



Sensitivity of wetland hydrology to external climate forcing in central Florida



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ABSTRACT

Available proxy records from the Florida peninsula give a varying view on hydrological changes during the late Holocene. Here we evaluate the consistency and sensitivity of local wetland records in relation to hydrological changes over the past ~5 ka based on pollen and diatom proxies from peat cores in Highlands Hammock State Park, central Florida. Around 5 cal ka BP, a dynamic floodplain environment is present. Subsequently, a wetland forest establishes, followed by a change to persistent wet conditions between ~2.5 and 2.0 ka. Long hydroperiods remain despite gradual succession and basin infilling with maximum wet conditions between ~1.3 and 1.0 ka. The wet phase and subsequent strong drying over the last millennium, as indicated by shifts in both pollen and diatom assemblages, can be linked to the early Medieval Warm Period and Little Ice Age, respectively, driven by regionally higher sea-surface temperatures and a temporary northward migration of the Intertropical Convergence Zone. Changes during the 20th century are the result of constructions intended to protect the Highlands Hammock State Park from wildfires. The multiple cores and proxies allow distinguishing local and regional hydrological changes. The peat records reflect relatively subtle climatic changes that are not evident from regional pollen records from lakes.

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Introduction

Hydrologic variability is inherent to the Florida peninsula over glacial to interglacial timescales due to the surrounding water masses that transport heat northward as part of the Atlantic meridional overturning circulation (AMOC). Major long-term hydrological changes have been reported in Quaternary pollen records from central Florida lake deposits, where the alteration between oak-ragweed and pine-dominated vegetation prominently reflects drier and wetter periods over the last glacial–interglacial cycle (Watts, 1969, 1971, 1975, 1980; Grimm et al., 1993, 2006; Watts and Hansen, 1994; Willard et al., 2007), and which are likely forced by changes in AMOC intensity (Donders et al., 2011). During the Holocene, regional vegetation again shifted from dry oak to wetter pine vegetation cover across the peninsula starting around 6.5 ± 1 cal ka BP (Watts and Hansen, 1994; Grimm et al., 2006), whereby the humidity increase was more prominent farther south, suggesting forcing through intensification of the El Niño Southern Oscillation (Donders, 2014). Florida estuarine deposits show that this

vegetation change co-occurs with an increase in runoff, pointing to increased precipitation in combination with sea-level rise as important driver (Van Soelen et al., 2012). Further humidity increase is evident in the southernmost lakes and local wetland records between 2 and 3 ka in central Florida (Watts and Hansen, 1994; Donders et al., 2005a; Willard and Bernhardt, 2011). This change is rather variable in expression and in some sections shows an opposite trend (Glaser et al., 2013).

Sensitivity of proxy records

While they are very relevant for estimating sensitivities in future fresh water availability, higher order humidity changes are difficult to detect for various reasons. The available lake records show little expression of sub-millennial climatic changes due to the averaging effect of regional pollen rain (see Donders, 2014 and references therein) and are therefore not suitable for deducing more detailed evidence of changes in precipitation on sub-millennial timescales. Local wetland sites are potentially more sensitive to small-scale humidity changes but highly variable in their expression due to high spatial variability, local succession, and influence of sea-level change (Donders et al., 2005b; Willard et al., 2006; Willard and Bernhardt, 2011; Dekker et

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al., 2015). Here we test the sensitivity and consistency of such wetland records for hydrology reconstructions in a multi-proxy and multi-site approach.

Available palynological evidence for late Holocene centennial-scale hydrological variability in Florida comes primarily from wetland environments in the southern part of the peninsula (Gleason and Stone, 1994; Willard et al., 2001a; Donders et al., 2005a; Willard and Bernhardt, 2011). Peat-based pollen records from the Everglades indicate two dry intervals around 1.0 ka and 0.4 ka, reflected by transition from long hydroperiod slough vegetation to moderate hydroperiod sawgrasses (Bernhardt and Willard, 2009; Willard et al., 2001a; Sanchez et al., 2013). Additional evidence for precipitation-linked hydrological changes are available from speleothem growth rate analysis (Van Beynen et al., 2007, 2008), otoliths, and shell stable isotopes ratios from coastal archaeological mounts (Wang et al., 2011), and on ostracod assemblages and stable isotope ratios from lake deposits (Alvarez Zarkian et al., 2005). In particular, the latter study provides a full Holocene record, but the strong influence of other (ground- and sea-water) sources also strongly affects the isotopic composition at these sites, potentially masking precipitation-related changes. Overall, the variety in environments studied and proxies used so far hamper the construction of detailed late Holocene hydrological changes for Florida, since few sensitivity tests and little multi-proxy data from well-dated wetland sections are available. Moreover, the low elevation of the coastal sites might induce an overprint of the signal of precipitation change by the Holocene relative sea-level (RSL) rise (Donders, 2014).

Reconstruction approach in wetlands

Ideally, a relatively upland wetland basin independent of RSL would be used for reconstructions of other hydrologic forcings, investigated through multiple sections and independent proxies to separate local effects from more regional humidity trends. The abundant wetlands and lakes of the elevated central Lakes Wales Ridge of Florida are known to have hydrology largely dependent on precipitation, or precipitation-induced seepage from the surface aquifers (Gaiser et al., 2009a,b). The plant associations in Florida wetlands are directly related to surface-water depth and ponding duration (hydroperiod) (Kushlan, 1990; Givnish et al., 2008), and the palynological signal reflects this variation as well (Willard et al., 2001b; Donders et al., 2005b; Bernhardt and Willard, 2009; Sanchez et al., 2013). Besides pollen-based vegetation reconstructions, diatoms (siliceous algae) have proven to be a highly useful tool for determining aquatic environmental change in such wetland settings (Gaiser et al., 1998, 2001, 2004; Gaiser and Johansen, 2000; Pearce et al., 2011; Quillen et al., 2013). Due to their short reproductive cycle and sensitivity to environmental conditions as water depth, acidity, and hydroperiod (Battarbee et al., 1986; Gaiser et al., 2001; Smol and Stoermer, 2010), changes in their assemblages can be applied for reconstructing local changes in freshwater environments.

Here we present sub-centennial-scale resolution pollen and diatom records from two nearby peat sections from Highlands Hammock State Park in central Florida to test the consistency and sensitivity of local wetland proxy records to centennial-scale wetland changes. Interpretation of the records is aided by comparison with a large surface sample dataset from the Southeastern USA, allowing reconstruction of wetland type and associated hydroperiod. Regional precipitation forcing through sea-surface temperature (SST) changes of the water masses surrounding Florida indicate increased temperatures around 2.5 ka and 1.1 ka (Keigwin, 1996; Richey et al., 2007), and higher order variability coupled to the solar irradiance minima during the Little Ice Age (Poore et al., 2004). Such SST changes cause precipitation anomalies in Florida (Donders et al., 2011) and, if large enough, are expected to produce a wetland humidity increase that is consistent between both sites and proxies.

Regional setting

Geomorphology and climate

Highlands Hammock State Park (HHSP) is located near Sebring in the broad, gently sloping DeSoto Plain along the western edge of the Lake Wales Ridge in Highlands County, central Florida (Fig. 1A). This area is characterized by a series of north-south-oriented relict shorelines and dunes formed during Pleistocene sea-level highstands. These sandy deposits overlay a karstic Eocene to Miocene limestone bedrock (Scott et al., 2001). Generally, central Florida contains many basins in the sand hills and ridges, where rainfall easily percolates the permeable sands, favoring groundwater flow over surface-water drainage (Sacks et al., 1998). In this setting, the HHSP is exceptional as it includes a low-energy riparian wetland with a peaty soil located in a basin between two sandy beach ridges. Elevation ranges within the park between ~45 and 24 m above sea level (m asl). The Lake Wales Ridge forms the surface-water divide between the Kissimmee River basin to the east, the Peace River basin to the west, and the tributaries to the south that flow into Lake Okeechobee.

The investigated section is part of the surficial aquifer, which is confined by a sequence of low-porosity carbonates and clay lenses (part of the Hawthorn Group), restricting the flow of water between the surficial aquifer and the underlying Upper Florida aquifer (Spechler, 2010; Gates, 2012). Groundwater in the surficial aquifer is recharged primarily by precipitation, but also by septic tanks, irrigation from wells, seepage from lakes and streams, and the lateral groundwater inflow from adjacent areas (FDEP, 2007). Rain water percolates through the sandy ridges and seeps out at the slopes and base of low-lying sites like HHSP, resulting in two seasonal creeks (Haw Branch and Tiger Branch) that enter the park from the sandy paleoshore ridge to the east. Before drainage canals were dug around AD 1930, water moved overland as sheet flow through several broad marshes with stable wet conditions. Typical seepage slope communities with grass or fern understories and open pine/palm canopy with occasional hardwood species where present, requiring frequent burning and uninterrupted lateral ground-water flow (FDEP, 2007). Flow through HHSP is south to north into Little Charley Bowlegs Creek and eventually into the Peace River, which discharges into the northeastern part of Charlotte Harbor. Presently, the water depth and discharge of this system are subject to highly seasonal fluctuations, resulting in water level ranging from about 0.3 to 1.5 m (Spechler, 2010).

