

# Impacts of past climate and sea level change on Everglades wetlands: placing a century of anthropogenic change into a late-Holocene context

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**Abstract** We synthesize existing evidence on the ecological history of the Florida Everglades since its inception  $\sim 7$  ka (calibrated kiloannum) and evaluate the relative impacts of sea level rise, climate variability, and human alteration of Everglades hydrology on wetland plant communities. Initial freshwater peat accumulation began between 6 and 7 ka on the platform underlying modern Florida Bay when sea level was  $\sim 6.2$  m below its current position. By 5 ka, sawgrass and waterlily peats covered the area bounded by Lake Okeechobee to the north and the Florida Keys to the south. Slower rates of relative sea level rise  $\sim 3$  ka stabilized the south Florida coastline and initiated transitions from freshwater to mangrove peats near the coast. Hydrologic changes in freshwater marshes also are indicated  $\sim 3$  ka. During the last  $\sim 2$  ka, the Everglades wetland was affected by a series of hydrologic fluctuations related to regional to global-scale fluctuations in climate and sea level. Pollen evidence indicates that regional-scale droughts lasting two to four centuries occurred  $\sim 1$  ka and  $\sim 0.4$  ka, altering wetland community composition and triggering development of characteristic Everglades habitats such as sawgrass ridges and tree islands. Intercalation of mangrove peats with estuarine muds  $\sim 1$  ka indicates a temporary slowing or stillstand of sea level. Although sustained droughts and Holocene sea level rise played large roles in structuring the greater Everglades ecosystem, twentieth century reductions in freshwater flow, compartmentalization of the wetland, and accelerated rates of sea level rise had unprecedented impacts on oxidation and subsidence of organic soils, changes/loss of key Everglades habitats, and altered distribution of coastal vegetation.

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## 1 Introduction

A significant component of resource management involves defining boundary conditions that are broad enough to maintain healthy ecosystem function while accommodating natural fluctuations of climate and environmental parameters. On a global scale, boundaries for variables such as climate change and global freshwater budgets have been proposed to minimize disruption of the planet's biophysical processes and avoid shifts of ecosystem components to new states (Rockström et al. 2009). On local and regional scales, monitoring data (spanning <50 years) often are integrated with historical evidence and model results to develop target values for environmental parameters. Such an approach assumes both climatic and hydrologic stationarity and may ignore both the occurrence of multidecadal- and centennial-scale climate patterns as well as the potential impacts of future climate change and sea level rise (Jackson and Hobbs 2009). Recent efforts focus on more dynamic restoration targets that incorporate the inherent variability of ecosystems in order to increase the likelihood of sustainable restoration. The greater Everglades ecosystem in south Florida, currently the topic of a >\$20 billion restoration program, provides an excellent example of a restoration strategy that is evolving to integrate the growing body of evidence on the current state and past variability of the system with the socio-economic needs of the population. Everglades restoration planning has depended primarily on mathematical models such as the Natural Systems Model (NSM) to estimate predrainage hydrology (Fennema et al. 1994; Sklar et al. 2005), and the rapidly expanding archive of paleoecological data provides both a check on the validity of NSM estimates and a method to reconstruct the magnitude, frequency, and directions of hydrologic fluctuations in the predrainage system.

This paper synthesizes the ecological history of the Everglades wetland since it first formed in the middle Holocene ~7 ka (calibrated kiloannum). We rely primarily on the interpretation of past vegetation and hydrology based on pollen and spore assemblages from sediments (Willard et al. 2001a, 2006), peat petrography (Cohen and Spackman 1977; Cohen et al. 1999), and seed assemblages (Saunders et al. 2006). The combined use of radiocarbon dating, short-lived radioisotopes (lead-210, cesium-137), and pollen biostratigraphy provide the robust geochronologies needed to compare hydrologic trends throughout the Everglades wetland (Gleason and Stone 1994; Chmura et al. 2006; Gaiser et al. 2006; Willard et al. 2006; Bernhardt and Willard 2009) with changes in salinity and water quality in Florida and Biscayne Bays (Brewster-Wingard and Ishman 1999; Cronin et al. 2002). Because most previously published radiocarbon dates were presented as conventional (uncalibrated) dates, we recalibrated dates obtained on basal peats and marls using Calib 6.0 (Stuiver and Reimer 1993; Stuiver et al. 2010). Both conventional and calibrated dates are presented in Table 1. We begin by summarizing the regional framework of the south Florida system, then synthesize current knowledge on the mid- to late Holocene development of coastal and freshwater wetlands, and finally discuss wetland impacts of water management and land cover change in the context of Holocene sea level rise and decadal to centennial-scale hydrologic variability.

**Table 1** Radiocarbon dates of basal samples considered in this study in Fig. 1

Indication in Fig. 1	Location	Material	Lab no.	<sup>14</sup> C age (year BP)	Error	2σ plus calibration (year BP)	2σ minus calibration (year BP)
	Taylor creek-site 7 <sup>a</sup>	Basal sample	Beta 86785	1,610	60	1,367	1,690
Site 2	Mud Creek-site 8 <sup>a</sup>	Basal sample	Beta 93312	1,950	70	1,717	2,096
Site 5	WCA 3A—site 4 <sup>a</sup>	Basal sample	Beta 110294	2,470	40	2,363	2,713
Site 6	Manatee Hammock Near Tail <sup>b</sup>	Basal sample	Beta 155692	2,660	70	2,509	2,950
Star	Whitewater Bay—sample 62-116d <sup>c</sup>	Mangrove and freshwater peat		2,894	273	2,353	3,686
Star	Cape Sable-site 62-100c <sup>e</sup>	Basal mangrove peat		2,985	169	2,763	3,555
	C-111 Canal <sup>d</sup>	Basal peat	OS-2739	3,010	50	3,044	3,358
	Pigeon Key Core II <sup>e</sup>	Basal freshwater peat		3,155	90	3,082	3,606
Star	Gopher Key-Core 9411-7 <sup>f</sup>	<i>Rhizophora</i> peat		3,200	100*	3,164	3,686
Star	Chain of Bays-Core FUB1—sample 3 <sup>g</sup>	Basal mangrove peat		3,500	100*	3,485	4,079
Star	Ten Thousand Islands—sample 62-260d <sup>c</sup>	Mangrove peat		3,344	245	2,955	4,242
Site 3	Central Taylor Slough—site 5 <sup>a</sup>	Basal sample	Beta 110300	3,560	40	3,721	3,972
	Eastern shore, Cape Sable <sup>h</sup>	Near basal freshwater peat		3,900	265	3,593	5,039
	Ten Thousand Islands—sample P4 <sup>g</sup>	Basal freshwater peat		3,900	100*	3,989	4,782
	Joe Kemp Key <sup>e</sup>	Basal freshwater peat		3,965	70	4,158	4,784
	Crane Key II <sup>e</sup>	Basal freshwater peat		4,015	90	4,243	4,821
	Harney River-core 59-T1 <sup>h</sup>	Basal freshwater peat		4,080	180	3,995	5,211
	Dildo Key bank—Core RC-9 <sup>i</sup>	Basal freshwater peat		4,105	95	4,412	4,852
	Dildo Key bank—Core RC-10 <sup>j</sup>	Basal freshwater peat		4,265	165	4,416	5,312
Site 4	Fakahatchee Strand-Core FAX 11198 <sup>j</sup>	Basal peat	UIC 12110	4,290	60	4,629	5,041
Circle	Spy Key Core II <sup>e</sup>	Basal freshwater peat		4,310	100	4,579	5,283
Site 1	Tarpon Bay-Core GLW504-TBB	Basal sample	Beta 278426	4,360	40	4,849	5,039
Circle	Harney River—Core 59-T6 <sup>h</sup>	Basal freshwater peat		4,420	200	4,527	5,581
Circle	WCA 3A by gage 3-26 <sup>k</sup>	Basal peat	UM-664	4,520	160	4,829	5,587

