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# Carbon and sediment accumulation in the Everglades (USA) during the past 4000 years: Rates, drivers, and sources of error

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[1] Tropical and subtropical wetlands are considered to be globally important sources of greenhouse gases, but their capacity to store carbon is presumably limited by warm soil temperatures and high rates of decomposition. Unfortunately, these assumptions can be difficult to test across long timescales because the chronology, cumulative mass, and completeness of a sedimentary profile are often difficult to establish. We therefore made a detailed analysis of a core from the principal drainage outlet of the Everglades of South Florida in order to assess these problems and determine the factors that could govern carbon accumulation in this large subtropical wetland. Accelerator mass spectroscopy dating provided direct evidence for both hard-water and open-system sources of dating errors, whereas cumulative mass varied depending upon the type of method used. Radiocarbon dates of gastropod shells, nevertheless, seemed to provide a reliable chronology for this core once the hard-water error was quantified and subtracted. Long-term accumulation rates were then calculated to be 12.1 g $m^{-2}$ $yr^{-1}$ for carbon, which is less than half the average rate reported for northern and tropical peatlands. Moreover, accumulation rates remained slow and relatively steady for both organic and inorganic strata, and the slow rate of sediment accretion (0.2 mm $yr^{-1}$) tracked the correspondingly slow rise in sea level (0.35 mm $yr^{-1}$) reported for South Florida over the past 4000 years. These results suggest that sea level and the local geologic setting may impose long-term constraints on rates of sediment and carbon accumulation in the Everglades and other wetlands.

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## 1. Introduction

[2] Natural wetlands are important sources and sinks for greenhouse gases, but their carbon balance changes dramatically from boreal to tropical regions [*Matthews*, 2000; *Maltby and Immirzi*, 1993]. Carbon sequestration is largely centered in northern peatlands, which cover more than 320 million hectares and store an estimated 200–455 Pg of carbon in thick waterlogged peat deposits [*Harden et al.*, 1992; *Gorham*, 1991; *Kivinen and Pakarinen*, 1981]. In contrast, peat formation is less common in tropical and subtropical regions where soil organic matter is thought to be more efficiently mineralized to carbon dioxide and methane [*Gore*, 1983]. The warm soil temperatures of the tropics and subtropics should theoretically stimulate microbial metabolism and more rapid turnover of soil organic matter [*Chapin et al.*, 2002; *Davidson et al.*, 2000; *Trumbore et al.*, 1996]. In addition, high rates of evapotranspiration may limit the distribution of waterlogged soils, which are necessary precursors for peat formation. As a result subtropical and tropical peatlands are largely restricted to poorly drained coastal regions or farther inland to fluvial plains, subsiding forelands, and mountainous settings where a positive water balance can be maintained throughout the year [*Gore*, 1983; *Maltby and Immirzi*, 1993].

[3] The rapid cycling of carbon through low-latitude wetlands is manifested by their disproportionately large emissions of methane relative to their land cover. Tropical and subtropical wetlands are estimated to emit 50%–75% of the 100 Tg $CH_4$ released by all wetlands each year while only accounting for about a third of global wetland cover [*Matthews*, 2000]. Although these estimates are based on a growing body of flux data, relatively little information is available on the long-term rate of carbon sequestration in warm-climate wetlands except for peatlands in Southeast

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Asia [e.g., *Neuzil*, 1997; *Page et al.*, 2004; *Dommain et al.*, 2011]. Unfortunately, low-latitude wetlands often present complex sets of problems for determining reliable long-term estimates for carbon accumulation that are often overlooked.

### 1.1. Sources of Error

[4] Long-term rates of carbon accumulation (LORCA) in wetlands are generally based on the analysis of sediment cores [*Tolonen and Turunen*, 1996; *Cohen*, 2003]. The reliability of these estimates are subject to four main sources of error related to 1) coring artifacts, 2) dating sedimentary profiles, 3) measuring dry-bulk density, and 4) detecting sedimentary gaps. Although most attention is usually placed on constructing a chronology for carbon accumulation at a site the other factors can also introduce serious errors that are often overlooked. These problems seem to be especially important for subtropical wetlands such as the Everglades of South Florida, where the environmental setting is apparently not favorable for the preservation of plant material suitable for dating and gaps in the sedimentary record are likely to be present.

#### 1.1.1. Coring Artifacts

[5] The most serious problems associated with coring wetland sediments include 1) sediment deformation, 2) incomplete core recovery, 3) gaps between successive coring drives, and 4) coring drives that deviate from a vertical orientation. These problems are particularly serious in profiles that contain a high fraction of fibrous and woody material that is difficult to cut and prone to form plugs that can clog a core barrel and prevent a full recovery of sediment. The most common solution has been to use either a Russian-type (or Hiller) or piston corer [*Wright et al.*, 1965, 1984]. Russian samplers have the disadvantage of collecting only a small volume of sediment and leaving large gaps between successive cores taken from the same borehole. These samplers also cannot cut through large pieces of wood. The piston samplers on the other hand are designed to prevent the escape of pore waters during the coring and extrusion process and therefore minimize or eliminate core compression [cf. *Wright*, 1993; *Cumming et al.*, 1993]. They can also be equipped with a large diameter (>7.5 cm) core barrel and a serrated cutting edge to cut through wood and fibrous material thereby preventing the formation of plugs [*Wright et al.*, 1984].

#### 1.1.2. Chronology for Sedimentation

[6] Radiocarbon dating is now the most important and widely used method for establishing the chronology of lake and wetland sediments that are less than 50,000 years old [*Bradley*, 1999; *Cohen*, 2003]. This dating method is based on the assumption that all the carbon in a sample was derived from the atmosphere through either photosynthesis or precipitation contemporaneous with the time of burial [*Arnold and Libby*, 1949; *Libby*, 1955]. The age of a sample can then be determined by measuring the fraction of remaining radiocarbon and calculating the age based on the half-life of $^{14}$C. Since the concentration of $^{14}$C in the atmosphere has changed over time due to variations in the influx of cosmic rays, geomagnetic field of the Earth, and ocean overturning, calibration models have been developed to correct for this source of error and provide calibrated ages in terms of calendar years [e.g., *Stuiver and Reimer*, 1993; *Stuiver et al.*, 1998; *Reimer et al.*, 2004; *Guilderson et al.*, 2005].

[7] Radiocarbon dating is still subject to multiple sources of error. Counting errors have now been reduced at many radiocarbon-dating facilities to as low as ±40 years for samples with a sufficient mass of carbon [*Trumbore*, 2000]. However, calibration errors vary with age since the probability distribution of a calibrated $^{14}$C date varies according to its position on the calibration curve [e.g., *Guilderson et al.*, 2005]. Hard-water or reservoir effects will arise in carbonate terrains where aquatic plants assimilate bicarbonate leached from carbonate minerals having no radiocarbon activity [e.g., *Deevey et al.*, 1954]. In contrast, open-system effects can occur in vegetated sites where plant roots translocate modern carbon deep into a sedimentary profile or where carbonate minerals within the sediment freely exchange carbon with the surrounding pore waters [*Bradley*, 1999; *Cohen*, 2003]. Finally, vertical mixing or redeposition of sediment will compromise both the chronological and paleoenvironmental reconstruction [*Cohen*, 2003].

[8] These sources of dating errors have been rigorously studied in lake sediments by dating terrestrial plant macrofossils that are free from either hard-water or open-system effects or by counting annual laminations to create an independent chronology for a sedimentary profile [*Cohen*, 2003]. Many wetlands, however, lack these alternative means to establish a reliable chronology. This problem is particularly likely in warm regions where organic sediments are exposed to high rates of decay and seasonal water-level fluctuations. In addition, many wetlands support dense stands of vegetation with root systems that penetrate to unknown depths within the sedimentary column. As this contemporaneous material decays it may eventually become indistinguishable from the surrounding organic matrix.

#### 1.1.3. Sediment Bulk Density

[9] A potentially serious source of error for calculating mass accumulation rates is the determination of bulk density or mass per unit volume of sediment. Although the wet and dry mass of the sediment can be accurately determined with an analytical balance a potentially large and unknown source of error is associated with volume measurements [e.g., *Chason and Siegel*, 1986; *Breitzke*, 2006]. This problem is especially serious for sediments that contain an interlocking network of fibrous plant fragments and rootlets that cannot be cut and sampled without deforming the original fabric and altering the porosity of the in situ sediment. Most sediment cores, moreover, provide insufficient material to assess these problems by analyzing multiple replicate samples.

