the account given by Fontaneda, inhabitants of the Keys, otherwise known as the Matecumbe Indians, were small groups most likely associated with the Calusa or Tequesta tribes of the Florida mainland (Goggin 1950). Historical accounts suggest that they predominantly inhabited the upper and lower Matecumbe islands in the upper Florida Keys.

Pedro Menéndez de Avilés of Spain founded St. Augustine, FL in 1565, and then turned his attention to the exploration of Florida. During his exploration, Avilés made reference to a permanent Indian settlement in the Matecumbe area, although the exact location is unknown (Goggin 1950). In 1573, Avilés petitioned Spain requesting permission to enslave the Indians who were living there (Goggin 1950). The next mention of this settlement comes in 1605 from a group of Spanish missionaries. In route to St. Augustine, their ship ran aground off of the coast of Matecumbe. To free the ship, the missionaries received assistance and provisions from the Indians (Goggin 1950).

These references are in good agreement with the written accounts of Fontaneda. The names of two settlements, Guarungunve and Cuchiyaga, are noted in Fontaneda's manuscript, in which he also mentioned a combined population estimate of 1000 (Worth 2006). Later, in 1675, Gabrial Diez Vara Calderón, Bishop of Cuba, made a trip to Florida to inspect Franciscan missions. In his personal account, he listed a number of Indian groups living in camp settlements predominantly in the Matecumbe region. Among these groups were the "Cuchiagaros," who may have occupied Big Pine Key (Goggin 1950).

Based on these accounts, south Florida Indians inhabited portions of what today is the upper Florida Keys. Moreover, it seems possible that they might have migrated as far south as the lower Florida Keys. However, the limited archeological and historical evidence of aboriginal occupancy leaves many questions regarding the degree to which they may have modified the natural environment. Also unclear is whether they established permanent settlements anywhere in the Florida Keys prior to the late 16th century.

The 18th century saw many changes in land tenure in the Keys, as the islands passed from Spain to Britain, back to Spain, and finally to the United States (USFWS 2002). By the early 18th century, diseases spread by Spanish explorers and enslavement of indigenous people greatly reduced the population of Native Americans living on the Keys (Goggin 1950; Worth 2006). In 1704, Cuban authorities granted permission for the permanent immigration of a group of Indians from Key West (Cayo de Huesos) (Worth 2004). Surviving south Florida Indian refugees living between Miami and Key West did not create permanent settlements, perhaps to avoid the possibility of slavery (Worth 2004). The Seven Years War beginning in 1756 ultimately signaled the end of Indigenous Indian habitation in the Florida Keys. Beginning in 1757, a series of aggressive assaults by English-allied Creek Indians were aimed at remaining South Florida Indians living in Miami and the Florida Keys (Worth 2004). On May 17, 1760, under the repressive conditions associated with the Spanish occupation, remaining Native American inhabitants of the Keys and Miami fled to La Cabaña, Cuba, and were assimilated into the local population (Worth 2004). This ended the period of prehistoric culture in the Florida Keys (Clark 2002; Worth 2004, 2006).

European Settlement

Widespread European settlement in the Florida Keys did not occur until the early 19th century. Most permanent settlements were concentrated in the upper and middle Keys. Key West was the most densely populated island in the lower Florida Keys from the time of its initial settlement in the 1820s through the early years of the 20th century (Snyder *et al.* 1990). From 1845 to 1915, the U.S. government deeded to Florida 3208 acres on Big Pine Key (Simpson 1982; Wilkinson 2002*a*). Some was given to railroad companies and some was allocated for homesteading or industry. Still, until the middle 1900s, with the exception of Key West, the lower Florida Keys were sparsely populated.

In 1870, the census enumerator listed only one family on Big Pine Key (Wilkinson 2002*a*). In late 1906, The Florida East Coast Railroad came to Big Pine Key. The arrival of the railroad did affect Big Pine Key, but not to the same extent as it did other keys. No permanent facilities were built for laborers, in large part because Big Pine Key had only a very small population (Wilkinson 2002*a*). Instead, a temporary fresh water resource and camp for about 400 railroad employees were constructed. These facilities were abandoned after railroad construction was completed in Big Pine in 1907, and the entire work force moved to Sugar Loaf Key (Wilkinson 2002*a*). As a point of reference, the population of Big Pine Key in 1910 was 17 (Wilkinson 2002*a*). From 1914 to 1925, 10 subdivisions were filed on Big Pine Key (Wilkinson 2002*a*). By 1926, the majority of land on Big Pine Key had been taken, with most going to railroad companies and homesteading, but few people were living there (Simpson 1982; Wilkinson 2002*a*).

In the 19th and early 20th centuries, most Keys occupants supported themselves through fishing and other sea industry or farming of fruits such as pineapple, mango, Key limes, bananas, and tomatoes (Wilkinson 2002*a*). Not until 1906, when the Florida East Coast Railroad reached Miami, did commercial pine logging begin (Snyder *et al.* 1990). However, exploitation of pine rocklands for timber was concentrated in mainland Florida, and pine rocklands of the Lower Florida Keys escaped this logging (Simpson 1982; Doren *et al.* 1993; Ross *et al.* 1994; Wilkinson 2002*a*). Most clear-cutting that took place in the lower Keys was concentrated in Key West, where hammock trees were exploited for timber, firewood, and charcoal. Some early settlers practiced slash and burn agriculture within hammock communities (Snyder *et al*. 1990). Nevertheless, in the lower Florida Keys, logging and charcoal production were uncommon outside of Key West (Simpson 1982; Doren *et al.* 1993; Ross *et al.* 1994; Wilkinson 2002*a*).

Charcoal production was labor and time intensive in the Keys. Big Pine Key had only one resident listed as a charcoal burner (Wilkinson 2002*a*). The process involved cutting buttonwood shrubs, piling them in a pyramid, and covering them with canvas and seaweed to contain the heat. The fire was started in the bottom center. The process took several days, and the fire had to be monitored to ensure that the fire would neither go out nor escape into surrounding forests (Wilkinson 2002*a*).

The great depression of the early 1930s weakened the Keys economy, and the hurricane of 1935 destroyed the overseas railroad. This cut Big Pine Key off from the mainland, discouraging further settlement in the lower Keys (Simpson 1982). In 1938, Highway US 1 replaced the railroad, but it only ran from the mainland to the Matecumbe Islands. To travel to the lower Florida Keys, one had to take a 40 mile ferry ride from

Matecumbe to No Name Key, and then cross the "Old Wooden Bridge" to Big Pine Key (Clark 2002). As a result, only small farming and fishing industries remained (Wilkinson 2002*a*). The population on Big Pine Key did not begin to increase until the 1950s, when construction of the overseas highway began and a network of roads was established on the islands (Clark 2002; USFWS 2002). Piped drinking water, electricity, and other development quickly followed. Since about 1970, Big Pine Key has experienced roughly a 10-fold increase in human population and urban development (Harveson *et al*. 2007). At present, the population of Big Pine Key and neighboring No Name Key is approximately 5000 (Harveson *et al*. 2007).

Present Day Management of Pine Rockland Ecosystems of the Lower Florida Keys

Pine rockland is globally imperiled and extremely limited in distribution. Estimates are that pine rocklands once covered a combined ca. 65,000 ha on the Atlantic Coastal Ridge of southeast Florida, in today's Big Cypress Preserve and Everglades National Park, and in the lower Florida Keys (USFWS 1999*a*). Land development and other human impacts have significantly reduced and fragmented pine rockland habitat in Florida (Snyder *et al*. 2005). As a result, many critical ecosystem processes have been altered, including the natural fire regime (Snyder *et al.* 2005). Also, several non-native invasive plant species (e.g., *Casuarina*) have been observed in the pine rocklands (USFWS 1999*a*; Snyder *et al*. 2005; C. Bergh, *pers. communication*, Nov 21, 2007; P. Schmidt, *pers. communication*, Oct 26, 2007).

To conserve and protect pine rockland habitat and the diminutive Florida Key Deer that inhabit the pine rocklands, the United States Fish and Wildlife Service

established the National Key Deer Refuge (NKDR) in the lower Florida Keys in 1957. At present, approximately 700 ha of pine rockland habitat is scattered over seven islands in the lower Florida Keys, with most occurring within NKDR (USFWS 1999*a*; Snyder *et al.* 2005). Approximately 650 ha of Big Pine Key is pine rockland, 389 of which are protected within NKDR boundaries (Carlson *et al.* 1993). The majority of remaining portions are in small, privately owned parcels (Snyder *et al*. 2005).

Lower Keys pine rockland habitat supports several federally listed plant species including garber's spurge (*Chamaesyce garberi*), deltoid spurge (*Chamaesyce deltoidea* spp. *deltoidea*), and tiny polygala (*Polygala smallii*) (USFWS 1999*a*). Several of these species are endemic to south Florida, and some only occur in the Lower Keys. Pine rocklands also provide critical foraging habitat for an array of wildlife, including five federally listed species (USFWS 1999*a*).

One such species is the endangered Florida Key Deer (*Odocoileus virginianus clavium*), a subspecies of North American white-tailed deer endemic to the Florida Keys archipelago and the southern end of the Florida peninsula (USFWS 1999*a*). The current range of Key Deer, which lies completely within the boundaries of the NKDR, is restricted to 20−26 islands in the lower Florida Keys between West Summerland Key and Sugarloaf Key (Lopez 2001; Barrett and Stiling 2006). Only 12 of those islands are frequently used by Key deer and many of the smaller islands are used only transiently (mainly during the wet season) as the deer move from one island to another (Lopez 2001; Barrett *et al*. 2006).

The importance of pine rocklands in providing food sources and fawning habitat for Key deer is well documented (Carlson et al. 1993; USFWS 1999*a*; Lopez 2001;

Lopez *et al*. 2004). Many of the important Key deer food plants are stimulated by fire (Carlson *et al*. 1993; USFWS 1999*b*). Consequently, Key deer more often browse recently burned pine rocklands (Barrett 2004).

The uniqueness and rarity of pine rockland ecosystems, and the critical habitat these communities provide for many imperiled and endemic species, have led to strong efforts by NKDR management to appropriately manage and restore remaining rockland fragments (USFWS 1999*a*; P. Schmidt, *pers. communication*, Oct 26, 2007). Until recently, management activities have been limited to controlling access to the area and conducting sporadic prescribed burns. That the NKDR has not launched a comprehensive fire management program involving prescribed burns is in part because the proper fire frequency to maintain pine rocklands is not yet known (Snyder *et al*. 1990; Carlson *et al*. 1993; USFWS 1999*b*; Liu and Menges 2005; Snyder *et al*. 2005).

Florida pine rocklands are considered to be ecologically very similar to the Bahamian pine rocklands in terms of forest structure, species composition, pine regeneration, and responses to fire (Myers *et al.* 2004). The Nature Conservancy published a report (Myers *et al.* 2004) that described the fire management and research needs facing the conservation of the pine rockand ecosystems of Andros and Great Abaco Islands, The Bahamas. Myers and collaborators conjectured that a fire regime characterized by low-intensity, surface fires at intervals of one to seven or ten years is required to maintain the biodiversity characteristic of Bahamian pine rocklands. This fire return interval is consistent with the findings of Miller (2007), who conducted a dendrochronological study on *Pinus caribaea* (Caribbean pine) in pine rockland forests

of Abaco Island, The Bahamas. She found that these pine forests experience fire once every one to five years.

At present, few data exist on the history of fire in lower Keys pine rocklands. Bergh and Wisby (1996) mapped occurrences of controlled burns and wildfires between 1960 and 1996 within the NKDR. Certain areas of pine rockland habitat on Big Pine Key experienced fire in 1966, 1977, 1985, 1986, 1987, 1990, 1991, 1994, and 2003 whereas other areas have not burned in at least 50 years (Snyder *et al.* 2005; Barrett and Stiling 2006). Some of these fires were lightning induced, while others were management fires (Bergh and Wisby 1996; Barrett and Stiling 2006). The long-term, natural fire regime remains largely unknown (USFWS 1999*b*; Liu and Menges 2005). Based on observations over the past few decades, and studies of the dynamics of pine rockland vegetation, researchers have proposed that the shortest fire interval to maintain pine rockland vegetation may be 2 to 3 years and the longest interval 10 to 20 years (Snyder *et al.* 1990; Carlson *et al.* 1993; USFWS 1999*a*). However, field evidence of fire and vegetation history in particular places needs to be studied to test ideas on fire return intervals needed to maintain pine rocklands.

USFWS authorities and NKDR management have consequently identified fire history research, restoration of the "natural" fire regime, and increased public awareness of the role of fire as critical components to pine rockland recovery (USFWS 1999*a*; 1999*b*; P. Schmidt, *personal communication*). The NKDR and USFWS demonstrated interest in obtaining paleoecological evidence of past fire and vegetation in the NKDR as a means to provide a longer term perspective for management. Additionally, the USFWS is currently funding work on tree-ring evidence of fire history in the lower Keys pine

rocklands that will complement this research. This study of charcoal and pollen records from sediments in solution holes in pine rocklands aims to provide long-term evidence of vegetation and fire history that will help us better understand the environmental history of imperiled pine rockland habitat.

CHAPTER 4

Methods

Field Methods

Dr. Sally Horn, Dr. Ken Orvis, and I investigated potential core sites within the NKDR management area (Fig. 3.2) of the lower Florida Keys from February 25–27, 2007 with support from NKDR and The Nature Conservancy. Based on this reconnaissance, we selected two sites on Big Pine Key to be cored in a return visit: Key Deer Pond, the focus of this research, and Blue Hole Wetland, located ca. 500 m west of Key Deer Pond (Figure 3.3.). S. Horn and I, along with other students (Horn 2008), carried out initial analysis of pollen and charcoal in the Blue Hole Wetland core; undergraduate student Jeff Malik will expand upon these results for his undergraduate Honors Thesis.

In August 2007, Dr. Horn, Dr. Orvis, and I collected sediment cores from both sites using a Colinvaux-Vohnout locking piston corer (Colinvaux et al. 1999) operated from a platform extending across the solution holes. The platform at Key Deer Pond was constructed with an extension ladder and two 2x8 planks (Figure 4.1). We recovered overlapping core sections from a series of holes, along with two mud-water interface cores using a plastic tube fitted with a rubber piston. We also collected (in February 2007) a grab sample from the uppermost sediments.

Figure 4.1 Coring platform used at Key Deer Pond. Photograph by S. Horn.

Laboratory Methods

The sediment cores in their original aluminum coring tubes were returned to the Laboratory of Paleoenvironmental Research at the University of Tennessee. Core sections were opened longitudinally using a specialized router, and sediment inside the core tubes was then sliced longitudinally into two halves using a thin wire. The freshly cut core sections were then photographed by S. Horn and described by me and graduate students Maria Caffrey and Matt Valente on the basis of Munsell color, stratigraphy, and texture. Core halves were labeled A and B. One B half of each core was used for sampling and the A half was archived. My research focused on sediments from Holes 1A and 1C at Key Deer Pond, which together comprise a profile that spans 3.51 m. I sampled each B core half for pollen and microscopic charcoal at intervals of 16 cm, and the upper 1 m at Hole 1A for macroscopic charcoal at contiguous 1 cm intervals. I also analyzed the grab sample from the surface of Key Deer Pond for pollen and microscopic charcoal to document the modern palynological signature at the site.

Radiocarbon Dating and Core Chronology

With assistance from undergraduate student Charles Batey, I selected and removed a series of organic macrofossils from the Key Deer Pond core sections for radiocarbon dating. The macrofossils were removed at intervals of ca. 10–15 cm, or at closer intervals where abrupt changes in lithology occurred, or where we observed particular good samples for radiocarbon dating. The materials were rinsed with distilled water, transferred to Petri dishes, labeled, and oven dried over night. Dr. Horn and I selected eight organic macrofossil samples to submit for radiocarbon dating to determine

the chronology of the sediment profile. The eight samples consisted of macroscopic charcoal fragments, a pine needle and dicot leaf fragment, a fragment from a pine cone, a pine twig, and a piece of wood, and all were submitted to Beta Analytic Laboratory for Accelerator Mass Spectrometry (AMS) radiocarbon dating. The AMS dates provided by Beta Analytic were calibrated using CALIB 5.0.1 (Stuiver and Reimer 1993) and the dataset of Reimer *et al.* (2004). I created an age-depth model using the weighted means of the probability distributions of the calibrated radiocarbon dates.