Central Florida has a subtropical summer wet climate with day temperatures ranging between 23 and 33°C. The 30-year mean annual precipitation measured at Archbold Biological station (1978–2007) is 1325 mm, of which most is received between June and September during summer storms (Spechler, 2010). This weather pattern is strongly determined by the annual movement of the North Atlantic Subtropical (or Bermuda) High (BH) (Davis et al., 1997). On multi-decadal scale, enhanced summer precipitation over the Florida peninsula has been linked to warm phases of the Atlantic Multidecadal Oscillation (AMO) (Enfield et al., 2001), whereas anomalously high winter precipitation is related to the El Niño mode of the Pacific El Niño Southern Oscillation (Ropelewski and Halpert, 1987; Donders et al., 2013).

Present-day vegetation

Hydrological conditions are the main control on the composition of wetland vegetation communities in HHSP. Pine flatwoods are present on the elevated well-drained sandy ridges east and west of the park, characterized by longleaf pine (*Pinus palustris*) and slash pine (*P. elliotii*), accompanied by live oak (*Quercus virginiana*), with a palmetto (*Serenoa repens*) and wiregrass (*Aristida stricta*) ground cover. The central feature of the park is the hydric hammock located on the limestone hill, dominated by a variety of hardwood species like live oak, sweet gum (*Liquidambar styraciflua*), pignut hickory (*Carya glabra*),

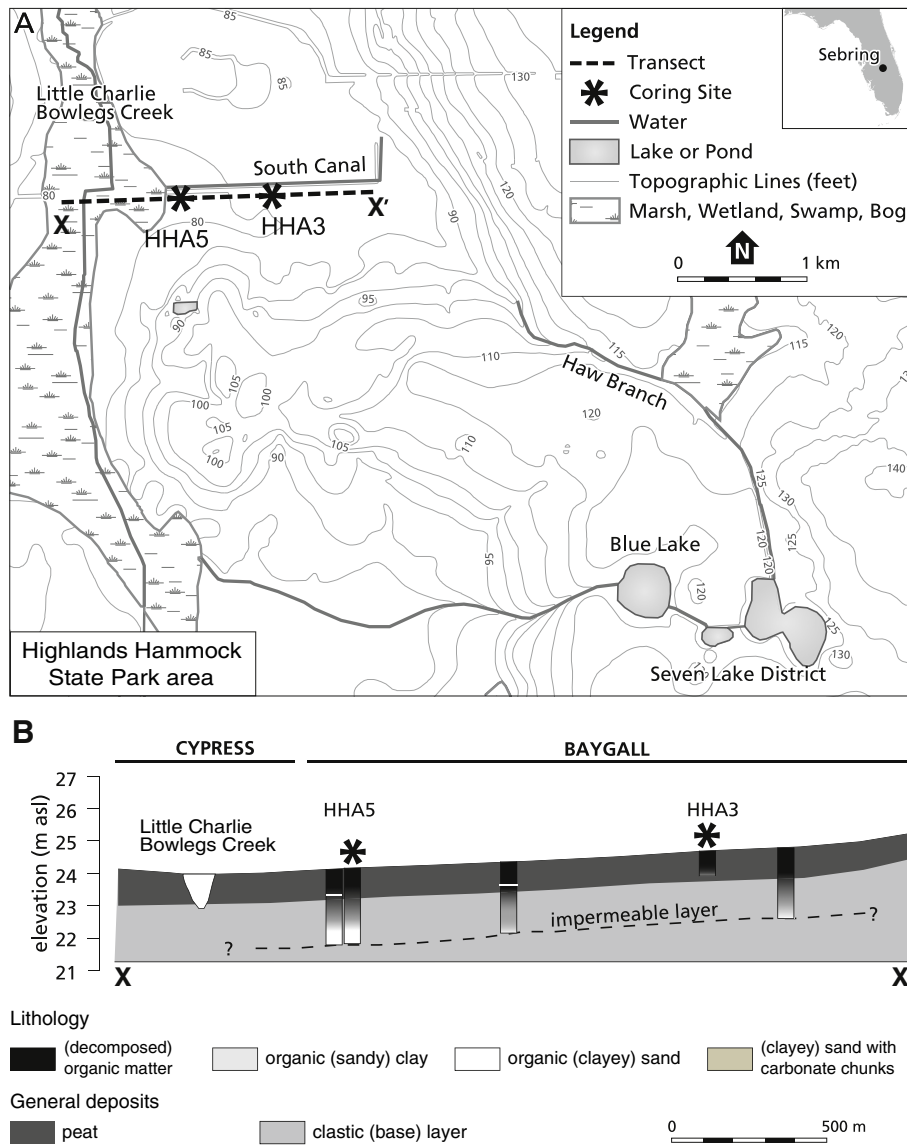


Fig. 1. A) Map of the Highlands Hammock State Park and surrounding area, with topographic lines (in feet above sea level). The coring transect X–X' is indicated by a dotted line, and locations of the sampled sites are indicated by asterisks. B) Cross-section of transect X–X' with main vegetation types and sampled sites (asterisks).

together with cabbage palm (*Sabal palmetto*) and a dense understory of various shrubs, ferns, and epiphytes. Within the hammock, a number of 'domes' are present due to karstic solution features, where pop ash (*Fraxinus caroliniana*) and swamp tupelo (*Nyssa biflora*) are common. Surrounding the central hammock, following the sheetflow drainage, a baygall swamp with mostly sweetbay (*Magnolia virginiana*), loblolly bay (*Gordonia lasianthus*), and red maple (*Acer rubrum*) is present, with a common understory of wax myrtle (*Morella cerifera*), dahoon holly (*Ilex cassine*), and a variety of ericaceous species and vines. The wettest section of the main drainage is dominated by swamp cypress (*Taxodium distichum*), accompanied by laurel oak (*Quercus laurifolia*) and red maple. At present, the area surrounding the park is mainly occupied by citrus plantations and urban areas.

Material and methods

Core collection

Prior to collecting the cores in April 2008, test gauges were made in an east-west transect along the park road south of the hydric hammock through the baygall swamp (Fig. 1B). Two cores were collected along

transect X–X': HHA3 (27°27'47.45"N, 81°32'21.48"W), 79 cm in length, was taken with a manual clymo-type peat corer (Clymo, 1988); HHA5 (27°27'47.40" N, 81°33'03.35" W), 231 cm in length, was taken with a vibracorer. The distance between the two cores is approximately 1100 m. Site HHA3 is at an elevation of ~24.5 m (80 feet) asl, whereas HHA5 is located closer to Little Charlie Bowlegs Creek at an elevation of ~24 m (79 feet) asl.

Sub-sampling and analyses

Total organic carbon and carbonate content was measured by loss-on-ignition (LOI) at 550°C and 950°C, respectively (Heiri et al., 2001), for core HHA3 at a resolution of 1 cm and for core HHA5 every 2.5 cm. Organic remains, including charcoal, seeds, and insect remains from the top sections of both peat cores and bulk material for the deeper core sections, was used for accelerated mass spectrometry (AMS) radiocarbon dating at Poznan Radiocarbon Laboratory (Poznan, Poland) for HHA5 (Table 1). Dating methods and results of HHA3 are outlined in Pearce et al. (2011). The AMS ¹⁴C dates are calibrated to calendar year before present (0 yr BP = 1950 AD), using the bomb-pulse method

Table 1
Radiocarbon ages HHA5. Conventional radiocarbon dates were given in years before present (^{14}C yr BP) or percentage modern carbon (pMC). All dates were calibrated into calendar years before present (ka; 0 ka refers to AD 1950) using the Levin ^{14}C (Levin and Kromer, 2004; indicated by *) and IntCal09 (Stuiver et al., 2010) calibration curves. Means and uncertainties were calculated from the lowest and highest dates at the 2σ probability distribution. Radiocarbon ages HHA3 are reported in Pearce et al. (2011).

