Available online at www.sciencedirect.com
SCIENCE DIRECT®
Quaternary Research 64 (2005) 333 – 342
QUATERNARY RESEARCH
www.elsevier.com/locate/yqres

# Quantification strategies for human-induced and natural hydrological changes in wetland vegetation, southern Florida, USA

Timme H. Donders *, Friederike Wagner, Henk Visscher

*Department of Palaeoecology, Laboratory of Palaeobotany and Palynology, Utrecht University, Budapestlaan 4, 3584 CD Utrecht, The Netherlands*

Received 7 September 2004
Available online 6 October 2005

**Abstract**

An accurately dated peat profile from a mixed cypress swamp in the Fakahatchee Strand Preserve State Park (FSPSP, Florida, USA) has been examined for pollen and spores. The near-annual resolved pollen record shows a gradual shift from a wet to a relatively dry assemblage during the past 100 years. Timing of drainage activities in the region is accurately reflected by the onset and duration of vegetation change in the swamp. The reconstructed vegetation record has been statistically related to pollen assemblages from surface sediment samples. The response range of the FSPSP wetland to environmental perturbations could thus be determined and this allows better understanding of naturally occurring vegetation changes. In addition, the human impact on Florida wetlands becomes increasingly apparent. Superimposed high-frequency variation in the record suggests a positive correlation between winter-precipitation and pollen productivity of the dominant tree taxa. However, further high-resolution analysis is needed to confirm this relation. The response range of the FSPSP wetland to environmental perturbations on both annual- and decadal-scales documented in this study allows recognition and quantification of natural hydrological changes in older deposits from southwest Florida. The strong link between local hydrology and the El Niño Southern Oscillation makes the palynological record from FSPSP highly relevant for studying past El Niño—variability.

*Keywords:* Florida; El Niño; Pollen; Vegetation change; Drainage; Precipitation; Modern analogues

## Introduction

The Florida peninsula is situated at the transition zone between the wet-subtropical and tropical rainy realms (Thomas, 1974). Apart from being broadly determined by this north-to-south temperature gradient, South Florida wetland ecosystems are strongly controlled by the precipitation-driven surface sheet flow originating from Lake Okeechobee (Burns, 1984; Duever et al., 1986).

Small altitude variations in the generally flat subsurface around Lake Okeechobee create distinctive patterns in local hydroperiod and water depth, which are the two main parameters determining the nature of local plant communities (Kushlan, 1990; Willard et al., 2001a). Hence, local vegetation composition directly reflects water availability and, when reconstructed through time, vegetation changes provide a valuable archive of past hydrologic conditions for the entire region. In South Florida, the strength of the El Niño Southern Oscillation (ENSO) accounts for over 50% of the precipitation available to the vegetation during the growing season (data available on: http://climexp.knmi.nl/ and http://www.cpc.ncep.noaa.gov, NOAA Climate Prediction Center; Cronin et al., 2002). A record of past hydrologic conditions will thus provide important clues about past El Niño-variability, magnitude and persistence. Although South-Florida swamp ecosystems are in general very sensitive to changes in water availability, the exact extent of vegetation response to changing hydrology needs to be determined in order to enable quantification of observed vegetation changes in the past.

Pollen analysis is the principle technique available for determining vegetation response to past terrestrial environmental change (Bennett and Willis, 2001). Traditionally, vegetation reconstructions based on pollen analysis have focused on long-term, (sub-) centennial to millennial time-scales. Pollen records from Florida are no exception to this practice (Watts, 1980; Watts and Hansen, 1994; Delcourt and

---

* Corresponding author. Fax: +31 30 253 5096.
*E-mail address:* t.h.donders@bio.uu.nl (T.H. Donders).

0033-5894/$ - see front matter © 2005 University of Washington. All rights reserved.
doi:10.1016/j.yqres.2005.08.016

Delcourt, 1985). However, the potential of high-resolution studies that focus on annual to decadal climate variability, as present in ENSO, has not been fully utilized (Green et al., 1988). Pollen production rates have been shown to depend on annual temperature (Hicks, 2001) and precipitation levels (Willard et al., 2003). Pollen analysis on very high temporal resolution can likely be used as a proxy for annual-scale climate variability, besides general long-term vegetation reconstructions.

This paper presents a well-dated 20th century pollen record at near-annual resolution from a South-Florida wetland. The response of local vegetation to known changes in environmental conditions is determined and the fossil data are compared to a surface-sample dataset previously published by Willard et al. (2001b), supplemented with new surface sample data from southwest Florida. Thereby, the magnitude of change in the pollen record and the wetland ecosystem sensitivity can be established. In addition, the relation between high-frequency variation in the pollen record and annual precipitation changes is investigated, the latter being strongly influenced by the ENSO climate system. Together, these approaches bridge the gap between present-day ecology and paleoecological reconstructions, and provide a solid framework for interpreting further pollen records from this locality.

## Site description

### Regional and local

The site studied is located in a relatively undisturbed section of the Fakahatchee Strand Preserve State Park (FSPSP) wetland (25° 95′N, 81° 49′W, Fig. 1). The FSPSP is part of the larger ‘Big Cypress National Forest’ in South-Central Florida, and its central ‘strand’ is an elongated karst structure forming a wide and shallow channel or slough. A peat layer seals off the underlying limestone deposits of the early Pleistocene Tamiami Formation (Gleason and Stone, 1994). The sheet flow through the 40-km long strand is slow due to high flow-resistance of the forest and generally low topography of the terrain (Watts and Hansen, 1994), where the maximum height difference is 2 m. This creates a stable low-energy depositional environment with undisturbed peat accumulation in the slough.

On the peaty soils, bald cypress (*Taxodium distichum*) dominates the central swamp forest, which is surrounded by prairie and pinelands and bordered by mangrove vegetation towards the coastal area in the south. Between 1947 and 1952, a network of tramways and borrows for logging was constructed in the adjacent area, but this did not directly affect the coring site itself (Burns, 1984), which is still dominated by a significant stand of old-growth *Taxodium*.

### Hydrology and vegetation

Annual precipitation in Southern-Florida has a bi-modal distribution, and the main precipitation is received during summer and an additional, frequently occurring, wet period in winter (Duever et al., 1986). The swamp forest largely depends on the water storage capacity of the peat to retain the water from winter precipitation into the spring growing season (Burns, 1984). The typical hydroperiod of the cypress swamp ecosystem is 6–9 months/year and it has a moderate fire frequency (5 times/century), which allows extensive organic matter accumulation (peat thickness >1 m.). To thrive in these conditions, *Taxodium* is highly tolerant to long hydroperiods, often associated with low oxygen levels, and is very fire-resistant (Myers and Ewel, 1990). Fires burn through the prairies and pinelands every 2–7 years (Austin et al., 1990), but they seldom penetrate the watterlogged, peaty cypress strands. Fire-frequency is a factor of ~4 lower in swamps than in the surrounding marshes and wet-prairie grasslands, and actual peat burns only occur during extreme droughts (Duever et al., 1986). *Taxodium* are deep-rooting trees and they usually resprout after fires, and only in case of extreme fire events the root system is consumed and tree recovery is no longer possible (Alexander and Crook, 1974).