**Table 1** (continued)

Indication in Fig. 1	Location	Material	Lab no.	$^{14}\text{C}$ age (year BP)	Error	2s plus calibration (year BP)	2s minus calibration (year BP)
	Dildo Key bank—Core RC-14 <sup>i</sup>	Basal freshwater peat		4,575	170	4,836	5,641
	Dildo Key bank—Core RC-13 <sup>i</sup>	Basal freshwater peat		4,465	100	4,850	5,440
	Dildo Key bank—Core RC-16 <sup>i</sup>	Basal freshwater peat		4,600	165	4,851	5,641
	Dildo Key bank—Core RC-17a <sup>i</sup>	Basal freshwater peat		4,670	175	4,869	5,723
Circle	Russell Key Core II <sup>e</sup>	Basal freshwater peat		4,695	105	5,053	5,642
	Corkscrew Swamp <sup>l</sup>	Basal peat	UM-635	4,720	90	5,088	5,645
Circle	Dildo Key bank—Core RC-17b <sup>i</sup>	Marl		4,765	100	5,297	5,719
Circle	Man-of-War Key <sup>e</sup>	Basal freshwater peat		4,770	100	5,300	5,718
Circle	Central WCA I <sup>m</sup>	Basal peat	UM-604	4,800	100	5,313	5,732
Circle	WCA 3A <sup>k</sup>	Marl		4,800	100*	5,313	5,732
Circle	WCA I—Core 20 near gage 1-9 <sup>n</sup>	Basal peat	UM-686	4,640	130	4,892	5,607
Circle	WCA 2A—northern section <sup>m</sup>	Basal peat	GX-3282	4,860	170	5,059	5,988
Circle	Lake Ingraham—sample I-3439 <sup>o</sup>	Basal peat		4,950	120	5,332	5,935
Circle	Core WCA 3B <sup>d</sup>	Basal peat	OS-2740	4,990	40	5,610	5,889
	Fort Pierce <sup>p</sup>	Basal peat	UM-961	5,022	123	5,475	6,171
Circle	Kreamer Island <sup>p</sup>	Basal peat	UM-192	5,000	90	5,592	5,915
Diamond	Ninemile Bank <sup>e</sup>	Basal freshwater peat		5,190	100	5,719	6,263
Diamond	Lake Okeechobee <sup>p</sup>	Submerged peat	UM-649	5,490	90	6,005	6,465
Diamond	Rodriguez Key <sup>q</sup>	Basal freshwater peat		5,500	100*	6,003	6,491
Diamond	Corkscrew Swamp <sup>l</sup>	Basal peat	UM-955	5,685	210	5,994	6,978
Diamond	Shell Key <sup>e</sup>	Basal freshwater peat		5,685	80	6,311	6,651

Diamond	Ten Thousand Islands-Core P5 <sup>g</sup>	Basal freshwater peat	5,900	150*	6,405	7,156
	Eastern shore of Okeechobee <sup>f</sup>	Calclitic mud under basal peat	6,320	100*	6,995	7,429
	Kreamer Island <sup>p</sup>	Basal calcitic mud	6,470	120	7,160	7,587
	Corkscrew Swamp <sup>f</sup>	Upper calcitic mud	6,620	105	7,323	7,669
	Corkscrew Swamp <sup>f</sup>	Basal calcitic mud	10,600	180	11,839	12,903
	Lake Okeechobee <sup>p</sup>	Basal calcitic mud	12,050	210	13,420	14,864
	Lake Okeechobee <sup>p</sup>	Basal calcitic mud	13,160	190	15,169	16,701

Designations in first column indicate the symbol representing the sample in Fig. 1. Where lab number is not identified, no information was provided in the source. The <sup>14</sup>C age and error are presented as conventional (uncalibrated) ages. Two sigma calibrations were calculated using Calib 6.0. Asterisk (\*) indicates that conventional radiocarbon date and error were estimated from figures provided in source paper. Superscript letters in Location column refer to the following sources: a—Willard et al. (2001a), b—Willard et al. (2006), c—Scholl and Stuiver (1967), d—Winkler et al. (2001), e—Davies (1980), f—O’Neal et al. (2001), g—Parkinson (1989), h—Spackman et al. (1966), i—Wanless and Tagett (1989), j—Donders et al. (2005), k—Altschuler et al. (1983) in Gleason and Stone (1994), l—Kropp (1976) in Gleason and Stone (1994), m—Gleason et al. (1975) in Gleason and Stone (1994), n—Gleason et al. (1980), o—Smith (1968), p—Gleason and Stone (1994), q—Stockman et al. (1967), r—Brooks (1974) in Gleason and Stone (1994)