HHA5 depth (cm)	Material	Lab ID	Conventional ^{14}C age	Cal yr BP
10–11	Leaf fragments, seeds	Poz-32700	107.7 \pm 0.35 pMC	-52.5 \pm 1*
19–20	Leaf fragments, charcoal	Poz-35336	103.55 \pm 0.34 pMC	-2.6 \pm 1*
29–30	Charcoal, chitin, seeds	Poz-35337	970 \pm 30 yr BP	835 \pm 40
40–41	Bulk organics	Poz-32701	680 \pm 30 yr BP	657 \pm 25
55–56	Bulk sediment	Poz-35338	1555 \pm 30 yr BP	1453 \pm 75
67–68	Bulk sediment	Poz-35339	4375 \pm 35 yr BP	4922.5 \pm 65
80–81	Bulk sediment	Poz-35340	4470 \pm 35 yr BP	5220 \pm 70
90–91	Bulk sediment	Poz-32753	6000 \pm 40 yr BP	6843 \pm 100
119–120	Bulk sediment	Poz-35372	4785 \pm 35 yr BP	5532 \pm 65
150–151	Bulk sediment	Poz-32750	7990 \pm 50 yr BP	8852 \pm 155
219–220	Bulk sediment	Poz-35343	5210 \pm 40 yr BP	5963 \pm 60
230.231	Bulk sediment	Poz-32752	5130 \pm 70 yr BP	5855 \pm 150

* Calibrated to atmospheric ^{14}C .

for the core top samples (Levin and Kromer, 2004) and IntCal09 (Stuiver et al., 2010) for the other samples.

Subsamples of ~0.1–0.3 g freeze-dried sediment were used for palynological analysis. Standard procedures by Fægri et al. (1989) were followed, including HCl (30%), HF (40%), KOH (10%), and acetolysis treatments, to remove carbonates, silicates, and organic matter, respectively. Prior to treatment *Lycopodium clavatum* tablets with a known amount of spores (18,583) were included for analysis of absolute quantities. Samples were sieved over a 250- μm and 10- μm mesh to further remove remaining organic detritus and clay-sized particles. Residues were mixed with glycerol and mounted on microscopic slides for analysis using a Leica light microscope (400 \times magnification). At least 300 pollen were counted for each slide, of which at least 200 pollen of non-arboreal species. Only the lowermost samples in HHA5 yielded lower counts between 230 and 280. Identification of the pollen was largely based on Willard et al. (2004) and the unpublished reference collection of the Utrecht University.

For diatom analysis, subsamples of ~0.5–1 g of freeze-dried sediment were subsequently treated with H_2O_2 (1.5 hours at 100 $^\circ\text{C}$), HCl, and HNO_3 (2 hours at 120 $^\circ\text{C}$) solutions to remove organic matter and carbonates. After seven cycles of decanting and refilling with demineralized water to attain a neutral pH, a known fraction of each sample was allowed to settle onto coverslips in evaporation trays (Battarbee, 1973) before being permanently fixed on slides using the high refraction mountant Naphrax $^\circledR$. On each slide at least 400 diatom valves were counted using a Leica DM2500 microscope, equipped with an oil immersion lens and differential interference contrast at a magnification of 945 \times . Diatom identification for most species followed Patrick and Reimer (1966), Camburn and Charles (2000), Gaiser and Johansen (2000), and Siver et al. (2005).

Data analysis

Zonation of the pollen (PAZ: pollen assemblage zone) diagrams is based on visual inspection supported by CONISS output on the non-transformed (Euclidean distance) percentage data. Across southern Florida extensive surface sampling has been performed in a variety of wetland types, covering a large range of hydrological conditions (Willard et al., 2001b, 2006; Donders et al., 2005b; Bernhardt and Willard, 2009). For consistency with the surface sample database, pollen assemblages are assigned to specific vegetation types in HHSP using relative abundances based on a pollen sum including all observed vascular plants (so excluding *Sphagnum*). Following the approach outlined in Donders et al. (2005b), we explicitly reconstruct the (variation in) local vegetation changes. Consistent changes in local hydrology are likely driven by sheet flow intensity and should be coherent with regional lake records (Gaiser et al., 2009a,b; Quillen et al., 2013; Donders, 2014).

Based on the diatom records, changes in hydroperiod or ponding duration were reconstructed for both sites, using a transfer function based on comparable wetlands in South Carolina and Georgia (Gaiser et al., 1998) and supplemented by hydroperiod values from the Everglades (Lee et al., 2013). We applied weighted averaging of taxon hydroperiod optima with tolerance weighing, using only species with a relative abundance of >3% in at least one sample. Following Gaiser et al. (1998), the hydroperiod index ranges from 1 to 5, corresponding to a ponding duration of <50% (<6 months), 50–75% (6–9 months), 75–83% (9–10 months), 83–98% (10 to almost 12 months) of the year and annual inundation, respectively. The model has a root mean square error (RMSEP) of 0.66 hydroperiod units determined by bootstrapping and it performs well ($r^2 = 0.81$) although it represents a relatively short environmental gradient. To detect potential non-analogue conditions in the downcore data, the % abundance of taxa represented in the training set data are calculated, as well as intersample similarity based on square-root transformed Bray–Curtis distances.

Results

Lithostratigraphy and chronology

The gauge data and core HHA5 show a compacted black horizon at a depth of ~230 cm with slightly enhanced organic content (~5% compared to 2–3% in the overlying sandy unit), which likely is a paleosol (Fig. 1B). This impermeable layer in the subsurface of the basin hampers water percolation and is a prerequisite for the formation of peat. Overlying deposits are predominantly sandy but from ~120 cm gradually become more clayey. Despite the blackish color of these deposits, LOI values of <5% indicate organic matter is practically absent in this core section (Fig. 2). From 55 cm upwards in HHA5 and from 79 cm upwards in HHA3, lithological changes are comparable between the cores: the deposits change to dark brown clay and become more organic, with LOI values gradually increasing from 20% to 80% (Fig. 2). Decomposition of these organic deposits becomes less toward the top, but only the top ~20 cm is rich in recognizable plant remains. The LOI at 950 $^\circ\text{C}$ values of core HHA3 of around 1% are close to the error range of the method (Heiri et al., 2001) and indicate that no considerable carbonate is present in the deposits. The cores reflect lithological changes that are found throughout this section of the swamp (see Fig. 1B). Because the clastic deposits are barren in pollen below the organic top 70 cm of HHA5, they are not considered in this study.

A detailed age–depth model for core HHA3 is reported in Pearce et al. (2011) (Fig. 2) and is based on eight AMS ^{14}C ages with sample-specific age ranges. Deposition rates change from ~0.03 cm/year at the base (20–79 cm), to ~0.1 cm/year (10–20 cm), to ~0.33 cm/year in the top (0–10 cm), reflecting the progressively increasing decomposition and compaction of organic matter downcore. The age model suggests a

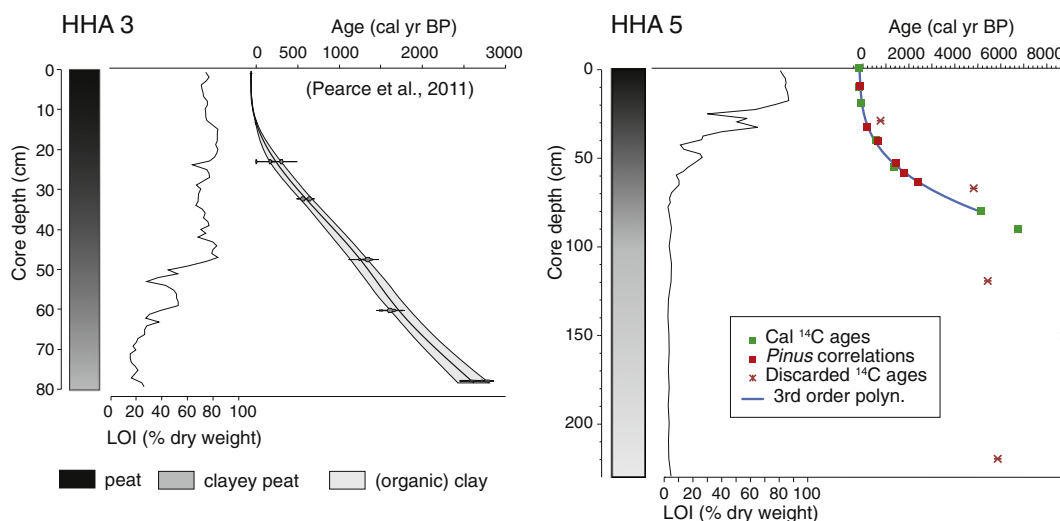


Fig. 2. Lithology, loss on ignition and available calibrated radiocarbon dates for cores HHA3 and HHA5. Age-depth model of HHA3 is derived from Pearce et al. (2011). Note different vertical scales.

basal age for core HHA3 of 2511 ± 177 cal yr BP. Additional AMS ^{14}C dating for HHA5 of seven samples is reported here (Table 1). Due to apparent age reversals and limited availability of macrofossils at this site, various age modes are potentially applicable, although the lithology does not show distinct bioturbation or indications for hiatuses in the upper ~90 cm. Below this depth, ages are no longer proportionally increasing and the sediment contains a high sand content, suggesting a different depositional regime. To securely identify outliers, an independent correlation with the established HHA3 chronology is performed based on regional pollen types (*Pinus* and *Quercus*) that do not occur locally at the coring locations (Table 2). These taxa are expected to vary approximately synchronously between sites at this spatial scale. Both the % *Pinus* relative to all other pollen and the ratio of *Pinus* to *Quercus* ($P/[P + Q]$) are compared between both cores, and resulting correlation horizons are indicated in Fig. 3. The age of these horizons, as determined at HHA3, are compared to the independent calibrated radiocarbon ages of HHA5 where they clearly agree with the relatively younger ages, identifying the radiocarbon ages at 29.5 and 67.5 cm as outliers (Fig. 2). Chronology results and potentially different depositional conditions limit the reliable stratigraphical record of HHA5 to the uppermost 90 cm. The sample ages were determined by fitting a 3rd-order polynomial through the age control points.