Microfossil Preparation and Loss-on-Ignition

I sampled the core sections from Key Deer Pond Holes 1A and 1C at 16 cm intervals for pollen and microscopic charcoal analyses and for water content and loss-on-ignition (LOI, Dean 1974). With assistance from graduate student Maria Caffrey, sediment samples of 0.5 cm^3 volume were processed for pollen and charcoal analysis using standard palynological procedures (HF, HCl, KOH, acetolysis; Berglund, 1986, Appendix A). Tablets with *Lycopodium* spores were added to enable calculation of pollen and charcoal concentrations and influx (Stockmarr 1971). Duplicate samples of 0.5 cm^3 were removed from the same core section intervals for the LOI analysis. These were placed in pre-weighed crucibles, weighed, dried for 24 hours at 100 $^{\circ}$C, and then reweighed to determine water content. Samples were then ignited in a muffle furnace at 550 $^{\circ}$C for 1 hour and again at 1000 $^{\circ}$C for 1 hour to estimate organic and carbonate content (Dean 1974).

Pollen Analysis

The processed pollen residues were mounted on microscope slides in silicone oil and counted at 400x magnification to a minimum of 300 pollen grains, exclusive of indeterminate pollen grains and fern spores. Pollen grains were counted on 21 out of the 22 levels in the profile because one sample, from 323 cm deep, was determined to be uncountable due to poor pollen preservation. I identified pollen grains to the lowest taxonomic level possible using pollen reference slides in our lab collection and various published keys including *Pollen and Spores of Barro Colorado Island* (Roubik and Moreno P. 1991), the *Atlas of Pollen and Spores of the Florida Everglades* (Willard *et al.* 2004), and the online *Key to Pollen of the Bahamas* (Snyder *et al.* 2007). I also referred to sketches of pollen grains that I made with the assistance of Dr. Suzanne Koptur, based on my examination of reference pollen slides in her collection at Florida International University. I distinguished *Conocarpus erectus* pollen based on its perfect spheroidal shape, but grouped other Combretaceae pollen with Melastomataceae pollen, as these families produce morphologically very similar heterocolpate pollen grains. I also grouped *Eugenia* and *Psidium* pollen grains. These taxa in the Myrtaceae have some morphological differences, but I did not recognize the differences until late in the process of counting my samples.

Indeterminate pollen grains were classified as such based on four factors: corrosion, degradation, mechanical damage, or concealment by detritus (Delcourt and Delcourt 1980). However, I did not keep track of each category, as indeterminate pollen grains made up only a very small percentage of the total pollen sum. I sketched and described all unknown pollen grains for later reexamination. Unknown grains made up

only a very small fraction of total pollen grains. Fern spores were classified by morphology (monolete or trilete).

I compiled all pollen, fern spore, and LOI data into excel spreadsheets and produced pollen diagrams using the program C^2, which is a software program designed for ecological and paleoecological data analysis and visualization (Juggins 2003).

Microscopic Charcoal Analysis

I quantified microscopic charcoal (fragments <125 µm) on the pollen slides using a modified version of the point counting method described by Clark (1982). Using the ends of the major divisions of my eye piece reticule, I "applied" 11 points to an average of 15 fields of view along transects spaced 0.5 mm apart that covered the entire slide. The total points applied top each slide was from ca. 4500−7000. A "hit" was scored if a charcoal fragment was touching a point. I counted as charcoal only those fragments that appeared black, angular, and opaque (Anchukaitis and Horn 2005). The number of *Lycopodium* marker spores present in each field of view was also recorded. The charcoal hits, marker spore counts, points applied, and fields of view were used to estimate the total charcoal area in the entire pollen sample using calculations based on Clark (1982) with some modifications by S. Horn (Appendix B). For most samples, the relative error of the charcoal estimate was 10−25 %; a few samples with lower charcoal abundance had relative errors as high as 38% calculated as in Clark (1982). The total charcoal area values were then converted to influx values ($mm^2/cm^2/yr$), which take into account the varying number of years represented by each sediment sample; charcoal to pollen ratios;

and concentrations expressed as charcoal on a wet volume (mm^2/cm^3 wet sediment) and dry mass (mm^2/g dry) basis.

Macroscopic Charcoal Analysis

Macroscopic charcoal was examined at high resolution in the upper meter of the Key Deer Pond profile. With assistance from graduate student Alisa Hass, the uppermost core section (Hole 1A; 0.11–1.11 m) was sampled at contiguous 1-cm intervals using a brass sampler with a rectangular cutting edge. Designed and fabricated by R. Horn, the sampler extracts samples with a volume of 4 cm^3 over a core depth increment of 1 cm.

Samples were soaked overnight with cosmetic grade 3% hydrogen peroxide (Schlachter and Horn, in press). The samples were then gently wet-sieved through screens with mesh sizes of 250 and 500 μm using a spray of distilled water from a RL Flo-Master 7.6-1-capacity sprayer. Retained particles were transferred to Petri dishes and counted under a stereo binocular dissecting scope at 10–40x magnification. Particles that appeared black with an iridescent sheen, were angular, and showed cellular structure were identified as charcoal particles.

Charcoal counts were converted into charcoal concentrations (particles/cm^3). The charcoal concentration data were then divided by the time in years represented by the sample (yr/cm), as estimated by the age-depth model, to calculate charcoal influx (particles/cm^2/yr).

CHAPTER 5

Results

Sediments and Stratigraphy

The sediment corer we used at Key Deer Pond is designed to recover sediment cores in 1-m long sections. We collected a total of 9 core sections from two areas of the pond, including material from parallel holes at each site. We reached a depth of 3.51 m at site 1, and about 3.0 m at site 2. This thesis focuses on the deeper profile obtained at site 1. Here, we collected three successive core sections in Hole 1A (0.11–1.11 m, 1.11–2.11 m, and 2.11–2.64 m below the mud-water interface), two successive core sections from Hole 1B (0.61–1.61 m and 1.61–2.61 m below the mud-water interface), and two successive core sections from Hole 1C (1.61–2.61 m and 2.61–3.51 m below the mud-water interface). The deepest core section from Hole 1C bottomed out on rock. Hole 1B was located approximately 0.62 m east of Hole 1A, and Hole 1C was located approximately 0.93 m east of Hole 1A. Both core sections from Hole 1B were anomalously watery, either because of a malfunction with the corer or because the sediments had been disturbed by coring at 1A. For my thesis research, I analyzed the three core sections from Hole 1A and the lower section from Hole 1C.

The core sections from Holes 1A and 1C consist primarily of dark (mainly Munsell 10YR 3/2 to 2/1) sediments, generally becoming more organic with depth (Table 5.1, Figure 5.1). A 9-cm thick silty layer (10YR 6/3) from 122–131 cm marks the only interruption of organic sedimentation. Wood and other plant fragments are abundant in the core sections.

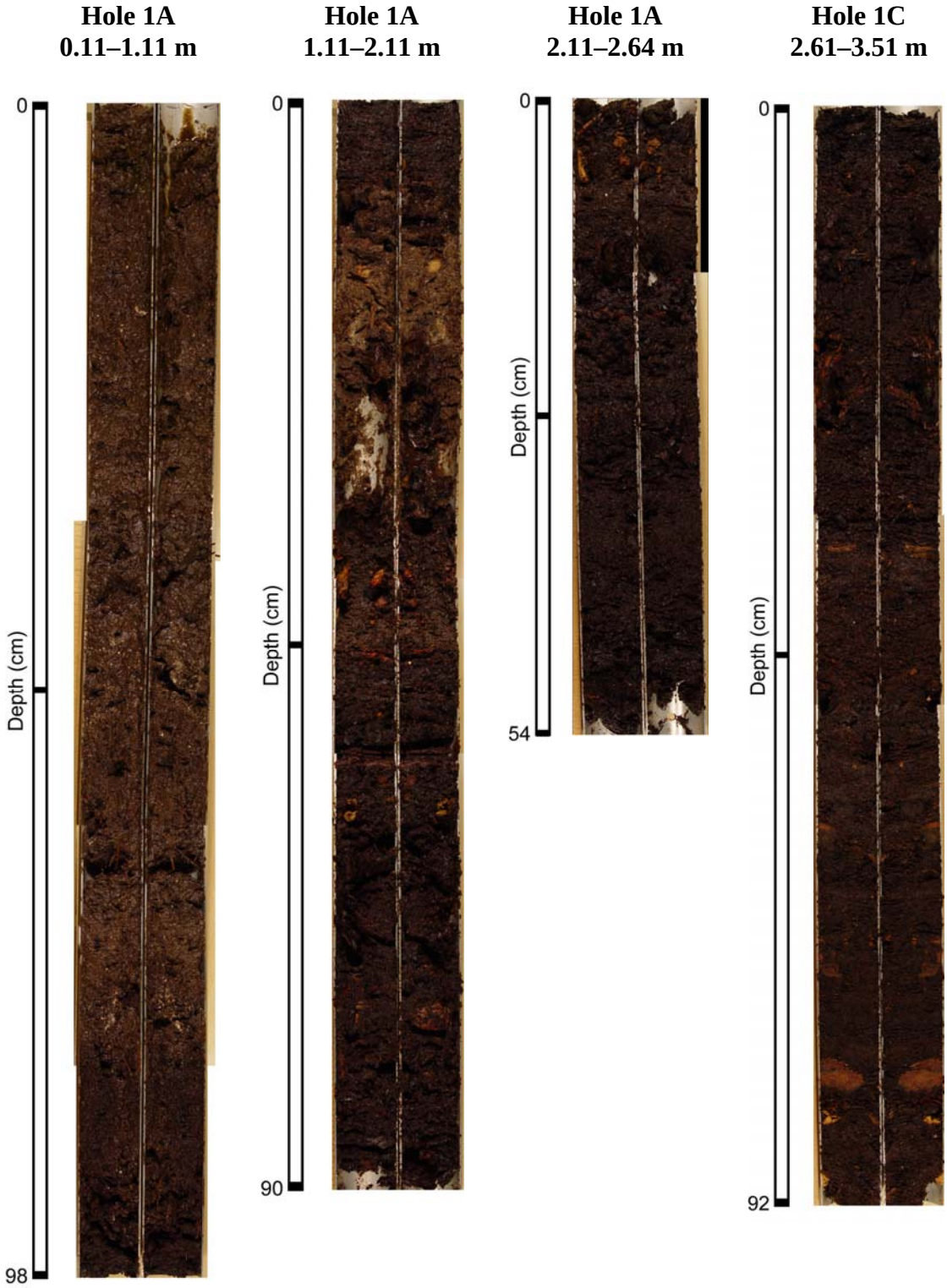

Figure 5.1 Sediment Stratigraphy of Hole 1A and 1C, Key Deer Pond. Numbers at ends of core sections indicate core section lengths, and center bars on each scale show mid-points of each core section.

Table 5.1 Sediment Stratigraphy of Hole 1A and 1C, Key Deer Pond.

Depth	Sediment Description	Munsell Colors
0–122 cm	organic-rich sediment, becoming more fibrous with depth	10YR 3/2 to 10 YR2/1
122–131 cm	Silty sediment with some organic mottling	10YR 6/3
131–156 cm	loose fibrous organics	10YR 4/2 to 10 YR3/2
156–351 cm	highly organic	10YR 2/1

Radiocarbon Analyses

AMS radiocarbon dating of a wood fragment at the base of the profile establishes that the Key Deer Pond sediment record extends to 1660 cal yr BP (AD 290) (1750 ± 40 ^{14}C yr BP). The radiocarbon results for samples higher in the core are mainly in stratigraphic sequence (Table 5.2). Two dates on charcoal were out of order, and were excluded from the age model (Figure 5.2). These two determinations likely reflect the in-built age of charred wood (Gavin 2001).

Sedimentation rates calculated from the weighted means of the probability distributions of the calibrated radiocarbon dates (Figure 5.2) show that sedimentation was slowest (0.09 cm/yr) during the initial ca. 630 years of sedimentation, from 1660–1028 cal yr BP (AD 290–922). The sedimentation rate from 1028 to AD 2007 (–57 cal yr BP) was from 0.21–0.38 cm/yr. In the lower 60 cm of the profile, each cm of core depth represents ca. 10 years of sediment accumulation. Above this in the profile, each cm of sediment represents from ca. 2.5–5 years of accumulation.

Loss-on-Ignition

The sediment is highly organic (Figure 5.3). Organic content is very high in the lower 1.9 m of the profile (1.61–3.51 m), constituting 85% or more of the dry weight of the sediment. Above that (0.11–1.61 m), organic contents vary between ca. 40% and 85%. Non-carbonate inorganic and carbonate content reach their highest values in the upper 1.5 m of the profile (0.11–1.61 m), with values ranging from 10–40% and 5–20%, respectively, on a dry weight basis.

Table 5.2 Radiocarbon determinations and calibrated ages for material from Key Deer Pond sediment profile.

Lab Number[a]	Depth Below Sediment/Water Interface (cm)	Material Dated	$\delta^{13}C$ (‰)	Conventional ^{14}C Age (^{14}C yr BP)	Calibrated Age Range[b] (cal yr BP) ±2 σ	Area Under Probability Curve	Weight mean cal years BP[c]
β -251140	41	Charcoal	–26.5	340 ± 40	408–308	1.000	396
β -251141	59	Charcoal	–25.7	230 ± 40	30 to –2 222–139 324–259 366–362 428–376	0.116 0.411 0.396 0.002 0.076	219
β -247699	79	Charcoal	–25.5	490 ± 40	557–485 626–605	0.950 0.050	526
β -247700	104	Charcoal	–26.2	320 ± 40	481–302	1.000	387
β -251142	192	Pine Needle and Dicot Leaf Fragment	–27.6	670 ± 40	609–555 682–622	0.459 0.541	619
β -251143	224	Partially Charred Pine Cone Bract	–25.9	790 ± 40	776–669	1.000	714
β -251144	291	Pine Twig	–24.2	1120 ± 40	1095–936 1140–1103 1168–1161	0.921 0.068 0.011	1028
β -235603	349	Wood Fragment	–27.4	1750 ± 40	1741–1553 1783–1755 1810–1796	0.950 0.035 0.016	1660

[a]Analyses were performed by Beta Analytic, Inc. Each charcoal or wood sample consisted of a single fragment.
[b]Calibrations were calculated using CALIB 5.0.1 (Stuiver and Reimer 1993) and the dataset of Reimer *et al*. (2004).
[C]Weighted mean of the 2 σ probability distribution of the calibrated radiocarbon dates.

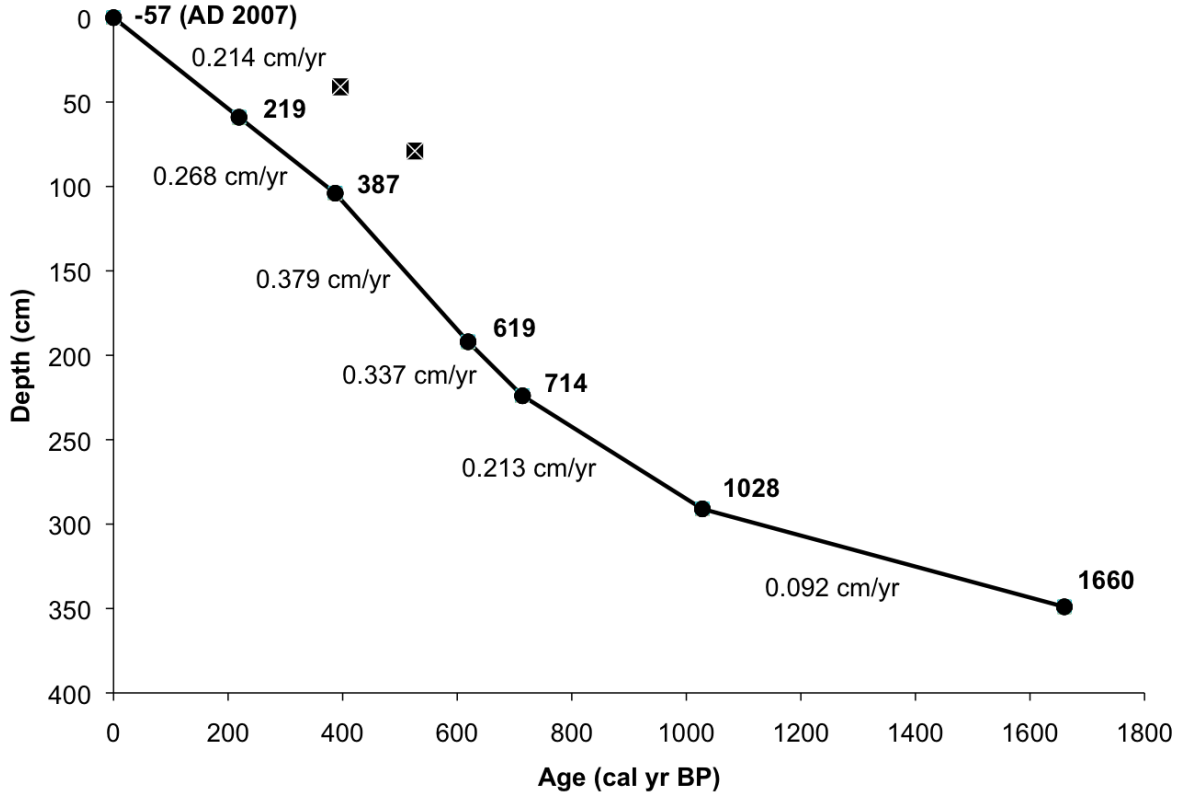

Figure 5.2 Age vs. depth relationship for Key Deer Pond, Big Pine Key, showing sedimentation rates. Model based on linear interpolation using depth intervals of dated samples and the weighted means of the probability distributions of the calibrated radiocarbon dates. The "x" symbols indicate dates excluded from the age model.