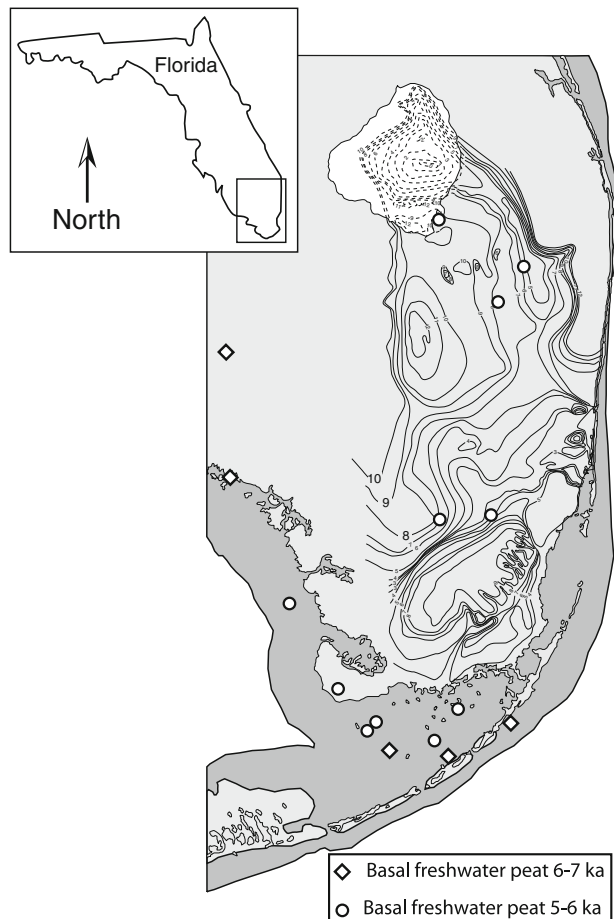
## 2 Regional framework

### 2.1 Geology and climate

The Florida Everglades owes its existence to the unique combination of sea level, climate, hydrology, and the geologic framework of the Florida platform. The long-term influence of sea level fluctuations on the region is represented by the stratigraphic record of alternating fresh-water marls and marine sediments deposited since the Pliocene. This record indicates that the modern Everglades is the most recent in a series of freshwater wetlands that have occupied the Everglades basin during the last few million years (Gleason and Stone 1994). Pliocene and Pleistocene limestone bedrock underlies the Holocene peats, marls, and aquatic habitats of the modern Everglades. Topographically low troughs in the bedrock directed seasonal freshwater flow from the Kissimmee River watershed and Lake Okeechobee in the north toward the Gulf of Mexico and Florida Bay to the south. The earliest peat accumulations

**Fig. 1** Geologic framework of greater Everglades ecosystem. *Dark gray shading outlines the 6 mbsl (meters below sea level) contour that represents the potential coastline position ~6 ka. Boundary between light and dark gray indicates the present position of the coast (0 m mbsl) (modified from Wanless et al. (1994).*

Approximate contours on top of the limestone bedrock underlying Everglades wetland sediments are drawn relative to the Okeechobee datum, 4.4 m below mean sea level, U.S. Coast and Geodetic Survey. Contour interval is 1 ft (0.3 m) (modified from Parker et al. 1955). *Diamonds and circles indicate locations of basal freshwater peats deposited from 6–7 ka and 5–6 ka, respectively. Stars indicate locations with mangrove peats deposited between 3.2 and 4.1 ka. Site numbers (solid circles) refer to cores discussed in text (see Table 2)*

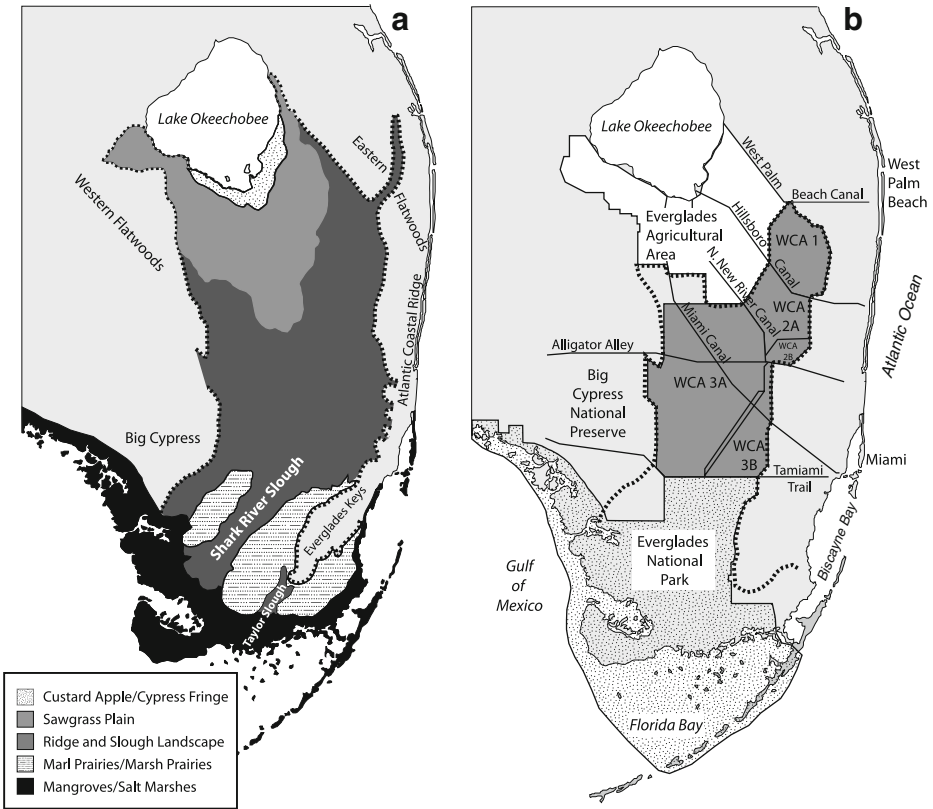


began between 7 and 6 ka in these topographically low sites (Fig. 1), where water depths and hydroperiods were long enough to preserve organic material.

In the natural system, Everglades hydrology was controlled by combined effects of limestone bedrock topography, seasonal precipitation patterns, and sediment thickness and topography. Wet summers (JJA) contribute 70–75% of annual precipitation, causing Lake Okeechobee to overtop its banks and flow southward along the gentle slope of  $3 \text{ cm km}^{-1}$  through Shark River Slough and Taylor Slough (Kushlan 1990). The seasonal precipitation pattern is driven, in large part, by the position of the Bermuda High (BH). In the wet season (summer–fall), the BH is located near Bermuda; in the dry season, it is located near the Azores (Stahle and Cleaveland 1992). Interannual variability is influenced by El Niño–Southern Oscillation, and El Niño (La Niña) events are characterized by high (low) winter rainfall (Kiladis and Diaz 1989; Beckage et al. 2003). Inter-seasonal temperature variability is minimal, with mean daily maximum temperatures  $>25^\circ\text{C}$  in the winter and  $>27^\circ\text{C}$  in the summer; during the winter season, mean daily minimum temperatures typically are  $>10^\circ\text{C}$  compared to  $>15^\circ\text{C}$  in the summer (Deuver et al. 1994). Precipitation and evaporation rates that sustain water tables above the ground surface for extended periods of time are enhanced by capillary action in wetland peats that serves to sequester water and maintain water tables even during dry intervals (Brady and Weil 2002).

