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The Holocene 2011 21: 967 originally published online 20 April 2011

DOI: 10.1177/0959683611400204

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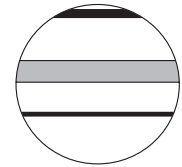
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The Holocene
21(6) 967–978
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DOI: 10.1177/0959683611400204
hol.sagepub.com


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Abstract

This study uses palynologic data to determine the effects of regional climate variability and human activity on the formation and development of tree islands during the last ~4000 years. Although prolonged periods of aridity have been invoked as one mechanism for their formation, Native American land use has also been hypothesized as a driver of tree island development. Using pollen assemblages from head and near tail sediments collected on two tree islands and documented archeological data, the relative roles of Native Americans, climate variability, and recent water-management practices in forming and structuring Everglades tree islands are examined. The timing of changes recorded in the pollen record indicates that tree islands developed from sawgrass marshes ~3800 cal. yr BP, prior to human occupation. Major tree island expansion, recorded near tail sediments, occurred ~1000 years after initial tree island formation. Comparison of the timing of pollen assemblages with other proxy records indicates that tree island expansion is related to regional and global aridity correlated with southward migration of the Intertropical Convergence Zone. Local fire associated with droughts may also have influenced tree island expansion. This work suggests that Native American occupation did not significantly influence tree island formation and that the most important factors governing tree island expansion are extreme hydrologic events due to droughts and intense twentieth century water management.

Keywords

climate variability, drought, Everglades, late Holocene, Native Americans, pollen, tree island

Introduction

Climate processes associated with deglaciation, insolation, and natural climate variability played a primary role in determining the spatial distribution of vegetation on local, regional, and global scales. These vegetation patterns have been altered to varying degrees by human activities such as land clearance, burning, agriculture and selective planting (Abrams and Nowacki, 2008; Day, 1953; Delcourt and Delcourt, 2004; Denevan, 1992; Heckenberger et al., 2007; McLauchlan, 2003; Meadows and Baxter, 2001; Vale, 1982; Williams, 2000). However, in the Americas for example, the spatial scale of these human-modified landscapes by pre-Columbian people is thought to be exaggerated and limited to localized areas (Bush et al., 2007). Regardless, since their arrival in the New World, European settlers have continually modified the landscape of eastern North America vegetation resulting in the highly altered vegetational landscape of the twenty-first century (Brush and Davis, 1984).

Native Americans in South Florida lived primarily along the coast of southern Florida, utilizing tree islands of the Everglades as temporary fishing and hunting camps during the winter (Griffin, 1988). One proposed mechanism of tree island formation involves Native American modification of the landscape (Carr, 2002). Deposition of thick (10–30 cm) faunal middens and the collapse of wooden platforms have been hypothesized as loci for sediment accumulation, raising the elevation of the tree island surface above the adjacent marsh and initiating the establishment of woody taxa (Carr, 2002).

However, another hypothesis suggests that tree islands formed over topographic highs in the underlying limestone bedrock and developed through positive biogeochemical feedback (Ross et al.,

2006). This hypothesis is consistent with previous paleoecological studies indicating that tree islands formed during periods of regional aridity (Willard et al., 2006), possibly tied to southward displacement of the mean position of the Intertropical Convergence Zone (ITCZ). The ITCZ is a low latitude belt of convective storms circling the Earth, whose northerly or southerly position is driven by changes in insolation. The relative strengths of the North Atlantic Oscillation (NAO) and the El Niño Southern Oscillation (ENSO) have also been invoked as important mechanisms controlling precipitation in the circum-Caribbean and the Everglades (Cronin et al., 2002; Haug et al., 2001, 2003). Proxy records show that prolonged changes in precipitation during the late Holocene drove changes in the wetland plant assemblages throughout the Everglades (Bernhardt and Willard, 2009; Donders et al., 2005; Willard et al., 2006). These extreme hydrologic events are thought to be more important than average annual conditions in shaping tree island vegetation (Wetzel et al., 2008).

Here, paleoecological analysis is used to quantify the relative roles of humans and climate as drivers of the formation

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Received 11 June 2010; revised manuscript accepted 29 October 2010

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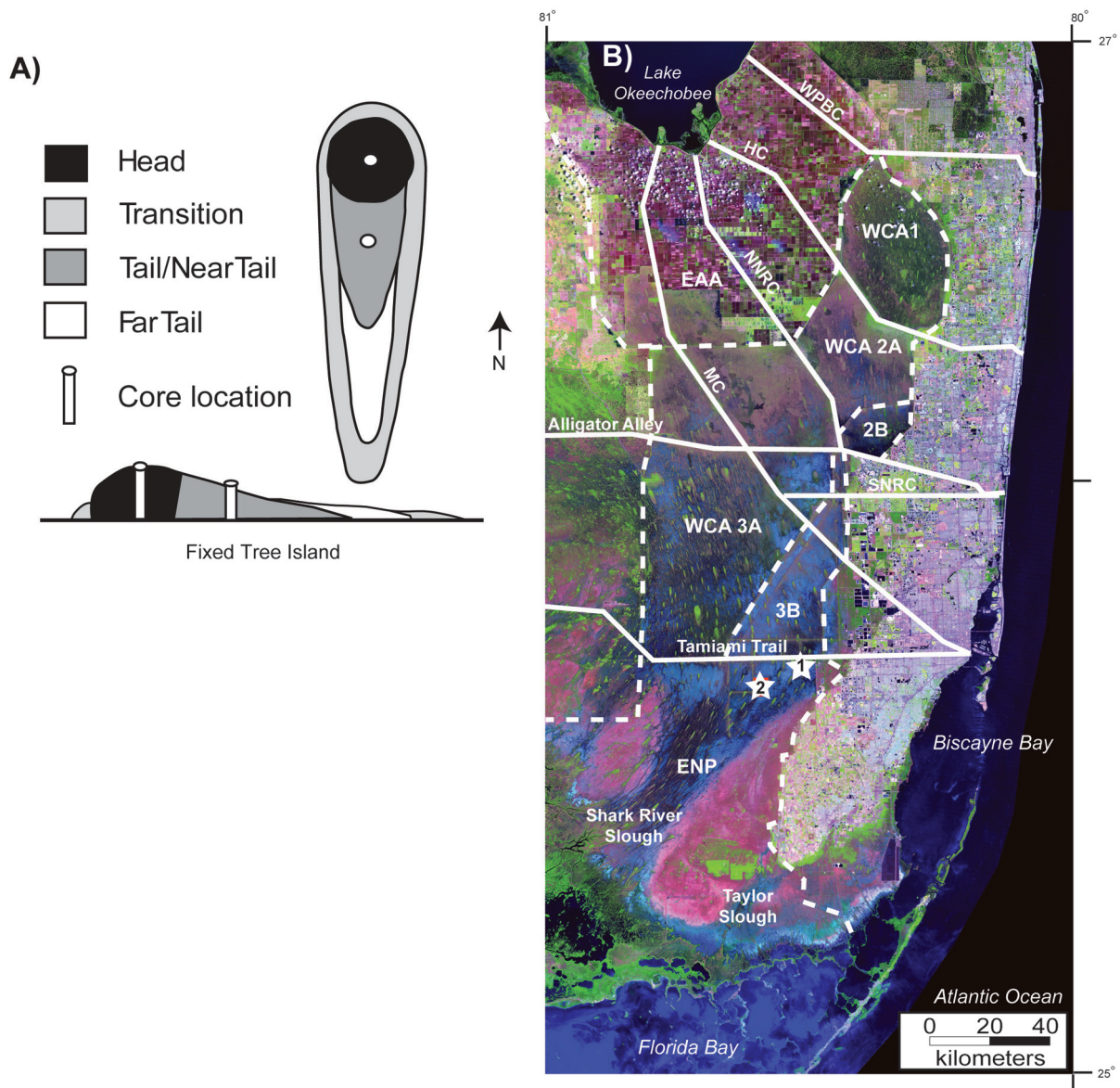