Vegetation in the FSPSP is very diverse and considered a rare mix of tropical and temperate plants. At least 477 vascular plant species have been identified, of which the major part is tropical (69% of trees and 87% of orchids, epiphytes and ferns, Austin et al., 1990).

In the wet central slough, the dominant *Taxodium distichum* is complemented by canopy species typical for swamp soils in Florida (Davis, 1943). At relatively dry sites these are primarily: palms (*Roystonea elata* and *Sabal palmetto*), *Quercus virginiana*, *Q. laurifolia*, *Acer rubrum*, *Pinus elliotii*, *Persea palustris*, *Magnolia virginiana*, *Chrysobalanus icaco*, *Ficus aurea*, *Ilex cassine*, *Rapanea punctata* and *Myrica cerifera*. Ferns (37 species, including epiphytic forms) constitute the predominant undergrowth in these moist areas that are not inundated for very long periods. At wetter sites where water is relatively deep and hydroperiods are long (>9 months/year) *Salix caroliniana*, *Cephalanthus occidentalis*, *Fraxinus caroliniana* and *Annona glabra* are more abundant.

The central slough is surrounded by wet prairie with numerous tree island stands. The prairie consists mainly of grasses (*Muhlenbergia capillaris*, *Phragmites australis*), sedges (*Cladium jamaicense*, *Cyperus* sp.), Amaranthaceae and Asteraceae (typical of fluctuating water levels) as well as aquatic plants (*Sagittaria graminea*, *Nymphea* sp.) in somewhat wetter areas. With respect to the wet prairie, tree islands are slightly elevated areas dominated by trees and ferns. Their vegetation varies between mixed-temperate and tropical species, even exclusively palms. Wet prairies have a moderate and fluctuating water depth (<0.5 m) and hydroperiod (<6 months/year, Willard et al., 2001b).

Cypress are generally stressed by dewatering and, unlike most other trees, they can survive permanent inundation, although new saplings do need a dry season to germinate (Alexander and Crook, 1974). As a result of this limitation to reproduction, cypress regeneration is generally low (Visser and Sasser, 1994). A study to detect forest stress in response to increased river flow has revealed that increasing water level

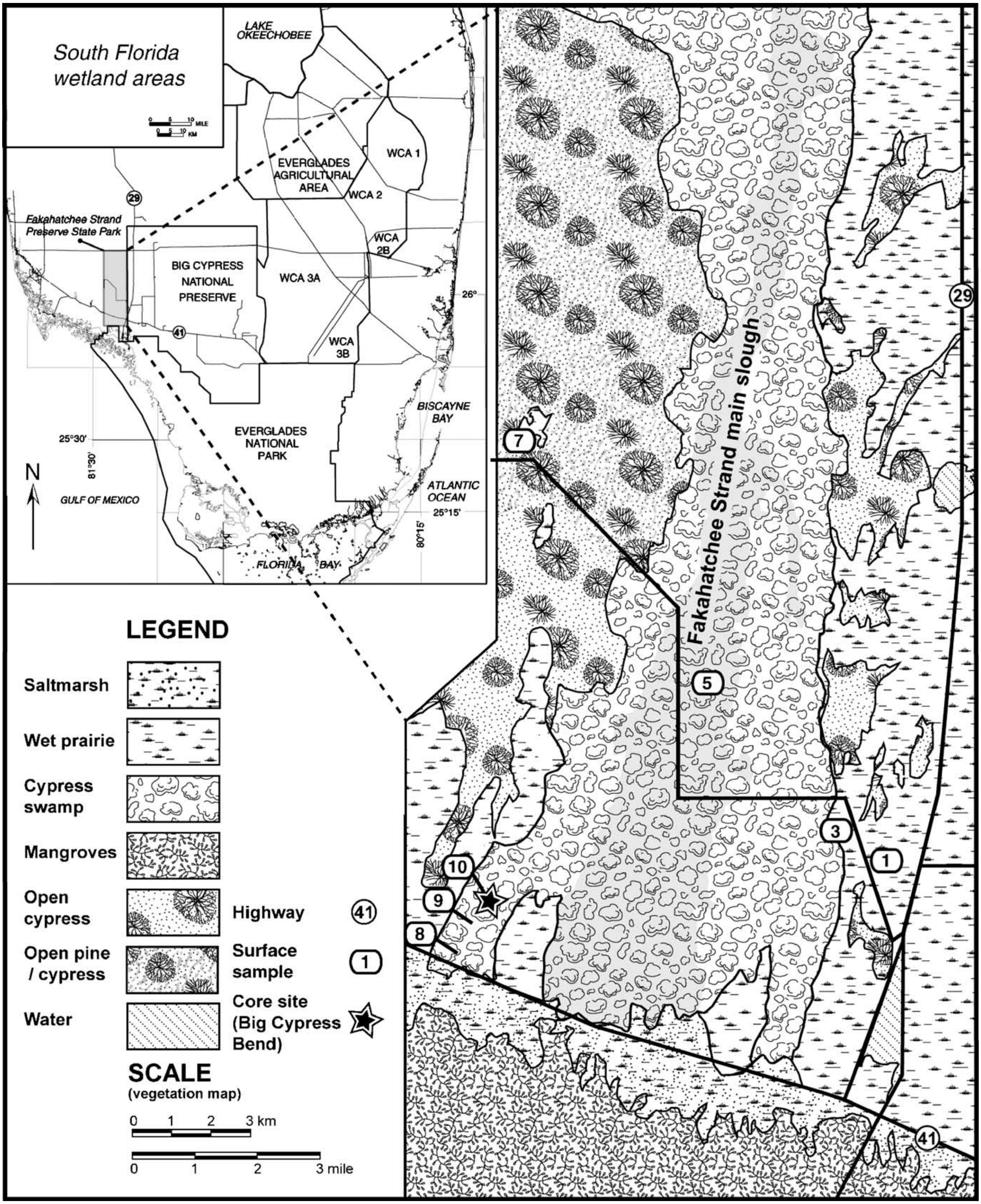


Figure 1. Location and natural communities map of the Fakahatchee Strand Preserve State Park (FSPSP), Florida, USA. Coring site (FAK I98, ★) and surface samples sites (①) are indicated. Regional map adapted from Willard et al. (2001b).

has a stressing effect in *Q. laurifolia* and to a lesser extent in *F. caroliniana* (Ford and Brooks, 2002). Trees were shown to suffer from trunk rot, increased parasitism, crown thinning, branch mortality and even death. However, no such effects were observed in *Taxodium* trees present in the studied area. *F. caroliniana* is generally considered a wet-tolerant species

(Austin et al., 1990; Dunson, W.A., Florida Water Resource Management Department, personal communication, 2002), although the study by Ford and Brooks (2002) shows there are certain limits to this tolerance. Presently, *F. caroliniana* occurs together with *A. glabra* in the deepest areas of the FSPSP slough but the slow-growing *Taxodium* will most likely replace these trees since the area was logged only 50 years ago (Burns, 1984).