Pollen and diatom relative abundances

The pollen assemblages in both cores as well as major shifts through time are highly comparable, including 42 taxa of which 22 are non-

Table 2

Grouping of pollen according to eco-hydrological preference of parent plants in this region.

Growth type	Taxa
Ferns	<i>Monolete</i> spores, <i>Polypodium</i> , <i>Osmunda</i> , <i>trilete</i> spores (excl. <i>Sphagnum</i>)
Aquatic	<i>Nymphaea</i> , <i>Utricularia</i> , <i>Potamogeton</i>
Riparians/marsh	<i>Sagittaria</i> , <i>Pontederia</i> , Typhaceae, Cyperaceae, <i>Polygonum hydropiperoides</i> , <i>Cladium</i>
Herbs	Asteraceae, Amaranthaceae, Poaceae, Apiaceae, <i>Sabatia</i> , <i>Urtica</i>
Wetland tree/shrub	<i>Acer</i> , <i>Alnus</i> , <i>Carya</i> , <i>Cephalanthus</i> , <i>Fraxinus</i> , <i>Itea</i> , <i>Liquidambar</i> , <i>Magnolia</i> , <i>Morella</i> , <i>Nyssa</i> , <i>Salix</i> , <i>Taxodium</i> .
Upland trees/shrub	<i>Pinus</i> , <i>Quercus</i> , <i>Casuarina</i> , <i>Carpinus</i> , <i>Celtis</i> , <i>Ilex</i> , <i>Ulmus</i> , <i>Vitis</i> , <i>Ericaceae</i> , <i>Rhus</i> , <i>Sabal</i> .

arboreal (Figs. 4 and 5). In HHA5 from ~70 cm up, and throughout HHA3, pollen and spores are found well-preserved and abundant. Diatom valves are moderately to well-preserved in all studied samples. The diatom composition in both cores is similar, encompassing a total of 45 taxa representing 16 different genera (Figs. 6 and 7). Other frequently observed siliceous microfossil remains include phytoliths, sponge spicules, and chrysophyte statospores. A detailed description of siliceous microfossil assemblages in core HHA3, including photomicrographs of the most occurring diatom species, was published by Pearce et al. (2011). Changes in the dominant pollen and diatom taxa over depth are described by core. Stratigraphic zones are based on the pollen assemblages.

HHA3 pollen and diatom assemblages

The pollen record is subdivided into six pollen assemblage zones (PAZ) (Fig. 4). *Pinus* and *Quercus* dominate PAZ 1 with 55% and 15%, respectively. Of the herbaceous species *Sagittaria* is most common with 5–10% and Asteraceae, Poaceae, and Cyperaceae are consistently present with <5% (PAZ1). Monolete spores of unidentified fern species increase to 28% in PAZ2, together with *Sphagnum* spores up to 10%, while *Pinus* and *Quercus* are gradually reduced. *Sagittaria*, Poaceae, Cyperaceae, and Asteraceae remain present with 5–10% each. PAZ3 is very distinct with high *Pontederia* (to 25%) and *Nymphaea* (to 5%). PAZ 4 again show high *Sagittaria* and Poaceae (to 17% and 28%), increasing Asteraceae and *Sphagnum* (to 11%), and notable presence of *Magnolia* (6%) and *Morella* (2.5%). Monolete spores subsequently become dominant with values of 50–85% in PAZ 5, together with *Sphagnum* to 33%, and Asteraceae to 12%. A distinctly different assemblage and higher diversity is observed for the top (PAZ 6), where monolete spores and *Sphagnum* are reduced and the trees and shrubs *Morella*, *Acer*, *Itea*, *Vitis*, and fern *Osmunda* dominate with values of 10–20%, and hardwood taxa such as *Nyssa*, *Liquidambar*, *Magnolia*, and *Ilex* increase.

The diatom assemblages in the PAZ 1–4 are dominated by the tychoplanktonic species *Aulacoseira coroniformis* (>80%) (Fig. 6). Benthic species such as *Eunotia zygodon* and *Eunotia carolina* are also present. A rapid transition to a zone dominated by *Eunotia zygodon* (50–80%) and to a lesser extent, *Pinularia viridis* (to 14%), is observed in PAZ 5. In the top half of PAZ 5, *E. tautoniensis* (up to 22%) and *E. carolina* (up to 55%), were most frequently observed. Finally, in the top sediment layer during the past ~50 years (PAZ 6), the *Eunotia* species are accompanied by a number of tychoplanktonic species such as *Fragilaria javanica* (up to 40%), species of the genus *Frustulia* (up to 20%), along with *Pinnularia*

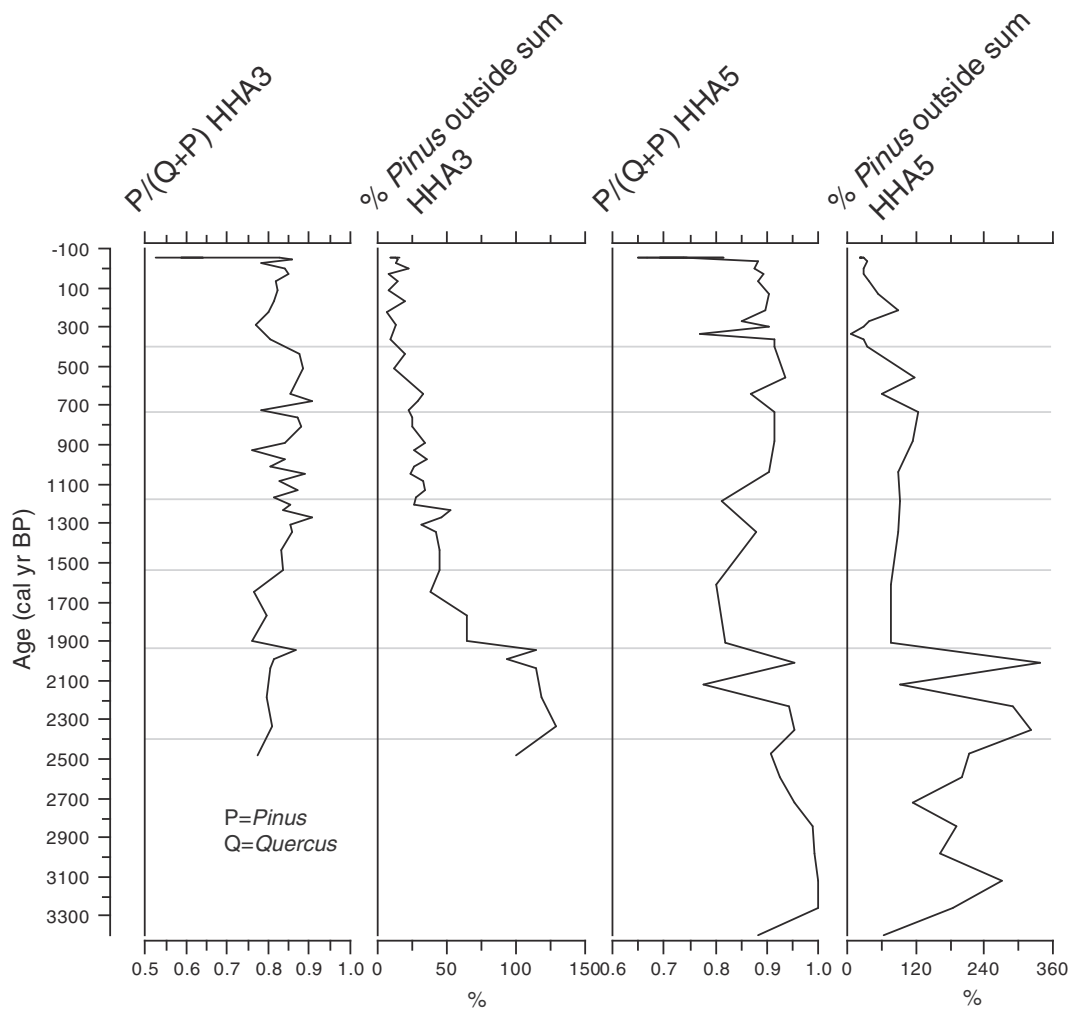


Fig. 3. Result of the core correlation between HHA3 and HHA5 based on indices of regional pollen types *Pinus* and *Quercus* plotted against age. Horizontal lines represent correlated levels used in the final age-depth model.

parvulissima (up to ~10%, likely benthic). The hydroperiod index is continuously high during PAZ 1–4, and maximal during PAZ 3 and 4. Zones PAZ 5 and 6 have a lower hydroperiod. However, the hydroperiod index in the uppermost zone suffers from non-analogue conditions with the training set data (Gaiser et al., 1998).