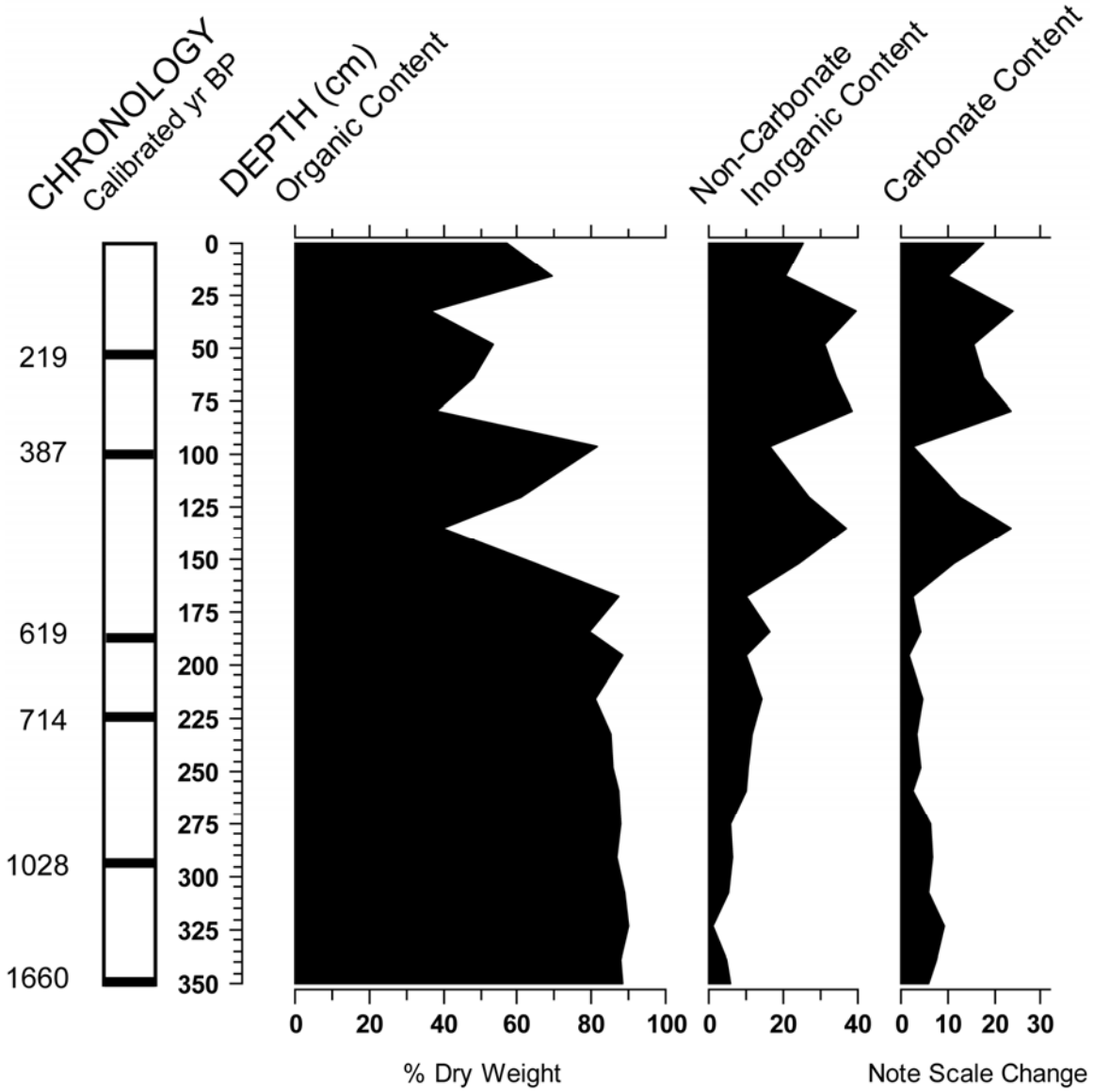

Figure 5.3 Loss-on-ignition results for the Key Deer Pond sediment profile.

The Pollen Record

I identified 45 different pollen types, including some from plant taxa that are rare, endangered, or invasive (Appendix C). Indeterminate pollen grains, which were not included in the pollen sums, comprised less than 2.5% of all pollen counted. In general, pollen preservation is good. Only one sample from a depth of 323 cm (Hole 1C 2.61–3.51 m; 62–63 cm) contained very few pollen grains, and was therefore excluded from analysis. Total pollen concentrations were variable in the profile, ranging from ca. 20,000 to 90,000 grains/cm^3 wet sediment (Table 5.3). Pollen diversity varied from 9–18 different types per level (Table 5.4).

Pollen was identified and counted from 21 samples from depths between 0 and 351 cm (Figure 5.4). Pine (*Pinus*) pollen dominates the record, accounting for ca. 50–90% of the pollen in all samples between ca. 30–351 cm depth in the sediment core. Only the uppermost ca. 30 cm of the record show relatively lower values for *Pinus*, less than 40% of total pollen. Values for pollen of hardwood taxa including wax-myrtle (*Myrica cerifera* L., Myricaceae), buttonwood mangrove (*Conocarpus erectus* L., Combretaceae), poisonwood (*Metopium*, Anacardiaceae), and Melastomataceae/ Combretaceae increase in the uppermost sediments, beginning at ca. 334 cal yr BP (96 cm). Above this level, values for *C. erectus* vary between ca. 5–15% of all pollen counted, and pollen of *M. cerifera* reaches values as high as 30%.

Pollen from Myrtaceous shrubs (*Eugenia*/*Psidium*, common name stopper) shows higher values in lower 170 cm of the sediment profile. Above this interval, the pollen is virtually absent from the record. In the upper 310 cm of the sediment profile, Arecaceae

Table 5.3 Pollen concentrations exclusive of fern spores and indeterminate pollen grains for the Key Deer Pond sediment profile.

Depth (cm)	Pollen Concentration (grains/cm^3 wet sediment)
0	18756
16	63231
32	42368
48	50046
64	49682
80	37767
96	27457
120	37261
135	42368
152	25461
168	27276
184	34348
195	20711
216	49979
232	41319
248	88793
259	83201
275	67311
291	51522
307	27638
323	not counted
339	20883
350	59195

Table 5.4 Pollen diversity for the Key Deer Pond sediment profile. The pollen sum was very close to identical for all samples (300–318), so the values were not corrected using rarefaction.

Depth (cm)	Number of Different Pollen Types
0	16
16	13
32	15
48	17
64	14
80	13
96	11
120	14
135	9
152	13
168	9
184	15
195	14
216	13
232	13
248	14
259	14
275	10
291	18
307	14
323	not counted
339	16
350	14

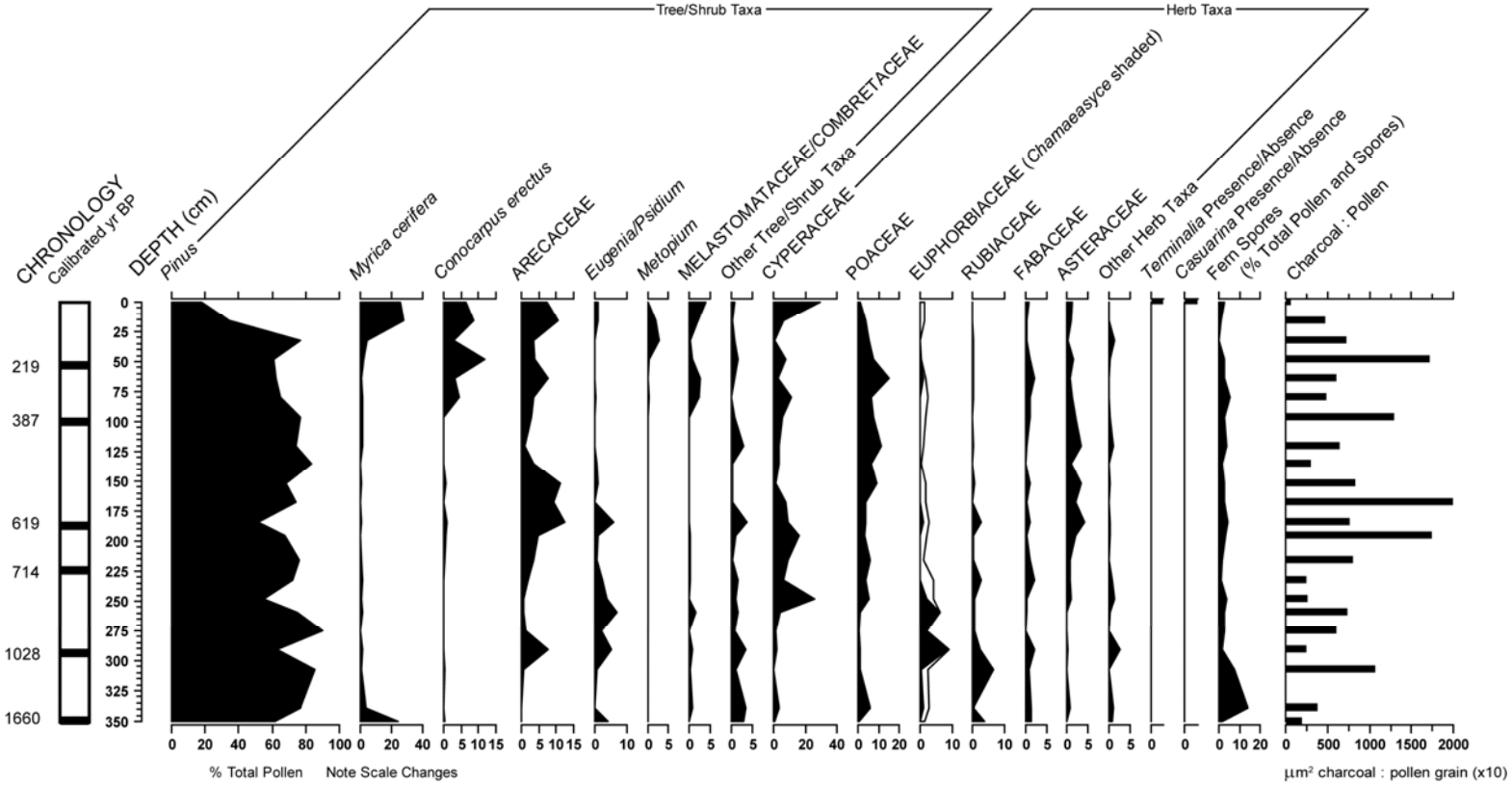

Figure 5.4 Percentage pollen diagram for the Key Deer Pond sediment profile showing main pollen types, total fern spores, and charcoal to pollen ratios. The "Other Tree/Shrub Taxa" group includes Apiaceae, Anacardiaceae, *Batis, Piscidia*, *Acacia*, *Cassia*, Bignoniaceae, *Myrsine*, *Rhizophora*, *Guettarda*, *Randia*, *Psychotria*, *Cephalanthus*, *Annona*, Ulmaceae, *Trema*, *Celtis*, *Byrsonima*, and Urticaceae (diporate). The "Other Herb Taxa" group includes Amaranthaceae, Araceae, Boraginaceae, Apocynaceae, *Polygala*, Solanaceae, and *Capsicum*. Herbs in the Euphorbiaceae and Rubiaceae families are common in the pine rocklands of south Florida, and I expect that most pollen in these groups represent herbaceous plants, but some may represent woody genera. Further, several members of the genus *Chamaesyce* sometimes take on shrubby characteristics (Nelson 1996). The "0" sample is the surface grab sample from Key Deer Pond.

(palm) pollen shows fluctuating peaks, with values ranging between ca. 2–15% of all pollen counted. Values for other tree and shrub taxa are generally low, representing less than ca. 4% of the total pollen sum at all sample intervals.

Grass (Poaceae) and sedge (Cyperaceae) pollen fluctuate throughout the profile, with generally higher values in the upper 250 cm of the profile. Peaks in Cyperaceae pollen occur at 250 cm and again in the uppermost sediments, beginning at ca. 20 cm depth in the profile. These two peaks are coincident with decreases in *Pinus* pollen. Other taxa characteristic of the herb layer in pine rocklands, including several species of sandmat (*Chamaesyce* spp., Euphorbiaceae) and other species in the spurge family (Euphorbiaceae) and the madder family (Rubiaceae), show generally higher percentages in the lower 170 cm of the profile. The contribution of other herbaceous taxa, including the pea (Fabaceae) and aster (Asteraceae) families, is generally low, less than 5% of the total pollen sum in all samples. Fern spore percentages show little change over time, except for a prominent peak at 339 cm.

The Microscopic Charcoal Record

Microscopic charcoal is abundant in the pollen samples throughout the sediment profile (Figure 5.5). Charcoal concentrations in wet sediment vary from 90–900 mm^2/cm^3. Values for charcoal influx range from ca. 20–220 $mm^2/cm^2/yr$, and show generally lower values in the lower 40 cm of the profile. Charcoal concentrations in dry sediment are more variable throughout the profile, ranging from ca. 500–8500 mm^2/g dry sediment. Charcoal to pollen ratios vary from ca. 200–2000 μm^2 charcoal : pollen grain, and are near-zero in the surface sample.

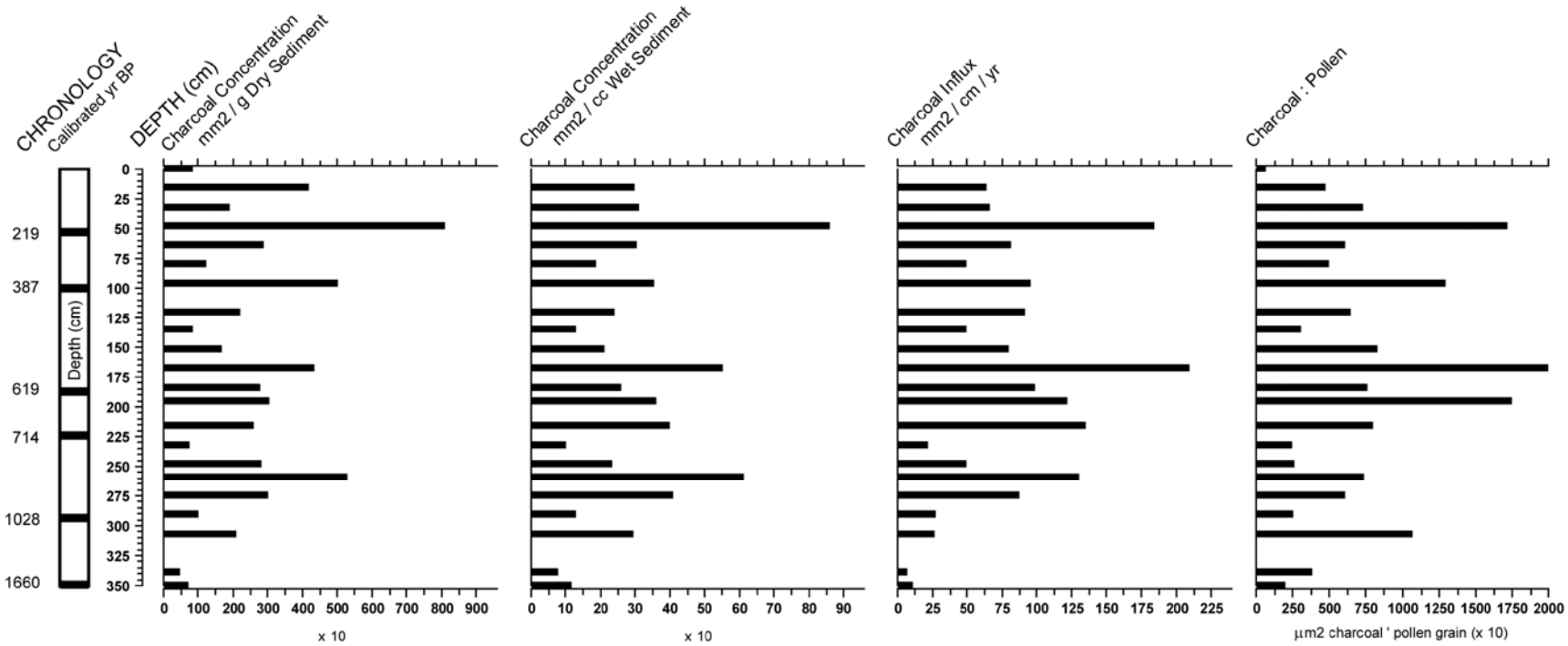

Figure 5.5 Concentration of microscopic charcoal fragments (<125 µm) expressed as charcoal area per g dry sediment, charcoal area per cm^3 wet sediment, influx ($mm^2/cm^2/yr$), and charcoal to pollen ratios for the Key Deer Pond sediment profile. Due to the relatively high water content of the surface grab sample, this level was excluded from in the profiles for charcoal concentration in wet sediment and charcoal influx.