## Material and methods

### Coring and processing

A peat core was taken in 1998 from the end of a 300-m boardwalk, which penetrates into old-growth mixed cypress forest. A large-diameter (20-cm) manual surface corer (Clymo, 1988) was used to obtain a 43-cm sediment column (FAK I98), consisting of dark peat with abundant leaf fragments in the uppermost 20 cm. It was sliced and sub-sampled at 1-cm intervals for pollen analysis with a small volumetric peat drill. In addition, seven surface sediment samples from different vegetation units within the FSPSP were collected using a small 4-cm-diameter push core (Fig. 1, Table 1). These samples were homogenized before sub-sampling for pollen analysis.

Pollen and spores were isolated from samples following standard palynological peat processing techniques adapted from Faegri et al. (1989) now in use at the Laboratory of Palaeobotany and Palynology (LPP), Utrecht University, the Netherlands. *Eucalyptus* pollen tablets were added prior to processing to determine pollen concentrations in sediment. *Eucalyptus* was used instead of standard *Lycopodium clavatum,* which occurs naturally in the FSPSP. Processing included carbonate and silicate removal with HCl and HF, sieving over 7-μm and 120-μm mesh to remove fine and coarse fractions, respectively, boiling in KOH to remove organic fractions and acetolysis for removal of polysaccharides and coloring of the pollen. Residues were mounted in

Table 1
Location of surface samples from FSPSP with local vegetation at time of collection (February 2004)

| Number and name | Dominant vegetation | Sec. vegetation | Tert. vegetation | Hydrology |
|---|---|---|---|---|
| 1 Wet prairie “Fak1 prairie” | In order of importance<br>*Muhlenbergia capillaris*<br>*Cladium jamaicense*<br>*Spartina bakeri* | In order of importance<br>*Lobelia feayana*<br>*Phragmites australis* | In order of importance<br>*Sagittaria graminea*<br>*Crinum americanum* | At time of collection<br>5–10 cm standing water |
| 3 Pine prairie “Fak3 pine” | *Pinus elliottii*<br>*Taxodium distichum*<br>*Eupatorium capillifolium*<br>*Cladium jamaicense* | *Sabal palmetto*<br>*Rapanea punctata*<br>*Persea palustris*<br>*Serenoa repens*<br>cf. *Baccharis halimifolia* | *Quercus virginiana*<br>*Psychotria nervosa* | Moist soil |
| 5 Ballard’s pond “Fak5 pond” | *Taxodium distichum*<br>*Quercus laurifolia*<br>*Fraxinus caroliniana*<br>*Rapanea punctata*<br>*Roystonea regia*<br>*Itea virginica* | *Ilex cassine*<br>*Annona glabra*<br>*Psychotria nervosa*<br>*Fern* indet.<br>*Persea palustris*<br>cf. *Baccharis halimifolia* | | 10–20 cm<br>Standing water |
| 7 Palm prairie “Fak7 palm” | *Cladium jamaicense*<br><br>*Myrica cerifera*<br>*Ilex cassine*<br>*Pinus elliottii*<br>*Sideroxylon* sp.<br>*Muhlenbergia capillaris*<br>*Spartina bakeri* | *(Dominant continued)*<br><br>*Berchemia scandens*<br>cf. *Baccharis glomeruliflora*<br><br>*(Sec. Vegetation)*<br>*Taxodium distichum*<br>*Sabal palmetto* | | Very moist,<br>waterlogged soil |
| 8 Begin boardwalk “Fak8 beginB” | *Acer rubrum*<br>*Quercus laurifolia*<br>*Sabal palmetto*<br>*Roystonea regia* | *Rapanea punctata*<br>*Taxodium distichum*<br>*Acrostichum danaeifolium*<br>*Thelypteris* sp. | | 20 cm<br>Standing water |
| 9 Mid of boardwalk “Fak9 midB” | *Taxodium distichum*<br>*Fraxinus caroliniana*<br>*Rapanea punctata*<br>*Ilex cassine* | *Sabal palmetto*<br>*Quercus laurifolia* | | 30 cm<br>Standing water |
| 10 End boardwalk “Fak10endB” | *Taxodium distichum*<br>*Fraxinus caroliniana*<br>*Acer rubrum* | *Ficus aurea*<br>*Quercus laurifolia*<br>*Rapanea punctata*<br>*Thelypteris* sp. | *Saururus cernuus*<br>*Sabal palmetto* | >50 cm<br>Standing water |
| Tree island tail[a] “97-10-09-3”<br>(Willard et al., 2001a) | *Magnolia* sp.<br>*Smilax* sp.<br>*Ficus* sp. | *Thalia* sp.<br>*Mikania scandens*<br>*Peltandra virginica* | *Cladium jamaicense* | No standing water<br>Note: not from FSPSP |

[a] This sample is identified as a close analogue to core samples from zone FIII in Figure 4b. Location is WCA 3A, see map Figure 1.

silicon oil on microscopic slides for analysis by light-microscopy at 400× magnification.

### Chronology

Core chronology is described in detail in Donders et al. (2004). Dating is based on high-resolution AMS $^{14}$C dating of leaf macrofossils from nine horizons. Data were calibrated with the $^{14}$C-anomaly caused by nuclear testing during the 20th century. An accurate age-depth model was thus obtained, especially for the top half of the core. The base of the core was dated at 1910 AD, in accordance with dates from a core nearby (Donders et al., 2004). Apart from a compaction effect, sedimentation rates are stable, as confirmed by loss-on-ignition (LOI) analysis of a parallel core.

### Pollen analysis and data-handling

A minimum of 300 pollen and spores were identified to calculate percent abundances. Pollen and spore identification was based on Jones et al. (1995, 1999), Kapp et al. (2000) and the reference collections of the United States Geological Survey (Reston, VA), and LPP Utrecht, the Netherlands. To delimit pollen assemblage zones in the record, samples were numerically zoned using optimal sum-of-squares partitioning of Birks and Gordon (1985) as implemented in the program ZONE (Lotter and Juggins, 1991). The significant number of stratigraphic zones was assessed using the broken stick model (Bennett, 1996). With the Tilia/TiliaGraph 2.0.b.5 and TGView 1.3.1.1. computer programs (Grimm, 1991–2001) pollen percentages were calculated and plotted. Taxa with a maximum abundance lower than 2% and/or with less than five occurrences were omitted.

A summary of the data was made using PCA (principal component analysis) ordination methods with the program Canoco 4.0 (ter Braak and Smilauer, 1998). A linear model was used because the gradient length of the pollen data did not exceed 1.5 SD (standard deviations).

The fossil and surface sample pollen data were compared in a Correspondence Analysis (CA) to establish the magnitude of change recorded in the core. The extensive dataset published by Willard et al. (2001b) covers a broad range of South-Florida wetland ecosystems. However, most were collected in the Everglades National Park and adjacent natural areas and do not fully encompass the FSPSP ecosystem. Surface samples collected for this study are used to supplement this dataset with samples from cypress forest and other vegetation units dominating the FSPSP. In this manner, pollen ‘fingerprints’ of modern environments can be used to find similar sedimentary environments in cores, irrelevant of taxa that might be over- or underrepresented compared to their actual abundance (Cohen, 1975). Although deposition rates can vary strongly between sites (Willard et al., 2001a), the low-relief Florida wetland areas are not an erosive setting. Therefore, the surface samples are considered to represent recent sedimentary conditions.