## 2.2 Natural Everglades wetlands

The primary controls on distribution of vegetation within the greater Everglades ecosystem are hydroperiod (annual duration of inundation), water depth, substrate, fire regime, and salinity (Kushlan 1990). In the pre-drainage (pre AD 1850) Everglades, *Annona* (pond apple) and *Taxodium* (cypress) swamps lined the southern and eastern banks of Lake Okeechobee, and *Cladium* (sawgrass) plains stretched southward from the pond apple swamp for nearly 24 km (Fig. 2a). Sawgrass plains consisted of unbroken expanses of sawgrass reaching  $>3 \text{ m}$  tall on thick peats (Lodge 2010). Between the sawgrass plain and coastal mangrove swamps lay the Ridge and Slough landscape, a mosaic of long (9–12 month) to moderate (6–9 month) hydroperiod wetlands interspersed with seasonally dry tree islands. In the Ridge & Slough landscape, linear ridges of dense *Cladium*, oriented parallel to flow, were separated by open-water sloughs dominated by *Nymphaea* (water lily). In the modern system, sawgrass ridges are characterized by greater peat thickness, shallower water, and shorter hydroperiod than the water lily sloughs, and the observed landscape pattern appears to be unrelated to changes in bedrock topography (Larsen et al. 2007; Bernhardt and Willard 2009; Larsen et al. 2011). Tree islands in the Ridge & Slough landscape include elongate, fixed tree islands and circular bayheads. Although considerable variability exists in vegetation and hydrology within and among Everglades tree islands, they are characterized by elevated soil surfaces that are seasonally dry. Because tree islands are the driest sites in the Everglades wetland, they have the greatest biodiversity of the system and provide refuge and nesting sites for a variety of wildlife species. Marl prairies bordered the Ridge & Slough landscape on higher elevation sites adjacent to Shark River and Taylor Sloughs (Fig. 2a). These short hydroperiod (3–7 months) marshes now occur on marl (calcitic soil) and are



**Fig. 2** Predrainage (~AD 1850) and twentieth century extent of the Everglades wetland. **a** Distribution of major vegetation classes circa AD 1850, before significant human alteration of Everglades hydrology (modified from Lodge 2010). *Thick dashed line* indicates the pre-drainage extent of the Everglades wetland. **b** Present (AD 2010) water control structures and institutional boundaries in south Florida. *Thick dashed line* indicates the present extent of the Everglades wetland. Water Conservation Area (WCA) 1 includes the Arthur R. Marshall Loxahatchee National Wildlife Refuge. Boundaries of Everglades National Park are shown in the *stippled pattern*

characterized by shallow water depths and sparse vegetation including sawgrass and many species of grasses and sedges (Lodge 2010).

Cypress swamp and pineland habitats were adjacent to the Ridge & Slough landscape, and brackish marshes and mangroves occurred near the coast. Cypress strands were most common west of the Ridge & Slough landscape in what now is Big Cypress National Preserve. Pinelands occurred on sandy soils (flatwoods) or limestone (pine rockland communities) that were flooded seasonally throughout Big Cypress National Preserve and Everglades National Park. Hardwood shrubs and small trees were common in pineland communities, and periodic fires influenced the open pineland communities (Lodge 2010). Brackish marshes, dominated by *Spartina*, *Scirpus*, *Distichlis*, and *Juncus*, were transitional between fresh-water marshes of the Ridge & Slough landscape and coastal mangrove forests. Species composition of modern brackish marshes is influenced significantly by salinity fluctuations tied both to tidal cycles and changes in freshwater flow (Davis 1943). Mangrove forests



**Table 2** Locality and core information for cores discussed in paper (sites 1–6 in Fig. 1)

Site no.	Core	Core location	Administrative unit	Lat (°N)	Long (°W)	Core length (cm)
1	<b>GLW504-TBB</b> (Wingard et al. 2005)	Tarpon Bay	Everglades National Park	25.4205	80.9992	66
2	<b>96-3-15-1</b> (Willard et al. 2001a)	Mud Creek	Everglades National Park	25.2198	80.60465	85
3	<b>96-TS7</b> (Willard et al. 2001a)	Central Taylor Slough	Everglades National Park	25.2872	80.6463	76
4	<b>FAK III98</b> (Donders et al. 2005)	Cypress Slough	Fakahatchee Strand Preserve State Park	25.95	81.49	195
5	<b>95-4-27-1</b> (Willard et al. 2001b)	Site 3A 15	Water Conservation Area 3A	25.97425	80.6688	71.5
6	<b>00-8-9-5</b> (Willard et al. 2006)	Manatee Hammock Near Tail	Everglades National Park	25.494	80.8226	72

fringed the coastline, ranging from dwarf mangrove scrub along the northern shore of Florida Bay to tall mangrove forests along the southwest Florida coast. Mangrove communities have a complex spatial zonation related to salinity gradients and edaphic conditions, grading from saline forests on the coast to freshwater marshes at inland sites. *Rhizophora mangle* (red mangrove) is the dominant tree in most modern mangrove forests of south Florida, but *Avicennia germinans* (black mangrove), *Laguncularia racemosa* (white mangrove), and *Conocarpus erecta* (buttonwood) also occur within the mangrove habitat (Riegel 1965; Spackman et al. 1966). Because mangrove peats form within the upper half of the tidal range, their occurrence is considered a useful indicator of past sea level (Scholl 1964).

### 2.3 Managed Everglades wetlands

Although sporadic attempts to “reclaim” the Everglades wetland by draining it began in AD 1882, the first project with ecosystem-wide impacts was initiated in AD 1907 when the Everglades Drainage District was established. Four canals were dug to connect Lake Okeechobee to the Atlantic Ocean by AD 1917 (West Palm Beach, Hillsboro, North New River, and Miami Canals; Fig. 2b). Collectively, these canals drained ~607,000 ha annually and removed a volume of water that exceeded net precipitation by two times (Sklar and van der Valk 2002). By AD 1928, the Tamiami Trail was completed, and, during the 1930’s, the Hoover Dike was constructed around the southern rim of Lake Okeechobee (Light and Dineen 1994; Lodge 2010). Although no data are available to quantify the combined hydrologic impact of these structures, they substantially altered the quantity of water that reached most of the original Everglades wetland and Florida Bay.

After major hurricanes and severe flooding in AD 1947–1948, a comprehensive plan to encompass all phases of water management was designed, and “The Central and Southern Florida Project for Flood Control and Other Purposes” (C&SF Project) was passed by the U.S. Congress in 1948. Under the C&SF Project, an extensive series of canals, levees, and pump stations were installed to regulate freshwater flow, ensuring adequate water supply during droughts and preventing flooding during wet years. Thus, the C&SF Project altered both the quantity and the timing (seasonality) of flow through the Everglades. The C&SF Project also had the unintended consequence of fragmenting the Everglades ecosystem into multiple compartments (Fig. 2b) with distinctive individual hydrology, nutrient status, and wetland community composition (Davis et al. 1994; Light and Dineen 1994). Numerous changes to wetlands and their communities were observed during the late twentieth century, including subsidence of organic soils by as much as 2 m, significant reductions in number and size of tree islands, expansion of cattail (*Typha domingensis*) in areas of increased phosphorus input, and rapid population increases by invasive plant and animal species (Davis 1994; Sklar et al. 2005; Wu et al. 2006). The recognition that such changes had detrimental effects not only on health of the Everglades ecosystem but also on the economy and culture of south Florida prompted development of the Comprehensive Everglades Restoration Plan (CERP) in 2000. Included in CERP are plans to restore natural hydroperiods, seasonal flow, and connectivity to the wetland system by changing and removing existing water-control structures under the assumption that restoration of “natural” water quantity and quality will result in ecosystem recovery to a more natural state. Critical