#### 1.1.4. Sedimentary Gaps

[10] All sedimentary records contain gaps that are attributable to periods of non-deposition (hiatus) or loss of previously deposited sediment (erosional surface) [*Sadler*, 1981, 1999; *Sommerfield*, 2006]. These gaps occur at all spatial and temporal scales but are often too indistinct to be recognized by the lithology or age model of a core alone. By examining a large number of stratigraphic profiles *Sadler* [1981, 1999] noted that mass accumulation rates consistently decline over longer time spans of averaging since longer records tend to incorporate a greater number of gaps of varying frequency and duration. He therefore devised a quantitative method for estimating the degree of sedimentary completeness based on the ratio of the mass accumulation

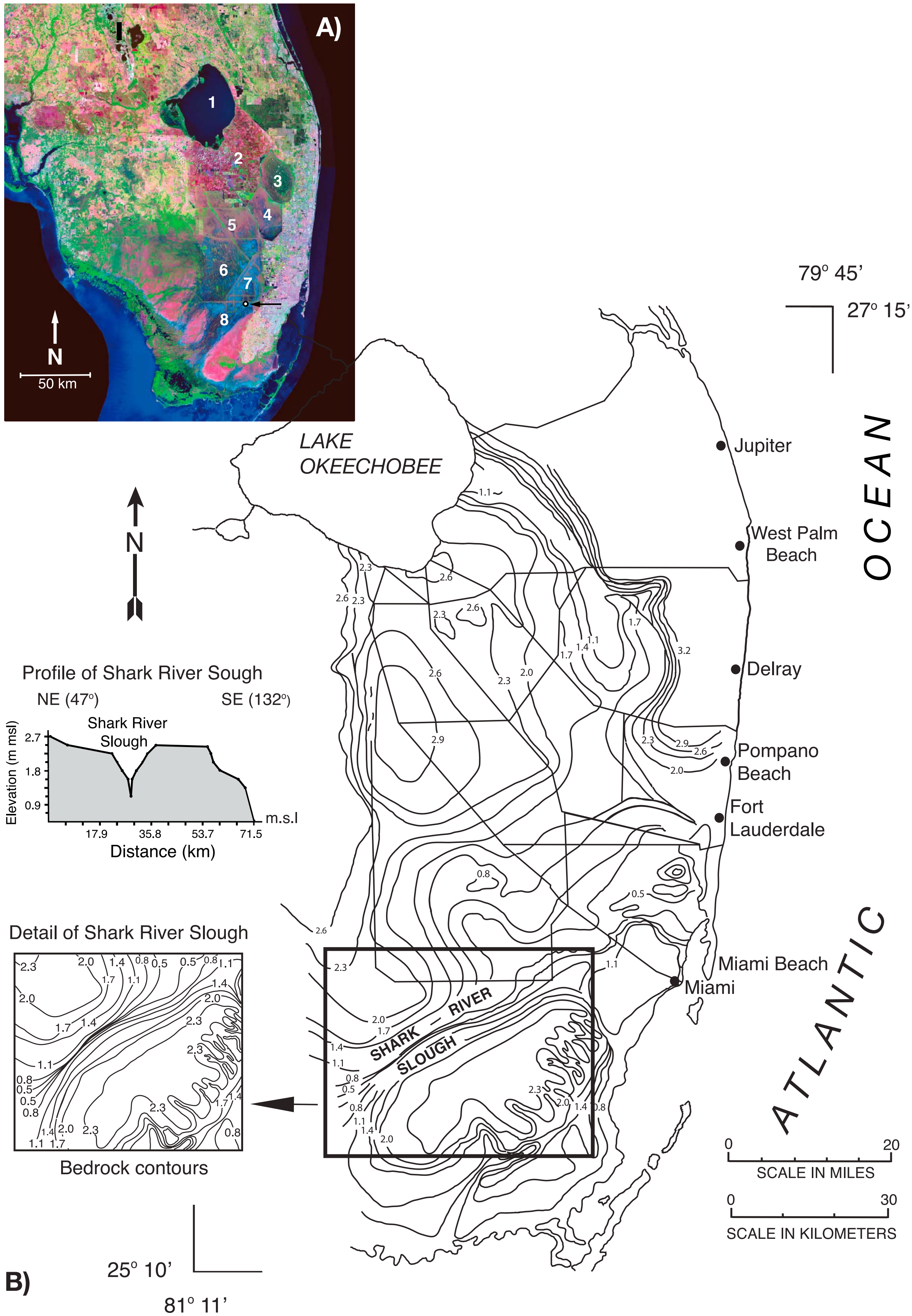
A)
N
50 km
79° 45'
27° 15'
LAKE OKEECHOBEE
Jupiter
West Palm Beach
Delray
Pompano Beach
Fort Lauderdale
Miami Beach
Miami
OCEAN
ATLANTIC
SHARK RIVER SLOUGH
Profile of Shark River Sough
NE (47°)
SE (132°)
Shark River Slough
Elevation (m msl)
Distance (km)
m.s.l
Detail of Shark River Slough
Bedrock contours
SCALE IN MILES
SCALE IN KILOMETERS
B)
25° 10'
81° 11'

**Figure 1**

rate for the entire time span of a sedimentary section to that of a much shorter time interval. In addition, organic carbon is continually lost from a sedimentary record through the mineralization of organic matter by microbial decomposers. This decay process has been assessed for long timespans by a series of mathematical models generally based on first-order reaction kinetics of soil organic matter [e.g., *Clymo*, 1984, 1992; *Clymo et al.*, 1998; *Trumbore and Harden*, 1997; *Frolking et al.*, 2010]. However, these different models can only be tested by comparing model simulations to long-term records of mass accumulation in radiometrically dated profiles.

### 1.2. Sampling Strategy and Objectives

[11] We adopted a 2-stage sampling approach to assess these problems and also obtain a long-term record of carbon accumulation from the Northeast Shark River Slough (NESRS) in Everglades National Park (Figure 1a). The first stage comprised a synoptic collection of cores across Water Conservation Area 3A and the Northeast Shark River Slough (NESRS) to determine the range of variability of sediment depths and lithology within these relatively shallow portions of the Everglades basin (Figures 1a and 1b). Only a few basal $^{14}$C dates have been previously reported from this area [cf. *Willard et al.*, 2006; *Richardson*, 2008] where a relatively thin sediment profile may accentuate dating errors associated with both a hard-water effect and contamination by root biomass. This survey also provided a basis for selecting a core that was most suited for the detailed analyses needed to assess problems related to dating, cumulative mass, and sedimentary completeness.

[12] The objectives for analyzing this core from the NESRS were to 1) examine the various sources of error that can affect LORCA estimates in the Everglades and other wetlands, 2) establish a reliable radiocarbon chronology for the sediment profile at the NESRS site, and 3) determine if the long-term rates of sediment accretion and carbon accumulation at this site change through time as a function of sediment type or other factors such as sea level. This last objective was evaluated by selecting a coring site at the mouth of the principal drainage outlet of the pre-historic Everglades directly to the ocean at Florida Bay.

## 2. Study Area

[13] The Everglades of South Florida is the most distinctive subtropical wetland in North America and once covered more than one million hectares prior to the onset of drainage operations in 1881 [*Davis and Ogden*, 1994]. This important wetland ecosystem is today distinguished by its large area, distinctive surface patterning of ridge, slough, and tree islands, and extensive network of drainage canals (Figure 1a). Recent efforts to restore the Everglades recognize the importance of sedimentation rates for understanding the hydrodynamics, surface patterning, and long-term development of this subtropical wetland [*Givnish et al.*, 2008; *Larsen et al.*, 2011]. However, these sediments present an array of problems for determining reliable sedimentation rates. Some of the most important sources of error are related to the hydrogeologic setting of this wetland and the potential effects of drainage operations over the past century.