Total palynomorph influx is stable averaging $\sim 20 \times 10^3$ grains $\text{cm}^{-2} \text{yr}^{-1}$ during PAZ 1 and 2, and gradually increases from PAZ 3 upwards. The increase is mainly due to the expansion of fern spores in the count. Ferns grow locally as understory plant in the swamp forest, increasing palynomorph concentrations. The uppermost zone shows artificially high influx level as a result of sampling in the unconsolidated core top.

HHA5 pollen and diatom assemblages

This pollen record is subdivided into seven PAZs (Fig. 5). At the base (PAZ 1), pollen of *Pinus* dominate with 70%, together with high values of Amaranthaceae and Asteraceae up to 30%, and presence of Poaceae and Cyperaceae (5%). In PAZ 2, *Pinus* remains high but the herbs are replaced by *Sagittaria* (up to 13%), and swamp forest taxa *Quercus*, *Morella*, and *Carya* appear. In PAZ 3, Amaranthaceae increase again to 5–10%, Cyperaceae, and Poaceae expand, whereas *Pinus* is abruptly reduced to ~40%. In the second half of PAZ 3, ferns and moss increase. This trend continues into PAZ 4, where monolet spores peak to 50% together with the aquatic *Potamogeton* (single sample of 40%), and a minor but consistent presence of *Nymphaea* (1%) and *Polygonum hydropiperoides*.

An assemblage similar to PAZ3 then re-establishes, but with a higher presence of *Sphagnum* to 13% (PAZ 5). Monolet spores again increase and become dominant (up to 55%) in PAZ 6. In the top (PAZ 7), the assemblage changes distinctly with increasing values of baygall wetland trees *Magnolia*, *Liquidambar*, *Morella*, *Vitis* (2–10%), *Taxodium*, and fern *Osmunda* (up to 20%). Total palynomorph influx is more variable compared to HHA 3, with low values in PAZ 1, increased values of $10\text{--}20 \times 10^3$ grains $\text{cm}^{-2} \text{yr}^{-1}$ in PAZ 2 and 3, and a strong increase again related to the fern expansion during PAZ 4 and low sediment compaction in the top. The striking decrease of palynomorph influx at the PAZ 2–3 transition interrupts the trend and could point to uncertainties in the age-depth model.

The diatom record of HHA5 extends below the pollen record and displays more variability relative to HHA3 (Fig. 7), as reflected in the intersample similarity. Deposits below the studied organic top layer are characterized by low organic matter content (LOI <5%) and are almost barren in pollen. These facts point to overall short hydroperiod conditions, in which organic material of potentially present vegetation is not preserved. The diatom assemblages below ~100 cm (Fig. S1) show a mixed signal with heavily silicified eutrophic, planktonic (partly open river), taxa (*Cyclotella* spp., *Stephanodiscus* spp.) occurring together with aerophilic *Hantzschia amphioxys* and oligotrophic, karst wetland species *E. silesiacum* (Lee et al., 2013). The basal part up to PAZ 1 and 2 is generally dominated by epiphytic species of the genus *Eunotia* (mostly *E. monodon* with 40%), together with *Gomphonema* spp. and *Nitzschia* spp. (each up to 10%). *Encyonema silesiacum* is abundant (30%) in the

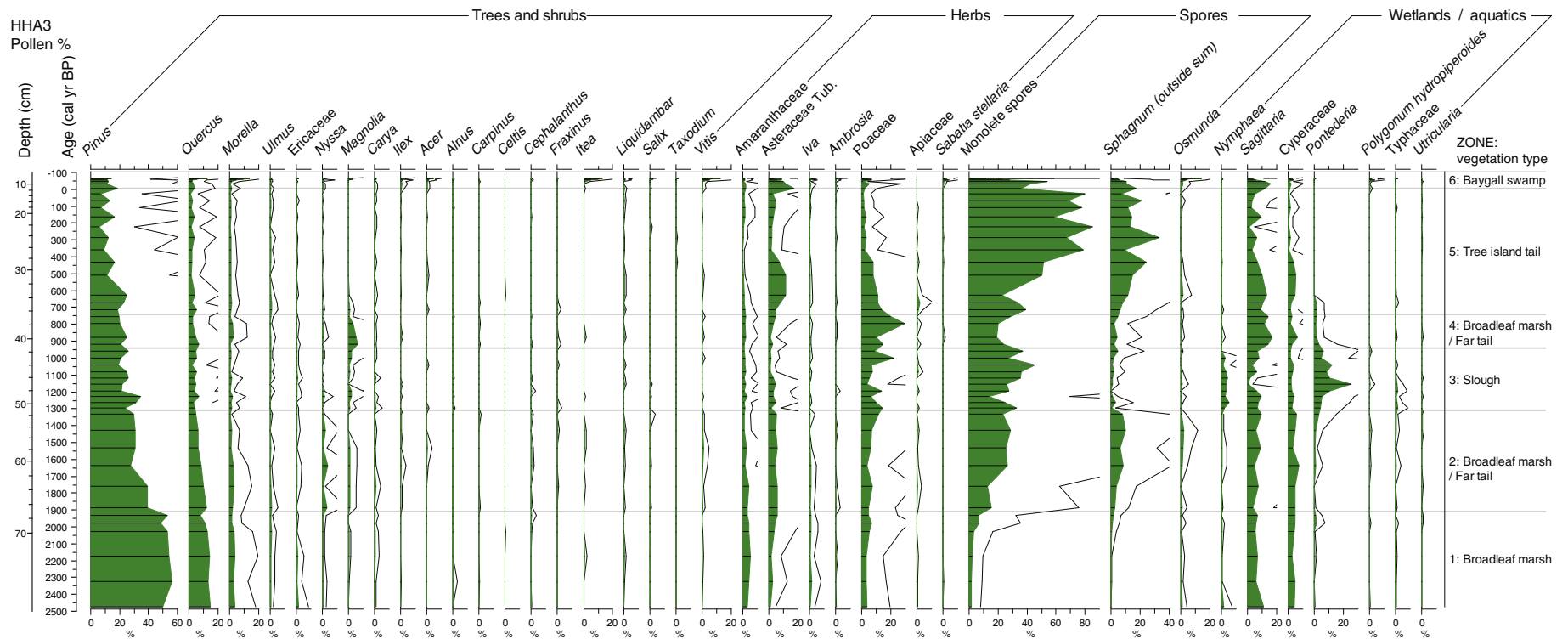


Fig. 4. HHA3 pollen percentage diagram showing the most abundant pollen taxa divided by pollen assemblages zones (ZONE) and associated vegetation types.