Figure 1. Location map. (A) Idealized illustration of the structure and vegetation types of a typical fixed, or teardrop-shaped, tree island. The figure is modified after Willard et al. (2006). (B) Satellite image of Florida Everglades with core locations (Image modified from South Florida Water Management District, 2009). Solid white lines note major canals and roads. WPBC, West Palm Beach Canal; HC, Hillsborough Canal; NNRC, New North River Canal; SNRC, South North River Canal; and MC, Miami Canal. Dotted lines mark the boundaries of Water conservation areas and Everglades National Park. WCA, Water Conservation Area; ENP, Everglades National Park; EAA, Everglades Agricultural Area. White stars with numbers indicate cores examined in this study. 1, Heartleaf Hammock; and 2, Duck Club Hammock

and succession of tree islands. The following questions are addressed: (1) what was the pre-tree island vegetation on the elevated heads and near tails; (2) did Native American activity initiate tree island formation or modify the structure of previously established tree islands; and (3) how did regional climate affect tree islands and Native American cultures? Detailed records from tree island heads and near tails are used to clarify the timing of tree island formation and integrate the resulting data with archeological analyses from the same tree islands. Previous research (e.g. Willard et al., 2006) focused almost exclusively on sedimentary sequences collected in the near tails of tree islands. Although near tail sediments have well-dated pollen sequences detailing tree island development, it is unknown how they compare to sediment cores collected on tree island heads. This study compares pollen records from tree island heads and near tails to further refine the patterns and timing of tree island formation.

Regional overview

The Everglades presently covers an area of $\sim 6000 \text{ km}^2$ and is a phosphorus-limited, precipitation-driven, subtropical wetland system (Figure 1; Davis et al., 1994). The natural hydrologic system covered an area of $\sim 12\,000 \text{ km}^2$ (Davis et al., 1994) and reflected the seasonal precipitation pattern. The distribution of Everglades wetland plant communities is controlled by water depth, hydroperiod, substrate type, and fire regime (Kushlan, 1990). Tree islands comprise approximately 14% of the Everglades (Sklar and van der Valk, 2002). Fixed tree islands are teardrop-shaped features, oriented parallel to flow, formed over topographic highs in the underlying Pliocene and Pleistocene limestone bedrock (Gleason and Stone, 1994; Heisler et al., 2002; Loveless, 1959). The elevated dry head serves as a refuge for flora and fauna that cannot tolerate prolonged flooding and consists primarily of subtropical hardwoods, shrubs, and ferns

Table 1. Chronology of human occupation on tree islands

BC/AD	cal. yr BP	Culture
1870–Present	130–Present	Modern Seminole/Historic American
AD 1760–1870	240–130	Seminole
AD 1513–1760	487–240	Glades IIIc
AD 1400–1513	600–487	Glades IIIb
AD 1200–1400	800–600	Glades IIIa
AD 1100–1200	900–800	Glades IIc
AD 900–1100	1100–900	Glades IIb
AD 750–900	1250–1100	Glades IIa
AD 500–750	1500–1250	Glades I (late)
500 BC – AD 500	2500–1500	Glades I (early)
3000–500 BC	5000–2500	Late Archaic

(Heisler et al., 2002). General examples of woody vegetation found on elevated, teardrop-shaped, tree islands include *Bursera simaruba*, *Rivina humilis*, *Eugenia axillaris*, *Annona glabra*, *Chrysobalanus icaco*, *Persea borbonia*, *Ilex* sp., *Salix carolina*, *Myrsine floridana*, and *Morella cerifera* (Heisler et al., 2002). The near tail lies downstream of the head (Figure 1) and experiences longer hydroperiods and water depths. Accordingly, the vegetation is composed of plants with a greater tolerance for flooding, including water-tolerant hardwoods (*Morella* and *Cephalanthus*), ferns (*Osmunda regalis*), sedges (e.g. *Cladium*), and other marsh taxa (e.g. *Sagittaria* and *Pontederia*) (Heisler et al., 2002).

During the late nineteenth and early twentieth century European-American settlers constructed fishing and hunting cabins and some permanent domiciles on tree islands of the Everglades, as well as drainage efforts rendering parts of the Everglades usable for agricultural and urban development (Light and Dineen, 1994). The first major drainage phase began in the AD 1910s with excavation of four canals (North New River, Hillsboro, Miami, and West Palm Beach Canals) that linked Lake Okeechobee to the Atlantic Ocean and drained an area of 6071 km² (Figure 1; Sklar and van der Valk, 2002). Shortly thereafter, the Tamiami Trail was completed, and the Hoover Dike encircled Lake Okeechobee, greatly reducing freshwater flow across the wetlands. The second drainage phase began in AD 1948 when Congress signed the 'Central and Southern Florida Project for Flood Control and other Purposes' (C&SF Project) into law. The C&SF Project used an extensive system of levees, canals, and pump stations to ensure water supply during droughts and to store large quantities of water to protect urban areas during unusually wet years. This construction effectively fragmented the Everglades wetland into distinct compartments with different hydrologic conditions (i.e. hydroperiod and stage) in each Water Conservation Area (WCA) (Figure 1).

Climate and hydrology

The Everglades is characterized by seasonal precipitation, with most rain (70%) falling during the wet season from May through November (average 86 cm; range 58–135 cm), resulting in high Everglades water levels in the summer and fall (Duever et al., 1994). An average of 43 cm of rain (17–78 cm) falls during the remainder of the year (McPherson and Halley, 1996). This seasonal precipitation pattern is driven by migration of the Bermuda High (BH). In the wet season (summer–fall), the system is

located near Bermuda, and in the dry season, the BH is located near the Azores (Stahle and Cleaveland, 1992). The El Niño–Southern Oscillation influences interannual climate variability, with heavy winter rainfall during large El Niño warm events and low winter precipitation, severe lightning strikes, and increased fire during La Niña events (Beckage et al., 2003; Kiladis and Diaz, 1989).

In the natural Everglades system, water flowed southward during the wet season along a gentle slope of 3 cm/km (Kushlan, 1990) from Lake Okeechobee toward Florida Bay and the Gulf of Mexico through Shark River Slough and, to a lesser extent, Taylor Slough. Water depth and hydroperiod were controlled by a combination of the regional trends in precipitation and substrate elevation. The latter is influenced by bedrock topography, sediment accumulation rates (which also are influenced by vegetation type), and sediment loss from exposure or fire.