Curves for charcoal concentrations in wet sediment and influx generally mirror each other over much of the profile. All charcoal indices and charcoal to pollen ratios show distinct peaks at 50 cm (ca. 177 cal yr BP) (AD 1773), 165 cm (548 cal yr BP) (AD 1402), and 260 cm (ca. 883 cal yr BP) (AD 1067). I use charcoal peaks to refer to sample intervals with higher amounts of charcoal relative to the rest of the record. Charcoal concentrations in dry sediment also show peaks at 16 cm (18 cal yr BP) (AD 1932) and 96 cm (357 cal yr BP) (AD 1593).

The Macroscopic Charcoal Record

The uppermost core section of Hole 1A (0.11–1.11 m) was sectioned and sieved for macroscopic charcoal at contiguous 1-cm intervals (Figures 5.6–5.7). We chose to examine the upper core section to elucidate pre and post-settlement fire history so as to inform modern fire management. Charcoal is abundant in every interval of the core. A visual assessment of the charcoal concentrations (particles/cm^3) and influx (particles/cm^2/yr) reveals close agreement between the different size classes (250–499 and >500 µm particle sizes) of charcoal particles (Figure 5.6). Concentration and influx values for the largest particle size (>500 µm) show distinct charcoal peaks at 25, 34, 49, 56, 79, 88, and 104 cm. Total charcoal concentrations (all particles >250 µm) vary from 10–180 particles/cm^3, and charcoal influx values (all particles >250 µm) range from 2–40 particles/cm^2/yr (Figure 5.7).

Charcoal values for both records are generally highest from ca. 350 to 200 cal yr BP (AD 1600–1750). Both particles size classes show a trend of decreasing

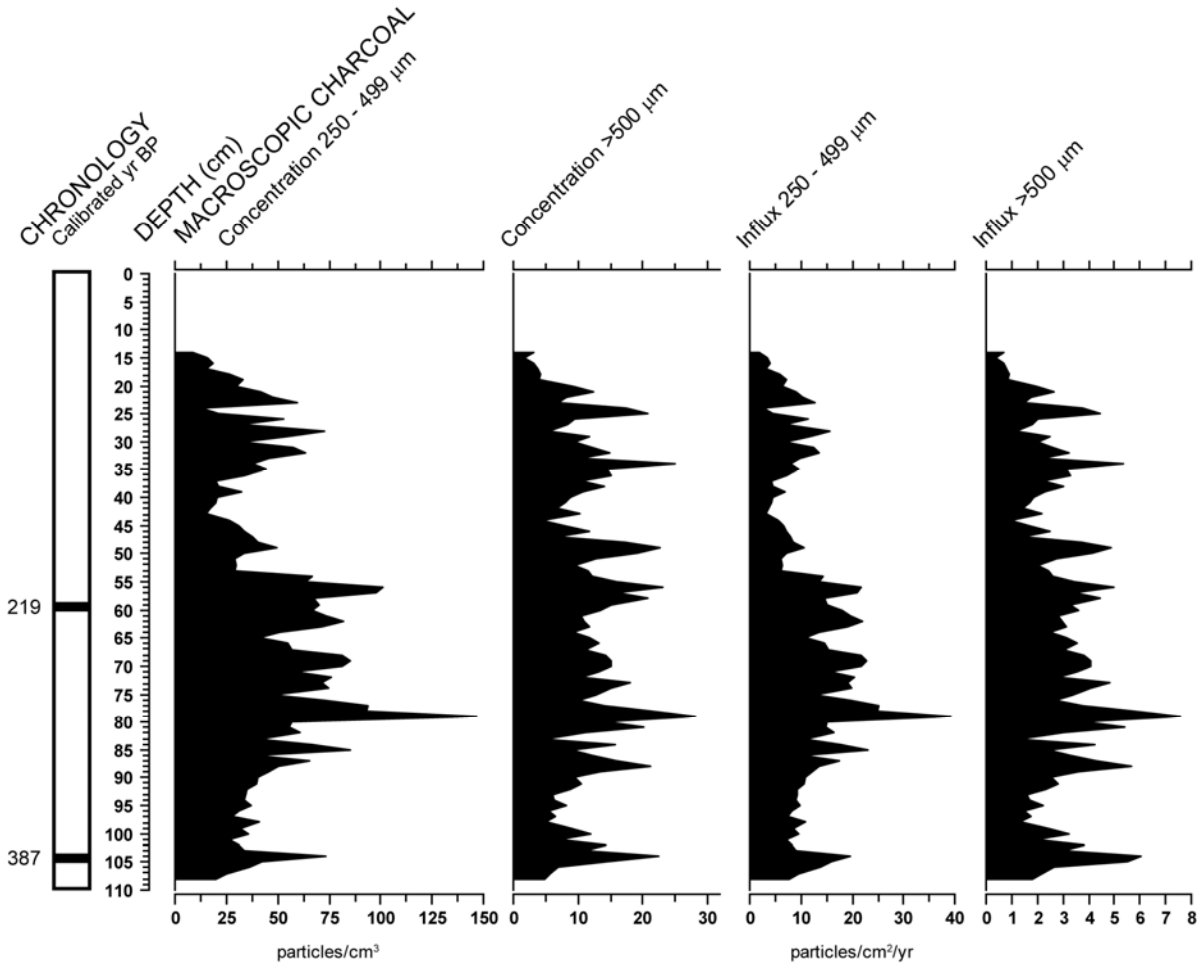

Figure 5.6 Macroscopic charcoal in the upper ca. 1 m of the Key Deer Pond sediment profile (core section 0.11–1.11 m in Hole 1A). Charcoal counts are expressed as concentrations and influx for two particles size classes of 250–499 and >500 µm). Due to the relatively high water content of the sediments in the upper 3 cm of the core section (0.11–0.14 m), these intervals were excluded from analysis.

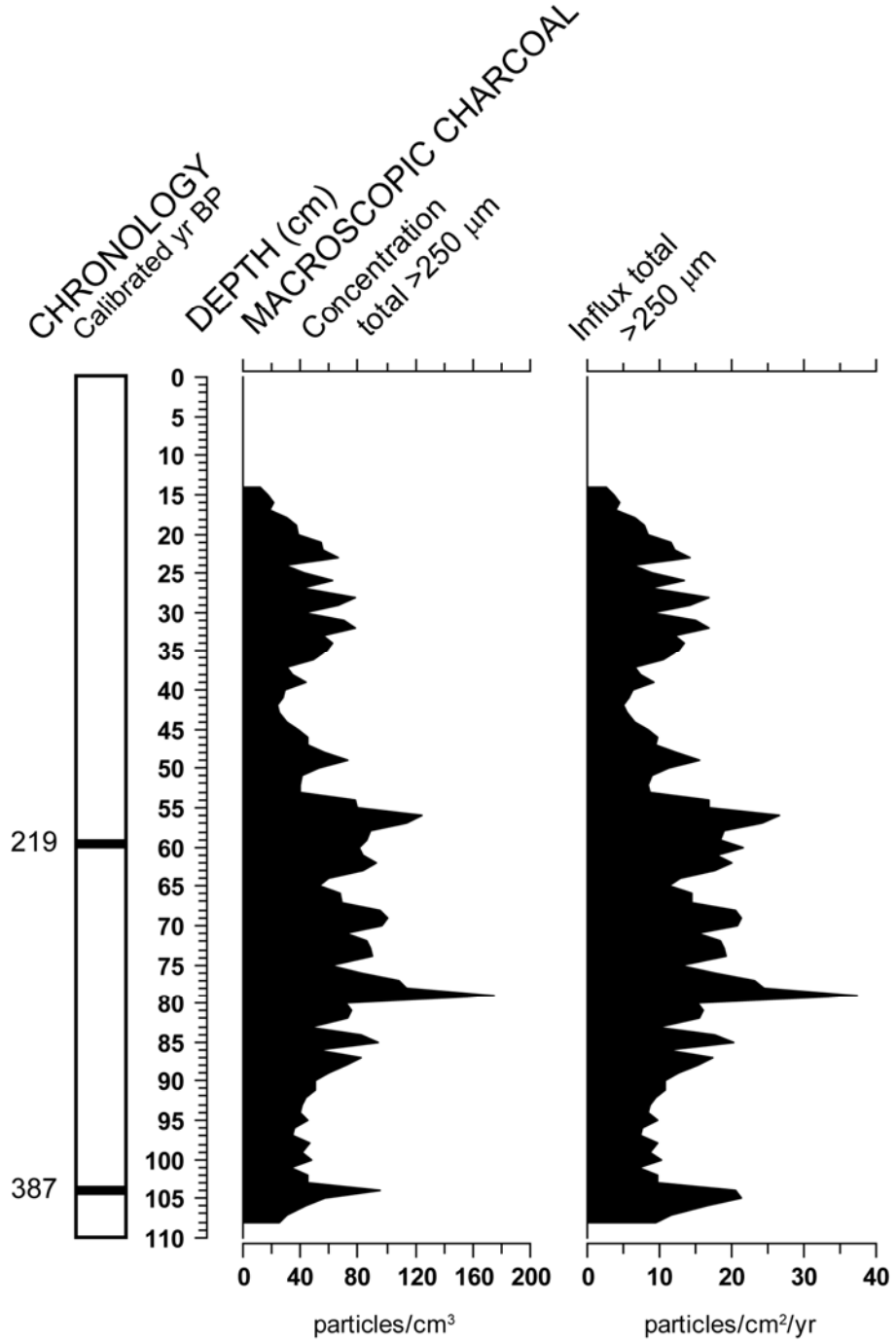

Figure 5.7 Macroscopic charcoal in the upper ca. 1 m of the Key Deer Pond Sediment profile (core section 0.11–1.11 m in Hole 1A), expressed as concentrations and influx for all particles >250 µm in size.

concentration and influx values in the most recent sediments examined, from ca. 23–11 cm, or about AD 1900 to 1956.

Comparing Microscopic and Macroscopic Charcoal Records

A peak in microscopic charcoal concentration at ca. 168 cal yr BP (AD 1782) is coincident with a moderate peak in macroscopic charcoal in the Key Deer Pond sediment profile (Figure 5.8). Overall, trends in microscopic charcoal do not match the macroscopic charcoal data. However, the microscopic charcoal record is coarse (16-cm sample interval) in comparison to the high-resolution macroscopic charcoal record (1-cm sample interval). This difference made comparison between the two records difficult. For example, because of the wide sampling interval used for microscopic charcoal, some sample intervals with abundant charcoal may have been missed.

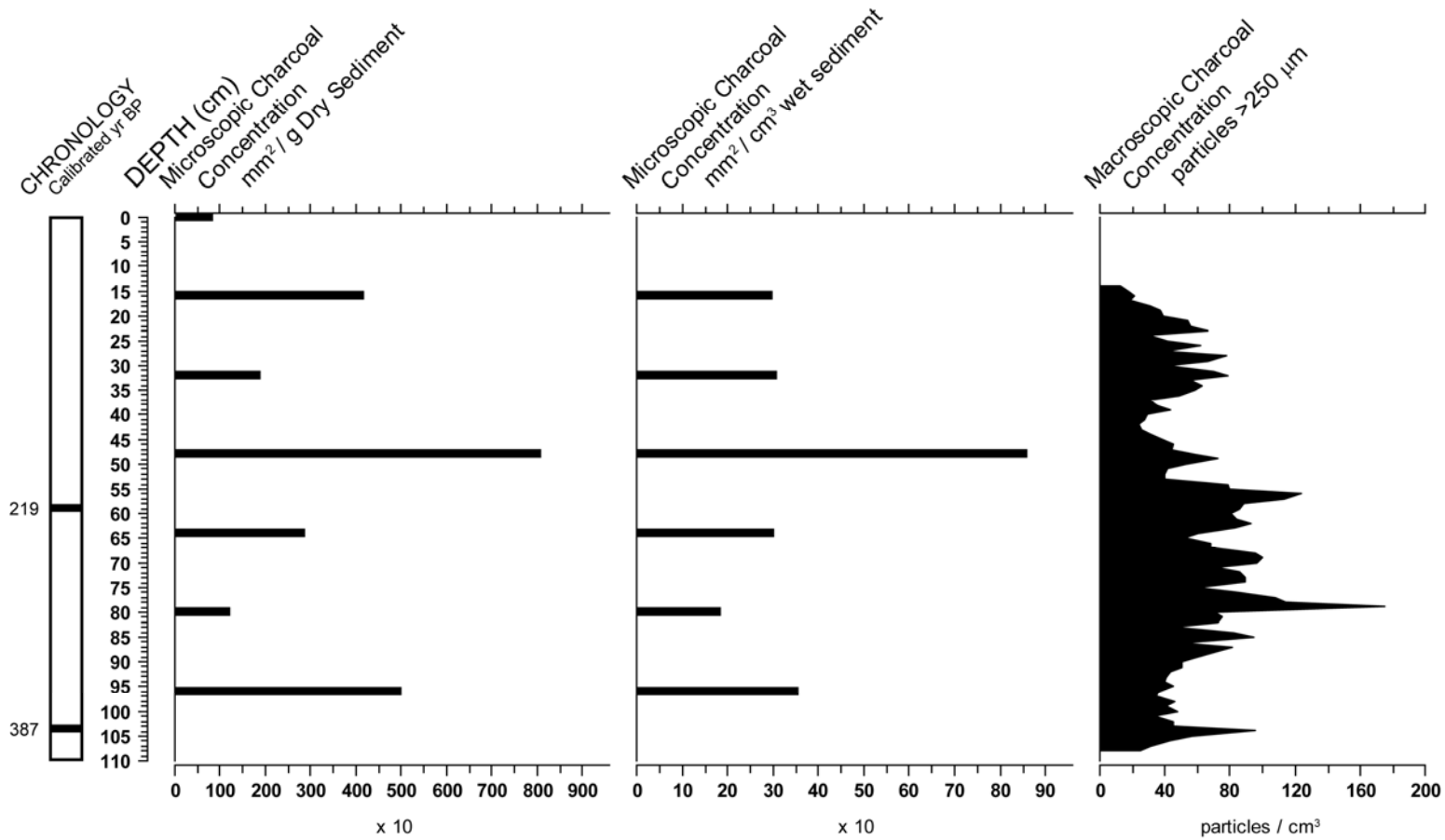

Figure 5.8 Comparison of microscopic and macroscopic charcoal concentrations in the upper ca. 1 m of the Key Deer Pond sediment profile (core section 0.11–1.11 m in Hole 1A). Charcoal counts are expressed as charcoal area per g dry sediment and charcoal area per cm^3 wet sediment for microscopic charcoal and as particles per cm^3 wet sediment for macroscopic charcoal.

CHAPTER 6

Discussion

This research provides a first look at the long-term vegetation and fire history of pine rockland habitats in the lower Florida Keys. Pollen assemblages and macroscopic and microscopic charcoal in the sediment profile from Key Deer Pond provide a 1700-yr record of vegetation shifts and fire history in the pine rocklands on Big Pine Key. This study demonstrates the long-term presence of fire in pine rocklands of the lower Florida Keys; documents vegetation and fire dynamics that may be associated with climate variability; shows possible historic human influences on vegetation and fire occurrence; and reveals vegetation shifts related to historic sea level rise. Below, I discuss my interpretation of these various lines of evidence, as well as other aspects of the Key Deer Pond sediment record, using the questions I posed in chapter one as a framework.

What are the general trends in the fire history through time in the pine rockland ecosystem as shown by microscopic and macroscopic charcoal analysis of the Key Deer Pond sediments?