## Results

### Pollen record, general description and zonation

A total of 42 core samples were analyzed for pollen and spores. Results are plotted as percentages in Figure 2a. Pollen and spore preservation was good although abundant organic matter complicated the analysis. Since the material is recent no large shifts are present in the record. Any changes are limited to trends within the mixed cypress swamp vegetation-unit. No charcoal particles or other indications of fire events (e.g., peaks of fern abundance) were found, corroborating the dating results (Donders et al., 2004).

The numerical zonation indicates two significant splits (95% confidence level), which results in three distinct pollen zones (Fig. 2a). Zone FI has the highest amount of *Taxodium* pollen, varying between 70% and 90% (lowermost sample clearly lower, around 60%). Herbs average around 10%, and consist mainly of Amaranthaceae-type pollen although many different species occur in small peaks or as single grains, reflecting the large species diversity. Trees and shrubs, other than *Taxodium*, are not very abundant but slightly increase in the top half of the zone.

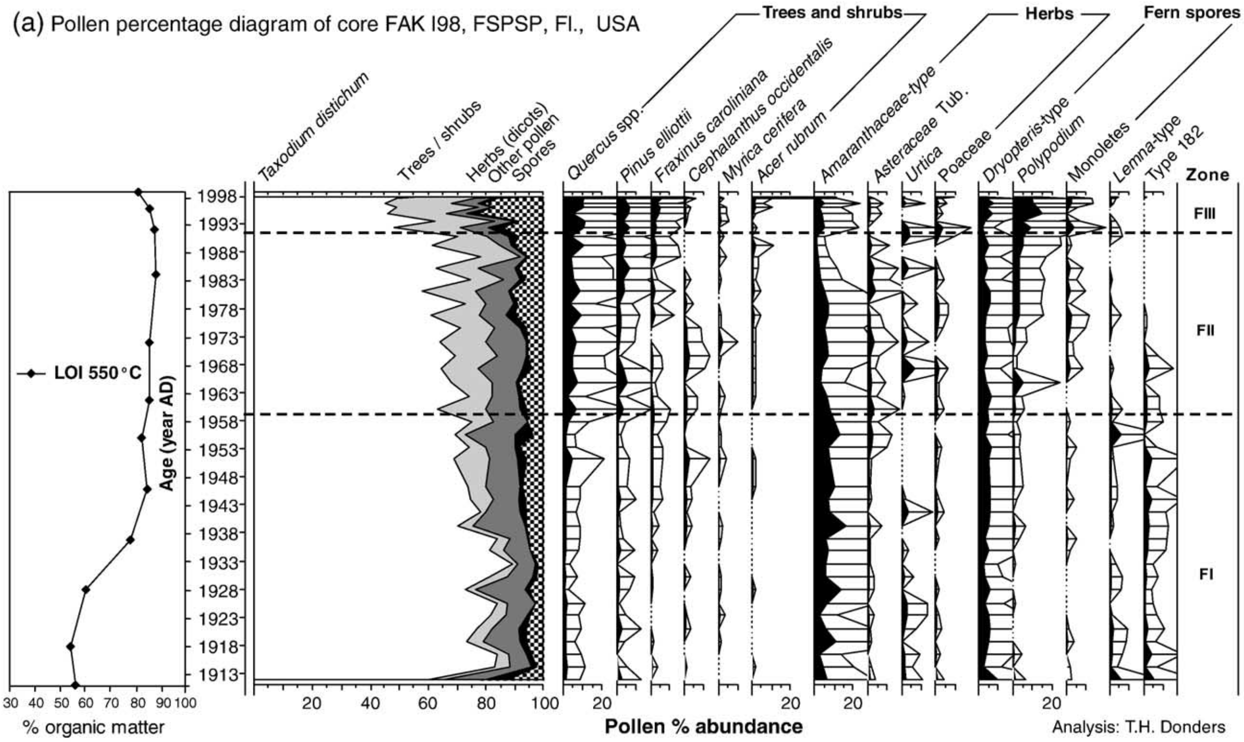
Zone FII marks a clear increase of temperate trees and shrubs (mainly *Quercus* and *Pinus*) from 5% in zone FI to approximately 15% in FII. The total number of herbs remains constant but shifts towards a more mixed assemblage with Asteraceae and Poaceae. Ferns become more abundant and diverse, notably *Polypodium* sp. that grows on trunks of *Quercus* trees.

Zone FIII shows a further (recent) increase of temperate trees such as *A. rubrum*, *M. cerifera* and notably *F. caroliniana*. Although the latter occurs in the deepest parts of the swamp it is also a fast-growing opportunistic species. Here, it concurs with the rise in less wet-tolerant species, such as *Quercus* sp. and *P. elliottii*.

Although the site is largely inundated, true aquatic plants (*Utricularia* sp., *Myriophyllum aquaticum* and *Typha* sp.) occur infrequently since the swamp experiences seasonal drying and little light penetrates the canopy. The presence of *Lemna*-type pollen and Type 182 spores, described by van Geel et al. (1983) to occur in marshland, indicate a wet environment in zones I and (part of) II.

The major trends are also present in the concentration data. However, detailed reliable interpretation is hampered by low exotic counts per sample.

Results of the surface sample counts from FSPSP yield distinctly different pollen assemblages (Fig. 2b). Evident is the clear separation between pine-pollen dominated prairie environments and cypress/oak dominated long-hydroperiod swamp forest. The mixed hardwood pollen assemblage in sample ‘Fak8 beginB’ reflects well the transition zone between short-hydroperiod wet prairie and long-hydroperiod cypress swamp present at the site (Table 1). The samples were considered suitable for comparison with fossil data and the available surface sample data of Willard et al. (2001b). To combine and compare our data with the results of Willard et al. (2001b), the


(a) Pollen percentage diagram of core FAK I98, FSPSP, Fl., USA

(b) Pollen percentage diagram of FSPSP surface samples

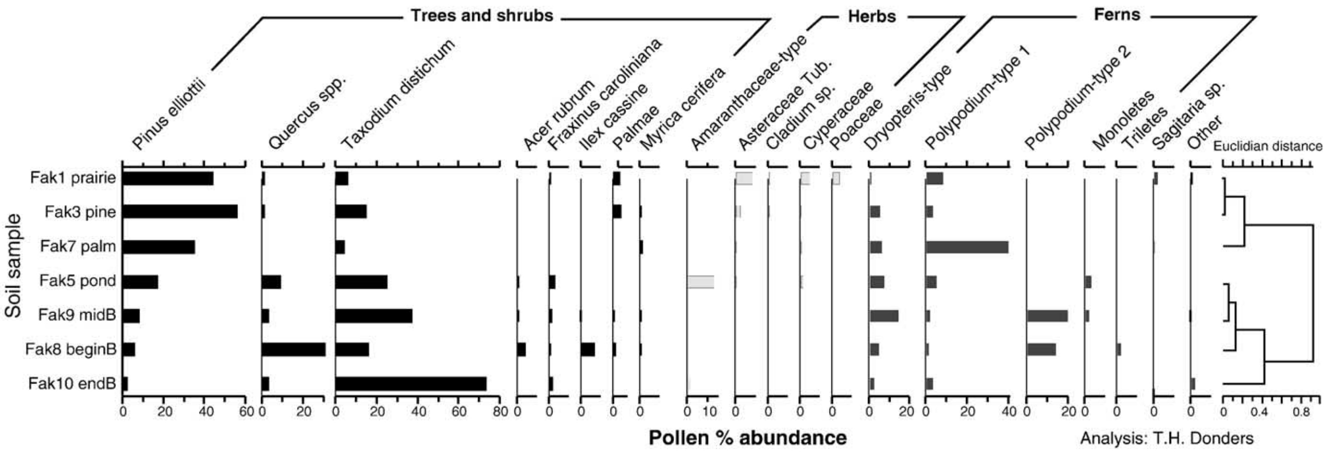


Figure 2. Pollen percentage diagrams of core FAK I98 (a) and FSPSP surface sample counts (b). Pollen are grouped according to their ecological characteristics, rare types are omitted. Note that *Taxodium* sp. is only presented in the grouped diagram. Loss-on-ignition (LOI) was measured on a parallel core to quantify organic content, following methods outlined by (Dean, 1974).

taxa grouping used in that study was followed. Consequently, some loss of information is inevitable.