Settlement history of two Everglades tree islands

Two teardrop-shaped tree islands with archeological evidence of Native American activity were chosen for this study (Table 1). Heartleaf Hammock (also known as Billboard Hammock; site 1, Figure 1) is approximately 0.8 km long by 0.3 km wide. Archeological test pits along with radiocarbon dating of artifacts indicate human activity since the late Archaic (5000–2500 calibrated years before present or cal. yr BP). The earliest dated artifact is a marine shell dated at 4520–4250 cal. yr BP (Schwadron, 2009). Because this shell could have been transported from the coast at any time since that date, it does not provide definitive evidence for the onset of human occupation. However, archeological evidence does indicate that tree island settlement still could be much older than originally thought (~2500 cal. yr BP; after Widmer, 1988) for the interior of the Everglades (Schwadron, 2006). Near continuous occupation persisted until ~500 cal. yr BP, with a hiatus, or lack of artifacts, during Glades IIIc (900–800 cal. yr BP).

Duck Club Hammock (also known as Sour Orange Hammock; site 2, Figure 1) is approximately 2.4 km long by 0.5 km wide. Human activity dates from the late Archaic to historical time (5000–50 cal. yr BP). Evidence of human activity is based on archeological material such as middens (Archaic), a kaolin pipe and a glass button (Seminole and historic), and more recently a hunting cabin and picnic tables (nineteenth to twentieth centuries) (Schwadron, 2009).

Table 2. Radiocarbon dates^a

Beta number	Core	Depth (cm)	Measured radiocarbon age (BP)	Plus/minus	Conventional radiocarbon age	Plus/minus	¹³ C/ ¹² C	2Sigma Plus	2Sigma Minus	Intercept ^b	1Sigma Plus	1Sigma Minus
234867	26-9-02-1	20–22	107.7 pMC	.04	na	na	–23.7	na	na	na	na	na
234866	26-9-02-1	32–34	700	40	760	40	–21.1	660	740	680	670	700
235865	26-9-02-1	60–62	1540	40	1650	40	–18.4	1500	1620	1540	1520	1570
234864	05-7-28-1	20–21	610	40	640	40	–22.9	550	670	580	560	600
234863	05-7-28-1	35–36	1400	40	1400	40	–22.7	1290	1400	1330	1300	1360
234862	05-7-28-1	62–63	1210	40	1230	40	–24	1060	1270	1170	1080	1190
234861	05-7-28-1	95–96	3720	40	3740	40	–23.6	3980	4190	4090	4080	4150
219676	05-7-28-1	115–116	4130	100	4160	100	–23.4	4420	4870	4700	4530	4840
219677	05-7-28-2	10–11	116.5 pMC	.04	na	na	na	na	na	na	na	na
240433	05-7-28-2	16–17	1550	40	1540	40	–25.9	1340	1530	1410	1380	1430
219673	05-7-28-2	20–21	2120	60	2090	60	–26.6	1900	2170	2050	1990	2140
219674	05-7-28-2	40–42	2610	90	2580	90	–27	2360	2850	2740	2710	2770
242162	05-7-28-2	45–46	3170	70	3180	70	–24.3	3260	3560	3390	3350	3460
240434	05-7-28-2	49–50	2680	40	2680	40	–25.2	2740	2860	2770	2750	2790
242163	05-7-28-2	55–56	3440	60	3420	60	–26.1	3550	3840	3690	3600	3720
219675	05-7-28-2	61–62	3450	60	3430	60	–26	3550	3840	3680	3620	3720
246798	05-7-27-9	20–21	80	40	60	40	–26	0	260	0	0	240
246799	05-7-27-9	55–56	3180	40	3230	40	–22.2	3370	3560	3450	3400	3470
246800	05-7-27-9	69–70	3050	40	3070	40	–23.7	3210	3370	3280	3250	3350
246801	05-7-27-10	20–22	690	40	670	40	–26.1	620	680	660	570	670
246802	05-7-27-10	40–42	2920	40	2910	40	–25.8	2940	3210	3060	2980	3090
246803	05-7-27-10	60–62	3590	40	3580	40	–25.6	3820	3980	3880	3840	3920

^aAll dates were obtained on bulk peat samples and analyzed by Beta Analytic (Miami FL, USA).

Upper and lower limits based on two sigma errors in calibration. ^bCalibrated against the Intcal98 database after Stuiver and van der Plicht (1998), Stuiver et al. (1998), and Talma and Vogel (1993).

Methods

Core collection and sampling

A 4 cm diameter vibracore was used to penetrate dry, mineral sediments on the elevated head and reach the underlying bedrock. Cores in near tail sediments were collected using a piston corer with a 10 cm diameter barrel. For all cores, sediment lithology was described, and sediment was sampled for pollen and microscopic charcoal in 1 cm increments for the top 20 cm and in 2 cm increments from 20 cm to the base of the core. All samples were dried in an oven at 50°C.

Geochronology

Chronology of these cores is based on radiocarbon dates (¹⁴C) and pollen biostratigraphy. Radiocarbon dates were obtained on bulk sediments by Beta Analytic and calibrated to calendar years using the Pretoria Calibration Procedure (Stuiver et al., 1998; Talma and Vogel, 1993). Dates in Table 2 are presented as calibrated years before AD 1950 (presented herein as cal. yr BP). Age models for the last century of deposition were based on the first occurrence of pollen of *Casuarina equisetifolia*, an exotic species introduced to South Florida about AD 1900 (Langeland, 1990). Pollen of *C. equisetifolia* first occurs in South Florida sediments at AD 1910 ± 15 years and is common only in sediments deposited after 1940 (Wingard et al., 2003). Age models were constructed using the computer program Bchron (Figure 2: methodology described in Parnell et al., 2008).

Pollen analysis

Palynomorphs (pollen and fern spores) were isolated using standard palynological preparation techniques (Traverse, 2007; Willard et al.,

2001). For each sample, one tablet of *Lycopodium* spores was added to between 0.5 and 1.5 g dry sediment to calculate palynomorph concentration (grains/g). Samples were processed with HCl and HF to remove carbonates and silicates, respectively, acetylated (1 part sulfuric acid:9 parts acetic anhydride) in a boiling water bath for 10 min, neutralized, and treated with 10% KOH for 10 min in a water bath at 70°C. After neutralization, residues were sieved with 149 µm and 10 µm nylon mesh to remove the coarse and clay fractions, respectively. When necessary, samples were swirled in a watch glass to remove mineral matter. After staining with Bismarck Brown, palynomorph residues were mounted on microscope slides in glycerin jelly. In general, at least 300 pollen grains and spores were counted from each sample to determine percent abundance and concentration of palynomorphs. Identification was aided by slides from the United States Geological Survey (Reston, Virginia) reference collection and Willard et al. (2004). Pollen data are archived on the SOFIA (South Florida Information Access <http://sofia.usgs.gov>) and North American Pollen Database at the World Data Center for Paleoclimatology in Boulder, CO (<http://www.ngdc.noaa.gov/paleo/pollen.html>).