The microscopic charcoal record from the Key Deer Pond sediment profile reveals that fire has been a long-term and important element of the pine rocklands on Big Pine Key—at least since 1660 cal yr BP (approximately AD 300, the beginning of the sediment core). The macroscopic charcoal record in the uppermost meter of the sediment profile provides a more detailed history of local fires, and shows repeated fires occurred

around the pond between ca. 8 cal yr BP and 397 cal yr BP (mid-1500s through mid-1900s).

Beyond the interpretations of long-term fire occurrence and repeated fires in the pine rocklands on Big Pine Key, the use of sedimentary charcoal to determine spatial patterns of fire events encounters interpretation challenges. Microscopic charcoal in lake sediments is generally assumed to reflect fires on a regional or broader scale, and macroscopic charcoal to reflect fires on a local scale (Whitlock and Larsen 2001). However, Pitkänen (1999) demonstrated that local, low-intensity fires in eastern Finland deposited abundant microscopic charcoal. A series of decanters were placed at distances of 20, 50, and 100 m from the edge of a low-intensity experimental burn. The most numerous particles deposited in the immediate vicinity of the fire were particles <50 µm in size. The authors also found good agreement between fire scar data and the abundance of microscopic charcoal in two sediment cores from Lake Pönttölampi. Pitkänen (1999) concluded that microscopic charcoal particles, even particles <50 µm in size, can be deposited locally, although they have a potentially large source area. The researchers further noted that this may be due to the low-intensity nature of fires in their study area. Patterson *et al.* (1987) suggested that most microscopic charcoal in small ponds (<25 m in diameter) is derived from local area fires, within about 20–30 m of the sampling site. An additional complication is that charcoal, whether microscopic or macroscopic, can be remobilized from soils, or detached from previously burned vegetation, by wind or water, and deposited in a lake several years after a fire event (Whitlock and Millspaugh 1996; Gardner and Whitlock 2001).

These considerations prompt caution in the interpretation of the charcoal records from Key Deer Pond. However, the small size of Key Deer Pond (surface area of ca. 78m^2 (0.008 ha)) leads me to expect that at least some of the microscopic charcoal indicates local burning, as the macroscopic charcoal surely must.

Microscopic charcoal is generally less abundant in the early part of the record, whether expressed as concentrations on a wet volume or dry mass basis, or as influx. Charcoal to pollen ratios show a slightly different pattern, but are also generally lower in the lower portion of the profile. Charcoal concentrations on a wet volume and dry mass basis, and charcoal to pollen ratios, increase ca. 1201 cal yr BP (AD 749) (307 cm), and influx values begin to increase ca. 953 cal yr BP (AD 997) (275 cm). Higher overall charcoal to pollen ratios persist until the uppermost sample interval (the surface grab sample). The microscopic charcoal curves for concentrations and influx show five distinct charcoal peaks at 18 (AD 1932) (16 cm), 177 (AD 1773) (50 cm), 357 (AD 1593) (96 cm), 548 (AD 1402) (165 cm), and 883 cal yr BP (AD 1067) (260 cm). Three of these peaks (177, 548, and 883 cal yr BP) correspond across all microscopic charcoal indices.

Higher values for microscopic charcoal indices since ca. 1200 cal yr BP (approximately AD 750) suggest increased fire in the region, and likely around Key Deer Pond. Greater fire activity after 1200 cal yr BP may signal generally drier conditions, increased frequency of drought, or both. Several sediment records from the circum-Caribbean Region have revealed climate variation during this interval, and drought around 1200 cal yr BP (Lane *et al.* in press). Pollen records from sediment cores from tree islands in the Everglades show the development of tree island vegetation in response

to a drying trend ca. 3000 cal yr BP, with significant development during dry intervals from 1200–1000 cal yr BP (AD 750–950) and 500–200 cal yr BP (AD 1450–1750) (Willard *et al.* 2006). These phases of tree island development correlate with evidence of dry conditions during the Terminal Classic drought and Little Ice Age identified in sediment cores from lakes in the Yucatan peninsula (Hodell *et al.* 2005*a*, *b*).

The charcoal indices at Key Deer Pond may also reflect shorter-term variations in climate. Changes in charcoal abundance appear uniformly episodic over much of the sediment profile. The episodic nature of the charcoal trends suggests variations in fire activity may have been related to changes in precipitation or storm frequency linked to global climate cycles.

Best known in this context is the El Niño-Southern Oscillation (ENSO), which has been a persistent component of global climate over the past 130,000 years (Tudhope *et al.* 2001; Cane 2005). ENSO, which is characterized by alternating periods of warm (El Niño phase) or cold (La Niña phase) sea surface temperatures in the central and eastern Pacific, has a periodicity ranging from about 3 to 7 years (Beckage *et al.* 2003). ENSO events affect global rainfall activity, and have been associated with increased fire activity on sub-continental scales (Horn and Sanford 2000; Beckage *et al.* 2003). Even more is that substantial changes in the strength of ENSO cycling have occurred over time. For example, unusually strong ENSO events occurred in 1982–83 and 1997–98 with widespread ecological impacts in both cases (Tudhope *et al.* 2001). On a much longer time scale, the amplitude of ENSO during the last 5000 years appears to have been significantly greater than during most other periods in the past (Tudhope *et al.* 2001). ENSO variability may have influenced fire activity in the Florida Keys. In south Florida,

El Niño phases are associated with increased dry-season rainfall, while La Niña phases are associated with decreased dry-season rainfall. Beckage *et al.* (2003) found a strong association between fire occurrence in the Everglades and ENSO conditions. The researchers found that decreased dry-season rainfall, increased lightning strikes, more fires, and more extensive burning in the early part of the wet season were associated with La Niña phases of ENSO. In the Everglades, more extensive fires occur in the early wet season because lightning strikes are frequent, but fuels are still dry (Liu and Menges 2005). This same relationship may exist in the lower Florida Keys. During strong ENSO cycling, decreased dry-season rainfall associated with La Niña phases may have increased the probability of lightning ignition of still-dry fuels in the early part of the wet season, leading to more frequent or extensive fires in the lower Florida Keys landscape, including the area around Key Deer Pond.

Another climate cycle that could be reflected in the Key Deer Pond fire record is the Atlantic Multidecadal Oscillation (AMO). AMO is identified as a 60–80 year coherent pattern of variability in North Atlantic sea surface temperature (SSTs), and is characterized by warm and cool phases, each lasting approximately 20–40 years (Enfield *et al.* 2001; Trenberth and Shea 2005). Observational records show that AMO cool phases occurred during 1905–1925 and 1970–1990, and warm phases during 1860–1880 and 1940–1960, and since about the mid-1990s (Enfield *et al.* 2001). Warm-phase AMO conditions generally correspond with increased summer rainfall over Florida, and conversely for cool-phase AMO conditions (Enfield *et al.* 2001). AMO also has been shown to affect hurricane activity. Warm-phase AMO conditions are associated with increased hurricane activity and/or a higher frequency of major hurricanes (category 3 or

greater) in the tropical North Atlantic and Caribbean Sea (Trenberth and Shea 2005). AMO phase changes could have affected fire activity in the lower Florida Keys through increased potential for ignition of fuels by lightning caused by convectional thunderstorms and hurricanes during the summer.

The macroscopic charcoal record produced at contiguous 1-cm intervals from the upper meter of the Key Deer Pond sediment profile revealed abundant macroscopic charcoal in every sample analyzed. This finding is consistent with the interpretation that lower Keys pine rocklands are a fire-dependent ecosystem characterized by frequent surface fires (Snyder *et al.* 1990; Ross *et al.* 1994; USFWS 1999*a*). Additionally, the macroscopic charcoal data show a pattern of several distinct peaks recurring at regular intervals. In the upper 45 cm of the macroscopic charcoal record, one cm of sediment accumulation represents 4.7 years. In the lower 52 cm of the record, 1 cm of accumulation represents from 2.6–3.7 years. Based on these estimates, the charcoal data are consistent with the view that pine rocklands burn once every 3–7 years (USFWS 1999*a*). Fire return intervals of much longer duration would be expected to result in some sample intervals with less or no charcoal (Horn 2008). This interpretation is also consistent with the findings of Miller (2007) in Bahamian pine rocklands believed to be ecologically similar to Florida pine rocklands (Myers *et al.* 2004). Miller conducted a dendrochronological study on *Pinus caribaea* (Caribbean pine) and found that these pine forests experience fire once every 1–5 years.

Although this evidence supports the idea that the fire regime of lower Keys pine rocklands is characterized by a short fire return interval, developing a fine-scale reconstruction of local fire history depends upon calibrating charcoal peaks with known

fire events from dendrochronological records or other historical accounts (Whitlock and Millspaugh 1996; Whitlock and Larsen 2001). In principle, by comparing charcoal peaks with known fire events, it would be possible to determine if the peaks correspond with local fires, or if they represent fires from a larger source area or charcoal redeposited several years after fire (Whitlock and Larsen 2001). Lacking such comparison data, it is difficult to interpret fire return intervals for pine rocklands on Big Pine Key based on sedimentary charcoal records alone. Ongoing dendrochronological analyses of fire history on Big Pine Key by graduate student Grant Harley together with H. Grissino-Mayer and S. Horn will shed light on the historical fire regime of the area around Key Deer Pond, and in doing so, may improve interpretation of the Key Deer Pond charcoal record.

Variations in macroscopic charcoal data suggest two periods of slightly higher fire activity. Charcoal concentrations and influx increase from ca. 312–195 cal yr BP (AD 1638–1755) (84–54 cm), and again from 93–46 cal yr BP (AD 1857–1904) (32–22 cm) (Figure 5.6–5.7). These periods of increased charcoal values likely reflect increased fires around Key Deer Pond.

The first period, from about the mid-17th to mid-18th century period, overlaps with the Little Ice Age (LIA), which has been recognized as a time of cooler, drier climate in some paleoecological records from Florida and the Caribbean region (Lane *et al.* in press). Pollen records from the Everglades show development of tree island vegetation in response to drying conditions from AD 1550–1850 (Willard *et al.* 2006). Trace metal concentrations in sediments from the Caraico Basin reach their lowest levels since the Younger Dryas during the LIA, indicating extreme drought conditions in northern South

America (Peterson and Haug 2006). Peterson and Haug (2006) interpreted this as evidence of regional precipitation shifts resulting from cooler Atlantic sea surface temperatures, which are hypothesized to have led to a southward shift in the mean latitudinal position of the Intertropical Convergence Zone (Peterson and Haug 2006). Such a shift could bring drier conditions to much of the circum-Caribbean, including the Florida Keys. Increased percentages of macroscopic charcoal from 312–195 cal yr BP (AD 1638–1755) in the Key Deer Pond sediment record may reflect generally drier conditions during the LIA.

How do the microscopic and macroscopic charcoal curves compare, and what does this reveal about the microscopic charcoal signal in the sediments?

The uppermost charcoal peak in microscopic charcoal at 177 cal yr BP (AD 1773) (50 cm) is coincident with a moderate peak in macroscopic charcoal. Overall, however, the microscopic and macroscopic charcoal records do not show strong conformity. This may be attributable to the wide sampling interval (16 cm) used for microscopic charcoal analysis. The wide sampling interval undoubtedly missed high and low microscopic charcoal values in between the sampled levels, which would need to be included to compare the patterns.

The presence of macroscopic charcoal in all levels sampled argues that at least some of the microscopic charcoal in the profile derives from local fires. We know such fires were common during the ca. 400-yr period (mid-1500s through mid-1900s) spanned by the macroscopic charcoal record, and likely they also occurred in earlier periods with similar amounts of microscopic charcoal.

Are there identifiable differences in fire activity between the modern, early historic, and prehistoric periods that would help identify differences between natural and anthropogenic (human-altered) fire regimes?

Archaeological evidence for human presence in the lower Florida Keys prior to the early to middle 19th century has yet to be uncovered. Historical evidence reveals permanent Native American settlement in the upper Florida Keys by the middle to late 16th century. Historical accounts suggest that Indians could have been present in the lower Florida Keys beginning around the early 18th century, although evidence for their presence is scant at best (Goggin 1950; Worth 1995, 2004, 2006). The scant amount of evidence for Native American presence in the lower Florida Keys precludes any strong inference of human-induced fires prior to ca. AD 1820. Based on this evidence, fires prior to that period were most likely a result of natural ignition caused by lightning strikes, although, human ignition cannot be ruled out. Bergh and Wisby (1996) mapped occurrences (and causes) of fire between 1960 and 1996 within the NKDR. A number of those fires were lightning-induced. Additionally, the generally uniform pattern of higher and lower microscopic charcoal values over much of the Key Deer Pond sediment profile is perhaps evidence for lightning ignitions. Significant human pressures may have produced greater variation in the microscopic charcoal indices over longer time intervals. This variation, however, is not evident in the microscopic charcoal record.

AD 1820 corresponds to ca. 40 cm depth in the Key Deer Pond sediment core, based on linear interpolation. Previous research on oceanic islands postulated that a sudden increase in sedimentary charcoal may signal initial human arrival on an island and increased burning (Burney *et al.* 1994, Burney and Burney 2003). If the first

colonization of Big Pine Key indeed occurred around AD 1820, then evidence suggests that human colonization did not lead to a spike in burning, as microscopic and macroscopic charcoal concentrations and influx, and charcoal to pollen ratios, are generally low at this level in the Key Deer Pond sediment profile. The absence of increased charcoal concentrations and influx at ca. 40 cm may be because the Florida Keys are such a lightning-prone area.

The presence of humans on Big Pine Key seems not to have increased fires. The result of human settlement may have been the reverse: a reduction in wildfires. Charcoal concentrations and influx reach their lowest levels in the uppermost samples of the macroscopic charcoal record (18–14 cm), which correspond to AD 1923–1942. Additionally, charcoal to pollen ratios show extremely low values in the surface grab sample, corresponding to the last ca. 10–15 years (AD 1992–2007). Human habitation on Big Pine Key increased significantly after the arrival of the Florida East Coast Railroad in 1906. Several subdivisions were put in place between 1914 and 1925. The National Key Deer Refuge was not established until 1957, and management fires did not commence until the 1970s. From 1957 until the late 1970s, fire suppression was the primary fire management practice (Bergh and Wisby 1996). Slightly lower charcoal values above the 18-cm level of the macroscopic charcoal record could be partially attributable to increased development on Big Pine Key, which began to fragment the pine rockland landscape, reducing the spread of natural fire. Additionally, the advent of fire suppression due to increased human presence on the island likely reduced the number of fires in the pine rockland landscape.

Has the vegetation surrounding Key Deer Pond changed through time?

Models of pollen deposition suggest that a pollen record from a pond as small as Key Deer Pond should predominantly reflect the composition of local vegetation, within a radius of <100 m from the lake edge (Sugita 1994; Odgaard 1999). Given the potential for long-distance transport of some anemophilous (wind-pollinated) pollen types (e.g. *Pinus* or *Myrica cerifera*) (Kjellmark 1996), it is not possible to rule out some extralocal pollen input. Overall, however, I interpret the pollen record from Key Deer Pond to represent mostly the deposition of pollen from plants growing within ca. 100 m of the lake edge.

Changes in pollen percentages in the Key Deer Pond sediment profile suggest only moderate vegetation change around the site over the past 1700 years. The most prominent signal in the pollen record is the continuous history of pine dominance. Although pine pollen is known for long distance transport, the high percentages of pine suggest that pine has been common around Key Deer Pond since 1660 cal yr BP.

Beginning ca. 1126 cal yr BP (AD 824) (300 cm), I found several significant peaks in palm (Arecaceae) pollen. Percentages for this taxon increase from less than a few percent to near 15%. I interpret these peaks to indicate periods in which palm was more abundant at the site. Four palm species occur in the lower Florida Keys pine rocklands: saw palmetto (*Serenoa repens*), silver palm (*Coccothrinax argentata*), thatch palm (*Thrinax morissii*), and infrequently cabbage palm (*Sabal palmetto*) (USFWS 1999*a*; Snyder *et al.* 2005). Today, *S. repens*, *C. argentata*, and *T. morissii* are abundant around Key Deer Pond, and much of the palm pollen identified in the Key Deer Pond sediment profile may derive from these three species.

Fluctuations in pollen percentages of Euphorbiaceae, Poaceae, Asteraceae, and other herb taxa may be associated with natural disturbance. Prominent peaks in pollen of *Chamaesyce* (Euphorbiaceae) occur at 883 cal yr BP (AD 1067) (260 cm) and 1028 cal yr BP (AD (922) (291 cm). This genus is commonly found in open sites and early successional environments (Kennedy and Horn 2008). Kennedy and Horn (2008) suggested that this species may signal opening of the canopy, perhaps by fire-assisted forest clearance. Several species of *Chamaesyce* occur in the pine rockland habitats of the lower Florida Keys. Today, many of these species (e.g. *C. garberi* and *C. deltoidea* ssp. *deltoidea*) are federally listed as threatened. Percentages of other herbaceous taxa, including pollen of Poaceae and Asteraceae, moderately increase ca. 836 cal yr BP (AD 1114) (250 cm). As with *Chamaesyce*, increased abundance of Poaceae and Asteraceae may indicate a relatively open canopy (Kjellmark 1996).