[14] The Everglades occupies a shallow bedrock trough that exerts a strong control on the local hydrology and sedimentation processes [*Petuch and Roberts*, 2007]. The trough extends in a SW-trending arc from Lake Okeechobee to the Northeast Shark River Slough and is confined along most of its length by bedrock ridges and plateaus to the east and west (Figure 1b). Natural drainage is directed southward to a channel that was incised into the southwestern edge of the basin forming a natural drainage outlet to the sea through the Shark River Slough. The bedrock floor of this channel rises less than a meter above modern sea level, whereas the highest elevations of the Everglades bedrock basin itself are only about 3 m above sea level at its upslope margin around the southern edge of the Lake Okeechobee [*Parker and Cooke*, 1944]. The Everglades bedrock basin dips very gently from Lake Okeechobee to the south and southwest and has relatively little surface topography except for several depressions less than 4 m deep [*Parker and Cooke*, 1944].

[15] The carbonate bedrock is covered by only a relatively thin veneer of wetland sediments, ranging from less than 4 m within the deepest bedrock depressions to less than 1 m across large portions of the southern and central Everglades where the bedrock is higher [*Gleason and Stone*, 1994; *Willard et al.*, 2006; *Richardson*, 2008]. The wetland sediments rest directly on top of the limestone bedrock, with little or no prior evidence of sediment accumulation or weathered soil horizons before the mid-Holocene. The Everglades wetland is now characterized by dense stands of sawgrass (*Cladium jamaicense*) and other emergent or aquatic plants in the ridges and sloughs and by various tropical hardwoods on the tree islands. The ridges and sloughs are generally inundated with circumneutral waters during the most of the year but are subject to drawdown during droughts and seasonal dry periods [*Harvey et al.*, 2004, 2005]. The construction of drainage networks during the 20th century apparently favored these drawdown events and the spread of fires that consumed an unknown mass of the organic-rich sediments [*Loveless*, 1959].

## 3. Materials and Procedures

[16] A suite of 42 sediment cores was collected across the Northeast Shark River Slough in Everglades National Park and adjacent areas in Water Conservation Area 3A in the Everglades of South Florida in 2003 and 2004. All cores

**Figure 1.** (a) A satellite image of the South Florida Everglades showing (1) Lake Okeechobee, (2) Everglades agricultural areas, (3) Loxahatchee Wildlife Refuge (WCA-1), (4) WCA-2, (5) WCA-3 (north), (6) WCA-3A (south), (7) WCA-3B, and (8) Shark River Slough (in Everglades National Park). (b) A topographic map of the Everglades basin showing bedrock elevation contours relative to mean sea level. In Figure 1a the arrow points to the Northeast Shark River Slough (NESRS) coring site, and the insets below in Figure 1b provide detailed views of the bedrock topography of the Shark River Slough in (top) cross section and (bottom) plan view. This feature functioned as the principal drainage outlet to the Everglades basin prior to the late nineteenth century. This map was modified from *Parker and Cooke* [1944] and *Gleason and Spackman* [1974].

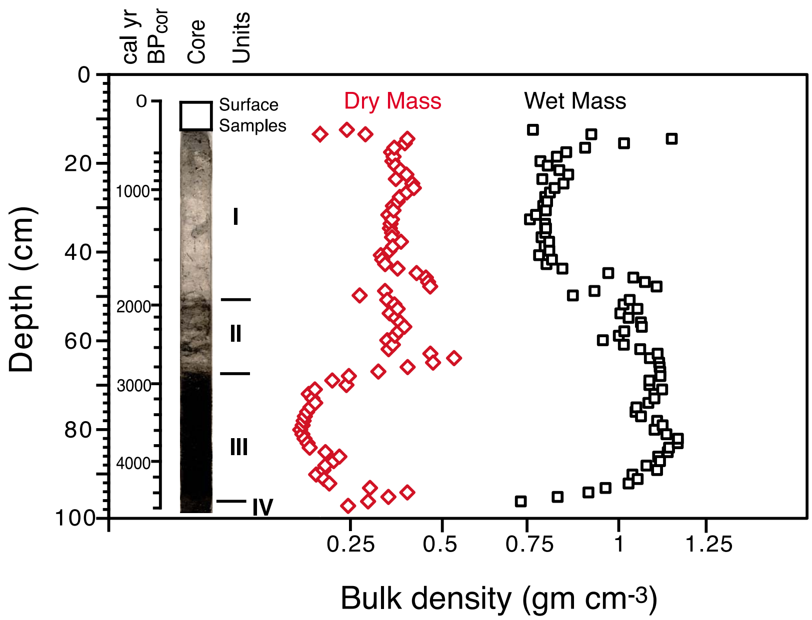


**Figure 2.** Lithology of the NESRS core. The lithologic units (Roman numerals) are shown in relation to a digital image of the core; profiles for bulk density, from the Geotek data; and chronology based on the TGV age model and corrected ages of the gastropod shells.

were collected with a modified piston sampler equipped with a polycarbonate core barrel (7.5 cm in diameter), and a sharp cutting edge. The piston prevents core compression [*Wright et al.*, 1984; *Cumming et al.* 1993; *Wright*, 1993], whereas the 1.5 m long core barrel was sufficient to core the entire sedimentary profile in a single drive. The cores were extruded in a standardized two-step process to recover both the very-soft sediments at the top of the sedimentary profile and the more cohesive sediment below [e.g., *Glaser and Griffith*, 2007]. The soft near-surface sediments (uppermost 5–20 cm of sediment depending on the site) were first extruded vertically in 1 cm increments and stored in separate sample containers. The firmer remainder of the core was then extruded horizontally in one continuous section and stored in PVC section for shipment to the lab.

[17] The intact core sections were first scanned for wet bulk density by gamma-ray attenuation [*Breitzke*, 2006] at 1 cm depth intervals on a Geotek multisensor core logger located at the University of Minnesota. The cores were then split longitudinally and imaged on a color RGB digital line scanner at 300 dpi. The lithologic units of the cores were next described by examining small samples of sediment under both dissecting and petrographic microscopes. After the initial lithologic descriptions were completed, the NESRS-4-23-04 SRS-4 core was selected for more detailed analysis based on its length, lithology, and suitability for dating. This core was recovered from a *Cladium jamaicense* ridge in the Northeast Shark River Slough just south of the Tamiami Trail at 25.746N latitude and 80.583W longitude (Figure 1a). A single drive recovered the entire sedimentary sequence from the water/sediment interface to the underlying bedrock. The recovery was nearly 100% based on the measured depth to bedrock and the length of the core section within the polycarbonate tube. The depth interval for the near-surface samples (6–13 cm) and intact core section (13–97 cm) are shown in Figure 2. The datum for these depth intervals was the water level.

[18] Subsamples (1 $cm^{-3}$) were collected at 2 cm depth intervals for destructive analysis of bulk density, mass (both wet and dry), and carbon. These subsamples were collected using a small piston sampler that was modified from a standard laboratory syringe (6 $cm^{-3}$) by cutting off the tip of the syringe while retaining the piston (plunger) and an open-mouthed tube with its graduated scale. The volume of each sample was determined using the tube's graduated scale, whereas an analytical balance was used to determine the wet mass (after extrusion from the sampler) and dry mass (after being left in a freeze dryer for 24 h and attaining constant weight). The calculations for bulk density followed the standardized procedures for determining volumetric density that are part of the protocol of the loss-on-ignition (LOI) analysis [e.g., *Dean*, 1974; *Heiri et al.*, 2001; *Last and Smol*, 2001]. The dried sediment samples were next ground into a powder with a mortar and pestle and later determined for total carbon content using a Carlo Erba, NC2500 elemental analyzer.

[19] Subsamples were also collected at 2 cm intervals near the top of the profile for pollen analysis to locate the depth of the *Ambrosia* rise. These samples were collected with the syringe sampler described above and prepared by standard methods [*Faegri and Iversen*, 1964]. The counts for *Ambrosia* pollen were plotted as percentages based on a sum of 300 pollen grains and spores. The weedy species of *Ambrosia* produce abundant pollen that is widely dispersed across a region by wind providing a faithful time-stratigraphic marker for recent (past 150 years) anthropogenic disturbance in eastern North America [e.g., *Webb et al.*, 1984; *Jacobson et al.*, 1987]. In South Florida the *Ambrosia* rise has been reliably dated to the post-WWII era by a high-resolution $^{210}Pb$ dated core from Lake

Okeechobee [*Schottler and Engstrom*, 2006]. This record corresponds to the vegetational changes described for this period by *Craighead* [1971] and also agrees with similar studies of short cores from the Everglades [e.g., *Bartow et al.*, 1996; *Willard et al*, 2001; *Richardson*, 2008]. However, the Lake Okeechobee chronology has the added advantage of being anchored not only by $^{137}$Cs analyses but also depth profiles for heavy metals and PCBs.