Charcoal analysis

The metric of charcoal area per pollen grain (C/P) was used to quantify changes in local fire regime. The C/P ratio has been successfully used in other wetlands to reconstruct fire history (see Pederson et al., 2005). Microscopic charcoal particles greater than 50 by 10 µm (500 µm²) were counted on slides made for pollen analysis. This size fraction is considered to represent local fire events within 20 km (Clark, 1988; Pederson et al., 2005). Several samples were barren of pollen and the C/P method could not be

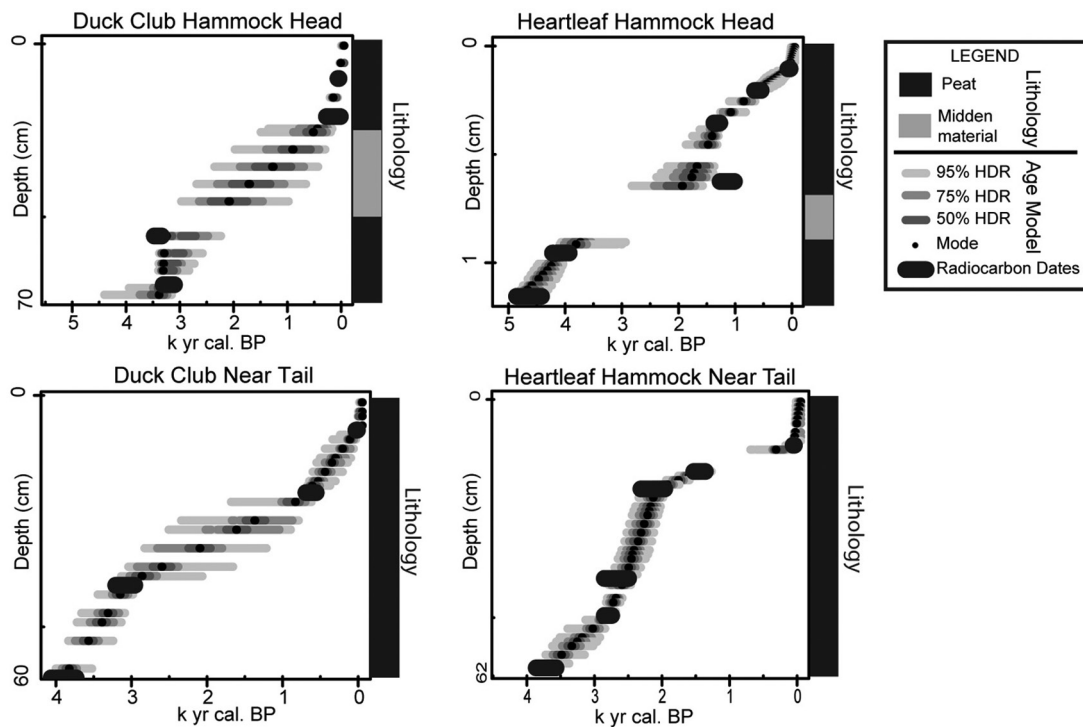


Figure 2. Age models show age plotted in calibrated years before present (AD 1950) versus depth (cm). Age models were calculated using the computer program Bchron (Parnell et al., 2008) from radiocarbon dates (Table 2) and the occurrence of *Casuarina equisetifolia*. Pollen of *C. equisetifolia* first occurs in south Florida sediments at AD 1910 \pm 15 years and is common only in sediments deposited after AD 1940 (Wingard et al., 2003)

used, therefore the absolute concentration of charcoal fragments (greater than 500 μm^2) was calculated and compared with the C/P ratio (Figure 3). Charcoal concentration and C/P show similar patterns and therefore only the C/P data are presented with pollen data (Figures 4 and 5).

Statistical analysis

Reconstruction of past plant communities was based on statistical comparison of fossil and modern assemblages from different wetland communities throughout the Everglades (Willard et al., 2001). Using the modern analog technique (Overpeck et al., 1985), we calculated squared chord distance between down-core pollen assemblages and surface samples collected throughout the Everglades (Willard et al., 2001, 2006; this research) to define the dissimilarity between each fossil and modern assemblage. Squared chord distance was chosen because it is not influenced by rare pollen taxa in the data set (Overpeck et al., 1985). Down-core samples with dissimilarity coefficients equal to or less than the critical value 0.15 are considered to share similar vegetation and environmental parameters with their modern analog (Willard et al., 2001).

Pollen zones were based on a combination of ecological reasoning, visual inspection, modern analogs, and objective zonation using the program CONISS (Grimm, 1987). Zonation is used to assist description and correlation of down-core pollen assemblages within and between cores. The method used to define zones in this study is constrained cluster analysis by method of incremental sum of squares (CONISS; after Grimm, 1987). In this method of numerical zonation, clusters are constrained to only have stratigraphically adjacent samples. Resultant zones are defined and plotted next to pollen diagrams.

Pollen assemblages and source vegetation

Tree island vegetation is characterized by high abundance of fern spores (>40%). *Acrostichum* spores, as well as *Blechnum* and *Thelypteris*, typically dominate head assemblages, whereas tail assemblages are characterized by high abundances of *Osmunda* spores (Willard et al., 2006). Amaranthaceae (>20%), Cyperaceae (5–30%), *Nymphaea* (>10%) pollen and low fern spore abundances (<30%) characterize marsh/ridge-slough vegetation. *Pinus* pollen is transported in from the surrounding areas. *Morella*, Asteraceae, *Cephalanthus*, *Quercus*, and *Ilex* are taxa indicative of drier conditions (Bernhardt and Willard, 2009; Willard et al., 2001, 2006).

Results

Duck Club Hammock

A vibracore recovered from the elevated dry head is 73 cm long and has a chronology provided by three radiocarbon dates and the first occurrence of *Casuarina* pollen at 5 cm (Figure 4A and Table 2). The base of the core dates to 3370–3210 cal. yr BP. On Duck Club Hammock, previous studies identified a calcrete layer at approximately 50 cm (Schwadron, 2009), but this core did not penetrate 100 cm of sediment before hitting bedrock. The sediment consists of 30 cm of peat overlain by an organic, sand-sized faunal midden layer from 30 to 47 cm (Figure 4A). The midden material is primarily charred animal bone. No seeds or macroscopic plant material are present and this interval is barren of palynomorphs. The upper 30 cm of the core, directly above the midden layer, consists entirely of black peat. A peak in microscopic charcoal (500 μm^2 /pollen grain) is present above the midden layer at 29–25 cm. Pollen is well preserved in all samples except those in the midden layer, which were barren.