Beginning ca. AD 1867 (30 cm), the abundance of pine pollen significantly decreases, and continues to decrease thereafter. This change occurs in association with increased percentages of taxa that reflect an assemblage of hardwood species, including wax-myrtle (*Myrica cerifera*), buttonwood mangrove (*Conocarpus erectus*), poisonwood (*Metopium*), and Melastomataceae-Combretaceae. Pollen of herbaceous taxa also reach their lowest levels above 30 cm depth in the profile. This vegetation change may reflect an increased hardwood canopy cover that perhaps shaded out grasses and other herbaceous taxa.

Noteworthy is the occurrence of pollen of *Casuarina* (Casuarinaceae) and *Terminalia* (Combretaceae) in the surface sample. These pollen types cannot be identified to species but are likely from *Casuarina equisetifolia* (Australian pine) and

tropical almond (*Terminalia catappa*). Both of these species are introduced exotics that have become invasive in southern Florida (Nelson 1994,1996; USFWS 1999*a*) and are present on Big Pine Key (http://www.floridainvasives.org/Keys/Distribution/index.html). Kjellmark (1995) also found *Casuarina* pollen in sediments from lakes in The Bahamas. This taxon was introduced in the circum-Caribbean in the past 100 years.

Do changes in vegetation inferred from pollen analysis match evidence of changes in fire activity or climate from charcoal?

The most prominent signal from the charcoal and pollen record is the continuous dominance of pine and fire over much of the record. This association is not surprising, given the strong relationship between pines and fire (Kennedy *et al.* 2006). Percentages of pine pollen begin to decrease at ca. 30 cm (AD 1867) in the Key Deer Pond sediment profile. Values for macroscopic charcoal concentrations and influx are lowest above the 18-cm level of the profile, and charcoal to pollen ratios show their lowest values in the surface grab sample. Lower percentages of pine above the 30-cm level may reflect habitat loss due to increased land occupation and development on Big Pine Key. Additionally, reduced pine may signal reduced fire frequency caused by increased human presence, fragmentation of the landscape, and the eventual advent of fire suppression. Under conditions of infrequent fire, south Florida Slash pines, which are well adapted to fire, lose dominance to hardwood taxa (Snyder *et al*. 1990; USFWS 1999*a*; Snyder *et al.* 2005).

Peaks in palm pollen after 1126 cal yr BP (AD 824) often occur in association with peaks in microscopic charcoal concentrations and influx, and charcoal to pollen

ratios. Prior to ca. 1200 cal yr BP (approximately AD 750), palm is nearly absent from the record. Snyder *et al.* (2005) studied post-burn recovery and mortality of pine rockland flora after a series of experimental surface fires on Big Pine Key. The researchers found *S. repens*, *T. morissii*, and *C. argentata* to be well adapted to surface fires, as all three species showed rapid recovery within 1–3 years after burning. Greater fire activity after 1200 cal yr BP near Key Deer Pond, perhaps characterized by low-intensity fires, may have favored a greater abundance of palms around the pond.

Higher percentages of herbaceous taxa, including Poaceae and Asteraceae, and peaks in pollen of *Chamaesyce* after 1126 cal yr BP could indicate shifts in fire frequency around Key Deer Pond. Microscopic charcoal values generally increase after ca. 1200 cal yr BP. Fire frequency may have been great enough to reduce understory hardwood canopy cover, thereby making conditions more favorable for extensive growth of herbaceous taxa. In their study of post-burn recovery of pine rockland vegetation after experimental burns on Big Pine Key, Snyder *et al.* (2005) found that herb taxa diversity and cover were greater in plots with lower hardwood shrub cover (Snyder *et al.* 2005).

Do stratigraphic layers exist in the sediment cores that indicate the impacts of hurricane or tropical storm events?

No stratigraphic or other evidence of hurricanes or tropical storm events was apparent in the Key Deer Pond sediment profile. Previous research at coastal lakes in the U.S. Gulf Coast region has documented the presence of overwash sand layers in sediment cores that correlate with known hurricane events (Liu and Fearn 1993, 2000). Additionally, defoliation of trees from hurricane force winds could lead to layers of

leaves in sediment cores (S. Horn, *pers. communication*, Oct 19, 2009). Hurricane Wilma, for example, deposited a 30–60 cm thick storm-deposit layer at a soil surface monitoring site in the southern Everglades that consisted of very fine material on top underlain by mangrove leaf matter (Whelan and Smith 2006).

The absence of any stratigraphic evidence of such storm events in the Key Deer Pond sediment profile may be a consequence of its location. Key Deer Pond is located approximately at the center of Big Pine Key on the north end of the Island. Based on elevation data derived from LIDAR images of Big Pine Key, the area surrounding Key Deer Pond is between 1.5 and 2.1 m (5 and 7 ft) above mean sea level (C. Bergh, *pers. communication*, Oct 21, 2009). This elevation most likely puts Key Deer Pond above the level of high storm surges. Hurricane Wilma, for example, was a category 3 hurricane when it struck southwest Florida. Wilma produced a storm surge of between 1.5 and 2 m, but it did not reach Key Deer Pond (C. Bergh, *pers. communication*, Oct 21, 2009). Alternatively, the absence of such evidence may be attributable, at least partially, to the very porous nature of Miami Oolitic Limestone, which may act to minimize storm surge, especially that far inland (K. Orvis, *pers. communication*, Nov 6, 2009).

Are changes in vegetation evident in the pollen record that indicate the impacts of sea level change?

Buttonwood mangrove (*Conocarpus erectus*) became significantly more abundant in the Key Deer Pond pollen record beginning ca. 357 cal yr BP (AD 1593) (96 cm), and remained generally high thereafter. Prior to 357 cal yr BP, *C. erectus* is nearly absent from the record. The cause for such a clear change in the Key Deer Pond pollen record is

of particular interest, as this species is generally characteristic of higher salinity environments (USFWS 1999*a*; Peros 2005; Peros *et al*. 2007; Gabriel *et al*. 2009).

In the lower Florida Keys, *C. erectus* tends to grow in the supratidal zone (sometimes considered the uppermost level of the intertidal zone), often in association with other halophytic (i.e., salt-tolerant) plant taxa (Ross *et al.* 1992). Here, ground water salinity levels range between 20–35‰, and *C. erectus* is generally the most abundant woody species (Ross *et al.* 1992; Lopez *et al.* 2004). These supratidal buttonwood areas (also referred to as supratidal scrub; Ross *et al.* 1992), transitional between mangrove forests and upland vegetation types, are inundated by high tide at certain times of the year, and remain relatively dry during others depending on the season (Ross *et al.* 1992).

Rising sea level could have led to the establishment of this species closer to the coring site, as mangrove zones migrate upward and landward when sea level rises (Blasco 1996; Peros 2005). The increased abundance of pollen of *C. erectus* in the upper section of the Key Deer Pond sediment profile may be linked to rising sea level. Kjellmark (1995) found increased *C. erectus* and decreased pine pollen above the 30-cm level in a sediment core from Stalactite Blue Hole on Andros Island, The Bahamas, and suggested that this change may be due to rising sea level.

The pine pollen decrease in the upper 30 cm of the Key Deer Pond sediment profile could also reflect the effects of local sea level rise, as at Stalactite Blue Hole (Kjellmark 1995). Continuous observations of sea level change at Key West, Florida began in 1913, but sporadic measurements date back to 1846 (Maul and Martin 1993). Maul and Martin (1993) estimate that sea level at Key West has risen about 30 cm since 1846, and that the rate of rise increased after about 1920 to ca. 0.23 cm/yr. These

observations are consistent with those from several other stations in mainland Florida (Maul and Martin 1993). Increasing ocean levels could have led to changes in the position of the water table, and the gradual salinization of the rooting environment (Ross *et al.* 1994), occasioned by increased groundwater and soil salinity. Ross *et al.* (1994) found reduced photosynthetic and growth rates in South Florida Slash Pine (*Pinus elliottii var. densa*) at salt concentrations as low as 3‰. Remnant stumps and historical accounts indicate that pine forests in the Florida Keys have been reduced in size, proceeding landward from the outward margins of the original forests (Snyder *et al*. 1990; Ross *et al*. 1994; USFWS 1999*a*). Alexander (1976) found pine remnants in areas of Key Largo now occupied by mangrove forests. He suggested that sea level rise was responsible for the displacement of pine forests by mangroves on that island. Ross *et al*. (1994) studied the historical and present distribution of pine forests on Sugarloaf Key, and found that the total area of pine forests on this island has declined from 88 ha to ca. 30 ha since 1935, and pine mortality has occurred at increasing elevation over time. The authors suggested that reductions in area of pine forests, and their gradual succession towards more salt-tolerant vegetation types, were caused by the effects of local sea level rise. A local rise in sea level could have led to a reduction in pine on Big Pine Key that reduced pine pollen percentages in the Key Deer Pond sediment profile.

CHAPTER 7

Conclusions

The paleoecological record from Key Deer Pond provides a 1700-year history of vegetation change and fire in pine rocklands on Big Pine Key, Florida. The microscopic charcoal record from the Key Deer Pond sediment profile demonstrates that fire has long played a role in the pine rockland ecosystem. Fluctuations in microscopic charcoal are consistent with evidence for regional dry phases. The high-resolution macroscopic charcoal record from the uppermost meter of the sediment profile provides compelling evidence for repeated fires in the area surrounding Key Deer Pond. That macroscopic charcoal was abundant in every interval of the record is consistent with the idea that pine rocklands are characterized by very frequent fire. The lack of archeological evidence for human presence on Big Pine Key prior to the early to mid-19th century suggests that early fires in the area were most likely a result of lightning strikes. Fire activity may have been influenced by changes in drought frequency or summer storm activity associated with ENSO or AMO phase changes.

The pollen record reveals that the vegetation around Key Deer Pond has changed only moderately since 1660 cal yr BP. Pine dominance over much of the record indicates that pine has long been abundant around Key Deer Pond. Increases in pollen of *Conocarpus erectus* since ca. 357 cal yr BP, and decreases in the abundance of pine since ca. 83 cal yr BP, may signal the impacts of rising sea level.

Evidence for prehistoric human impacts to vegetation composition or fire occurrence in the area around Key Deer Pond is not apparent in the sediment profile. This is, however, consistent with archaeological and historical evidence that suggests a lack of indigenous settlement in the lower Florida Keys. The very late colonization of Big Pine Key makes paleoecological records from this site especially valuable as indicators of prehistoric climate shifts.

Some historic human impacts are apparent in the Key Deer Pond record. Lower overall charcoal values above ca. 18 cm in the sediment profile suggest changes in the natural fire regime in pine rocklands near Key Deer Pond resulting from human presence, specifically a reduction in fire occurrence since the early part of the 20th century owing to fire suppression.

Key Deer Pond provides valuable paleoecological information with which to understand the long-term role of fire in pine rocklands. Ongoing dendrochronological analyses of fire history on Big Pine Key by graduate student Grant Harley together with H. Grissino-Mayer and S. Horn will test my interpretation from the macroscopic charcoal record of a recent reduction in fire frequency near Key Deer Pond. Sampling for macroscopic charcoal at contiguous 1-cm intervals over the full length of the Key Deer Pond profile, and in cores from other ponds on Big Pine Key, should provide additional insights on possible climate-driven shifts in fire activity. This, together with a paleoecological study on the development of mangrove ecosystems on the island, could help determine if pine reduction on Big Pine Key and nearby Keys has been a result of sea level rise, reduced fire frequency, or some combination. Sampling for pollen and charcoal from sediments from a banana hole (or other crack in the surface with an

extremely small surface area) could provide useful insights on local pollen and charcoal deposition, and a test of the potential value of sites of this nature, which are abundant near Key Deer Pond and likely elsewhere in the Florida Keys.

Under a scenario of reduced fire frequency, pine rocklands succeed to hardwood hammocks. However, the timing and nature of these successional dynamics have generated much discussion (USFWS 1999*a*). Factors such as the amount of hardwood hammock present in the vicinity of pine rockland habitat and time since last fire may all contribute to the pace of plant succession. Sampling for pollen and macroscopic charcoal in sediments from ponds or other wetlands in areas that are currently covered by hardwood hammock vegetation, but that may have been covered by pine rockland at some time in the past, may reveal information on successional relationships. This information would contribute to ecological knowledge of pine rockland and hammock communities, and could be useful to NKDR and USFWS officials in developing a fire management plan for pine rockland habitat in south Florida.

REFERENCES

Albritton, J.W. 2006. Fire history from lower montane and montane rainforests in Chirripó National Park, Costa Rica. Senior Honors Thesis, Department of Geography, University of Tennessee, Knoxville.

Alexander, T.R. 1967. A tropical hammock on the Miami (Florida) limestone –A twenty-five-year study. *Ecology* 48(5): 863–867.

Alexander, T.R. 1967. Evidence of recent sea level rise derived from ecological studies in Key Largo, Florida. In: Gleason, P.J. (Ed.), *Environments of South Florida, Past and Present.* Miami Geological Society, Miami, Florida, pp. 219–222.

Anchukaitis, K.J. and Horn, S.P. 2005. A 2000-year reconstruction of forest disturbance from southern Pacific Costa Rica. *Palaeogeography, Palaeoclimatology, Palaeoecology* 221: 35–54.

Arford, M.R. 2007. Middle to late Holocene environmental change and human impacts in seasonally dry neotropical forest of northwestern Costa Rica: Sedimentary evidence from six lakes. Ph.D. Dissertation, University of Tennessee, Knoxville.

Barrett, M.A. 2004. An analysis of Key Deer herbivory on forest communities in the lower Florida Keys. Ph.D. Dissertation, Department of Biology, University of South Florida, Tampa.

Barrett, M.A. and Stiling, P. 2006. Effects of Key Deer herbivory on forest communities in the lower Florida Keys. *Biological Conservation* 129: 100−108.

Barrett, M.A., Stiling, P., and Lopez, R.R. 2006. Long-term changes in plant communities influenced by Key Deer herbivory. *Natural Areas Journal.* 26: 235−243.

Beckage, B., Platt, W.J., Slocum, M.G., and Panko, B. 2003. Influence of the El Niño Southern Oscillation on fire regimes in the Florida Everglades. *Ecology* 84(12): 3124–3130.

Bergh, C. and Wisby, J. 1996. Fire history of lower Keys pine rocklands. The Nature Conservancy, Florida Keys Initiative, Key West, FL, 23 pp.

Berglund, B.E. (Ed.). 1986. *Handbook of Palaeoecology and Palaeohydrology*. John Wiley and Sons, New York.

Berman, M.J. and Gnivecki, P.L. 1994. The colonization of the Bahamian archipelago: A reappraisal. *World Archaeology* 26: 421–441.

Bernhardt, C.E., Willard, D.A., Marot, M., and Holmes, C.W. 2004. Anthropogenic and natural variation in ridge and slough pollen assemblages. USGS Open File Report OFR 2004–1448: 47 pp.

Birks, H.J.B. 1996. Contributions of Quaternary palaeoecology to nature conservation. *Journal of Vegetation Science* 7: 89–98.

Blasco, F., Saenger, P., and Janodet, E. 1996. Mangroves as indicators of coastal change. *Catena* 27: 167–178.

Burney, D.A. and Burney, L.P. 2003. Charcoal stratigraphies for Kaua‘i and the timing of human arrival. *Pacific Science* 57(2): 211–226.

Burney, D.A. and Burney, L.P. 2007. Paleoecology and "inter-situ" restoration on Kaua‘i, Hawai‘i. *Frontiers in Ecology and the Environment* 5(9): 483–490.

Burney, D.A., Burney, L.P., and MacPhee, R.D.E. 1994. Holocene charcoal stratigraphy from Laguna Tortuguero, Puerto Rico, and the timing of human arrival on the island. *Journal of Archaeological Science* 21: 273–281.

Cane, M.A. 2005. The evolution of El Niño, past and future. *Earth and Planetary Science Letters* 230: 227–240.

Carlson, P.C., Tanner, G.W., Wood, J.M., and Humphrey, S.R. 1993. Fire in Key Deer habitat improves browse, prevents succession, and preserves endemic herbs. *Journal of Wildlife Management* 57(4): 914–928.