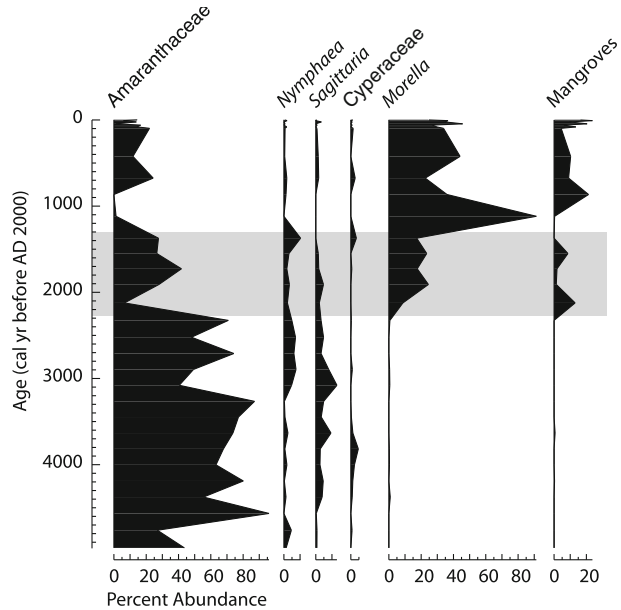
questions underlying Everglades restoration concern the accurate characterization of pre-drainage wetland habitats, hydroperiods, and water depths and the inherent natural variability of the system. Such information, available through paleoecological records, is necessary to evaluate the magnitude of post-drainage changes over multidecadal timescales and to improve predictions of ecosystem response to a range of future management scenarios.

### 3 Holocene sea level rise and coastal vegetation

The oldest wetland deposits of the Everglades consist of calcitic freshwater marls, deposited ~12–13 ka during sea level lowstands of the last deglaciation (Kropp 1976). By ~6.5 ka, sea level was at 6.2 mbsl (meters below sea level) relative to today (Wanless et al. 1994), and the modern Florida and Biscayne Bays were exposed as part of what we refer to here as the Florida Platform (Fig. 1). After sea level rose rapidly in the early Holocene, the rate of relative sea level rise (RSLR) slowed to 2.3 mm year<sup>-1</sup> between 6.5 and 3.5 ka (Wanless et al. 1994). These mid-Holocene rates were slow enough for up to 165 cm of freshwater peat to accumulate on the Florida Platform before an increased rate of RSLR deposited mangrove peats and estuarine muds (Davies 1980). The oldest freshwater peats on the Florida Platform are radiocarbon dated at 6–7 ka (Stockman et al. 1967; Scholl et al. 1969; Table 1). Petrographic studies of these peats indicate that they are comprised primarily of *Cladium* and *Sagittaria*. By 5 ka, such freshwater peats were accumulating on the Florida platform from the Florida Keys to Lake Okeechobee (Fig. 1) (Gleason and Stone 1994; Spackman et al. 1966; Davies 1980). Although no pollen evidence is available for sediments older than 5 ka, records encompassing the 5–3 ka interval contain common *Sagittaria*, Cyperaceae, and *Nymphaea* pollen (Fig. 3). These data are consistent with petrographic data and indicate the existence of moderate to long-hydroperiod wetlands (Riegel 1965; Smith 1968; Davies 1980).

Slower RSLR rates, averaging 0.4 mm year<sup>-1</sup> as early as 3.5 ka, resulted in stabilization of coastlines and establishment of marl levees and mangrove forests along the south Florida coast (Wanless 1989; Wanless et al. 1994). The oldest definitive mangrove peats are dated at 2.9–3.6 ka from the Ten Thousand Islands area, Whitewater Bay, and Gopher Key (Fig. 1; Parkinson 1989; O'Neal et al. 2001; Scholl and Stuiver 1967). In cores collected in Florida Bay, relatively thin mangrove peats are overlain by thick accumulations of marine carbonate mud (typically 2–3 m), but sites on the present coastline contain up to 3.4 m of mangrove peat overlying freshwater peat (Davies 1980; Riegel 1965; Spackman et al. 1966). Pollen assemblages from such thick late Holocene peat sequences (Site 1; Fig. 1) clearly document the shift from freshwater marshes to transitional vegetation and then to mangrove swamps. The transitional vegetation is characterized by increased abundance of shrub and tree pollen (*Morella*, *Ilex*, *Salix*, *Cephalanthus*), the common occurrence of freshwater marsh taxa, and reduced abundance of Amaranthaceae pollen (Davies 1980). The initiation of mangrove swamps is indicated by increased abundance of *Rhizophora* pollen and spores of the peripheral mangrove swamp species *Acrostichum* (Thanikaimoni 1987) (Fig. 3). Although the earliest phase of mangrove vegetation began ~3 ka at western sites (Parkinson 1989; Scholl and Stuiver 1967; O'Neal et al. 2001), the transition occurred later (~2.2 ka) in more

**Fig. 3** Percent abundance of pollen of important plant taxa during the last 5 ka, site 1, peat core from Tarpon Bay, Florida (see Fig. 1). *Gray box* indicates period of vegetational transition from freshwater marsh to mangrove forests

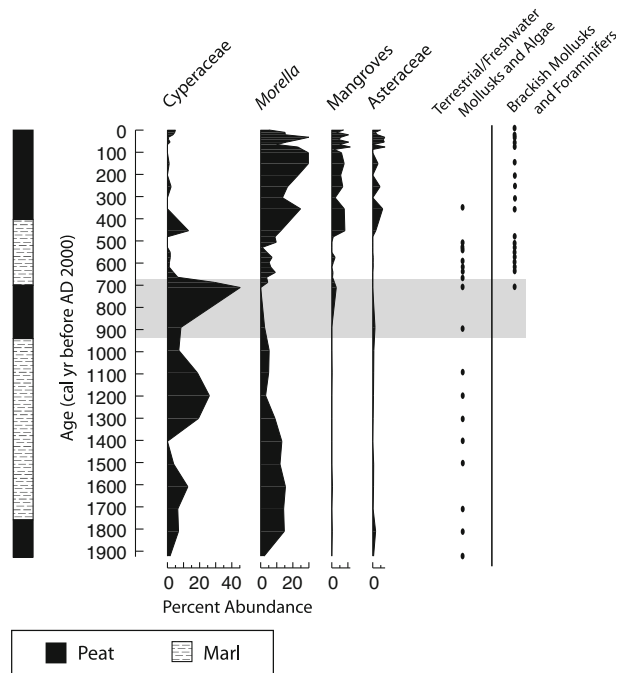


inland sites such as Tarpon Bay (Site 1; Fig. 1). There the final shift to mangrove swamps occurred between 1.2 and 1.0 ka (Fig. 3). These data highlight the diachronous nature of the freshwater-mangrove contact, which provides estimates of former positions of sea level (Scholl and Stuiver 1967).