[20] The strategy for the radiocarbon sampling was to compare dates from small 1-cm$^{-3}$ bulk samples to those of other sediment components. After an intensive search failed to locate plant macrofossils suitable for dating, the following material was selected for accelerator mass spectroscopy ($^{14}$C-AMS) dating: 1) gastropod shells (mostly *Physella cubensis* but also *Planorbella scalaris*), which were abundant in 2/3 of the core including the very top section for estimating the hard water error and the very bottom sediment for obtaining a basal date; 2) very fine rootlets and coarse plant detritus to quantify potential open-system type dating errors; 3) charcoal fragments, which are often used as a surrogate for plant macrofossils in radiocarbon dating; 4) vascular plant tissues in various stages of decomposition; and 5) small 1 cm$^3$ bulk samples. The 1 cm$^{-3}$ bulk samples were collected with the small piston sampler described above, whereas the other samples were extracted from 2–4 cm$^{-3}$ sediment samples collected with stainless steel forceps and a spatula to minimize potential contamination.

[21] The shells, charcoal, and fragments of plant detritus were removed from the sediment samples and initially cleaned in Petri dishes under a dissecting microscope, which was enclosed in a polycarbonate dead-air box to minimize contamination from airborne dust. All glassware used in preparing the radiocarbon samples was either burned in an oven at 450°C or washed with peroxide and high-purity distilled water to remove organic contaminants. Stainless steel forceps were used whenever possible in handling the materials for dating but the fragile charcoal particles required handling with a brush, which had most of its bristles removed. The charcoal fragments were cleaned with a weak 10% peroxide solution to remove surface contamination and also as an aid to separate charcoal from blackened plant detritus and refractory plant tissue (e.g., xylem and sclerenchyma tissue etc.). Although very small particles resembling charcoal were common at some depths the amount present was usually too small for dating. The other material for dating was repeatedly washed with high purity distilled water before being sent to the radiocarbon dating facility where all of the samples were cleaned more thoroughly and aggressively prior to analysis.

[22] All samples were dated by AMS-$^{14}$C at the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory in Livermore, California. The carbonate fraction was dated for the shells, whereas the organic carbon was dated for the charcoal, bulk samples, and plant detritus. Extracts of gas were removed from each sample for determination of $^{13}$C/$^{12}$C for correcting fractionation effects. The magnitude of the hard water effect was estimated by dating a shell from just below the post-World War II horizon as marked by the *Ambrosia* rise and therefore presumed to be uncontaminated by bomb $^{14}$C. A fuller justification for this procedure is presented below (Results). The magnitude of any age offset related to the hard water effect can then be calculated by subtracting the apparent radiocarbon age of this topmost sample from its "true" age inferred by reference to an independent time-stratigraphic maker [e.g., *Björck et al.*, 1998; *Trumbore*, 2000]. A further correction is also needed to account for the incorporation of radioactively "dead" (i.e., inert) carbon that was released into the atmosphere by the burning of fossil fuels during the industrial revolution. This additional age offset related to industrial pollution can be estimated by the expression [*Stuiver and Quay*, 1981; *Stuiver and Pearson*, 1993; *Rea and Colman*, 1995; *Moore et al.*, 1998]:

$$\text{Age-Offset} = -8033\ln\left(1 + \Delta^{14}\text{C}/1000\right). \qquad (1)$$

[23] The corrected radiocarbon age in $^{14}$C yr BP for the other gastropod dates was then estimated by subtracting the estimated hard-water error from each date assuming that the hard water effect had not changed in time. A justification for this assumption is provided below. All radiocarbon dates obtained in radiocarbon years before the present ($^{14}$C yr B.P.) were calibrated into calendar years before the present (cal. B.P.) using CALIB REV5.0.2 [*Stuiver and Reimer*, 1993; *Stuiver et al.*, 1998; *Reimer et al.*, 2004]. An age-versus-depth scale was then constructed using the spline-fitting function in TGView version 2.0.2 and the OxCal program, which is based on Bayesian statistics.

[24] Cumulative wet mass was calculated by adding either successive Geotek measurements from each 1-cm interval or the averaged volume-density determinations from each 2-cm increment. A similar approach was used for calculating cumulative dry mass or carbon mass except that the ratio of wet-to-dry mass for each 2-cm increment was based on the volume-density determination. Mass accumulation rates of sediment (both wet and dry) and carbon were determined as a function of time (cal. B.P.) using the corrected shell dates for the entire sediment profile and also for each lithologic unit. These data were then used to estimate the completeness of these units (ratio of sediment increments to gaps) using *Sadler*'s [1981] equation:

$$\frac{S}{S*} = \left(\frac{t_*}{t}\right)^{-m}, \qquad (2)$$

where $S$ equals the accumulation rate averaged over the full length of a section, $S*$ equals the accumulation rate averaged over a shorter specified level of resolution, $t$ equals the whole-section time span, $t*$ equals the time span at the specified resolution level, and $m$ equals the slope of the regression of $S$ on $t$ and varies from $-1$ to zero.

## 4. Results

### 4.1. Sediment Depth and Lithology

[25] The 42 sediment cores ranged in depth from 6 to 102 cm, consistent with sediment depths previously reported from this portion of the central and southern Everglades [*Davis*, 1943, 1946; *Davis and Ogden*, 1994; *Gleason and Spackman*, 1974; *Gleason and Stone*, 1994; *Willard et al.*, 2006; *Richardson*, 2008]. A histogram of these 42 core

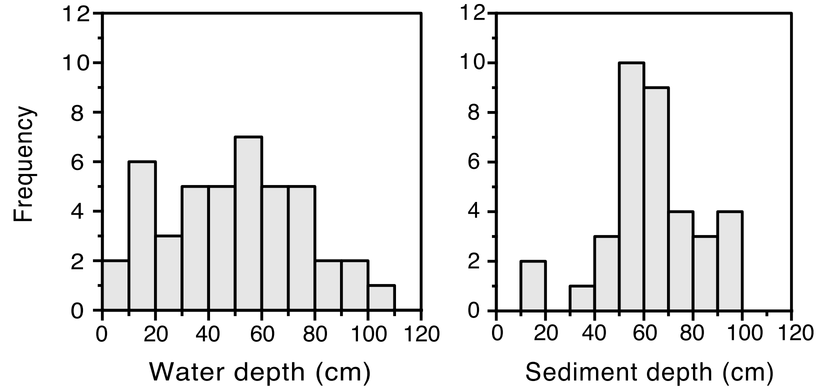


**Figure 3.** Surface water and sediment depths determined from the synoptic collection of cores in WCA-3 (north), WCA-3A (south), and the NESRS. Sediment depths were measured from the sediment-water interface at the top of the profile to the basal contact with bedrock below.

depths approximates a normal distribution with a mean value of 61 cm and a median of 63 cm (Figure 3). A sharp basal contact separated these wetland sediments from the underlying carbonate bedrock, which lacked a rind of weathered regolith. The lithology of these cores was relatively similar across the study area largely consisting of fine-grained organic matter more typical of lake sediment than a terrestrial peat. The organic sediment, however, was permeated with a fine mesh of fine rootlets and fibrous plant material in an advanced stage of decomposition and disaggregation. The resemblance of this material to lake sediment, nevertheless, is enhanced by the occurrence of marl (i.e., calcareous silt) bands in 28 of the 42 cores that varied in thickness and stratigraphic position.

[26] The widespread occurrence of the marl layers and abundant rootlets strongly suggest that these sediments are subject to significant dating errors from hard water and open system effects. In addition, the thin sedimentary profiles may be a product of past fires, erosional processes, or periods of non-deposition. The NESRS core provides excellent material to determine the magnitude of these potential sources of error because gastropod shells are abundant in 70% of the profile particularly within the critical near-surface and basal sediments. The thick marl and organic layers in this core also provide a means to assess the importance of decomposition as a driver for accumulation rates since marl (calcareous silt) is not susceptible to microbial decay.