Carr, R.S. and Beriault, J.G. 1984. Prehistoric man in south Florida. In: Gleason, P.G. (Ed.), *Environments of South Florida Present and Past II.* Miami Geological Society, Coral Gables, Florida, pp. 1–14.

Chambers, F.M., Mauquoy, D., and Todd, P.A. 1999. Recent rise to dominance of *Molinia caerulea* in environmentally sensitive areas: New perspectives from paleoecological data. *Journal of Applied Ecology* 36: 719–733.

Chmura, G.L., Stone, P.A., and Ross, M.S. 2006. Non-pollen microfossils in Everglades sediments. *Review of Palaeobotany and Paleoecology* 141: 103–119.

Clark, R.L. 1982. Point count estimation of charcoal in pollen preparations and thin sections of sediments. *Pollen et Spores* 24: 523–535.

Clark, J.S. 1988. Particle motion and theory of charcoal analysis: Source area, transport, deposition, and sampling. *Quaternary Research* 55: 67–80.

Clark, J.S., Lynch, J., Stocks, B.J., and Glodammer, J.G. 1998. Relationships between charcoal particles in air and sediments in west-central Siberia. *The Holocene* 8: 19–29.

Clark, J. 2002. Ramrod Key history. http://www.bigpinekey.com/History/remrod_key.htm. Viewed 10 March 2009.

Clement, R.L. and Horn, S.P. 2001. Pre-Columbian land use history in Costa Rica: a 3000-year record of forest clearance, agriculture and fires from Laguna Zoncho. *The Holocene* 11(4): 419–426.

Colinvaux, P.A., De Oliveira, P.E., and Moreno, J.E. 1999. *Amazon Pollen Manual and Atlas.* Hardwood Academic Publishers, Amsterdam. 332 Pp.

Cronin, T.M. and Walker, H.A. 2006. Restoring coastal ecosystems and abrupt climate change: an editorial essay. *Climate Change* 74: 369–376.

Curtis, J.H., Brenner, M., Hodell, D.A. 1999. Climate change in the Lake Valencia basin, Venezuela, ~12,600 yr BP to present. *The Holocene* 9: 609–619.

Dean Jr., W.E. 1974. Determinations of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss-on-ignition: Comparison with other methods. *Journal of Sedimentary Petrology* 44: 242–248.

Delcourt, P. and Delcourt, H. 1980. Pollen preservation and Quaternary environmental history in the southeastern United States. *Palynology* 4: 215–231.

Doren, R.F., Platt, W.J., and Whiteaker, L.D. 1993. Diversity and size structure of slash pine stands in the Everglades region of south Florida. *Forest Ecology and Management* 59: 295–311.

Enfield, D.B., Mestas-Nuñez, A.M., and Trimble, P.J. 2001. The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S. *Geophysical Research Letters* 28(10): 2077–2080.

Fairbanks, R.G. 1989. A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. *Nature* 342: 637–642.

Gabriel, J.J., einhardt, E.G., Peros, M.C., Davidson, D.E., van Hengstum, P.J., Beddows, P.A. 2009. Paleoenvironmental evolution of Cenote Aktun Ha (Carwash) on the Yucatan Peninsula, Mexico and its response to Holocene sea-level rise. *Journal of Paleolimnology* 42: 199–213.

Gardner, J.J. and Whitlock, C. 2001. Charcoal accumulation following a recent fire in the Cascade Range, northwestern USA, and its relevance for fire history studies. *The Holocene* 11(5): 541–549.

Gavin, D.G. 2001. Estimation of inbuilt age in radiocarbon ages of soil charcoal for fire history studies. *Radiocarbon* 43(1): 27–44.

Gavin, D.G. 2003. Forest soil disturbance intervals inferred from soil charcoal radiocarbon dates. *Canadian Journal of Forest Research* 33: 2514–2518.

Gavin, D.G., Hallett, D.J., Hu, F.S., Lertzman, K.P., Prichard, S.J., Brown, K.J., Lynch, J.A., Bartlein, P., and Peterson, D.L. 2007. Forest fire and climate change in western North America: Insights from sediment charcoal records. *Frontiers in Ecology and the Environment* 5(9): 499–506.

Goggin, J.M. 1950. The Indians and the history of the Matecumbe Region. *Tequesta* 10: 13–24.

Goldenberg, S.B., Landsea, C.W., Mestas-Nuñez, A.M., and Gray, W.M. 2001. The recent increase in Atlantic hurricane activity: Causes and implications. *Science* 293: 474–479.

Graham, J.E. 2008. Holocene fire history of Laguna Martínez, Costa Rica, based on high-resolution macroscopic charcoal analysis of an 8400 cal yr BP sediment record. M.S. Thesis, Department of Geography, University of Tennessee, Knoxville.

Grimm, E.C., Jacobson, G.L. Jr., Watts, W.A., Hansen, B.C.S., and Maasch, K.A. 1993. A 50,000-year record of climate oscillations from Florida and its temporal correlation with Heinrich Events. *Science* 261(5118): 198–200.

Hart, J.L., Horn, S.P., and Grissino-Mayer, H.D. 2008. Fire history from soil charcoal in a mixed hardwood forest on the Cumberland Plateau, Tennessee, USA. *Journal of the Torrey Botanical Society* 135(3): 401–410.

Harveson, P.M., Lopez, R.R., Collier, B.A., and Silvy, N.J. 2007. Impacts of urbanization of Florida Key Deer behavior and population dynamics. *Biological Conservation* 134: 321–331.

Higuera-Gundy, A., Brenner, M., Hodell, D.A., Curtis, J.H., Leyden, B.W., and Binford, M.W. 1999. A 10,300 14C yr record of climate and vegetation change from Haiti. *Quaternary Research* 52: 159–170.

Hodell, D.A., Brenner, M., and Curtis, J.H. 2005*a*. Terminal Classic Drought in the northern Maya lowlands inferred from multiple sediment cores in Lake Chichancanab (Mexico). *Quaternary Science Reviews* 24: 1413–1427.

Hodell, D.A., Curtis, J.H., and Brenner, M. 1995. Possible role of climate in the collapse of the classic Maya Civilization. *Nature* 375: 391–394.

Hodell, D.A., Brenner, M., Curtis, J.H., Medina-Gonzáles, R., Ildefonso-Chan Can, E., Albornaz-Pat, A., and Guilderson, T.P. 2005*b*. Climate change on the Yucatan Peninsula during the Little Ice Age. *Quaternary Research* 63: 109–121.

Hodell, D.A., Curtis, J.H., Jones, G.A., Higuera-Gundy, A., Brenner, M., Binford, M.W., and Dorsey, K.T. 1991. Reconstruction of Caribbean climate change over the past 10,500 Years. *Nature* 352: 790–793.

Horn, S.P. 1989. Postfire vegetation dynamics in the Costa Rican páramos. *Madroño* 36: 93–114.

Horn, S.P. 1993. Postglacial vegetation and fire history in the Chirripó páramo of Costa Rica. *Quaternary Research* 40: 107–116.

Horn, S.P. 1997. Postfire resprouting of *Hypericum irazuense* in the Costa Rican páramos: Cerro Asunción revisted. *Biotropica* 29(4): 529–531.

Horn, S.P. 1998. Fire management and natural landscapes in the Chirripó páramo, Chirripó National Park, Costa Rica. In: Zimmerer, K. and Young, K. (Eds.), *Nature's Geography. Biogeographical Landscapes and Conservation in Developing Countries.* University of Wisconsin Press, Madison, Wisconsin, pp. 125–146.

Horn, S.P. 2008. Sediment records of fire and vegetation history from solution holes in the National Key Deer Refuge, Monroe County, Florida. Unpublished report submitted to the U.S. Fish and Wildlife Service. 24 pp.

Horn, S.P. and Sanford, R.L. 1992. Holocene fires in Costa Rica. *Biotropica* 24(3): 354–361.

Horn, S.P., Orvis, K.H., Kennedy, L.M. and Clark, G.M. 2000. Prehistoric fires in the highlands of the Dominican Republic: evidence from charcoal in soils and sediments. *Caribbean Journal of Science* 36(1-2): 10–18.

Juggins, S. 2003. C2 Version 1.5: software for ecological and palaeoecological data analysis and visualization [program]. Newcastle upon Tyne: University of Newcastle.

Keim, B.D., Muller, R.A., Stone, G.W. 2004. Spatial and temporal variability of coastal storms in the North Atlantic Basin. *Marine Geology* 210: 7–15.

Kennedy, L.M. and Horn, S.P. 2008. A late Holocene pollen and charcoal record from La Selva Biological Station, Costa Rica. *Biotropica* 40(1): 11–19.

Kennedy, L.M., Horn, S.P., and Orvis, K.H. 2006. A 4,000-yr record of fire and forest history from Valle de Bao, Cordillera Central, Dominican Republic. *Palaeogeography, Palaeoclimatology, and Palaeoecology* 231: 279–290.

Kjellmark, E. 1995. The effects of late Holocene climate change and human disturbance on the vegetation and fire history of Andros Island, Bahamas. Ph.D. Dissertation, Department of Botany, Duke University.

Kjellmark, E. 1996. Late Holocene climate change and human disturbance on Andros Island, The Bahamas. *Journal of Paleolimnology* 15: 133–145.

Lane, C.S., Horn, S.P., Mora, C.I., and Orvis, K.H. In Press. Late-Holocene paleoenvironmental change at mid-elevation on the Caribbean slope of the Cordillera Central, Dominican Republic. *Quaternary Science Reviews*.

League, B.L. and Horn, S.P. 2000. A 10,000 year record of páramo fires in Costa Rica. *Journal of Tropical Ecology* 16: 747–752.

Lindbladh, M., Niklasson, M., and Nilsson, S.G. 2003. Long-time record of fire and open canopy in a high biodiversity forest in southeast Sweden. *Biological Conservation* 114: 231–243.

Lidz, B.H. and Shinn, E.A. 1991. Paleoshorelines, reefs, and a rising sea: south Florida, U.S.A. *Journal of Coastal Research* 7(1): 203–229.

Liu, K.-B. and Fearn, M.L. 1993. Lake-sediment record of late Holocene hurricane activities from coastal Alabama. *Geology* 21: 793–796.

Liu, K.-B. and Fearn, M.L. 2000. Reconstruction of prehistoric landfall frequencies of catastrophic hurricanes in northwestern Florida from lake sediment records. *Quaternary Research* 54: 238–245.

Liu, H. and Menges, E.S. 2005. Winter fires promote greater vital rates in the Florida Keys than summer fires. *Ecology* 86(6): 1483–1495.

Lopez, R.R. 2001. Population ecology of Florida Key Deer. Ph.D. Dissertation, Department of Wildlife and Fisheries Sciences, Texas A&M University, College Station.

Lopez, R.R., Silvy, N.J., Wilkins, R.N., Frank, P.A., Peterson, M.J., and Peterson, M.N. 2004. Habitat-use patterns of Florida Key Deer: Implications of urban development. *Journal of Wildlife Management* 68(4): 900–908.

MacDonald, G.M., Larsen, C.P.S., Szeicz, J.M., and Moser, K.A. 1991. The reconstruction of boreal forest fire history from lake sediments: A comparison of charcoal, pollen, sedimentological, and geochemical indices. *Quaternary Science Reviews* 10: 53–71.

Maul, G.A. and Martin D.M. 1993. Sea level rise at Key West, Florida, 1846–1992: Americas's longest instrument record? *Geophysical Research Letters* 20(18): 1955–1958.

Millspaugh, S.H. and Whitlock, C. 1995. A 750-year fire history based on lake sediment records in central Yellowstone National Park, USA. *The Holocene* 5(3): 283–292.

Miller, A.C. 2007. Fire history of Caribbean pine (*Pinus caribaea* var. *bahamensis* (Griseb.) W.H. Barrett & Golfari) forests on Abaco Island, The Bahamas. M.S. Research Paper, Department of Geography, University of Tennessee, Knoxville.

Myers, R., Wade, D., and Bergh, C. 2004. *Fire management assessment of the Caribbean pine (Pinus caribea) forest ecosystems on Andros and Abaco Islands, Bahamas.* GFI publications no. 2001-1. The Nature Conservancy, Arlington, VA.

Nelson, G. 1994. *The Trees of Florida*. Pineapple Press, Inc., Sarasota, Florida.

Nelson, G. 1996. *The Shrubs and Woody Vines of Florida*. Pineapple Press, Inc., Sarasota, Florida.

Obeysekera, J., Browder, J., Hornung, L., and Harwell, M.A. 1999. The natural south Florida system I: climate, geology, and hydrology. *Urban Ecosystems* 3: 223–244.

Odgaard, B.V. 1999. Fossil pollen as a record of past biodiversity. *Journal of Biogeography* 26(1): 7–17.

Ohlson, M. and Tryterud, E. 2000. Interpretation of the charcoal record in forest soils: forest fires and their production and deposition of macroscopic charcoal. *The Holocene* 10(4): 519–525.

Patterson, W.A., Edwards, K.J., and Maguire, D.J. 1987. Microscopic charcoal as a fossil indicator of fire. *Quaternary Science Reviews* 6: 3–23.

Peros, M.C. 2005. Middle to late Holocene environmental change and archaeology of the north coast of Central Cuba. Ph.D. Dissertation, Department of Geography, University of Toronto, Toronto.

Peros, M.C., Reinhardt, E.G., and Davis, A.M. 2007. A 6000-year record of ecological and hydrological changes from Laguna de la Leche, north coastal Cuba. *Quaternary Research* 67: 69–82.

Peters, M.E. and Higuera, P.E. 2007. Quantifying the source area of macroscopic charcoal with a particle dispersal model. *Quaternary Research* 67: 304–310.

Peterson, L.C. and Haug, G.H. 2006. Variability in the mean latitude of the Atlantic Intertropical Convergence Zone as recorded by riverine input of sediments to the Cariaco Basin (Venezuela). *Palaeogeography, Palaeoclimatology, Palaeoecology* 234: 97–113.

Pitkänen, A., Lehtonen, H., and Huttunen, P. 1999. Comparison of sedimentary microscopic charcoal particle records in a small lake with dendrochronological data: evidence for the local origin of produced by forest fires of low intensity in eastern Finland. *The Holocene* 9(5): 559–567.

Platt, W.J., Doren, R.F., and Armentano, T.V. 2000. Effects of Hurricane Andrew on stands of slash pine (*Pinus elliottii* var. *densa*) in the Everglades region of south Florida. *Plant Ecology* 146: 43–60.

Reimer, P.J., Baillie, M.G., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, G., Manning, S., Ramsey, C.B., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plincht, J., and Weyhenmeyer, C.E. 2004. IntCal04 terrrestrial radiocarbon age calibration, 0–26 cal kyr BP. *Radiocarbon* 46: 1029–1058.

Ross, M. S., O'Brien J.J., and Flynn, L.J. 1992. Ecological site classification of Florida Keys terrestrial habitats. *Biotropica* 24(4): 488–502.

Ross, M. S., O'Brien J.J., and Sternberg, L. 1994. Sea-level rise and the reduction in pine forests in the Florida Keys. *Ecological Applications* 4(1): 144–156.

Roubik, D.W. and Moreno, P.J.E. 1991. *Pollen and Spores of Barro Colorado Island*. Missouri Botanical Garden, St. Louis, Missouri.

Sanford Jr., R.L. and Horn, S.P. 2000. Holocene rain-forest wilderness: A neotropical perspective on humans as an exotic, invasive species. In McCool, S.F., David, N., Borrie, W.T., and O'Laughlin, J., (Eds.), *Wilderness Science in a Time of Change Volume 3: Wilderness as a Place for Scientific Inquiry*. U.S. Department of Agriculture Forest Service, Rocky Mountain Research Station, Ogden, Utah, pp. 168–173.

Schlachter, K.J. 2005. Macroscopic sedimentary charcoal as a proxy for past fire in northwestern Costa Rica. M.S. Thesis, Department of Geography, University of Tennessee, Knoxville.

Schlachter, K.J. and Horn, S.P. In Press. Sample preparation methods and replicability in macroscopic charcoal analysis. *Journal of Paleolimnology*. DOI 10.1007/s10933-009-9305-z.

Simpson, L. 1982. *History of Big Pine Key, Florida, 1873–1982*. Mayfield Printing Company, Mayfield, KY.

Smith III, T.S., Anderson, G.H., and Tiling, G. 2005. A tale of two storms: surges and sediment deposition from Hurricanes Andrew and Wilma in Florida's southwest coast mangrove forests. In: Science and the Storms: the USGS response to the Hurricanes of 2005. pp. 169–174.