Unlike the peat-dominated sediments of the southwest Florida coast, most Florida Bay sediments consist primarily of marine carbonate muds. However, a thin layer (10–15 cm) of mangrove peat is intercalated with marine muds at several offshore sites (Jim Foot Key, Crane Key, Spy Key, Russell Key) (Davies 1980), and a similar lithologic pattern was observed in a coastal core collected along Mud Creek (Site 2; Figs. 1, 4) (Willard et al. 2001a). Although radiocarbon dates obtained during the original studies were not intended to evaluate the precise timing of the transition from estuarine to mangrove sedimentation, the mangrove layer at the five sites yields an age of  $\sim$ 1.0–1.1 ka for this transition (Table 1). Such a temporary shift from estuarine to mangrove sedimentation is suggestive of a stillstand or slowing of RSLR before resumption of marine sedimentation and more rapid RSLR rates.

Limitations on temporal resolution of samples and absence of accurate elevation data preclude definitive comparison between terrestrial and marine sequences. However, several points are relevant. At Site 1 in Tarpon Bay (Fig. 1), the absence of mangrove pollen between 1.5 and 0.9 ka may have resulted from a temporary shift from mangrove forests to freshwater marshes as salinity decreased in response to slower RSLR rates and increased freshwater availability. At site 2, increased salinity between  $\sim$ 0.9 and 0.7 ka is reflected by first occurrences of brackish mollusks and foraminifers that may correspond to accelerated rates of RSLR associated with renewed marine sedimentation in Florida Bay. Assuming a constant late Holocene rate of subsidence of the Florida Platform, these data and other evidence for changing RSLR rates from the southwest Florida coast (Wanless et al. 1994) suggest that fluctuations in global RSLR are preserved in the lithologic and vegetation

**Fig. 4** Percent abundance of pollen of important plant taxa during last 2 ka, site 2, Mud Creek, Florida (see Fig. 1). *Gray box* indicates occurrence of vegetational transition from freshwater marsh to dwarf mangrove forests. *Ovals* indicate presence of foraminifera and mollusks (modified from Willard et al. 2001b)



records of the Florida coastline during the late Holocene. A coordinated study involving geochronology and multiproxy environmental indicators would be necessary to reconstruct a high-resolution late Holocene sea level record from the Florida Platform.

Since ~AD 1930, tide gauge records indicate that RSLR rates have increased to  $\sim 3.8 \text{ mm year}^{-1}$ , a more rapid rate than has occurred in the last 6.5 ka (Wanless et al. 1994). During this time, striking shifts in vegetation zonation occurred in the southeast saline Everglades, notably the inland replacement of freshwater *Cladium* marshes by *Rhizophora* swamps (Ross et al. 2000). Although these changes likely integrate impacts both of increased rates of relative sea level rise and decreased freshwater flow from the Everglades wetland, they provide important evidence necessary to predict wetland response to future sea level changes in the region.

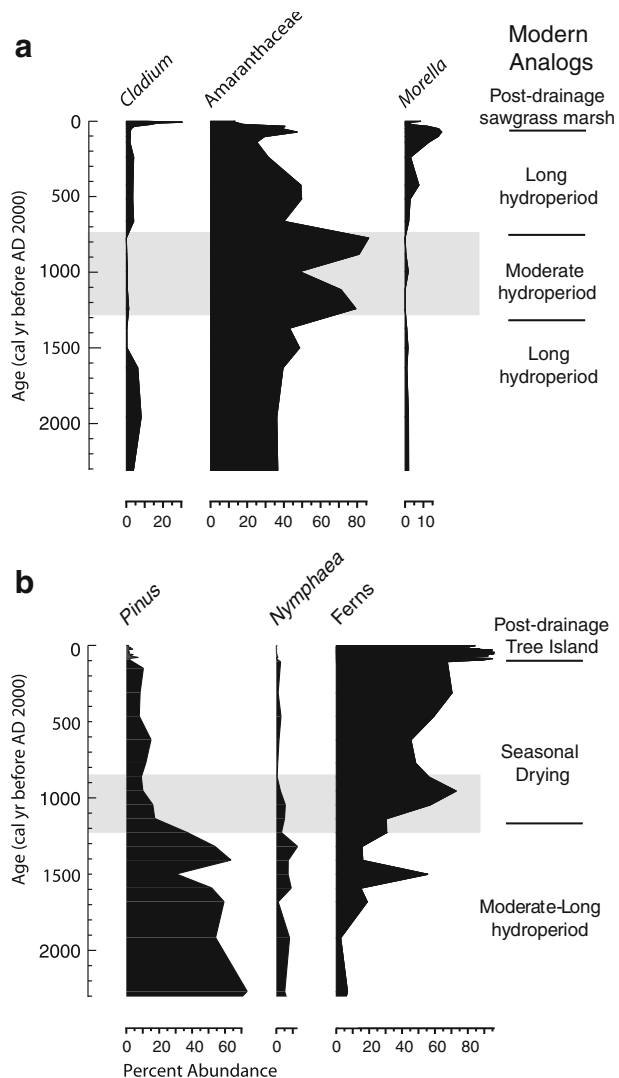
#### 4 Vegetation history of the freshwater ridge and slough landscape

Although the earliest freshwater peat accumulation began on the platform underlying modern Florida Bay, the thickest and most continuous accumulation of peat occurs in Arthur R. Marshall Loxahatchee National Wildlife Refuge in the northernmost Everglades. There, peat was 4.3 m thick before drainage activities in the early twentieth century caused its subsidence and oxidation (Dachnowski-Stokes 1930). Since Dachnowski-Stokes' early efforts to describe Everglades peats, only a few cores have captured the entire thickness of these deep peats (Gleason et al. 1980; Stone et al. 2002). Petrographic analysis of those cores indicates that waterlily peats, indicative of long hydroperiods and deep water, accumulated in the northern

Everglades as early as 5.6 ka (Gleason et al. 1980). These long hydroperiod marshes transitioned to moderate hydroperiod sawgrass marshes (Stone et al. 2002), but no radiocarbon dates are available to pinpoint the timing of this fundamental change.