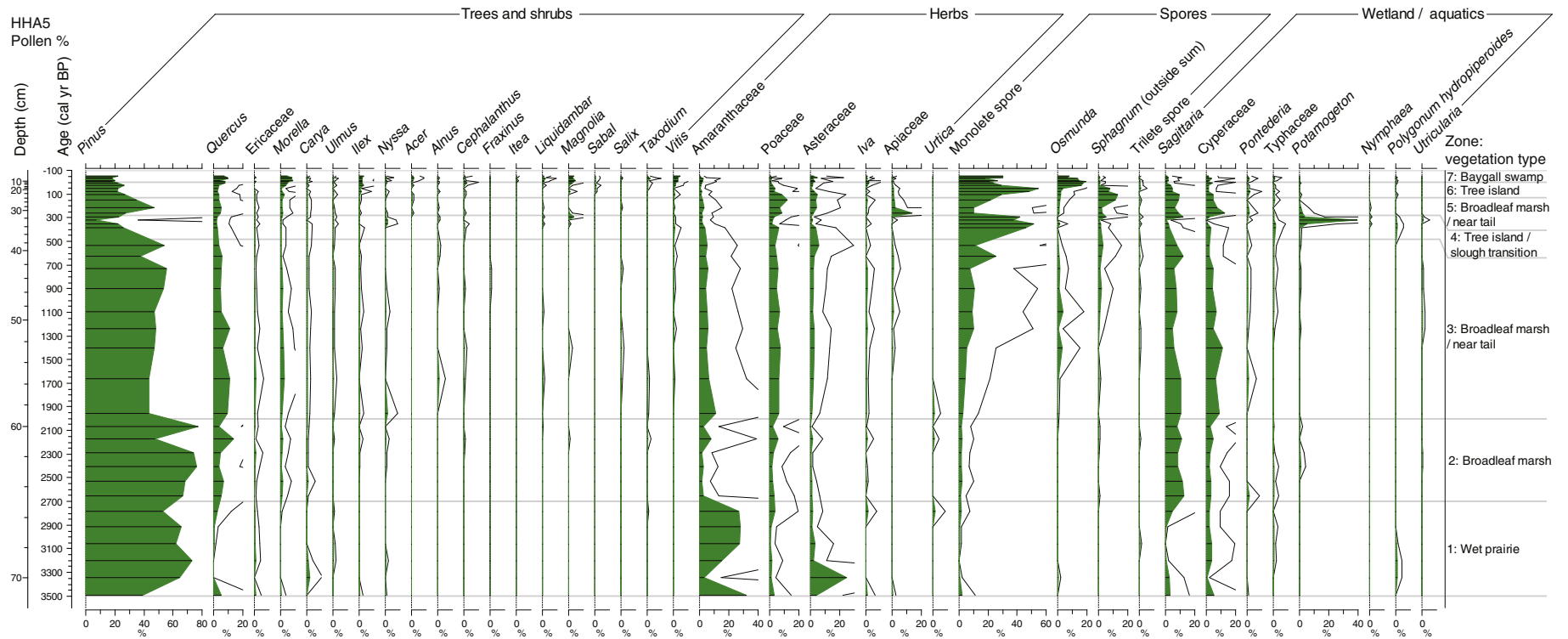


Fig. 5. HHA5 pollen percentage diagram showing the most abundant pollen taxa divided by pollen assemblages zones (ZONE) and associated vegetation types.

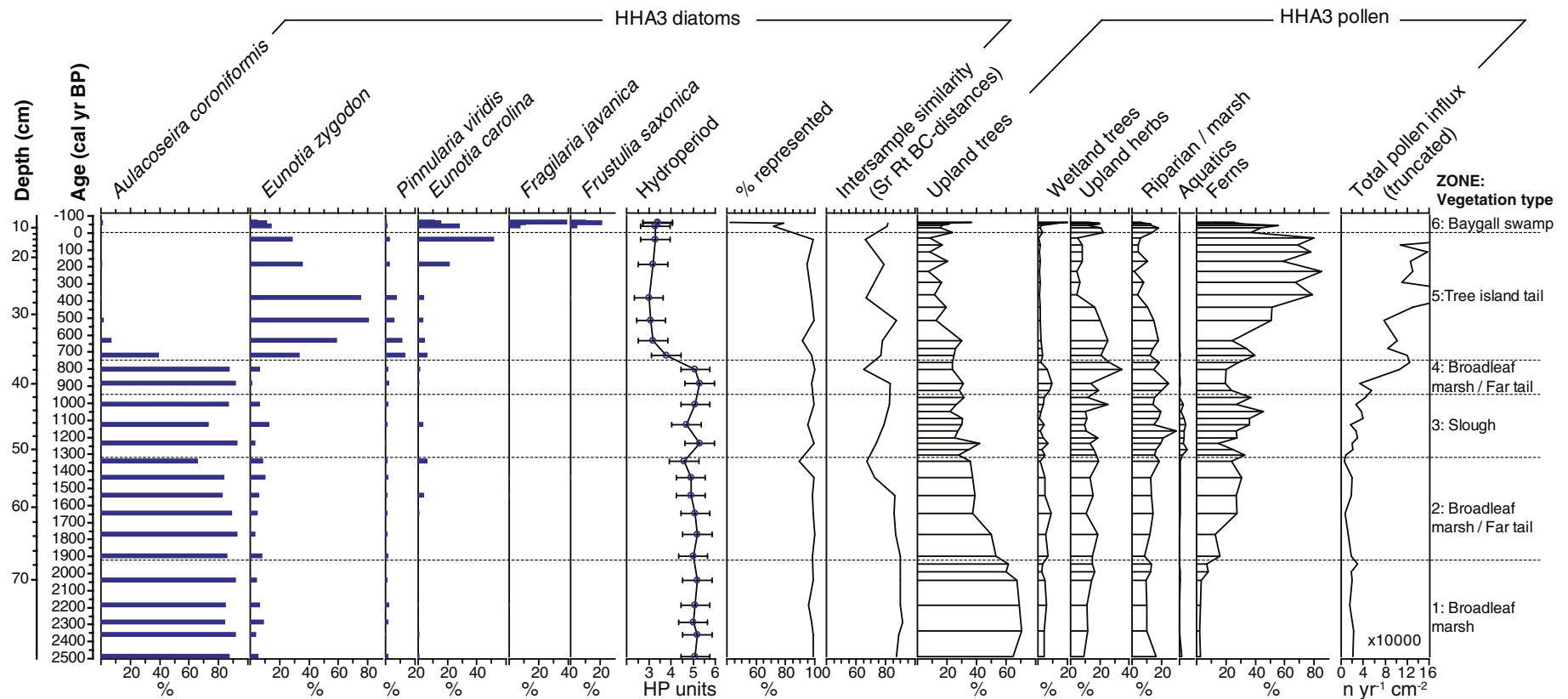


Fig. 6. HHA3 summary diagram showing the main diatom species and grouped pollen abundances plotted against age. Calculated hydroperiods, inter-sample variability, and % overlap are based on the diatom assemblages. Inferred vegetation type per pollen assemblage zone is indicated (see main text for details).

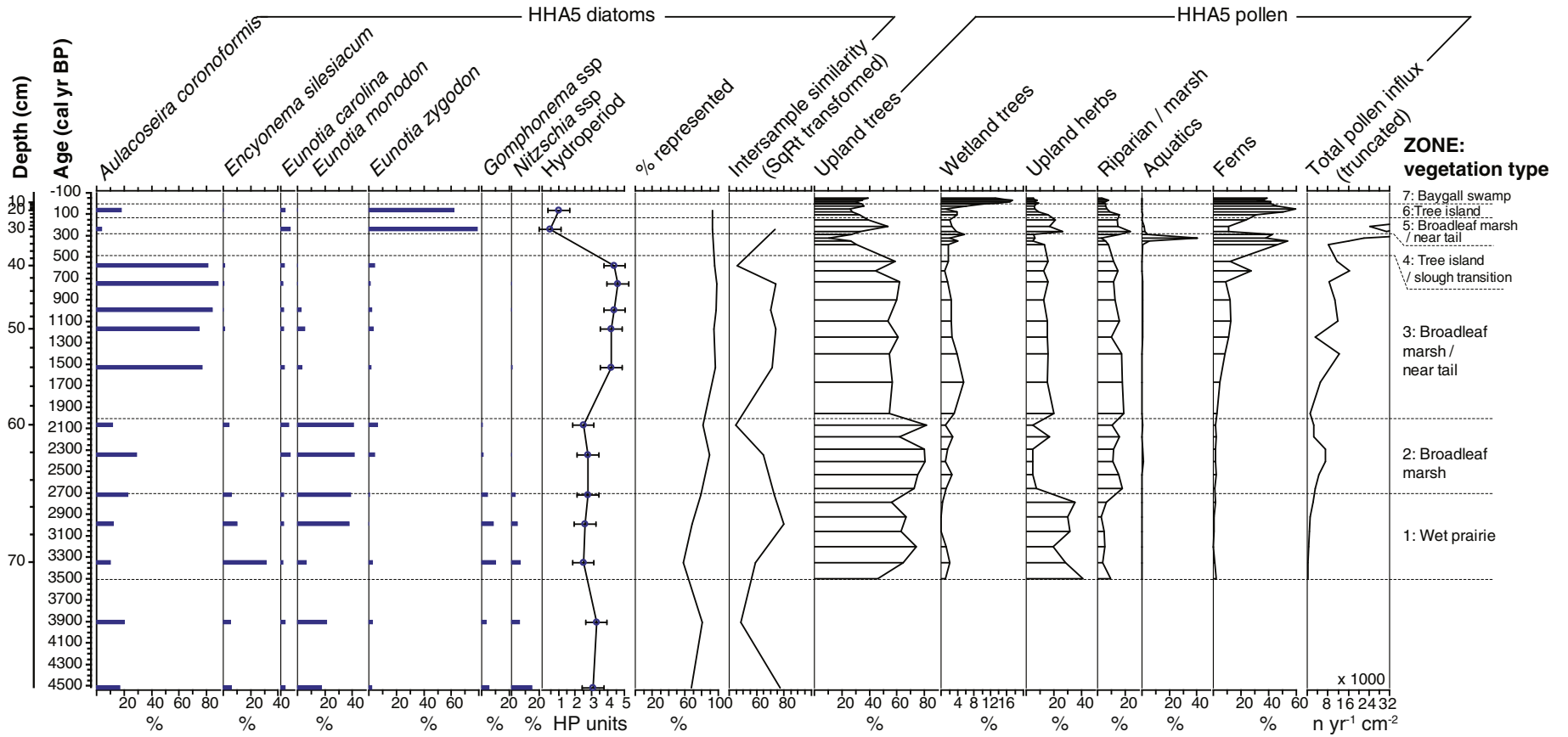


Fig. 7. HHA5 summary diagram showing the main diatom species and grouped pollen abundances plotted against age. Calculated hydroperiods, inter-sample variability, and % overlap are based on the diatom assemblages. Inferred vegetation type per pollen assemblage zone is indicated (see main text for details).