### *Ordination results and high-frequency changes*

The PCA ordination diagram shows a clear spread of fossil samples and taxa (Fig. 3a). The 1st axis of the plot is in concurrence with a hydrological gradient of taxa as described in the 'Hydrology and vegetation' section. Therefore, the value of the 1st PCA axis, explaining 35% of total variance, can be interpreted as a relative measure of the dry/wet species-index of a pollen assemblage. Plotted on a timescale, a trend from stable wet towards drier conditions becomes apparent (Fig. 3b). Continuously wet conditions are followed by an initially subtle drying trend around 1930. The drying accelerates after 1955 with a brief interruption by wetter conditions around 1970.

The CA results of all data (surface and fossil samples) show two distinct clusters, each with a separate gradient (Fig. 4a). Cluster A is represented by high abundances of mangrove taxa on the upper right (high salt/deepwater tolerant *Rhizophora mangle*, *Avicennia germinans* and *Laguncularia racemosa* and brackish water tolerant *Conocarpus erectus*) and salt-to-fresh marsh taxa on the opposite side (Spackman et al., 1966; Willard et al., 2001b). Thus, the gradient is mainly an indication of salinity, which is a prime parameter for Florida coastal wetlands (e.g., O'Neal et al., 2001). However, a water-

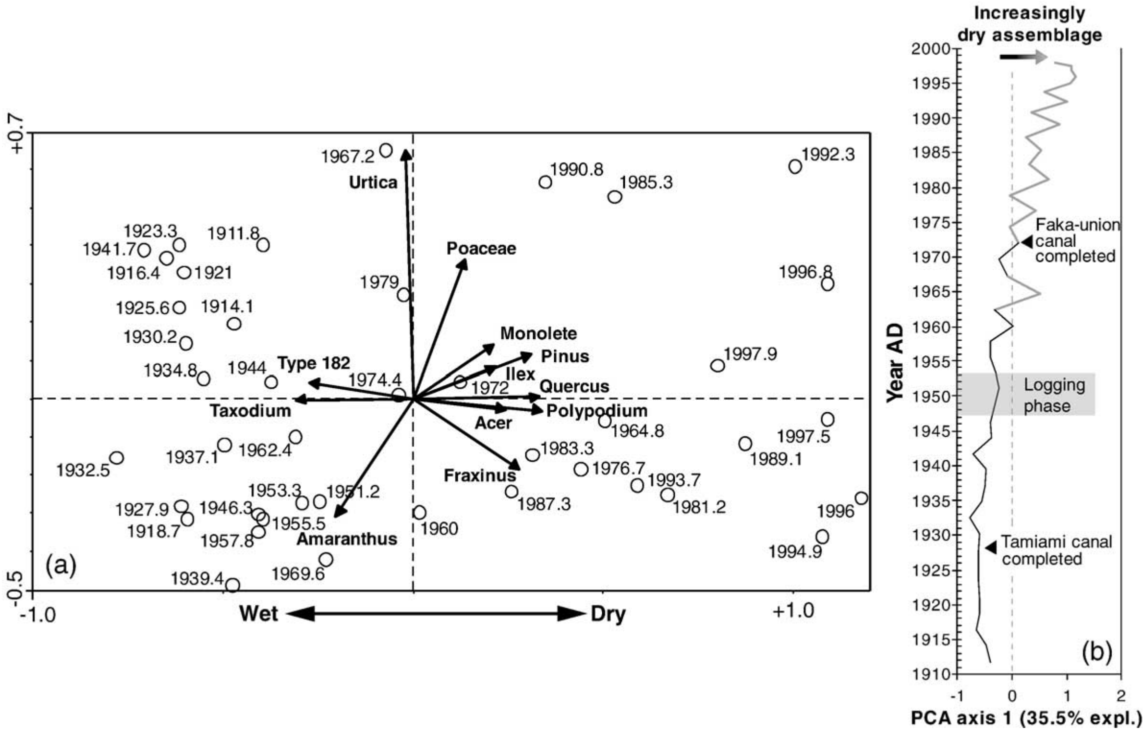


Figure 3. Principal component analysis (PCA) diagram of samples and major species in core FAK I98 (a). First axis of the PCA diagram explains 35% of total variance in the dataset and is concurrent with a hydrological gradient. The value of the 1st axis is plotted on a timescale (b) and is interpreted as a measure of wet/dry species-index of each assemblage.

depth factor is clearly influencing the distribution as well, since mangroves, in contrast to salt marshes, do not experience seasonal drying and can grow in relatively deep water.

Cluster B displays insignificant variation along the x-axis, effectively excluding salinity as a factor of influence. Cluster B includes all the fossil data and is mainly spread along the y-axis, which, analogous to Figure 3a, represents the gradient of relatively dry towards wet-tolerant taxa (Ewel, 1990; Kushlan, 1990; Willard et al., 2001b). The fossil samples overlap with the range of surface samples (Fig. 4b), although samples from zone FI with the highest abundances of *Taxodium* have no modern analogue. However, the upper samples plot close to