Two sites provide clues to the timing of mid- to late Holocene hydrologic change. Pollen from a peat core collected in central Taylor Slough (site 3: Fig. 1) indicates persistence of slough vegetation and long hydroperiods from ~3.8–3 ka, before shifting to sawgrass marshes and moderate hydroperiods (Willard et al. 2001b). A peat core collected from a cypress strand in Fakahatchee Strand Preserve State Park (Site 4: Fig. 1) also indicates vegetation changes between 3.5 and 2 ka, but the change from mixed prairie and pinelands to cypress forest is interpreted as a shift to wetter conditions (Donders et al. 2005). Regardless of the directionality

**Fig. 5** Percent abundance of pollen of important plant taxa through the last 2.5 ka from peat cores collected in WCA 3A and Everglades National Park. **a** Long hydroperiod sloughs characteristic of site 1 (WCA 3A: Fig. 2b) were temporarily replaced by moderate hydroperiod sawgrass marshes between ~AD 800 and 1200. Modern sawgrass marshes developed after onset of water management during the twentieth century. **b** Pollen assemblages from Manatee Hammock, a tree island in Everglades National Park (site 2: Fig. 2b) document the change from sawgrass marsh and slough vegetation to seasonally dry tree island vegetation ~AD 1000. Changes in composition and tree island size after AD 1900 correspond to reduced freshwater flow associated with water control practices (modified from Willard et al. 2006; Willard and Cronin 2007)



of hydrologic change, the timing is consistent with hydrologic changes observed in coastal settings and suggests a fundamental hydrologic shift throughout the greater Everglades ecosystem at  $\sim 3$  ka.

Pollen records from sediment cores collected throughout the Ridge & Slough landscape provide multi- to sub-decadal temporal resolution for the last 2.5 ka. Collectively, these records highlight two particularly critical intervals in terms of wetland hydrology. The first is centered on  $\sim 1$  ka, when drier conditions are indicated from multiple sites (i.e., Sites 5, 6; Fig. 1). This drying event was manifested by various vegetation changes: decreased abundance of *Nymphaea* pollen and other slough taxa, shorter hydroperiods in the ridge and slough habitat, increased abundance of weedy annuals such as *Amaranthus australis* (water hemp/pigweed), and changes in tree-island vegetation (Figs. 5a, b). Dry conditions persisted for 200–400 years and triggered development of Everglades habitats such as tree islands and sawgrass ridges. The second dry event began  $\sim 0.4$  ka, when *Morella* pollen abundance nearly doubled throughout the Ridge & Slough landscape, abundance of moderate hydroperiod taxa such as *Cladium* increased relative to long-hydroperiod taxa, and tree-island pollen abundance increased (Bernhardt and Willard 2009; Willard et al. 2001b, 2006). These conditions persisted until the early twentieth century.

## 5 Everglades vegetation changes since the twentieth century

Since the early twentieth century, the greater Everglades ecosystem has been influenced by combined effects of natural climate variability, water management practices, accelerated rates of sea level rise, and regional climate feedbacks from significant land-cover changes. Vegetation changes occurred in two phases. The first corresponds to the initial phase of water management that reduced the volume of freshwater flow through the wetland with little change in the timing of flow. The second occurred after the C&SF Project altered water quantity and availability as well as the timing of flow, essentially overriding the seasonal flow that characterized the natural wetland ecosystem. Paleocological data indicate a common ecosystem response to the initial reduction in flow throughout the Everglades: increased abundance of weedy species, expansion/increased density of sawgrass ridges, expansion of tree islands in southernmost parts of the system, and changes from peat to marl accumulation in some peripheral areas (Willard et al. 2001b, 2006; Bernhardt and Willard 2006, 2009). The paleocological record subsequent to compartmentalization of the wetland by water control structures associated with the C&SF Project indicates more variable responses. Long-term maintenance of high water levels in the southern reaches of the Water Conservation Areas (WCAs) increased hydroperiods sufficiently to shift sawgrass marshes to sloughs and lose the linear structure of the sawgrass ridge and slough landscape (Willard et al. 2008; Bernhardt and Willard 2009). Conversely, sites in the northern reaches of the WCAs became artificially dry, causing increased soil oxidation and subsidence. Both the number of Everglades tree islands and spatial extent of the greater Everglades wetland were reduced by half after AD 1950 (Lodge 2010; Sklar and van der Valk 2002). In the southern Everglades, the “white zone” changed in composition from a mixed vegetation of sedges and *Rhizophora* to a monotypic stand of *Rhizophora*, and the zone has migrated inland (Ross et al. 2000). The combined effects of reduced

freshwater flow and accelerated rates of sea level rise altered the distribution of coastal vegetation, and the paleoecological record throughout the greater Everglades ecosystem indicates unprecedented twentieth century changes in species composition and distribution relative to the last 2–3 ka.

## 6 Correlation of Florida records of Holocene sea level and climate change with other paleoclimate records

The mid-Holocene timing of Everglades wetland initiation coincides with development of swamps and peatlands throughout the Atlantic and Gulf Coastal Plains (Törnqvist et al. 2004; Watts 1980; Whitehead 1972) and appears to be related to combined effects of sea level rise, altered precipitation patterns associated with orbitally driven changes in atmospheric circulation patterns, and stabilization of high water tables. Rapid rates of early Holocene relative sea level rise ( $3.5\text{--}5.2\text{ mm year}^{-1}$ ), tied to meltwater influx during last deglacial period, raised sea level from 20 mbsl at  $\sim 9\text{ ka}$  to 6.2 mbsl at  $\sim 6.5\text{ ka}$  (Wanless et al. 1994). Similar patterns of rapid early Holocene sea level rise have been documented from sites throughout the western Atlantic Ocean and Gulf of Mexico, along with evidence for much slower RSLR rates ( $\sim 2.3\text{ mm year}^{-1}$ ) between 6.5 ka and 3.5 ka (Toscano and Macintyre 2003; Törnqvist et al. 2004). Progressive orbitally driven changes in insolation culminated in maximum late Holocene heating during boreal winters (Berger and Loutre 1991), reducing seasonal differences within the system. Larger amplitude and more frequent El Niño events, associated with mid-Holocene orbital changes (Clement et al. 2000), increased winter precipitation, raised water levels, and decreased fire frequency (Beckage et al. 2003). The decreased seasonal contrast in precipitation also is tied to a mean southward shift of the Intertropical Convergence Zone (ITCZ) (Haug et al. 2001), and water tables were stabilized at high enough levels to maintain Everglades wetlands throughout the late Holocene.