[27] The NESRS 4-23-04- SRS-4 core contains 4 lithostratigraphic units (Figure 2). The upper Unit I (13–50 cm) consists of a massive fine-grained, calcareous silt, apparently composed of biogenically precipitated calcite (i.e., marl). This calcareous silt layer contains abundant gastropod and ostracod shells, rootlets, diatoms, and plant detritus of various sizes. There is a gradational contact below with Unit II (50–68 cm), which is composed of a massive, fine-grained calcareous silt interbedded with bands of organic detritus. Shells are common and charcoal-like material is present but not abundant below 65 cm. There is also a gradational contact below with Unit III (68–97 cm), which is largely composed of fine-grained, organic detritus with a significant fraction of diatoms, sponge spicules, and aeolian sand and silt-sized minerals. Fragments of rootlets and vegetative plant tissue are common but the sediment in places resembles an aquatic peat [sensu *Faegri and Iversen*, 1964]. At the very base of the core, the fraction of organic matter declines and calcareous silt rises in basal Unit IV (97–99 cm), which contains abundant shells and rootlets.

## 4.2. Radiocarbon Dates

[28] The sediment cores recovered from the Northeast Shark River Slough in Everglades National Park, and Water Conservation Area 3A are problematic for radiocarbon dating. Plant macrofossils of *Cladium jamaicense* or other "terrestrial" vascular plants are surprisingly absent and the remains of the vascular plant material were too degraded to be reliably identified to taxon. The NESRS core, nevertheless, provides sufficient material to assess the magnitude of potential sources of error from both hard-water and open-system effects by dating different types of material by AMS-$^{14}$C.

[29] Radiocarbon dates from the gastropod shells indicate a significant hard-water type error produced by the assimilation of bicarbonate derived from the dissolution of calcite (Figures 4 and 5; Table 1). Shells from a depth of 16 cm had dates of 815–875 yrs B.P. although the sampling depth was located just below the post- World War II horizon marked by the rise in *Ambrosia* pollen (Figure 5). The regional rise of *Ambrosia* pollen was dated to the post–World War II horizon by a $^{210}$Pb dated core from nearby Lake Okeechobee [*Schottler and Engstrom*, 2006] and also corresponds to the record of recent vegetation change in South Florida [e.g., *Craighead*, 1971]. Lake Okeechobee provides the most reliable chronology for the rise in *Ambrosia* pollen in this region because 1) this chronology is anchored not only by profiles of $^{210}$Pb and $^{137}$Cs but also by heavy metals and PCBs; 2) both $^{137}$Cs and $^{210}$Pb are less subject to vertical mobility in lake sediments as opposed to peats [*Oldfield et al.*, 1995]; and 3) the lake never dried out during the Holocene and therefore satisfies the basic assumptions of the constant supply rate (CSR) model for $^{210}$Pb dating [*Appleby and Oldfield*, 1978]. Nevertheless, the timing of the *Ambrosia* rise in this core generally corresponds to that obtained from short cores in the Everglades proper [e.g., *Bartow et al.*, 1996; *Willard et al.*, 2001; *Richardson*, 2008].

[30] These radiocarbon dates therefore indicate an approximately 10% contamination of the shell samples with

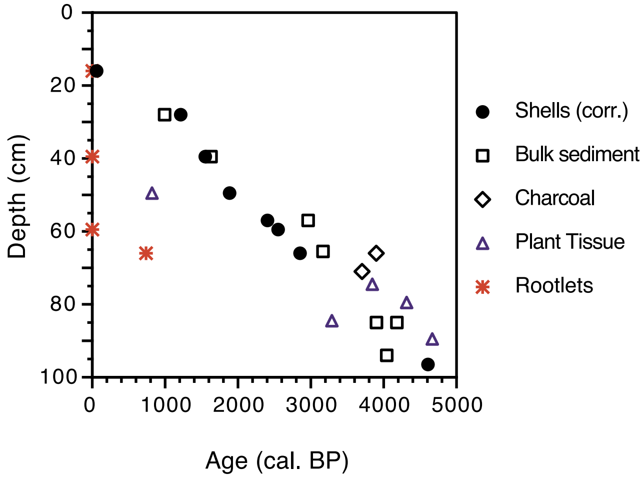


**Figure 4.** Radiocarbon ages for different components of the NESRS core. Note the wide scatter of these calibrated $^{14}$C dates with respect to depth except for those of the gastropod shells. The range for the 2-$\sigma$ confidence interval for these calibrated dates are presented in Table 1. The gastropod dates presented were corrected for the hard-water effect.

"old" carbon assuming a simple two-component isotopic mixing relationship [*Faure*, 1977], with one fraction corresponding to the activity of $^{14}CO_2$ in the atmosphere during the time of the *Ambrosia* rise and the other fraction corresponding to the $^{14}$C activity in calcite.

[31] Using 1950 as the standard origin for an uncalibrated radiocarbon chronology, the dates would be about 835 years too old. This error would remain constant through time as long as the surface waters contained the same mixing ratio of bicarbonate leached from carbonate minerals and $CO_2$ diffusing from the atmosphere. This assumption is supported by the 1) the nearly linear relationship of the shell ages with depth; 2) the consistent association of shells with marl (authogenic calcite) deposits, indicating depositional waters saturated with respect to calcite; and 3) the small storage capacity of this wetland for both surface and pore waters, which limits the diluting effect of precipitation. Further support is provided by the relatively narrow and invariant 2-$\sigma$ error envelope calculated by OxCal around the nearly linear age-versus-depth relationship.

[32] The radiocarbon dates for very small rootlets, in contrast, provide strong evidence for an open-system type of error in which plant roots translocate modern carbon deep into the sediment profile (Figure 4; Table 1). Modern dates were obtained for very fine rootlets (2–4 mm long) at depths of 16, 40, and 60 cm, indicating that living plant roots penetrate down to the middle of the sediment profile. In addition, radiocarbon dates for larger fragments of unidentifiable plant tissue did not fit a linear trend with depth but showed significant scatter suggesting different levels of contamination from either open-system or hard-water effects. These samples were generally but not always younger than the dates obtained for shells at corresponding depths with the most striking discrepancy occurring toward the base of the core where coarse

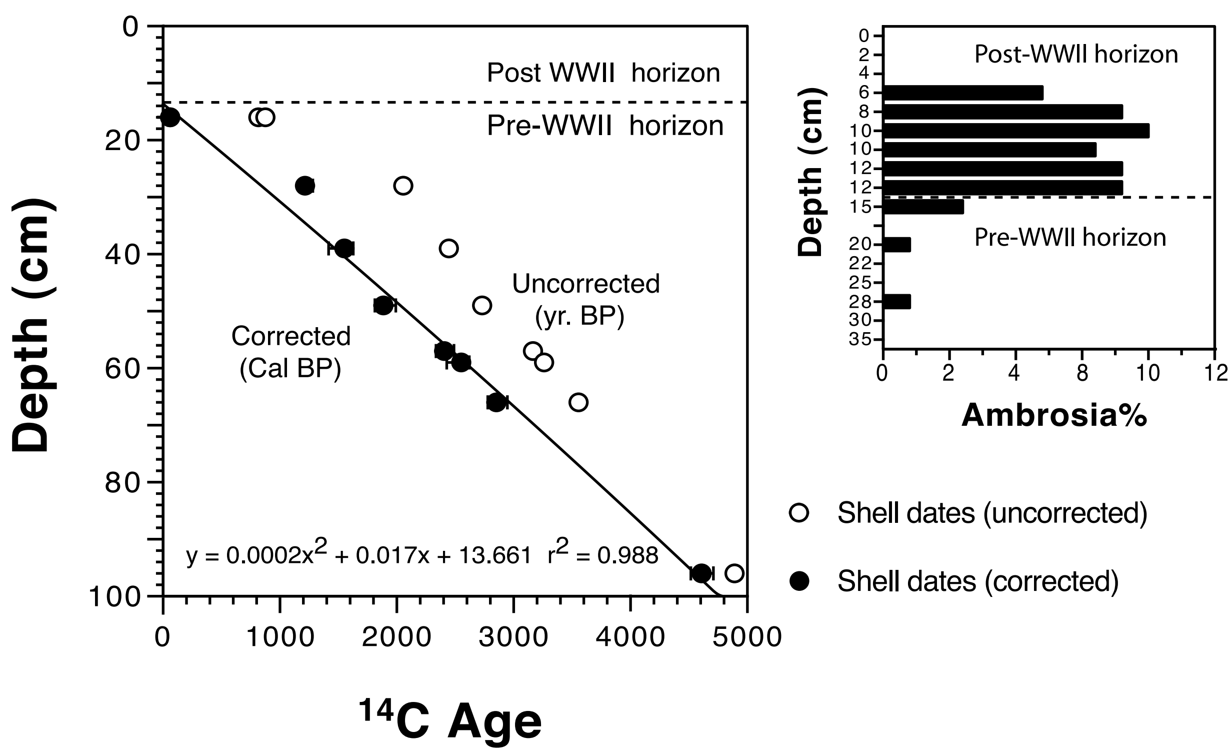


**Figure 5.** The gastropod chronology for the NESRS core. The uppermost gastropod sample was collected just below the post-WWII horizon indicated by the rise of *Ambrosia* pollen (shown at right). The radiocarbon date for this sample was then used to correct for the hard-water effect, producing the offset between the raw (uncorrected) and corrected radiocarbon dates in the graph at left.