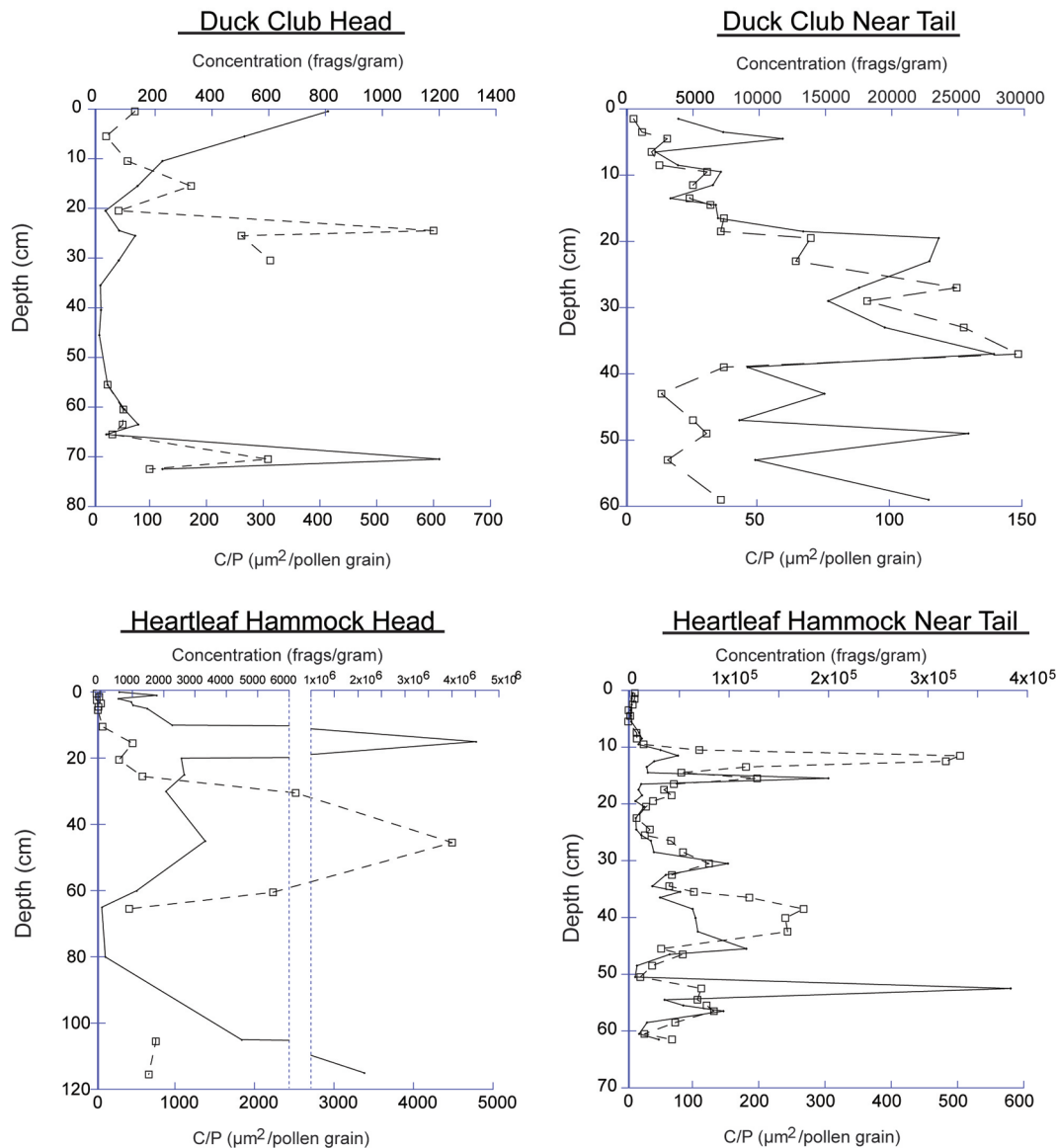


Figure 3. Microscopic charcoal from tree island sediments. The concentration of microscopic charcoal (fragments $\geq 500 \mu\text{m/g}$ sediment) is plotted against C/P ($\mu\text{m}^2/\text{pollen grain}$; methodology Pederson et al., 2005). C/P is the dashed line with open squares and concentration is solid black line

A piston core recovered from the near tail is 60 cm long and composed entirely of peat (Figure 4B). Three radiocarbon dates (Table 2) and the first occurrence of *Casuarina* pollen at 5 cm provide the chronology. The base of the core dates to 3980–3820 cal. yr BP. A microscopic charcoal peak ($145 \mu\text{m}^2/\text{pollen grain}$) is recorded at 39 cm above a radiocarbon date of 3210–2940 cal. yr BP. The amount of microscopic charcoal steadily declines upcore. Pollen is well preserved throughout the core.

Heartleaf Hammock

A vibracore recovered from the elevated, dry head is 116 cm long and composed of black peat and a sandier midden layer (Figure 5A). Chronology is based on five radiocarbon dates (Table 2) and the first occurrence of *Casuarina* at 10 cm. The midden was deposited sometime between 4230–3980 cal. yr BP and 1270–1060 cal. yr BP. The faunal midden of sand-sized

charred animal fragments occurs at 73 to 90 cm. This material is primarily composed of broken and burnt animal bone, turtle shell, and animal teeth, and it is barren of pollen. No seeds or macroscopic plant material were found in either core. The basal sample dates to 4870–4420 cal. yr BP. Microscopic charcoal is most abundant above the barren interval/midden layer ($\sim 4000 \mu\text{m}^2/\text{pollen grain}$). Pollen was well preserved except in the midden layer.

A piston core from Heartleaf Hammock near the tail is 62 cm long and comprised entirely of peat. Six radiocarbon dates and the first occurrence of *Casuarina* at 13 cm provide the chronology (Figure 5B). The base of the core dates to 3840–3550 cal. yr BP. A hiatus in deposition corresponding to a peak in microscopic charcoal is indicated at 13 cm ($480 \mu\text{m}^2/\text{pollen grain}$) dating to within the last century of deposition (presence of *Casuarina* pollen). The hiatus is at least 1000 years. Another peak in microscopic charcoal ($\sim 240 \mu\text{m}^2/\text{pollen grain}$) around 40 cm dates to 2860–2740 cal. yr BP. Pollen is well preserved throughout the core.