At least two intervals of reduced rates of RSLR characterize the late Holocene of the greater Everglades ecosystem. The first, which occurred by  $\sim 3\text{ ka}$ , resulted in deposition of mangrove peats and stabilization of the shoreline near its modern position (Wanless et al. 1994). A second apparent slowing of RSLR  $\sim 1\text{ ka}$  also is observed in sea level records from Maine, Connecticut, and Delaware (Varekamp et al. 1992; Gehrels 2000; Nikitina et al. 2000). The latter slowing occurred during the interval known as the Medieval Climate Anomaly (MCA:  $\sim 1.15\text{--}0.75\text{ ka}$ ), when Gulf of Mexico sea surface temperatures (SSTs) were as warm or warmer than modern (Richey et al. 2007). Evidence for decadal to centennial-scale droughts during the MCA in the circum-Caribbean region includes pollen indicators of shorter hydroperiods in south Florida, pollen and diatom indicators of drier conditions in central America, titanium records of decreased fluvial discharge from the Cariaco Basin, and increased sea surface salinity in the Pigmy Basin (Haug et al. 2003; Hodell et al. 2007; Richey et al. 2007). Although the mechanisms forcing changes in rates of RSLR, shifts in the position of the ITCZ, and fluctuating sea surface temperature were integrated to influence the regional hydrologic balance during the MCA, the impacts on Everglades plant and animal communities were significant.

A sustained shift in tropical and extratropical climate is evident during the Little Ice Age (LIA:  $0.6\text{--}0.1\text{ ka}$ ). Drier conditions characterize the Everglades, central



America, Cariaco Basin, and North Atlantic (Haug et al. 2001; Peterson and Haug 2006). Surface salinity increased in the Florida Straits and Gulf of Mexico (Lund and Curry 2006; Richey et al. 2007), and SSTs decreased by up to 2.5°C (Black et al. 2007; Richey et al. 2007). Significant increases in concentrations of glaciochemical proxies from the GISP2 ice core (marine-source seasalt sodium) at 0.6 ka indicate a fundamental shift in atmospheric circulation during the LIA, involving deepening of the Icelandic Low and increased intensity of winter circulation over the North Atlantic (Meeker and Mayewski 2002). In the tropics, the mean position of the ITCZ migrated southward (Lund et al. 2006). Feedbacks between such changes in tropical ocean-atmospheric circulation and thermohaline circulation have been shown to influence climates over centennial timescales (Vellinga and Wu 2005) and were likely responsible for many of the observed climate fluctuations.

## 7 Feedbacks between Everglades landcover and regional climate

Analyses of late Holocene records document the influence of different modes of natural climate variability on the south Florida ecosystem. There also is increasing recognition that human influences contribute to climate change on regional to global scales (Pielke et al. 1992). Human forcings include altered greenhouse gas concentrations, aerosol deposition, and changes in land use/land cover. Particularly relevant to the Florida peninsula are the impacts of land-cover change on energy balance and biophysical feedbacks to regional climate. Human modification of the Florida landscape includes: extensive urbanization of coastal areas; conversion of the peninsula interior from forests and wetlands to agriculture, roads, and cities; and a shift from an Everglades hydrologic system dominated by precipitation and evaporation to one dominated by runoff through a series of canals. Anecdotal and scientific evidence indicates that progressive decreases in summer convective rainfall and increases in maximum summer temperatures occurred during the twentieth century (Marshall et al. 2004a). Model experiments have been used to evaluate the possible contribution of land-cover change to these changes.

Reconstructions of pre-drainage (~AD 1850) natural cover and post-drainage (AD 1993) land cover were prepared for climate simulations using the Regional Atmospheric Modeling System (RAMS; Pielke et al. 1992). The pre-drainage dataset was compiled based on historical documents, vegetation maps, and pollen evidence from sediment cores; the post-drainage land cover was derived from Landsat satellite data. Comparison of simulations using pre- and post-drainage land cover datasets in RAMS showed significant changes in surface heat flux that altered surface-forced mesoscale circulation (Marshall et al. 2004a). These changes, driven by altered land cover alone, were sufficient to reduce warm-season convective precipitation by 10–12%, comparable to that observed from AD 1924–2000. The model results also indicated that land-cover changes would result in increased summer maximum temperatures, increased diurnal temperature variability, and changes in the severity of winter freezes, which occurred during the 1980's (Marshall et al. 2004a, b).

Current CERP plans include partial restoration of sheet flow across the Everglades, reduced channelization of the Kissimmee River, and reversion of part of the Everglades Agricultural Area to wetlands (Lodge 2010). Although the present urban footprint and use of water-control structures to protect the population from severe

floods and droughts will remain in the “restored” Everglades, climate feedbacks from the resulting changes in vegetation and energy budget are likely to influence regional precipitation and temperature variability. Integration of a range of climate scenarios that include natural climate variability, different greenhouse gas concentrations, and land-cover changes associated with restoration into hydrologic and ecological models would improve forecasts of ecosystem response to different management scenarios.

## 8 Final remarks

The existing body of information on the history of the greater Everglades ecosystem highlights the impacts of sustained droughts on the composition and distribution of wetland communities. In the pre-drainage system, multidecadal droughts catalyzed development of several distinctive Everglades habitats, including tree islands and sawgrass ridges. Although it still is unclear what underlying factors controlled the spatial distribution of such features, the correlation between their development and regional droughts indicates that large-scale patterns of ocean-atmospheric circulation exerted a strong influence on the Everglades wetland. Likewise, sea level changes have large impacts on both the lateral extent of the wetland and on vegetation zonation along the coast. Migration of vegetation zones has tracked sea level changes throughout the last 6–7 ka, providing a context to predict future changes associated with accelerated sea level rise. Likewise, vegetation responses to intervals of cooler and warmer SSTs provide a means to predict hydrologic impacts under a range of climate scenarios. Although the distribution of vegetation within the current Everglades wetland differs significantly from the pre-drainage system, paleoecological records yield evidence for vegetation response to a wide range of natural and anthropogenic stressors. These arguably provide our best estimates of the range of likely responses of this greatly modified ecosystem to restoration strategies and future climate change.

Several topics merit additional research to improve our ability to estimate future ecosystem response to climate and management changes.

1. Sea level reconstructions—To more clearly document the natural rate of sea level rise and retreat, future research should focus on documenting the timing of the freshwater—marine transitions in Florida Bay and coastal sediments. Such studies would clarify patterns of RSLR during the last decades to millennia and improve our predictive abilities for future sea level under different climate and restoration scenarios.
2. Calibration of paleoecological records of hydrology with monitoring measurements—Recently developed statistical models couple paleoecological salinity estimates from Florida Bay with observed meteorological and hydrologic data to estimate pre-drainage hydroperiod (Marshall et al. 2009). Similar efforts coupling wetland paleoecological records with monitoring data would provide more quantitative estimates of hydroperiod and water depth for validation of NSM estimates of pre-drainage wetland hydrology.
3. Integration of land cover-climate feedbacks into ecological and hydrologic models—Regional climate models indicate that post-drainage land-cover change altered the physics of the system enough to change the intensity and location of precipitation, diurnal temperature variability, and the latitudinal position of the

winter freeze line (Marshall et al. 2004a). These findings suggest that restoration of predrainage water depths and hydroperiods would, in turn, alter the regional climate in ways not accommodated by existing hydrologic and ecological models.

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