**Table 1.** Radiocarbon Dates for the Northeast Shark River Slough (NESRS) Core[a]

| CAMS ID | Sample ID | Depth (cm) | Type | $\delta^{13}C$ | $^{14}C$ yr BP | $^{14}C$ yr BP Corrected | Median-Calibrated BP | 95.4% ($2\sigma$) Calibrated Age Ranges | Median-Calibrated BP Corrected |
|---|---|---|---|---|---|---|---|---|---|
| 135154 | NESRS 21a | 16 | shells | 0 | 875 ± 40 | 10 | | | 60 |
| 135160 | NESRS 21a | 16 | shells | 0 | 815 ± 40 | 10 | | | 60 |
| 137544 | NESRS 3 | 28 | shells | 0 | 2055 ± 30 | 1260 | | 1166–1281 | 1214 |
| 135155 | NESRS 5 | 39–40 | shells | 0 | 2445 ± 40 | 1650 | | 1416–1627 | 1551 |
| 135156 | NESRS 7 | 49–50 | shells | 0 | 2730 ± 40 | 1935 | | 1812–1991 | 1885 |
| 135157 | NESRS 22A | 57 | shells | 0 | 3165 ± 35 | 2370 | | 2335–2489 | 2405 |
| 135158 | NESRS 9 | 59–60 | shells | 0 | 3260 ± 35 | 2465 | | 2427–2620 | 2551 |
| 135159 | NESRS 11 | 65.5–66.5 | shells | 0 | 3555 ± 35 | 2760 | | 2778–2946 | 2852 |
| 135223 | NESRS 19a | 96–97 | shells | 0 | 4890 ± 35 | 4095 | | 4516–4709 | 4608 |
| 137545 | NESRS 32 | 28–29 | marl | −25 | 1085 ± 30 | | 993 | 934–1018 | |
| 135396 | NESRS 27 | 39–40 | marl | −25 | 1720 ± 45 | | 1630 | 1528–1729 | |
| 135397 | NESRS 28 | 57 | marl + OM | −25 | 2850 ± 35 | | 2963 | 2868–3071 | |
| 137546 | NESRS 33 | 65–66 | marl + OM | −25 | 2980 ± 35 | | 3167 | 3061–3267 | |
| 135395 | NESRS 30 | 85 | OM + marl | −25 | 3595 ± 35 | | 3901 | 3828–3986 | |
| 135398 | NESRS 30 | 85 | OM + marl | −25 | 3795 ± 35 | | 4181 | 4083–4295 | |
| 137547 | NESRS 34 | 94 | marl + OM | −25 | 3705 ± 35 | | 4042 | 3965–4150 | |
| 135221 | NESRS 12A | 65.5–66.5 | charcoal | −25 | 3590 ± 100 | | 3898 | 3635–4155 | |
| 135222 | NESRS 23 | 70–72 | charcoal | −25 | 3440 ± 45 | | 3703 | 3608–3832 | |
| 135386 | NESRS 21c | 16 | rootlets | −25 | >modern | | >modern | >modern | |
| 135387 | NESRS 6 | 39–40 | VPT | −25 | >modern | | >modern | >modern | |
| 135388 | NESRS 8 | 49–50 | VPT | −25 | 895 ± 40 | | 820 | 733–915 | |
| 135389 | NESRS 10B | 59–60 | rootlets | −25 | >modern | | >modern | >modern | |
| 135390 | Sample 12B | 65.5–66.5 | R + VPT | −25 | 830 ± 35 | | 738 | 678–795 | |
| 135391 | Sample 14 | 74–75 | VPT | −25 | 3550 ± 35 | | 3844 | 3720–3926 | |
| 135392 | Sample 15S | 79–80 | VPT | −25 | 3875 ± 35 | | 4315 | 4227–4417 | |
| 135395 | Sample 16A | 84–85 | VPT | −25 | 3065 ± 40 | | 3289 | | |
| 135393 | Sample 17c | 89–90 | VPT | −25 | 4125 ± 40 | | 4667 | 4528–4730 | |
| 135223 | Sample 19a | 96–97 | VPT | −25 | 3035 ± 40 | | 3254 | 3141–3359 | |

[a]The table contains both the conventional ($^{14}C$ yr BP) and calibrated (median Cal BP) radiocarbon date in years before the present for each sample as well as its counting error (±yrs) and 2-$\sigma$ confidence interval for the calibrated age (95.4% (2s) cal age ranges). OM stands for fine-grained organic matter, and PVT stands for fragments of vegetative plant tissue. The steps toward calculating calibrated dates for the gastropod shells that were corrected for the hard water effect are shown from 1) the initial conventional date ($^{14}C$ yr BP); 2) the initial conventional date, corrected for the hard water effect ($^{14}C$ yr $BP_{cor}$.); and 3) the median age for each calibrated date, corrected for the hard water effect (Median Cal $BP_{cor}$.).

plant detritus had a radiocarbon date of 3035 yrs B.P. (3254 cal B.P.), which is over 1300 years younger than the corrected date of a shell at the same depth. Nevertheless, three radiocarbon dates of plant fragments between 75 and 85 cm deep fit a general linear trend that corresponds to the trend of the uncorrected shell dates suggesting that this material was largely derived from aquatic vascular plants.

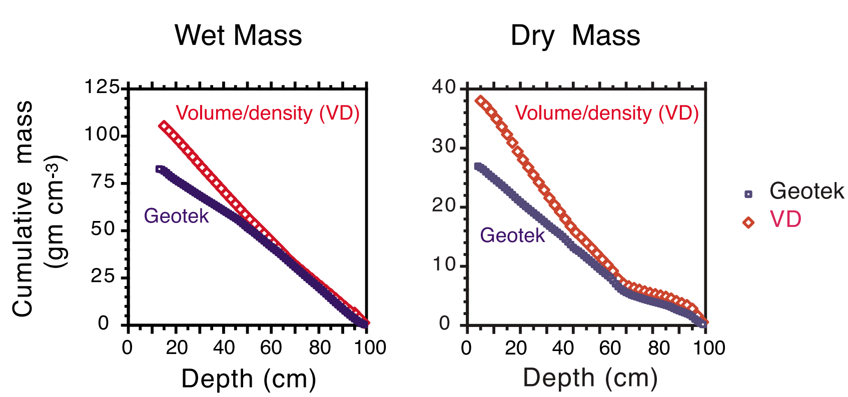


**Figure 6.** Comparison of bulk density measurements for the NESRS core. The traditional destructive sampling method based on volumetric density (VD) produces a cumulative value that is over 20% higher than that of the non-destructive method based on gamma-ray attenuation (Geotek). Both the wet and dry bulk density profiles provide no evidence for sedimentary gaps.