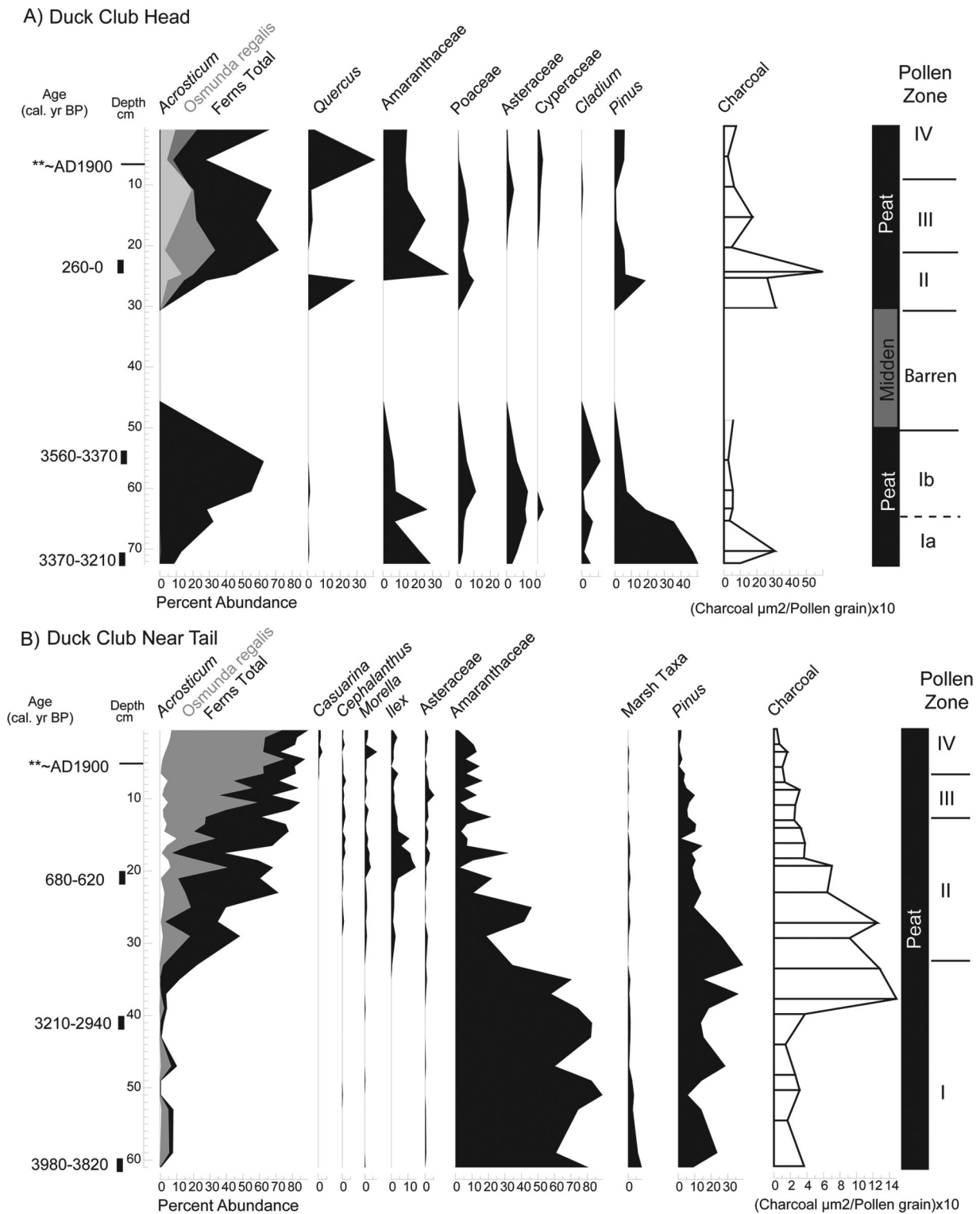


Figure 4. (A) Pollen assemblage from Duck Club Hammock head. (B) Pollen assemblage from Duck Club Hammock near tail. Pollen assemblages are shown for species with greater than 2% abundance. Radiocarbon dates are given as the intercept point and 2-sigma range as calibrated years before 1950 (cal. yr BP), see Table 2. Pollen zone I is analogous to sawgrass marsh/ridge vegetation; Pollen zones II–IV are analogous to tree island vegetation

Pollen zones

Pollen assemblages for all cores (Figures 4–5), have four distinct assemblage zones. Basal pollen zone Ia on the heads of Duck Club and Heartleaf Hammock is analogous to sawgrass marsh/ridge vegetation, characterized the common occurrence (combined percentages >10%) of *Nymphaea*, Cyperaceae (including *Cladium*), Poaceae, and *Sagittaria* pollen. Zone Ib is also

analogous to marsh vegetation but contains a rise in fern spores. Basal near tail sediments also are analogous to sawgrass marsh sites. Near tail assemblages in zone I of Duck Club and Heartleaf Hammocks are dominated by Amaranthaceae pollen (70–90%) and *Pinus*.

In cores from heads of Heartleaf and Duck Club Hammock, sediments deposited between pollen zones I and II are completely barren of pollen. The barren units are ~25 cm thick and are composed of

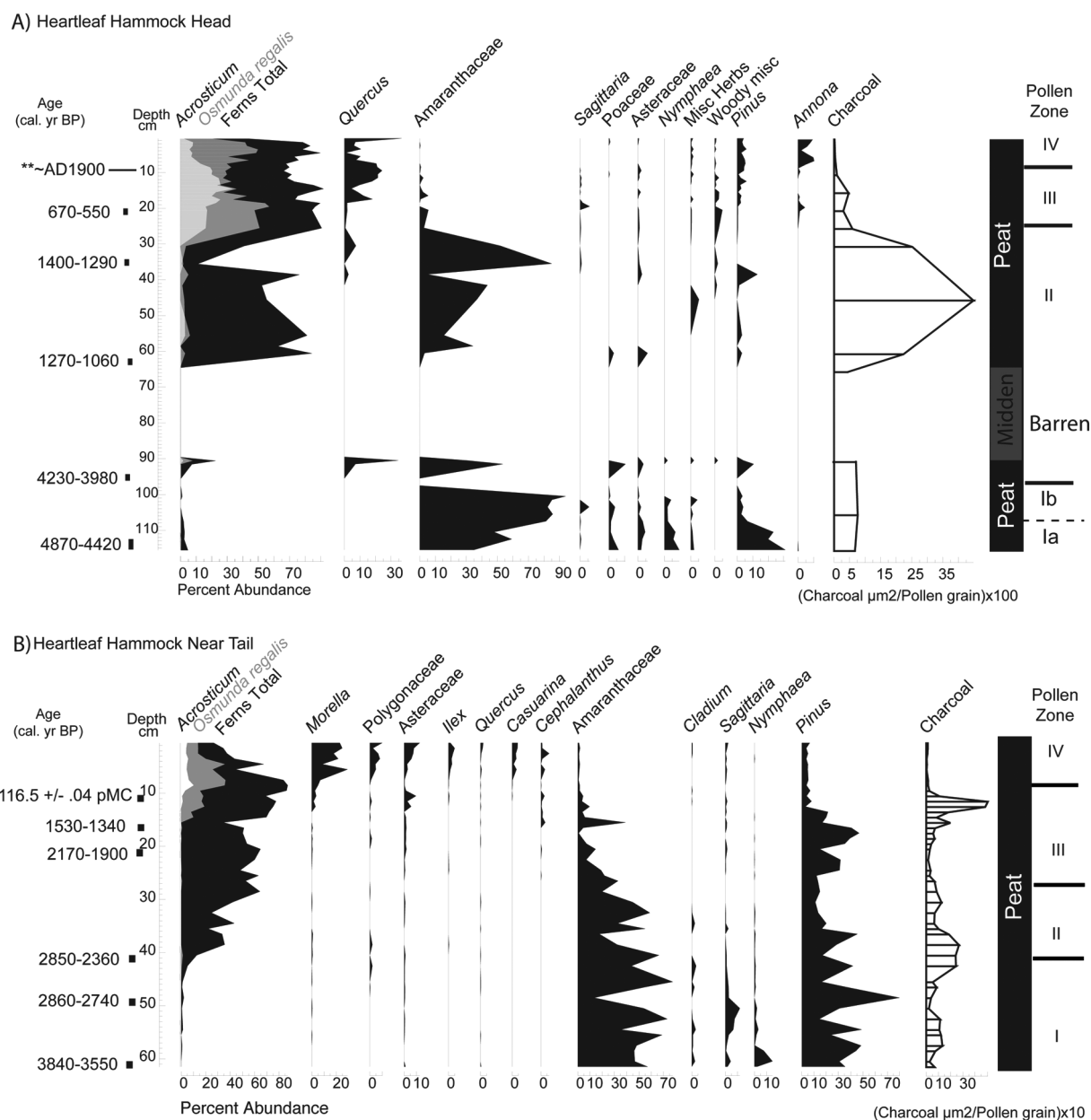


Figure 5. (A) Pollen assemblage from Heartleaf Hammock head. (B) Pollen assemblage from Heartleaf Hammock near tail. Pollen assemblages are shown for species with greater than 2% abundance. Radiocarbon dates are given as the intercept point and 2-sigma range as calibrated years before AD 1950 (cal. yr BP), see Table 2. Pollen zone I is analogous to sawgrass marsh/ridge vegetation; Pollen zones II–IV are analogous to tree island vegetation

sand-sized faunal midden material. In pollen zone II on tree island heads, fern spores dominate assemblages (~60–70%) and are analogous to tree island vegetation. Amaranthaceae pollen typically comprises ~20% of assemblages, except in Heartleaf Hammock head where there is one peak (90%) at 35 cm. Peat accumulation was continuous across the zone I to II transition in near tail cores and is dated ~2800 cal. yr BP. Amaranthaceae pollen decreases below 30% in near tail sediments, and pollen of typical marsh plants (*Sagittaria*, *Nymphaea*, and *Cyperaceae*) is nearly absent. One difference between near tail sites is the presence of *Ilex* after ~600 cal. yr BP in Duck Club. Pollen zone II in Heartleaf and Duck Club Hammocks represents initial occurrence of tree island vegetation.