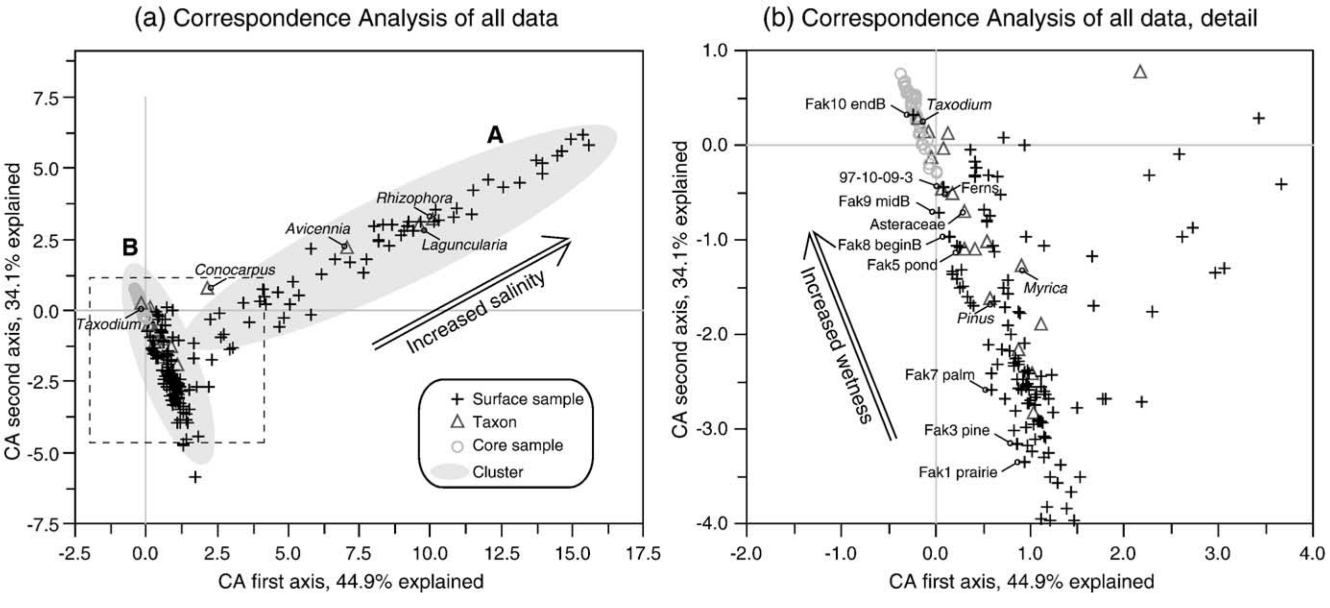


Figure 4. The relation of surface sample data from Willard et al. (2001b) to surface and fossil samples from the FSPSP based on a Correspondence Analysis of all data (a). The dashed area is given in detail (b), which shows that the fossil samples are distributed between the deep-water site 'Fak10 endB' and shallow water sites '97-10-09-3' and 'Fak9 midB' (Table 1). Important taxa are indicated and the gradients (arrows) within the clusters (A, B) are based on ecological descriptions of these taxa.

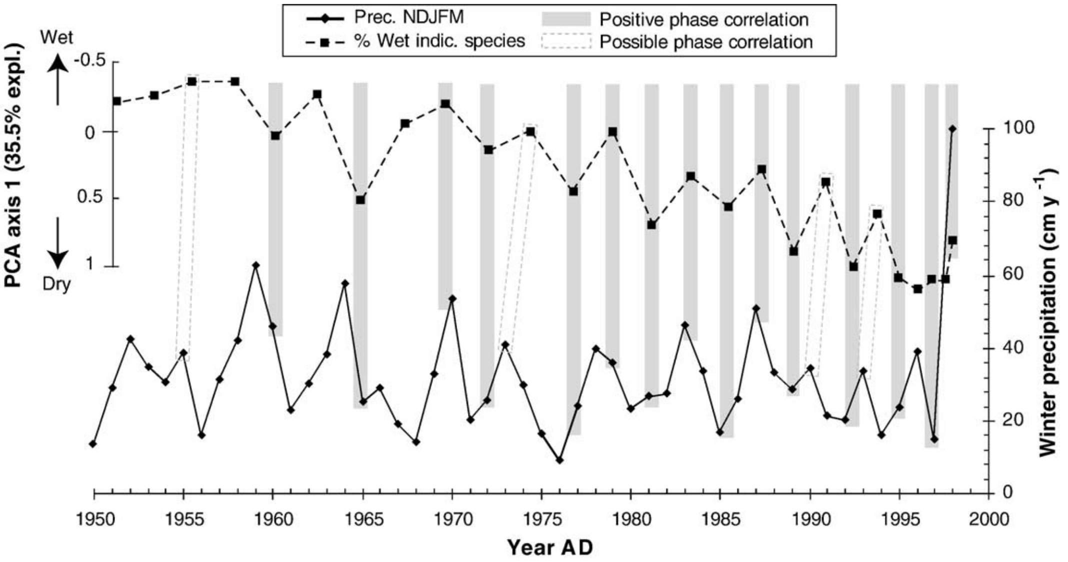


Figure 5. Comparison between wet/dry pollen index (PCA 1st axis) of core FAK I98 and annual winter precipitation recorded in nearby Tampa, Fl. Shaded bands indicate a positive phase relation between peaks of precipitation and shifts in the pollen assemblage. Dating uncertainties are about 2–3 years (Donders et al., 2004).

surface samples representing intermediate water depth ('9 Mid Boardwalk' and '97-10-09-3', Table 1), which confirms the vegetation development seen in Figure 3b.

Superimposed on the general trend, high-frequency variation is observed, in particular between AD 1950–1998. Comparison with a precipitation record from nearby Tampa reveals an in-phase correlation between the dry/wet pollen index (the PCA 1st axis) and winter precipitation for the period AD 1970–1998 (Fig. 5). This is in marked contrast to the pre-AD 1970 data points in which only few peaks show a positive correlation. Pre-AD 1950 data were not included in this comparison since little variability is present there and larger dating uncertainties hamper a year-to-year correlation in the lower part of the core (Donders et al., 2004).

## Discussion

The core top sample contains 60% *Taxodium* pollen, and though it is a dominant feature of the FSPSP vegetation, only approximately 50% of trees are *Taxodium*. The over-representation can partly be explained by the high abundance of tropical plants in the assemblages, which are known to produce low amounts of pollen (Kershaw and Hyland, 1975). *Taxodium* pollen do not disperse very far (Riegel, W.L., personal communication, 2003) and the relatively closed canopy settings and slow water flow at the site prevent pollen influx from large distances (Birks and Birks, 1980). Consequently, the presented record is predominantly local and must not be compared directly to regional pollen diagrams from large-catchment sites, which present a signal from a much broader, open area (Janssen, 1973). Local effects are normally considered disadvantageous for the interpretation of pollen records. However, since the local water level directly depends on the regional sheet-flow, the observed local vegetation changes can represent a large-scale signal by responding to changes in sheet-flow intensity. The natural drainage pattern has been altered substantially since the early 20th century by construction of levees, canals, the development of the Everglades Agricultural Area, and progressive urbanization (Light and Dineen, 1994). Thus, the drying trend in the pollen data can be explained by comparing the timing of the observed changes with man-made alterations of the sheet flow through South-Florida.

The drying in the pollen record starts shortly after the construction and the Tamiami Canal in 1928 (Duever et al., 1986) (Fig. 1), which drains large areas in South Florida and thus increases run-off. Construction of the Barron Collier Canal along State Road 29 in 1926 might also have had an impact, however, the canal is shallow and dug in a low-permeability surface. The drying trend accelerates after logging burrows and tramways were constructed between 1947 and 1952 (Burns, 1984). Finally, the completion of the Faka-Union canal in 1972 clearly had an impact by further drying the swamp (Fig. 3b). This canal drains the west side of the FSPSP, and lowered the water table from 0.90 to 0.30 m a.m.s.l. (Swayze and McPherson, 1977), although this decrease was in part temporary. These canals are located within the southwest Florida aquifer and therefore have a direct impact on the FSPSP hydrology (Duever et al., 1986). The water management is obvious from the decrease in Amaranthaceae-type pollen (Fig. 2a). Though they occur in dry periods, these annual weeds are characteristic of strongly fluctuating water levels (Willard et al., 2001a), which have been suppressed by the installation of water-control structures.