lowermost sample of this PAZ 1. The tycho planktonic species *Aulacoseira coroniformis* is present in the lower zones, but significantly less abundant compared to HHA3 in the equivalent interval. Its abundance increases up to >80% only in PAZ 3. In PAZ 5/6, the high abundance of *A. coroniformis* decreases and is replaced by *Eunotia zygodon* (80%) which is accompanied by *E. carolina* and *Pinnularia gigas* (both ~5%). The diatom-inferred hydroperiod reflects the higher variability in HHA5 (species representation with the Gaiser et al., 1998 training set is 60–100%), and indicates a shift from the relatively low value of ~3 in PAZ 1–2, to a high of ~4.5 in PAZ 3, after which it decreases sharply to 0.5–1 during PAZ 5/6.

Discussion

Wetland development

The pollen and diatom analyses on both HHSP cores reflect distinct changes over at least the past ~2.5 ka. The extended record of HHA5 dates back to 3.5 (pollen) and ~5 ka (diatoms), although the lowermost samples do not resemble a reliable stratigraphy as ages do no longer increase proportionally with depth below ~90–100 cm (~5 ka, see Fig. 2). The diatom assemblages prior to 5 ka contain contrasting taxa typical of both oligotrophic wetland and eutrophic river taxa between 230 and 150 cm point to periodic wetland flooding in a more dynamic river-dominated landscape with deposition and preservation of (possibly reworked) organic components of different ages. Conditions seem to stabilize as a wetland around ~150 cm, indicated by predominance of acidic, benthic taxa (Fig. S1).

Between both records, the higher upland tree % and greater intersample variability and diatom-inferred hydroperiod reconstructions point to slightly drier or more upland conditions at HHA5 relative to HHA3 on average. This results in greater potential sensitivity to hydrological changes, which is recorded in PAZ 1 at HHA5 in the comparatively drier conditions with high Amaranthaceae and Asteraceae and common Poaceae and Cyperaceae, typical of a seasonally wet prairie environment (Willard et al., 2001b) (although HHA3 does not extend back far enough to confirm the prairie environment).

Following the transition from short-hydroperiod wet prairie to moderate hydroperiod around 2.5 cal ka BP in HHA5, both sites (Figs. 4, 5) show a broadly similar vegetation development. The transition at 2.5 ka from a short to a moderate hydroperiod marsh type (Kushlan, 1990) is not directly concurrent with changes in the diatom assemblages. The diatom-inferred hydroperiod index in HHA5 of around 3 implies inundated conditions for 9–10 months of the year, which is suitable for a forested swamp and broadleaf marsh but higher than expected for the wet prairie (Kushlan, 1990; Givnish et al., 2008). Surface samples from the Everglades show distinctly different pollen assemblages for the various wetland types present over short distances (Willard et al., 2001b, 2006; Bernhardt and Willard, 2009; Bernhardt, 2011). However, diatoms in isolated basins likely give an even more local signal as the assemblage composition is largely dependent on *in situ* habitat conditions. A possible expansion for the observed changes in HHA5 therefore could be that vegetation changed close to, but not directly, at the site. Critical in this assumption is that some surface elevation variability is present within the basin, allowing for non-linear responses between the proxies to hydrological changes. Clearly, diatoms and wetland plants reflect the landscape at different spatial scales, which is also reflected in the differences in diatom-inferred hydroperiod at both sites between 2.5 and 2.0 ka. Despite the initial discrepancy between the pollen and diatom signal observed in the basal part of HHA5, clearly at ~2.5 ka, a broadleaf marsh is present with close to annual inundation.

From 2.0 cal ka BP, diatoms at both sites indicate long hydroperiods, and vegetation consistent with the modern analogue of broadleaf marshes 'close to tree islands' (Willard et al., 2001b). Although it is unlikely that actual tree islands were also present in the HHSP, these

assemblages with high abundances of fern spores and *Sphagnum* peat are characteristic for slightly elevated areas in the marsh landscape (Kushlan, 1990; Willard et al., 2001b, 2006). Here, the changes likely reflect gradual infill of the basin, reducing water depth that allow fern establishment on site, while abundant presence of tycho planktonic diatoms (*Aulacoseira coroniformis*) indicate continued long hydroperiods at both sites. The thick walls of *A. coroniformis* require some water turbulence to stay in the productive zone of the water column (Pearce et al., 2010), reflecting continuous inflow from the Haw Branch (Pearce et al., 2011). A similarly appearing but unidentified *Aulacoseira* species dominated the base of a sediment core of a wetland along the Savannah River drainage in interior South Carolina during a period of time when the depression appeared to be transitioning from an acidic floodplain pond to a wetland about 4 ka (Gaiser et al., 2001), suggesting this species complex may be indicative of high-energy oxbow conditions. Intervals of increased aquatic vegetation likely represent very local pond formation, representing a more open canopy with deeper water conditions. They occur at different intervals in the profiles and are neither synchronous between sites, nor consistent with variations in the diatom-inferred hydroperiods.

Starting at 0.7 cal ka BP, conditions at both sites return to slightly drier and, based on high fern abundance, more variable conditions, although the transition is not precisely synchronous (Figs. 6–8). The monolete spores dominance is characteristic for the short hydroperiod tails of tree islands in the Everglades (Willard et al., 2006). The abrupt shift in the diatom-inferred hydroperiods in both cores, characterized by the replacement of *A. coroniformis* by benthic (perhaps epiphytic) and acidophilic *Eunotia*, reflect a different hydrological regime more characteristic of stagnant wetland settings (Gaiser and Johansen, 2000). HHA5 shifts toward short hydroperiods, while hydroperiod of 2.5 at HHA3 implies that the site was inundated at least 9 months of year, which is within the range measured for tree island tails (Givnish et al., 2008).

The distinct change in the pollen assemblages in the top of both cores likely indicates the start of human alterations to the landscape. Initially, *Sagittaria* and Asteraceae increase again after AD 1950 (in HHA3) indicating wetter conditions. This is supported by a distinctly different and more diverse diatom assemblage at HHA3, which has been linked to a slightly greater water depth (Pearce et al., 2011), but the conditions are not reflected well in the training set data (Fig. 6). The pollen assemblage in the top of both cores is highly comparable and reflects the baygall swamp forest that is currently present (Figs. 4, 5). Aerial photographs of the region from the early 20th century show that an open landscape with scattered trees instead of dense swamp surrounded the hydric hammock at that time. In the 1930s and 1940s, the natural drainage was altered through the construction of dikes and canals by the Civilian Conservation Corps to protect the park's main attraction, the hydric hammock, from wildfires. Just north of our cored sites, an elevated road was built, which blocked the water flow and potentially led to increased and more stable wet conditions at these locations. With the exclusion of wild fires tree seedlings were able to mature, and the marsh was likely gradually replaced by swamp forest through natural succession. Diatom communities in HH3 suggest increased nutrient availability with increased abundance of *F. javanica* and benthic diatoms associated with acidic but more enriched settings (Quillen et al., 2013).