Zone III on both tree island heads is characterized by increases in *Osmunda regalis* and *Acrostichum* and by fern spores in general in near tails of all tree islands. Assemblages are analogous to mature tree island tails and are dominated by *Osmunda* spores (>70%).

Zone IV includes sediments deposited during the twentieth century, based on the occurrence of modern carbon and *Casuarina* pollen. *Osmunda* increases in all sites during by the late twentieth century. Woody vegetation such as *Cephalanthus*, *Annona*, *Quercus* and *Morella* reach their highest abundances in zone IV.

Discussion

Evolution of tree island vegetation

This study documents pre-tree island vegetation from modern tree island heads, evaluates the timing of tree island formation, and confirms earlier interpretations based on near tail sediments (Willard et al., 2006). Pollen assemblages from basal sediments recovered from tree island heads and near tails pre-date or are concurrent with earliest evidence for human occupation (Schwadron, 2009). These pre-occupation records lack abundant fern spores characteristic of

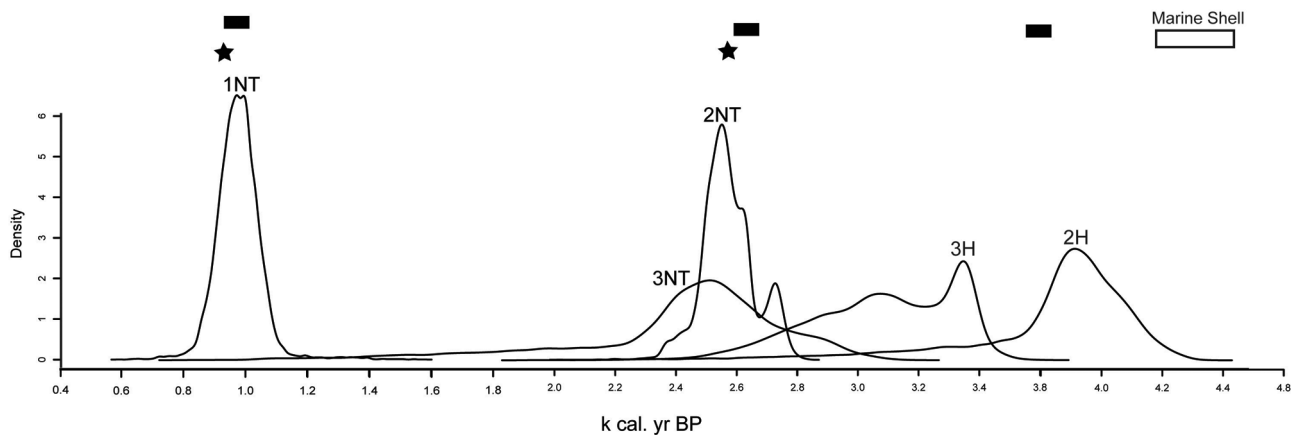


Figure 6. Probability distributions (posterior distribution) for the age of tree island initiation and expansion. Initiation and expansion of tree islands is based on the rise in fern spores. 1NT, Manatee Hammock near tail (Willard et al., 2006); 2NT, Heartleaf Hammock near tail; 3NT, Duck Club Hammock near tail; 2H, Heartleaf Hammock head; 3H, Duck Club head. Bars represent intervals of circum-Caribbean drought (Curtis and Hodell, 1993; Hodell et al., 2001; Polk et al., 2007). Stars represent time periods where shifts in Native American cultures in the Everglades are attributed to climate (Griffin, 1988). A white rectangle represents the calibrated age range of a marine shell interpreted as an archeological artifact recovered from Heartleaf Hammock (Schwadron, 2009)

tree islands and are dominated by taxa indicative of sawgrass marsh/ridge vegetation, including *Amaranthaceae*, *Cyperaceae* and *Nymphaea* pollen (Figures 4 and 5). The near absence of fern spores in near tail sediments suggest that the vegetation preceding the formation of the tree island was marsh-like and is consistent with results from previous studies (Willard et al., 2006).

Both Heartleaf and Duck Club Hammock begin to develop around 3800 cal. yr BP (Figures 4–6). Age estimates of tree island initiation and expansion are based on calculating the approximate age at which fern spores abruptly increase for all cores (Figure 6). A radiocarbon date on a marine shell on Heartleaf Hammock head, 4520–4250 cal. yr BP, indicate Native American activities on the islands after or concurrently with the initial formation of these islands (Schwadron, 2009). Faunal middens, barren of pollen, were deposited on Duck Club Hammock after initiation of tree island communities, and the dates of midden accumulation on Heartleaf Hammock are unclear. Microscopic charcoal peaks are recorded above each midden layer. Intense local burning and disturbance of the soil oxidized pollen and destroyed the record of community composition during this period of occupation. Pollen is readily destroyed by oxidation (Traverse, 2007). Middens may have further raised the surface elevation above the adjacent marshes, increasing colonization by woody tree island vegetation. However, the absence of pollen on the heads leaves us unable to address this hypothesis. In cores from the near tails, sedimentation appears to have been continuous and indicates tree island establishment in the near tails by ~2800–2600 cal. yr BP for Duck Club and Heartleaf Hammocks (Figure 5). However, the timing of this change is not uniform across the Everglades. A well-dated tree island examined by Willard et al. (2006) indicates tree island vegetation was established ~1000 cal. yr BP for Manatee Hammock. Comparison of head and near tail records from Duck Club Hammock indicate that establishment of tree island vegetation in the near tail lagged that on the head by 1000 years (Figure 5). Archeological excavations on both Duck Club and Heartleaf Hammock record continuous Native American occupation during this time period (zone III) (Schwadron 2009; Figures 3–5).

Tree island head vegetation changes are recorded ~1000 cal. yr BP on Duck Club and Heartleaf Hammock (Figures 3 and 4).

Both *Acrostichum* and *Osmunda* increase in both head and near tail sediments (Figures 3 and 4). This corresponds to a period of regional tree island maturation and changes in ridge and slough vegetation (Bernhardt and Willard, 2009; Willard et al., 2006).

Climate as a driver of vegetation change

Based on the timing of changes in pollen assemblages, this study suggests that that climate was a major factor initiating tree island growth and expansion. Wetzel et al. (2008) hypothesize that extreme hydrologic events such as drought are more important than average annual conditions in shaping tree island vegetation, whereas short-term (<10 years) flooding or perturbations do not alter vegetation composition (Zaffke, 1983). During dry season and droughts, nutrients, especially phosphorus, are redistributed from the adjacent marshes to the island through increased evapotranspiration by trees on the island (Ross et al., 2006; Wetzel et al., 2005). Increased soil phosphorus concentrations enhance peat accumulation rates, increasing tree island elevation relative to the adjacent marsh (Ross et al., 2006; Wetzel et al., 2008). Drought also allows recruitment of woody vegetation from the seed bank (Wetzel, 2002). Establishment of woody vegetation attracts more birds and other animals to the islands and further increases and concentrates phosphorus on the island (Orem et al., 2002). Overall, this positive feedback mechanism, driven by climate, enhances tree island growth and expansion. Fire is also a key factor in shaping tree island vegetation (Wetzel, 2002), and the occurrence and intensity of fires in the Everglades would increase as a result of periodic climate-driven droughts (Beckage et al., 2003). This study finds microscopic charcoal peaks correspond to periods of tree island expansion (Figures 5 and 6). It is probable that local fires induced by these prolonged periods of aridity further facilitated tree island expansion.