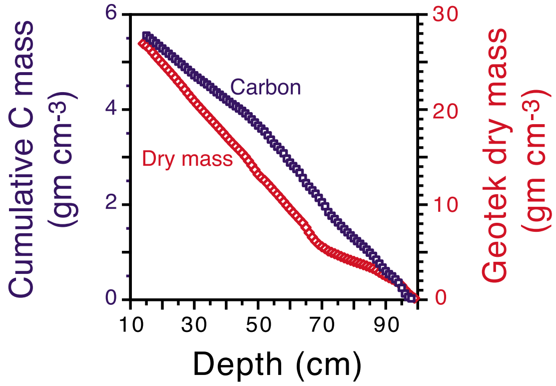


**Figure 7.** Comparison of cumulative dry-mass and carbon profiles in the NESRS core.

[33] The charcoal dates also suggest an apparent hard-water effect since they generally agree with the trend of the uncorrected shell dates except for the deepest sample, which is slightly younger than the one directly above (Table 1, Figure 4). These samples were apparently blackened fragments of aquatic plants that had assimilated similar fractions of old carbon derived from carbonate minerals. Unfortunately charcoal particles are usually so small that they could easily be confused with plant detritus blackened by decomposition.

[34] The radiocarbon dates for the six bulk samples are from 100 to more than 1400 calendar years older or younger than the adjacent corrected dates for shells except for one bulk date at 39 cm depth that was nearly identical to that of an adjacent shell (Figure 4, Table 1). These bulk dates fit a linear relationship ($r^2$ = 0.967) with depth that has slightly lower significance than that for the corrected shell dates ($r^2$ = 0.985; Figure 5) but with a different slope. However, the various types of dating errors associated with bulk sediment samples introduce more serious dating errors toward the lower portion of the core. The two replicate bulk samples from a depth of 85 cm, for example, provide median calibrated dates that are 280 years apart and have non-overlapping 2-$\sigma$ confidence limits. Furthermore these median dates are either 140 years younger or older than the bulk radiocarbon date below at a depth of 94 cm near the base of the core (Table 1). Since the composition of old versus young carbon in these bulk samples will change with depth, and horizontal position in a core, a high degree of caution must be used in interpreting bulk dates in the absence of an independent standard.

### 4.3. Bulk Density, Mass Accumulation Rates, and Sedimentary Gaps

[35] The bulk density of the NESRS sediments varied as a function of saturation, sediment type, and method of measurement. The Geotek measurements were consistently lower than those obtained by the standard volume-density (VD) method particularly for the largely inorganic sediments of Units I and II (Figure 6). The two methods produced very similar results for the lower organic-rich layers but the curves for cumulative mass begin diverging with the increase in carbonates toward the top of the core. The wet bulk density determinations, for example, begin diverging at a depth of 50 cm near the boundary between lithologic units I and II, whereas the dry bulk density determinations began diverging lower, at a depth of 63 cm, near the boundary for units II and III. However, the total range of values for both wet and dry bulk density for any particular sample varied by less than 1 g $cm^{-3}$ for both methods. The organic-rich sediment of Units III and IV, for example, had wet bulk density values of 0.78–1.35 g $cm^{-3}$, whereas the dry bulk density were 0.11 and 0.60 g $cm^{-3}$, using the Geotek and volume/density techniques, respectively. Both methods produced slightly higher values for the largely inorganic sediment of Units I and II with a combined range of 0.75–1.47 g $cm^{-3}$ for wet bulk density and 0.29–0.76 g $cm^{-3}$ for dry bulk density. Overall the Geotek measurements produced a 22% lower value (82.6 g $cm^{-3}$) for the cumulative wet bulk density of the entire core and a 30% lower value (26.9 g $cm^{-3}$) for the cumulative dry bulk density when compared to the VD method (Figure 6). The curve for cumulative dry mass had a slight concave

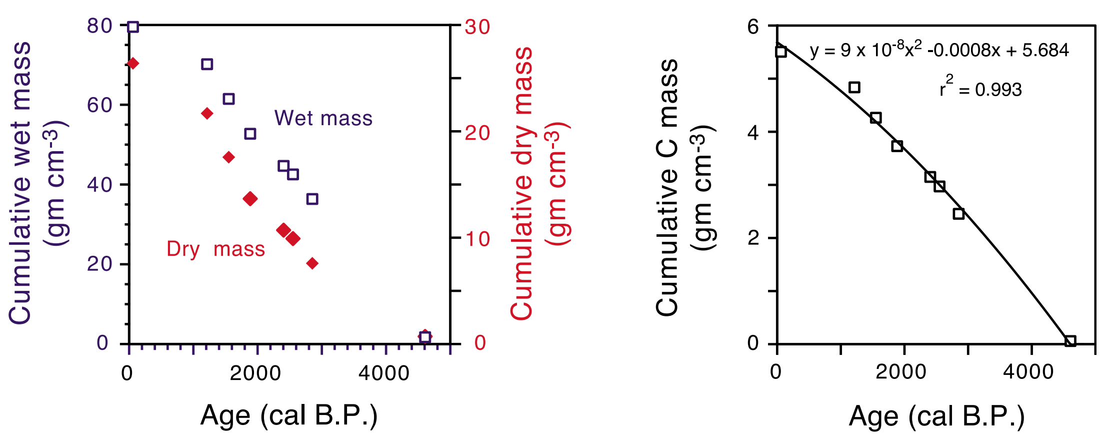


**Figure 8.** Carbon and mass accumulation rates for the NESRS core. Although both linear and second-order polynomial functions provide a statistically similar fit to the mass-versus-age data, the cumulative mass data has an apparent convex shape in contrast to the convex shape of cumulative carbon data. The chronology is based on the corrected $^{14}C$ dates for the gastropod shells.

**Table 2.** Curve-Fitting Functions for Age-Versus-Mass Data

| Model | Equation | $r^2$ | F-ratio | *p* value |
|---|---|---|---|---|
| | *Age vs Cumulative Dry Mass (Geotek)* | | | |
| Linear | y = 0.006x + 26.414 | 0.960 | 144.445 | ≪0.000 |
| Second-order polynomial | $y = 4.26 \times 10^{-7}x^2 + 0.008x + 28.103$ | 0.974 | 98.525 | ≪0.000 |
| | *Age vs Cumulative Dry Mass (Volume Density)* | | | |
| Linear | y = 0.008x + 35.591 | 0.927 | 76.584 | <0.000 |
| Second-order polynomial | $y = 0.013x^2 - 1.05 \times 10^{-6}x + 39.742$ | 0.969 | 64.802 | <0.000 |
| | *Age vs Cumulative Carbon* | | | |
| Linear | y = 0.001x + 6.034 | 0.979 | 278.461 | ≪0.000 |
| Second-order polynomial | $y = 9 \times 10^{-8}x^2 - 8 \times 10^{-5}x + 5.484$ | 0.993 | 199.341 | ≪0.000 |

shape as a function of depth, whereas the curve for cumulative carbon mass was convex (Figure 7).

[36] The relationship of cumulative dry-mass accumulation as a function of age was based on the gastropod chronology described above and the bulk density values obtained by the gamma-ray attenuation method. The gastropod dates seem to provide the most reliable chronology for this site based on their nearly linear age versus depth relationship and sensitivity to only hard-water sources of error, which can be quantified and corrected. In contrast, the Geotek measurements have the advantage of being non-destructive, non-invasive, and consistent over a much finer depth interval than the destructive method based on volume-density relationships.

[37] Over the past 4600 years the long-term rate of dry mass accumulation at this site was 58.5 g $m^{-2}$ $yr^{-1}$, whereas that for carbon was 12.1 g C $m^{-2}$ $yr^{-1}$. The sediment accretion rate was only 0.21 mm $yr^{-1}$ over the same time period. Both linear and quadratic polynomials were fit through the data for cumulative mass versus age with only a slight change in $r^2$ values for dry mass ($r^2$ = 0.960 and 0.974, respectively) and total carbon ($r^2$ = 0.979 and 0.993, respectively) (Figure 8; Table 2). However, the polynomial fit for dry mass showed a slightly concave shape, whereas that for total carbon showed a more linear and slightly convex shape.

[38] No physical evidence could be detected for hiatuses, erosional surfaces, or fire horizons either because these processes were not important at this site or their effects fell below the detection limit for the age/depth model or cumulative mass profile. A Sadler-type plot of mass accumulation rate as a function of time span of averaging, however, showed that these data fit the expected negative power law with slope of −0.614 producing expected completeness values $[(t^*/t)^{-m}]$ of 74% for the upper marl-rich Units I and II and 55% for the lower organic-rich layers of Units III and IV (Figure 9).