Climatic implications

The differences and similarities between both proxies and cores are summarized in Fig. 8, and compared to regional climate records. With exception of the observed changes during the 20th century, which can directly be related to anthropogenic interference, the vegetation and diatom developments likely reflect natural changes in the environment. The reconstructed stepwise increase in humidity between 3 and 2 cal ka BP is not entirely consistent between proxies, but the pollen signal is clear in both sites. The change cannot be explained due to natural

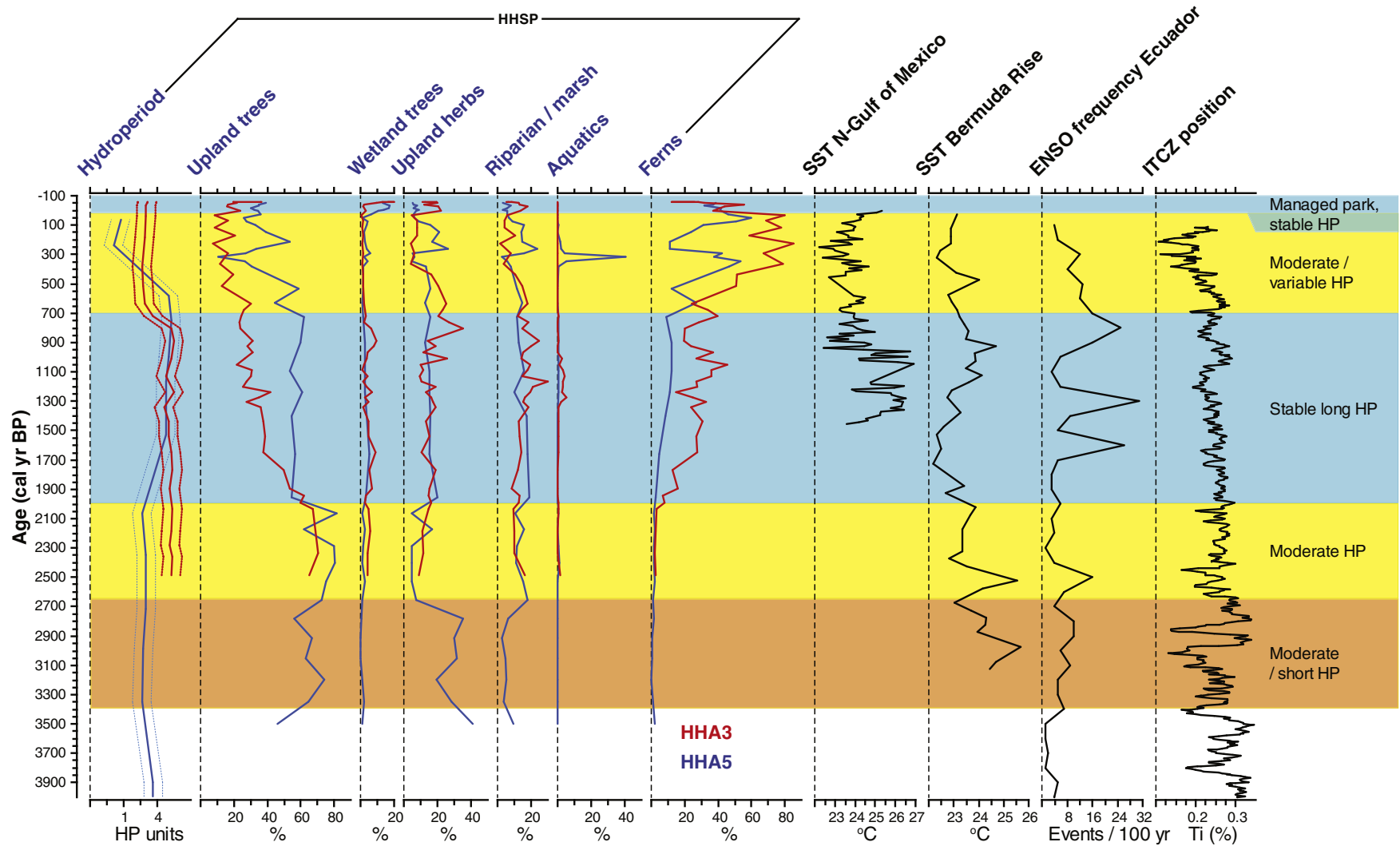


Fig. 8. Overview diagram showing a summarized hydrological development at HHSP based on hydroperiods and grouped pollen percentages. (see Table 2) Changes are compared to regional climate records: sea-surface temperatures (SSTs) from the northwestern Gulf of Mexico (Richey et al., 2007) and the Bermuda Rise (Keigwin, 1996), reconstructed El Niño frequency from Ecuador (Moy et al., 2002), and migration of the ITCZ (Haug et al., 2001).

wetland succession and basin infill as this would result in an opposite change. The change is consistent with increased presence of *Taxodium* pollen around 2.7 ka in the central Florida lake deposits and southern Florida wetlands (Watts and Hansen, 1994; Donders et al., 2005a). Also, shifts to wetter conditions around 2.5 ka and 1.1 ka are inferred from $\delta^{18}\text{O}$ in ostracods from Little Salt Spring (Alvarez Zarikian et al., 2005) and from deposition rates in stalagmites from Briars Cave (Van Beynen et al., 2008), both located on the eastern Gulf coast. These changes have been interpreted variously as e.g. increasingly wet conditions resulting from gradually rising sea level (Watts and Hansen, 1994) and intensification of the El Niño Southern Oscillation (Donders et al., 2005a). The relative upland location of Highland Hammock points to a prominent role of precipitation increase, consistent with more frequent ENSO-tied precipitation in Florida, which effectively prolongs the hydroperiod (Donders et al., 2013). Persistent El Niño modes between 2.7 and 2.5 ka, around 1.3 ka, and between 1.1 and 0.6 ka are inferred from Ecuador lake deposits (Moy et al., 2002) and may have triggered the initiation of the wetland and the later expansion of riparian species at HHSP (Fig. 8).

An environmental response to drier climate is hard to distinguish from that caused by the basin infilling, and the hydroperiod decrease starting at 0.7 cal ka BP is therefore potentially a local phenomenon. However, the change is recorded in both proxies and cores, and is relatively rapid. After a phase of maximum ENSO intensity, activity decreases around 0.6 ka, which is in agreement with the changes at HHSP. However, the Ecuadorian lake record also indicates phases of moderate El Niño activity between 2.4 and 1.1 ka, while the HHSP records show persistent moist conditions. Therefore, modes of the ENSO do not (fully) explain the hydrological trends in the central Florida wetland.

Long-term precipitation patterns in the Caribbean and Gulf of Mexico are strongly linked to the migration of the Intertropical Convergence Zone (ITCZ), in response to insolation changes (Hodell et al., 1991; Haug et al., 2001; Poore et al., 2003). During the northern hemisphere summer, sea-surface temperatures (SSTs) in the Atlantic Warm Pool (including the Gulf of Mexico) rise and the ITCZ precipitation belt migrates northward (Ziegler et al., 2008). Late Holocene Mg/Ca-based SST reconstructions from the Bermuda Rise (Keigwin, 1996), and the Gulf of Mexico (Richey et al., 2007) indicate increased temperatures around 2.5 ka and 1.1 ka (Fig. 8), consistent with the reconstructed ITCZ position. They relate the high SSTs around 1.1 ka and subsequent cooling to the Medieval Warm Period (MWP) and the Little Ice Age (LIA), respectively, forced by solar irradiance variability. The consistently more northward summer position of the ITCZ and increased convective precipitation related to warm SSTs (Cronin et al., 2002; Donders et al., 2011) can explain the consistently wet conditions between 2.0 and 0.7 ka in Florida. Although the subsequent drying trend observed in HHSP over the last millennium can arguably also be caused by basin infilling, the strong and concurrent shift in diatom and vegetation assemblages is consistent with both a more southern ITCZ position and decreased ENSO variability, confirming a strong link between (sub) millennial-scale high and low latitude climate variability during the late Holocene (deMenocal et al., 2000; Mann et al., 2009). Our reconstructions support the usability of local wetland records for reconstructing supraregional past climatological changes, provided that local variability is taken into account, preferably with multiple independent proxies. Relative contribution of the various climatic drivers can potentially be derived from a seasonal reconstruction of rainfall through improved calibration and/or isotope geochemistry aiming at source water origin.

Conclusions

The studied peat records from Highlands Hammock State Park in central Florida show distinct hydrological variability over the past ~2.5 ka in a unique, upland locality relatively independent of base

level. Differences in the timing of change between the pollen and diatom records are likely related to varying sensitivity to hydrological change and the spatial range they describe. However, an overall consistent environmental development can be deduced from the two proxy methods and two cores. The expansion of broadleaf marsh taxa and increased diatom-inferred hydroperiod around ~2.5 ka indicate wetter conditions and the initiation of the wetland, with consistently long hydroperiods at both sites between 2.0 and 0.7 ka. After ~0.7 ka vegetation and diatom assemblages consistently show an abrupt transition to drier and more variable conditions, which can be related to natural wetland succession due to gradual basin infilling, but seem rather abrupt to be fully explained as such. Short phases in aquatic plants are most likely local and not representative of broader conditions.

Implications

The observed humidity changes are explained by increased SSTs in the Gulf of Mexico and the Bermuda Rise, and a related temporary northward migration of the Intertropical Convergence Zone, and increased ENSO activity. The wet phase and subsequent strong drying in the last millennium can be linked to the early Medieval Climate Anomaly and Little Ice Age, respectively. Both the diatom and pollen records reflect the 20th century alterations to the landscape when the park was built. Our analysis shows that in these wetland settings a single record and proxy is not sufficient to reliably detect regional environmental changes. Multiple cores and proxies reveal the degree of consistency and local variability and allow more certain correlations to regional climatic trends.

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.yqres.2015.09.003>.

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