Initiation of tree island growth (Figure 6) is concomitant with regional periods of aridity at ~3800, ~2800, and ~1000 cal. yr BP in the circum-Caribbean (Curtis and Hodell, 1993; Hodell et al., 2001; Polk et al., 2007) and in South Florida (Alvarez Zarikian et al., 2005). Extended periods of aridity are likely influenced by the mean southward migration of the ITCZ (Haug et al., 2001).

Precipitation through the late Holocene on the Florida peninsula is also influenced by changes in intensity in the North Atlantic Oscillation (NAO) and the El Niño Southern Oscillation (ENSO) (Cronin et al., 2002; van Beynen et al., 2007, 2008). Tree island expansion occurs during periods of regional aridity centered around ~ 2800 and 1000 cal. yr BP. Microscopic charcoal increases during these periods of regional aridity and tree island expansion. Tree island vegetation matures around the ~1000 cal. yr BP aridity event, which is consistent with regional trends in other tree islands and Everglades' communities (Bernhardt and Willard, 2009; Willard et al., 2006).

Potential effects of climate variability on Native Americans and tree island vegetation

Cultural shifts in various civilizations around the globe have been linked to periods of extreme aridity (Brooks, 2006). For example, the collapse of the Mayan civilization (~1200 years ago) is attributed to extended periods of drought and changes in the mean position of the ITCZ (Haug et al., 2003; Hodell et al., 1995). Intervals of regional aridity have influenced Native American occupation patterns in Florida as far back as ~12 000 cal. yr BP (Faight and Carter, 1998). In the Everglades, the transition between Native American cultures has been indirectly related to both climate stability and change (Griffin, 1988). The cultural transition between the Archaic and Glades cultures (~2500 cal. yr BP) occurred during a period of regional and global aridity as well as changes in tree island vegetation (Figure 5).

Anomalous tree island abandonment during Glades IIc (~800–900 cal. yr BP) based on the absence of artifacts from 56 of 62 sites has been interpreted as a human response to changes in regional climate (Griffin, 1988). The lack of artifacts has also been interpreted as a change in the cultural development and introduction of new peoples into the region (Carr, 2002). This period of cultural change coincides with tree island initiation and expansion throughout the Everglades, as driven by regional climate (this study; Willard et al., 2006). Speleothem records from Central Florida document a severe drought during this time period (van Beynen et al., 2008). Tree islands were used for camps primarily during the winter. Changes in the strength of the North Atlantic Oscillation and El Niño, which influence winter precipitation in South Florida (Swart et al., 1996), could have made conditions unfavorable for tree island occupation. These data leave open the possibility for climate fluctuations playing a role in the cultural shifts recorded in the Everglades.

Native American and modern land use as a driver of tree island vegetation

Native American activities have been proposed as mechanisms of tree island initiation and growth (Carr, 2002). Deposition of thick (10–30 cm) faunal middens and the collapse of wooden platforms have been hypothesized as loci for sediment accumulation, raising the elevation of the surface above the adjacent marsh, and initiating the establishment of woody taxa (Carr, 2002). Native camps also may have altered the canopy structure on the islands, similar to reductions documented on sites of modern camps (Heisler et al., 2002). Further, Native Americans are thought to have used low intensity fires to modify the landscape (Robertson, 1953). Pollen evidence indicates that, at least at these sites, tree island vegetation pre-dates the appearance of Native American

artifacts. However, this hypothesis requires further coordinated sampling for both pollen and artifacts with precise dating of both sediments and artifacts.

The change in vegetation during the first millennium of Native American occupation (for example the period between ~3800 and 2600 cal. yr BP) appears to be minor compared with rapid changes documented in the last century of land use (Figures 3 and 4). Because humans did not permanently occupy tree islands, only during winters as temporary fishing and hunting camps (Carr, 2002), the overall development of the island does not appear to have been drastically altered.

The compartmentalization and alteration of the natural hydrology in the twentieth century had a larger impact on tree island vegetation in a shorter time period than the collective impacts of the occupation history of Native Americans. The effects of twentieth-century water management on tree islands are well documented (Heisler et al., 2002; Wetzel, 2002, 2008; Willard et al., 2001, 2006) and the construction of roads perpendicular to flow, including Alligator Alley and Tamiami Trail, compounded the alterations to the natural hydrology. The associated prolonged flooding and deeper water depths in parts of the system (particularly WCA 2A and southernmost 3A, 3B) killed subtropical hardwood trees, creating many 'ghost tree islands'. In contrast, shorter hydroperiods increase the tree island's vulnerability to fire (Sklar and van der Valk, 2002). Vegetation on Heartleaf Hammock reflects these drier conditions, as seen by the increase in *Morella*, *Quercus*, *Asteraceae*, and *Ilex*. Fire is important in shaping tree island vegetation (Wetzel, 2002), and fire suppression could be a factor in the distribution of modern vegetation. Three of the four sediment cores examined for this study indicate a reduction in fire as evidenced by the overall decrease in microscopic charcoal abundance during the twentieth century. The increase in concentration of charcoal on Duck Club during the twentieth century (Figure 3) could be due to the fact that people have turned this island into a recreation site, as seen by the cabin and manicured landscape on the head.

Conclusion

Pollen analysis of tree island sediments indicates that the tree island vegetation developed from a marsh environment on the heads. Initiation of head vegetation on these two tree islands is ~ 3800 cal. yr BP. Near tail sediments indicate a ~1000 year lag, after the formation of the initial tree island, in the development of neat tail vegetation. Native American occupation of tree islands occurred after and/or concurrent with the onset of tree island formation, during a period of regional aridity. Faunal middens as thick as ~27 cm on tree island heads appear to post-date the initiation of tree island vegetation, and their presence could have had an influence on the elevation of head sediments in relation to the adjacent marsh. Because of (poor) pollen preservation in midden sediments, it is difficult to identify vegetation assemblages during the accumulation of these sediments. Near tail sediments do not record any changes in vegetation during the same interval of occupation. Tree island expansion occurred during a period of regional aridity throughout the circum-Caribbean thought to be driven by the mean southward position of the ITCZ. During the onset of twentieth-century water management further changes in tree island vegetation are recorded. Changes in tree island vegetation, associated with climate variability ~2600 and 800 cal. yr BP, may have influenced cultural change in the Everglades. In order

to further clarify the role of Native Americans on tree island vegetation, more accurate dating of artifacts is needed to correlate changes in vegetation with human activities.

Acknowledgements

This research is supported by the USGS Greater Everglades Priority Ecosystem Studies Program and was carried out in partial fulfillment of a Ph.D. at the University of Pennsylvania, Department of Earth and Environmental Sciences. The author is extremely grateful to the Everglades National Park for site access. Margo Schwadron provided key guidance in site selection as well as field assistance. Thomas Sheehan, Bryan Landacre, and Adam Bentham assisted with field and laboratory work. Drs D. Willard and B. Horton helped guide this research. Drs L. Wingard, T. Cronin, F. Scatena, and H. Pfeifferkorn and two anonymous reviewers provided invaluable comments that greatly improved the quality of this manuscript.

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