An 1882 land survey carried out by Florida prospectors describes the area that is now the mangrove-dominated seashore of the FSPSP as 'left unsurveyed, consist(s) of salt marsh with a heavy growth of grass, cut up by saltwater layer(s) and mangrove' (Data available on http://www.labins.org). The area that was surveyed in more detail does not refer to mangrove anywhere else, and only hammocks (tree islands), prairies and swamp are mentioned. Presently, the section of the

FSPSP south of Tamiami Trail is dominated by mangrove forest (Fig. 1). These changes are consistent with more saltwater intrusion in recent years due to the before-mentioned reduced sheet flow. The historical record thus independently corroborates the changes caused by the water-control structures, and gives additional insight into the original state of the FSPSP wetland.

Within the FSPSP, reconstructed local vegetation appears to accurately reflect variations in regional hydrology. In both Figures 3b and 4b, the zone FIII samples are consistently related to drier conditions. In the first approach, historical information directly relates the pollen assemblages to past hydrological conditions. The second method compares pollen assemblages with surface samples along environmental gradients, and thus relates the upper samples to a surface sample with intermediate water depth (sites 'Fak9 midB' and '97-10-09-3', Table 1). Results of both methods point to a permanent lowering of the water table of between 0.2 and 0.5 m during the second half of the 20th century. Although the human impact in FSPSP is relatively small compared to changes in southeast Florida (Willard et al., 2001a), the ecological information available allows the reconstruction of even these moderate shifts within a fairly accurate range. An entirely quantitative reconstruction is not yet possible, since hydroperiod data are difficult to obtain, but the statistical analysis (CA) of surface and core samples is a valid approach to interpret past vegetation changes in this type of setting.

The high-frequency correlation between the dry/wet index and the winter precipitation shown in Figure 5 indicates a sensitivity of pollen production rates to annual climate variability. Winter precipitation is the main water supply for the growing season (Burns, 1984), and thus an important parameter. A positive correlation between *Pinus* pollen deposition and precipitation has been observed from pollen trap counts (Willard et al., 2003). *Taxodium*, the main component of the pollen record, favors long hydroperiods for optimal growth conditions (Keeland et al., 1997), likely leading to increased flowering intensity. This relation can offer a mechanism for the observed correlation in Figure 5, analogous to the response seen in *Pinus* (Willard et al., 2003). The observed response can serve as a proxy to detect short periods in increased winter precipitation, which is crucial for ENSO climate reconstruction studies.

The pollen assemblage before AD 1970 is dominated to such a degree by wet-indicating *Taxodium* pollen that short increases in precipitation cannot further change the assemblage (Figs. 2a, 3a). Therefore, the correlation between winter precipitation and pollen assemblage composition is not visible here. Accurate analysis of single-taxa pollen concentrations might solve this percentage effect. Additionally, slight dating inaccuracies may inhibit the analysis in the early part of the record and although sampling resolution is high, samples contain slightly more sediment than a single year. Generally, the pattern observed from the high-resolution analysis agrees well with a similar study performed by Green et al. (1988) on peat material and pollen traps from South-Eastern Australia, which implied that short-term changes in rainfall effect ecological change and are reflected in the pollen record.

## Conclusions

The pattern observed in the pollen data from the Fakahatchee Strand Preserve State Park is consistent with the alterations of water flow in southwest Florida, and thus the local effects of drainage activities and lumbering on Florida wetlands can be clearly defined. The annual variability and decadal trends can be distinguished in palynological analysis on high-resolution, although this can be further improved by using concentration-based pollen data. Such records are crucial for bridging the gap between present-day ecology and palaeoecological reconstructions.

The response range of the FSPSP wetland to environmental perturbations on both annual- and decadal-scale documented in this study, allows recognition of natural hydrological changes in older deposits from southwest Florida. Spatial patterns of the vegetation (Spackman et al., 1969; Duever et al., 1986; Myers and Ewel, 1990; Dennis, 1988) and water regime (Gleason, 1974; Burns, 1984) are well studied and, combined with the surface sample data now available (Willard et al., 2001b; this study), variations in past precipitation and sheet flow intensity can be reconstructed and quantified. Since the strength of ENSO accounts for over 50% of the winter precipitation in Florida, the palynological record from FSPSP is highly relevant for studying past El Niño-variability, magnitude and persistence.

## Acknowledgments

The authors are indebted to the Fakahatchee Strand Preserve State Park staff for great cooperation and technical support. We thank Debra Willard for reviewing the manuscript, her indispensable help with the Florida pollen and for kindly providing datasets. We are grateful to Eric Grimm for his revision of the manuscript. Fieldwork support from Ton van Druten, Wolfram Kürschner and Thomas van Hoof is greatly appreciated. Thanks to Oliver Heiri for his skills in statistics, Klaas van der Borg and Arie de Jong from the AMS radiocarbon dating facility in Utrecht. This research was supported by the Council of Earth and Life Sciences, Netherlands organization for Scientific Research (NWO). This is publication number 20041203 of the Netherlands school of Sedimentary Geology (NSG).

## References

Alexander, T.J., Crook, A.G., 1974. Recent vegetational changes in Southern Florida. In: Gleason, P.J. (Ed.), Environments of South Florida: Present and Past. The Miami Geological Society, Miami, pp. 61–72.

Austin, D.F., Jones, J.L., Bennett, B.C., 1990. Vascular plants of the Fakahatchee Strand. Florida Scientist 53, 85–88.

Bennett, K.D., 1996. Determination of the number of zones in a biostratigraphical sequence. New Phytologist 132, 155–170.

Bennett, K.D., Willis, K.J., 2001. Pollen. In: Smol, J.P., Birks, J.B., Last, W.M. (Eds.), Tracking Environmental Change using Lake Sediments. Developments in Paleoenvironmental Research. Kluwer, Dordrecht, the Netherlands, pp. 5–32.

Birks, H.J.B., Birks, H.H., 1980. Quaternary Palaeoecology. Edward Arnold, London.

Birks, H.J.B., Gordon, A.D., 1985. Numerical Methods in Quaternary Pollen Analysis. Academic Press, London.

Burns, L.A., 1984. Productivity and water relations in the Fakahatchee Strand of South Florida. In: Ewel, K.C., Odum, H.T. (Eds.), Cypress Swamps. University Press of Florida, Gainesville, pp. 318–333.

Clymo, R.S., 1988. A high resolution sampler of surface peat. Functional Ecology 2, 425–431.

Cohen, A.D., 1975. Peats from the Okeefenokee swamp–marsh complex. Geoscience and Man 11, 123–131.

Cronin, T.M., Dwyer, G.S., Schwede, S.B., Vann, C.D., Dowsett, H., 2002. Climate variability from the Florida Bay sedimentary record: possible teleconnections to ENSO, PNA and CNP. Climate Research 19, 233–245.

Davis, J.H., 1943. The Natural Features of Southern Florida, Especially the Vegetation, and the Everglades. The Florida Geological Society, Tallahassee, Florida.

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

Delcourt, H.R., Delcourt, P.A., 1985. Quaternary Palynology and Vegetational History of the Southeastern United States. In: Bryant, V.M., Holloway, R.G. (Eds.), Pollen Records of Late Quaternary North American Sediments. AASP Foundation, pp. 1–37.