Snyder, J.R., A. Herndon, and W.B. Robertson Jr. 1990. South Florida rocklands. In: Myers, R.L. and Ewel, J.J. (Eds), *Ecosystems of Florida*. University of Central Florida Press, Orlando, Florida, pp. 230–277.

Snyder, R.J., Ross, M.S., Koptur, S., and Sah, J.P. 2005. Developing ecological criteria for prescribed fire in south Florida pine rockland ecosystems. USGS Open File Report OF 2006-1062: Southeast Environmental Research Center. 109 pp.

Snyder, T.P., Chiantello, J.L., Kjellmark, E., and Baumgardner, K.B. 2007. Key to the pollen of The Bahamas, Version 1. http://www.pollen.mtu.edu/.

Stockmarr, J. 1971. Tablets with spores used in absolute pollen analysis. *Pollen et Spores* 13: 615–621.

Stork, A.J. 2006. A paleoecological history of West Pond on Great Abaco Island, The Bahamas, based on pollen and charcoal analyses of lake sediments. M.S. Thesis, Department of Geography, University of Tennessee, Knoxville.

Stuiver, M., and Reimer, P.J. 1993. Extended C-14 database and revised Calib 3.0 C-14 age calibration program. *Radiocarbon* 35: 215–230.

Sugita, S. 1994. Pollen representation of vegetation in Quaternary sediments: theory and method in patchy vegetation. *Journal of Ecology* 82: 881–897.

Swetnam, T.W. and Betancourt, J.L. 1990. Fire-southern oscillation relations in the southwestern United States. *Science* 249: 1017–1020.

Swetnam, T.W., Allen, C.D., Betancourt, J.L. 1999. Applied historical ecology: using the past to manage for the future. *Ecological Applications* 9(4): 1189–1206.

Titiz, B. and Sanford Jr., R.L. 2007. Soil charcoal in old-growth rain forests from sea level to the continental divide. *Biotropica* 39(6): 673–682.

Torrescano, N. and Islebe, G.A. 2006. Tropical forest and mangrove history from southeastern Mexico: A 5000 yr pollen record and implications for sea level rise. *Vegetation History and Archaeobotany* 15: 191–195.

Toscano, M.A. and Macintyre, I.G. 2003. Corrected western Atlantic sea-level curve for the last 11,000 years based on calibrated ^{14}C dates from *Acropora palmata* framework and intertidal mangrove peat. *Coral Reefs* 22: 257–270.

Trenberth, K.E. 2005. Uncertainty in hurricanes and global warming. *Science* 308: 1753–1754.

Trenberth, K.E. and Shea, D.J. 2006. Atlantic hurricanes and natural variability in 2005. *Geophysical Research Letters* 33. doi: 10.1029/2006GL026894.

Tudhop, A.W., Chilcott, C.P., McCulloch, M.T., Cook, E.R., Chappell, J., Ellam, R.M., Lea, D.W., Lough, J.M., and Shimmield, G.B. 2001. Variability in the El Niño-Southern Oscillation through a glacial-interglacial cycle. *Science* 291: 1511–1517.

USFWS (United States Fish and Wildlife Service). 1999*a*. South Florida multi-species recovery plan for south Florida. Southeast Region U.S. Fish Wildlife Service, Atlanta, Georgia.

USFWS (United States Fish and Wildlife Service). 1999*b*. Key Deer recovery plan. A revision. U.S. Fish and Wildlife Service, Atlanta, Georgia.

USFWS (United States Fish and Wildlife Service). 2002. "Florida Keys national wildlife refuges: National Key Deer, Key West, Great White Heron, Crocodile Lake." http://www.fws.gov/southeast/pubs/nkdgen.pdf. Viewed 30 November 2007.

Watts, W.A. and Hansen, B.C.S. 1994. Pre-Holocene and Holocene pollen records of vegetation history from the Florida peninsula and their climatic implications. *Palaeogeography, Palaeoclimatology, Palaeoecology* 109: 163–176.

Watts, W.A. and Stuiver, M. 1980. Late Wisconsin climate of northern Florida and the origin of species-rich deciduous forest. *Science* 210(4467): 325–327.

Watts, W.A., Hansen, B.C.S., and Grimm, E.C. 1992. Camel Lake: a 40,000-yr record of vegetational and forest history from northwest Florida. *Ecology* 73(3): 1056–1066.

West, D. 2007. Late Holocene charcoal stratigraphy and modern charcoal deposition in the pine rocklands of Great Abaco Island, The Bahamas. M.S. Thesis, Department of Geography, University of Tennessee, Knoxville.

Whelan, K.R.T. and Smith T.J. III. 2006. NPS natural resource year in review—2006: Hurricane Wilma benefits mangrove forests at Everglades National Park. http://www.nature.nps.gov/YearinReview/YIR2006/02 1.html. Viewed 24 October 2009.

Whitlock, C. 2004. Forests, fires and climate. *Nature* 432: 28–29.

Whitlock, C. and Anderson, R.S. 2003. Fire history reconstructions based on sediment records from lakes and wetlands. In: Veblen, T.T., Baker, W.L., Montenegro, G., and Swetnam, T.W. (Eds.), *Fire and Climatic Change in Temperate Ecosystems of the Western Americas.* Springer, New York, New York, pp. 3–31.

Whitlock, C. and Larsen, C. 2001. Charcoal as a fire proxy. In: Smol, J.P.. Birks, H.J., and Last, W.M. (Eds.), *Tracking Environmental Change Using Lake Sediments. Vol. 3: Terrestrial, Algal, and Siliceous Indicators.* Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 75–97.

Whitlock, C. and Millspaugh, S.H. 1996. Testing the assumptions of fire-history studies: An examination of modern charcoal accumulation in Yellowstone National Park, USA. *The Holocene* 6(1): 7–15.

Wilkinson, J. 2002*a*. *Big Pine Key History.* http://www.bigpinekey.com/History/history_page1.htm. Viewed 3 March 2009.

Wilkinson, J. 2002*b*. *Historic Florida Indians*. http://www.keyshistory.org/histindians.html. Viewed 12 November 2009.

Willard, D.A. 2004. Tree islands of the Florida Everglades—long-term stability and response to hydrologic change. USGS Fact Sheet 2004-3095.

Willard, D.A. and Cronin, T.M. 2007. Paleoecology and ecosystem restoration: case studies from chesapeake bay and the Florida Everglades. *Frontiers in Ecology and the Environment* 5(9): 491–498.

Willard, D.A. and Holmes, C.W. 1997. Pollen and geochronological data from south Florida: Wilkinson Creek Site 2. U.S. Geological Survey Open-File Report 97-35, pp. 1–28.

Willard, D.A., and Weimer, L.M. 1997. Palynological census from surface samples in south Florida. U.S. Geological Survey Open-File Report 97-867, pp. 1–22.

Willard, D.A., Weimer, L.M., and Riegel, W.L. 2001. Pollen assemblages as paleoenvironmental proxies in the Florida Everglades. *Review of Palaeobotany and Palynology* 113: 213–235.

Willard, D.A., Bernhardt, C.E., Holmes, C.W., Landacre, B., and Marot, M. 2006. Response of everglades tree islands to environmental change. *Ecological Monographs* 76(4): 565–583.

Willard, D.A., Bernhardt, C.E., Weimer, L.M., Cooper, S.R., Gamez, D., and Jensen, J. 2004. Atlas of pollen and spores of the Florida Everglades. *Palynology* 28: 175–277.

Willis, K.J. and Birks, H.J.B. 2006. What is natural? The need for a long-term perspective in biodiversity conservation. *Science* 314: 2161–1265.

Worth, J.E. 1995. Fontaneda revisted: Five descriptions of sixteenth-century Florida. *The Florida Historical Quarterly* 73(3): 339–352.

Worth, J.E. 2004. A history of southeastern Indians in Cuba, 1513–1823. Paper presented at the 61st Annual Meeting of the Southeastern Archaeology Conference, St. Louis, Missouri.

Worth, J.E. 2006. The social geography of south Florida during the Spanish Colonial Era. Paper presented at the 71st Annual Meeting of the Society for American Archaeology, San Juan, Puerto Rico.

APPENDICES

APPENDIX A: Pollen Processing Procedure

The following procedure was used to process sediment samples from Key Deer Pond for pollen and microscopic charcoal analysis. Samples were processed in 15 ml Nalgene® polypropylene centrifuge tubes. The centrifuge used was an IEC model CL benchtop centrifuge with a 6 x 15 ml swinging bucket rotor. All centrifugations were carried out at the highest speed.

1. Add 1 *Lycopodium* tablet to each centrifuge tube.

2. Add a few ml 10% HCl, and let reaction proceed; slowly fill tubes until there is about 10 ml in each tube. Stir well, and place in hot water bath for 3 minutes. Remove from bath, centrifuge for 2 minutes, and decant.

3. Add hot distilled water, stir, centrifuge for 2 minutes, and decant. Repeat for a total of 2 washes.

4. Add about 10 ml 5% KOH, stir, remove stick, and place in boiling bath for 10 minutes, stirring after 5 minutes. Remove from bath and stir again. Centrifuge 2 minutes and decant.

5. Wash 4 times with hot distilled water. Centrifuge for 2 minutes each time.

6. Fill tubes about halfway with distilled water, stir, and pour through 125 µm mesh screen, collecting liquid in a labeled beaker underneath. Use a squirt bottle of distilled water to wash the screen, and to wash out any material remaining in the centrifuge tube.

7. Centrifuge down material in beaker by repeatedly pouring beaker contents into correct tube, centrifuging for 2 minutes, and decanting.

8. Add 8 ml of 49–52% HF and stir. Place tubes in boiling bath for 20 minutes, stirring after 10 minutes. Centrifuge 2 minutes and decant.

9. Add 10 ml 10% HCl. Stir well, and place in hot water bath for 3 minutes. Remove from bath, centrifuge for 2 minutes, and decant.

10. Add 10 ml hot Alconox® solution, made by dissolving 4.9 cm^3 dry commercial Alconox® powder in 1000 ml distilled water. Stir well and let sit for 5 minutes. Then centrifuge and decant.

11. Add more than 10 ml hot distilled water to each tube, so top of water comes close to top of tube. Stir, centrifuge for 2 minutes, and decant.

    Assuming that no samples need treatment with HF, continue washing with hot distilled water as above for a total of 3 water washes.

12. Add 10 ml of glacial acetic acid, stir, centrifuge for 2 minutes, and decant.

13. Make acetolysis mixture by mixing together 9 parts acetic anhydride and 1 part concentrated sulfuric acid. Add about 8 ml to each tube and stir. Remove stirring sticks and place in boiling bath for 5 minutes. Stir after 2.5 minutes. Centrifuge for 2 minutes and decant.

14. Add 10 ml glacial acetic acid, stir, centrifuge for 2 minutes and decant.

15. Wash with hot distilled water, centrifuge and decant.

16. Add 10 ml 5% KOH, stir, remove sticks, and heat in vigorously boiling bath for 5 minutes. Stir after 2.5 minutes. After 5 minutes, centrifuge for 2 minutes, and decant.

17. Add 10 ml hot distilled water, centrifuge for 2 minutes, and decant for a total of 3 washes.

18. After decanting last water wash, use the vortex genie for 20 seconds to mix sediment in tube.

19. Add 1 drop of safranin stain to each tube. Use vortex genie for 10 seconds. Add distilled water to make 10 ml. Stir, centrifuge for 2 minutes, and decant.

20. Add a few ml TBA, use the vortex genie for 20 seconds. Fill to 10 ml with TBA, stir, centrifuge for 2 minutes, and decant.

21. Add 10 ml TBA, stir, centrifuge for 2 minutes, and decant.

22. Vibrate samples using the vortex genie to mix the small amount of TBA left in the tubes with the microfossils. Centrifuge down vials.

23. Add several drops of 2000 cs silicone oil to each vial. Stir with a clean toothpick.

24. Place uncorked samples in the dust free cabinet to let the TBA evaporate. Stir again after one hour, adding more silicone oil if necessary.

25. Check samples the following day; if there is no alcohol smell, cap the samples. If the alcohol smell persists, give them more time to evaporate.

APPENDIX B: Charcoal Point Counting Calculations

Calculations below are based on Clark (1982), with modifications in some cases by S. Horn. This appendix is based on an unpublished laboratory handout by S. Horn prepared February 8, 2005 and modified May 3, 2006.

Areal density of charcoal on the slide (P) (e.g., the estimated probability that a random point will fall on charcoal):

$$P = C/N$$

The accuracy, or relative error, of the estimate of P (S_p/P):

$$(S_p/P) = \sqrt{(1-P)/C}$$

Area of charcoal (total) in mm^2 in all fields of view you counted (Af):

$$Af = P \times Fat$$

Estimated area of charcoal in mm^2 in the entire pollen sample (Aps):

$$Aps = \frac{M \times Af}{Mc}$$

Charcoal area in mm^2 expressed on the basis of volume of wet sediment (Acc):

$$Acc = Aps/V$$

Charcoal area in mm^2 expressed on the basis of wet sediment mass (Awm):

$$Awm = Aps/W$$

Charcoal area in mm^2 expressed on the basis of annual influx (Acy):

$$Acy = Acc * \text{sedimentation rate expressed in cm/yr}$$

Charcoal:Pollen ratio (C:P) expressed as mm^2 charcoal per pollen grain:

$$C{:}P = \frac{Mpo \times Af}{Mc \times Popc}$$

Charcoal:Pollen ratio (C:P) expressed as μm^2 charcoal per pollen grain:

$$C:P = \frac{Mpo \times Af \times 10^6}{Mc \times Popc}$$

Po = points applied in each field of view

F = the number of fields of view you looked at

N = total number of points applied (equal to Po x F)

Fa = area in mm^2 of each field of view

Fat = total area in mm^2 on slide in which you looked at charcoal (equal to Fa x F)

C = the number of applied points that "touched" charcoal

V = volume in cm^3 of original wet sediment sample processed for pollen

W = mass in g of original wet sediment processed for pollen (from LOI sheet)

Pw = percent water in the wet LOI sample from the same level as pollen sample

M = number of *Lycopodium* marker spores added to original sample processed for pollen

Mc = number of *Lycopodium* marker spores you counted in the fields of view in which you did the point counting

Mpo = number of *Lycopodium* marker spores you counted in the pollen count from the same level

Popc = the total number of pollen grains (excluding spores and indeterminate) counted in the pollen count from the same level

APPENDIX C: Identified Pollen Taxa

Tree – Shrub Taxa

Pinaceae
- *Pinus elliottii* var. *densa*

Myricaceae
- *Myrica cerifera*

Rubiaceae
- *Cephalanthus*
- *Guettarda*
- *Psychotria*
- *Randia*

Combretaceae-Melastomataceae

Combretaceae
- *Conocarpus erectus*
- *Terminalia*

Annonaceae
- *Annona*

Rhizophoraceae
- *Rhizophora mangle*

Malphigiaceae
- *Byrsonima*

Solanaceae

Myrtaceae
- *Eugenia-Psidium*

Moraceae
- *Ficus*

Fabaceae
- *Acacia*
- *Cassia*
- *Piscidia*

Anacardiaceae
- *Metopium toxiferum*

Ulmaceae
- *Celtis*
- *Trema*

Bataceae
- *Batis*

Casuarinaceae
- *Casuarina*

Bignoniaceae

Myrsinaceae
- *Myrsine*

Apiaceae

Herbaceous Taxa

Euphorbiaceae
- *Chamaeasyce*

Polygalaceae
- *Polygala*

Poaceae

Asteraceae

Cyperaceae

Fabaceae

Rubiaceae
- *Borreria (*also referred to as *Spermacoce)*

Amaranthaceae

Apocynaceae

Boraginaceae

Solanaceae
- *Capsicum*

Urticaceae

Araceae

Aquatics

Alismataceae
- *Sagittaria*

VITA

Joshua Wright Albritton was born in St. Petersburg, Florida. He attended Gatlinburg-Pittman High School in Gatlinburg, Tennessee, before entering the University of Tennessee, Knoxville. As an undergraduate student, he received a grant from the W.K. McClure Scholarship Fund for the Study of World Affairs to support a research project in Chirripó National Park, Costa Rica, on soil charcoal evidence of long-term fire history.

Following the completion of his B.A. in Geography in Fall 2006, Joshua entered the graduate program in Geography at the University of Tennessee, where he served as a teaching assistant, and later teaching associate with full lecturing responsibilities for a course in introductory physical geography. Joshua was also employed as an environmental technician for the Environmental Protection Agency Mountain Acid Deposition Program at Clingmans Dome, Great Smoky Mountains National Park, Tennessee. Joshua received his M.S. in Geography from the University of Tennessee, Knoxville in December 2009, and plans to pursue a career in natural resource management or education.