Dennis, J.V., 1988. The Great Cypress Swamps. Louisiana State University Press.

Donders, T.H., Wagner, F., Van der Borg, K., de Jong, A.F.M., Visscher, H., 2004. A novel approach for developing high-resolution sub-fossil peat chronologies with $^{14}$C dating. Radiocarbon 46, 455–463.

Duever, M.J., Carlson, J.E., Meeder, J.F., Duever, L.C., Gunderson, L.H., Riopelle, L.A., Alexander, T.R., Myers, R.L., Spangler, D.P., 1986. The Big Cypress National Preserve. National Audubon Society, New York.

Ewel, K.C., 1990. Freshwater wetlands and aquatic ecosystems: swamps. In: Myers, R.L., Ewel, J.J. (Eds.), Ecosystems of Florida. University of Central Florida Press, Orlando, pp. 281–323.

Faegri, K., Kaland, P.E., Krzywinski, K., 1989. Textbook of Pollen Analysis. John Wiley and Sons, Chichester.

Ford, C.R., Brooks, J.R., 2002. Detecting forest stress and decline in response to increasing river flow in southwest Florida, USA. Forest Ecology and Management 160, 45–64.

Gleason, P.J., 1974. Environments of South Florida: Present and Past. Miami Geological Society, Miami, p. 452.

Gleason, P.J., Stone, P., 1994. Age, origin, and landscape evolution of the Everglades peatland. In: Davis, S.M., Ogden, J.C. (Eds.), Everglades: the Ecosystem and its Restoration. St. Lucie Press, Delray beach, Florida, pp. 149–197.

Green, D., Singh, G., Polach, H., Moss, D., Banks, J., Geissler, E.A., 1988. A fine-resolution palaeoecology and palaeoclimatology from South-Eastern Australia. Journal of Ecology 76, 790–806.

Grimm, E.C., 1991–2001. Tilia, TiliaGraph and TGView. Illinois State Museum, Springfield, Illinois, USA.

Hicks, S., 2001. The use of annual arboreal pollen deposition values for delimiting tree-lines in the landscape and exploring models of pollen dispersal. Review of Palaeobotany and Palynology 117, 1–29.

Janssen, C.R., 1973. Local and regional pollen deposition. In: Birks, H.J.B., West, R.G. (Eds.), Quaternary Plant Ecology. 14th symposium of the British Ecological Society. Blackwell, Oxford, pp. 31–42.

Jones, G.D., Bryant, V.M.J., Lieux, M.H., Jones, S.D., Lingren, P.D., 1995. Pollen of the Southeastern United States: with Emphasis on Melissopalynology and Entomopalynology. American Association of Stratigraphic Palynologists, Texas A and M University, College Station, Texas.

Jones, G.D., Lieux, M.H., Wilson, E.F., Martin, J.A., 1999. Light Micrograph Pollen Identification Reference, Modern Pollen Poster. AASP Foundation, Texas A and M University, College Station, Texas.

Kapp, R.O., Davis, O.K., King, J.E., 2000. Pollen and Spores. AASP Foundation, Texas A and M University, College Station, Texas.

Keeland, B.D., Conner, W.H., Sharitz, R.R., 1997. A comparison of wetland tree growth response to hydrologic regime in Louisiana and South Carolina. Forest Ecology and Management 90, 237–250.

Kershaw, A.P., Hyland, B.P.M., 1975. Pollen transfer and periodicity in a rainforest situation. Review of Palaeobotany and Palynology 19, 129–138.

Kushlan, J.A., 1990. Freshwater wetlands and aquatic ecosystems: freshwater marshes. In: Myers, R.L., Ewel, J.J. (Eds.), Ecosystems of Florida. University of Central Florida Press, Orlando, pp. 324–363.

Light, S.S., Dineen, J.W., 1994. Water control in the Everglades: a historical perspective. In: Davis, S.M., Ogden, J.C. (Eds.), Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, pp. 47–84.

Lotter, A.F., Juggins, S., 1991. POLPROF, TRAN and ZONE: programs for plotting, editing and zoning pollen and diatom data. INQUA-Subcommission for the study of the Holocene Working Group on Data-Handling Methods. Newletters 4, 4–6.

Myers, R.L., Ewel, J.J., 1990. Ecosystems of Florida. University of Central Florida Press, Orlando, FL, USA, p. 765.

O'Neal, M.A., Tedesco, L.P., Sough, C., Pachut, J.F., 2001. A pollen zonations of southwestern Florida using multivariate statistical methods and its application to two vertical sedimentary sequences. Bulletins of American Paleontology 361, 101–132.

Spackman, W., Dolsen, C.P., Riegel, W.L., 1966. Phytogenic organic sediments and sedimentary environments in the Everglades–Mangrove complex. Part I: evidence of a transgressing sea and its effects on environments of the Shark River areas of southwestern Florida. Palaeontographica Abteilung B 117, 135–152.

Spackman, W., Riegel, W.L., Dolsen, C.P., 1969. Geological and biological interactions in the swamp–marsh complex of southern Florida. In: Dapples, E.C., Hopkins, M.E. (Eds.), Environments of Coal Deposition. The Geological Society of America Special Paper, Boulder, CO, pp. 1–35.

Swayze, L.J., McPherson, B.F., 1977. The Effect of the Faka Union Canal System on Water Levels in the Fakahatchee Strand, Collier County, Florida. US Geological Survey, Water Recources Division, Tallahassee, pp. 1–19.

ter Braak, C.J.F., Smilauer, P., 1998. Canoco Reference Manual and User's Guide for Canoco for Windows. Software for Canonical Community Ordination (version 4). Microcomputer Power, Ithaca, NY, USA.

Thomas, T.M., 1974. A detailed analysis of climatological and hydrological records of South Florida with reference to man's influence upon ecosystem evolution. In: Gleason, P.J. (Ed.), Environments of South Florida: Present and Past. Miami Geological Society, Miami, pp. 82–122.

van Geel, B., van Hallewas, D.P., Pals, J.P., 1983. A late Holocene deposit under the Westfriese Zeedijk near Enkhuizen (Prov. of N-Holland, the Netherlands): palaeoecological and archaeological aspects. Review of Palaeobotany and Palynology 38, 269–335.

Visser, J.M., Sasser, C.E., 1994. Changes in tree species composition, structure and growth in a bald cypress-water tupelo swamp forest, 1980–1990. Forest Ecology and Management 72, 119–129.

Watts, W.A., 1980. The late Quaternary vegetation history of the Southeastern United States. Annual Review of Ecology and Systematics 11, 387–409.

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

Willard, D.A., Holmes, C.W., Weimer, L.M., 2001a. The Florida Everglades ecosystem: climatic and anthropogenic impacts over the last two millennia. Bulletins of American Paleontology 361, 41–55.

Willard, D.A., Weimer, L.M., Riegel, W.L., 2001b. Pollen Assemblages as Paleoenvironmental Proxies in the Florida Everglades. Review of Palaeobotany and Palynology 113, 213–235.

Willard, D.A., Cronin, T.M., Verardo, S., 2003. Late Holocene climate and ecosystem history from Chesapeake Bay sediment cores. The Holocene 13, 201–214.