## 5. Discussion

[39] Sedimentation is a key process that drives the development and rate of carbon storage in both lakes and wetlands. Barring some large change in the regional climate or base-level the slow infilling of a wetland basin with sediment will alter the local hydrology, vegetation assemblages, and topography in a developmental sequence similar to that first described by *Weber* [1902]. In many wetlands, sedimentation is largely controlled by two biological processes. Organic matter may accumulate in wetland soils through the incomplete mineralization of plant tissues produced by primary production [*Chapin et al.*, 2002; *Clymo*, 1984]. In addition, sediment can also be deposited by the biogenic precipitation of calcium carbonate (marl), iron hydroxides (bog iron), or other solutes in specific hydrogeologic settings [*Cohen*, 2003]. Hard-water wetlands such as the Everglades therefore have complex modes of autogenic sediment accumulation governed by different biotic processes and controls. Whereas rates of soil organic matter turnover are closely tied to the seasonality of precipitation and temperature, the deposition of marl depends mostly on water depth and surface water chemistry [*Gleason and Spackman*, 1974; *Browder et al.*, 1994; *Cohen*, 2003]. These two contrasting modes of sediment accumulation should therefore sequester carbon at different rates because organic matter typically contains three times the carbon content of calcium bicarbonate on a per molecule basis but is subject to mineralization by microbial decomposers [*Cohen*, 2003].

[40] The occurrence of both marl and largely organic strata in the NESRS core therefore provides important insights on the factors controlling the long-term rates of sediment accretion and carbon accumulation within the Everglades.

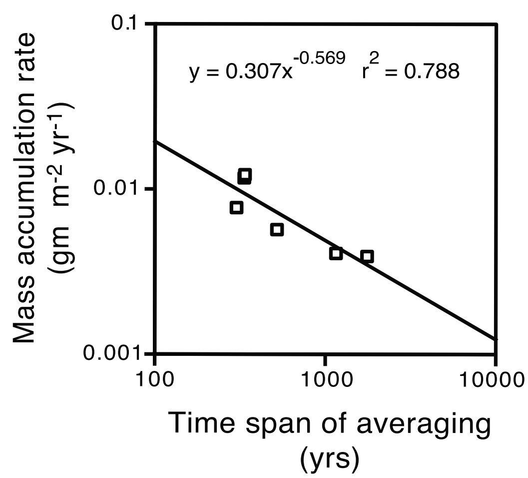


**Figure 9.** Log plot of accumulation rate trends for the NESRS core as a function of time span of averaging. The trend fits the general inverse relationship predicted by the *Sadler* [1981] model. The steepness of the slope is indicative of the degree of sedimentary completeness, with a slope of zero representing the absence of sedimentary gaps.

These rates should change abruptly at the organic/inorganic boundary of the sediment profile if accumulation rates are in fact controlled by the warm temperatures and high decomposition rates of the subtropics. However, a nearly linear rate sediment accumulation throughout the core would imply the role of some external driver that can alter local hydraulic gradients such as the slow rise in sea level since the mid-Holocene. The extensive distribution of marl layers with gastropod shells throughout the NESRS core also provides a robust means to establish a reliable age model for these sediments, which are otherwise susceptible to multiple sources of dating error.

### 5.1. Dating Problems

[41] Stratigraphic studies in the Everglades were begun before the time of radiocarbon dating, and this important body of older work lacks the chronological control needed to make reliable paleoenvironmental reconstructions [*Dachnowski-Stokes*, 1930; *Davis* 1943, 1946; *Parker and Cooke*, 1944]. With the advent of $^{14}C$ dating most subsequent investigations in the Everglades were based on conventional $^{14}C$ dating of bulk sediment samples [*Gleason and Stone*, 1994; *Willard et al.*, 2006]. Initially bulk samples were mandated by the large sample size needed to obtain a reliable date but also by the rarity of terrestrial plant macrofossils in the deeper sediments. However, even after the introduction of radiocarbon dating by accelerator mass spectroscopy (AMS-$^{14}C$) *Gleason and Stone* [1994] argued that bulk samples could still provide reliable $^{14}C$ dates because the surface waters in the Everglades were well-mixed with $CO_2$ diffusing from the atmosphere. They apparently presumed that potential problems of contamination by modern roots or disruptions of the stratigraphy by vertical mixing could be avoided by careful selection of sites or samples.

[42] The development of AMS-$^{14}C$ dating made it possible to date samples containing much smaller amounts of carbon allowing 1) the dating of individual pieces of plant detritus, shells, or charcoal fragments; and 2) an analysis of the sources of error associated with the different carbon fractions in sediments. The AMS dates from the NESRS-4-23-04-SRS-4 core clearly shows that both open-system and hard-water sources of error are serious problems for radiocarbon dating of Everglades sediments. A conventional bulk sample, for example, will include an unknown fraction of very fine rootlets and the partially decomposed tissues of roots that translocated younger carbon into deeper and older layers of the sediment. This problem is particularly serious in the Everglades since disaggregated root tissue represents a significant fraction of the organic matter in these sediments [*Gleason and Stone*, 1994; *Gleason and Spackman*, 1974; *Cohen and Spackman*, 1974]. Bulk samples will also contain an indeterminable fraction of "old" carbon leached from carbonate minerals that was incorporated into algae and aquatic vascular plants that form an important component of our cores from the southern and central Everglades. This type of problem should be common across the southern and central Everglades, where marl layers were found in 2/3 of our sediment cores. Both hard-water and open-system errors should become most serious toward the base of a profile, where the sedimentary sequence is thinnest.

[43] Gastropod shells seem to provide the most reliable material for constructing a chronology since the carbonate fraction of these shells is only susceptible to hard-water type errors. However, shells must be present near the very top of a sedimentary profile for quantifying the hard-water effect and also near the base for determining a basal date. A scattering of shells throughout a profile also provides an opportunty to assess whether the hard-water effect has changed in magnitude through time. The nearly linear age-versus-depth profile provided by the nine shell dates from the NESRS core indicates little change in the magnitude of the hard-water effect during the sedimentary record at a site. Since shells are largely confined to depths where calcareous silt is abundant, chronologies based on shell dates may need to be supplemented at other sites by some other method such as time-stratigraphic correlations using the regional pollen stratigraphy.

### 5.2. Problems Related to Measuring Bulk Density

[44] Both the gamma-ray attenuation (Geotek) and volume-density (VD) measurements are sensitve to water losses arising from the routine handling and storage of sediment cores. Water losses can be further amplified by extracting samples for VD measurements, whereas the Geotek measurements are more sensitive to calibration offsets created by scanning contrasting sediment types [*Breitzke*, 2006]. A comparative analysis of the NESRS core suggests that these Geotek calibration errors are minor compared to those related to dewatering, which preferentially affect silty sediments. Cores with thick silt layers are especially prone to dewatering as the silt grains settle during routine handing and storage. It is therefore not surprising that the cumulative mass profiles of the Geotek and VD methods only begin to diverge as the silt fraction increases in abundance above a depth of 68 cm.

[45] Dewatering effects would also help explain why the dry-mass profiles for the Geotek and VD methods begin to diverge much lower in the core profile (near boundary between Units II and III) than those for wet mass. The dry-mass profiles are apparently more sensitive to dewatering errors because both methods require invasive subsampling to determine the ratio of wet-to-dry mass, whereas the Geotek method only relies on non-invasive scans to measure wet-bulk density. Despite the dewatering effects, both methods produce similar results suggesting that the overall measurement errors for bulk density are small relative to the much larger error bars for calibrated radiocarbon dates. Overall, bulk density measurements seem to produce less significant errors than those related to a core's age model for calculating mass accumulation rates.

### 5.3. Mass Accumulation Rates

[46] The NESRS core contained a 4600 year record of sediment accumulation in a sedimentary profile of less than a meter. This slow rate of sediment accumulation could be a product of three different factors: 1) formation of gaps in the profile related to environmental perturbations such as fire, droughts, or drainage operations, 2) high rates of decomposition driven by warm soil temperatures, or 3) external climatic or geologic controls on the hydrology of the Everglades basin.

#### 5.3.1. Sedimentary Completeness

[47] The hydrology of the Everglades has been altered by a massive drainage program that changed the hydraulics of this wetland and may have caused widespread loss of

organic sediment. *Stevens and Johnson* [1951] estimated that as much as 2 m of organic sediment had been lost in the northern agricultural areas of the Everglades since 1880, whereas *Sklar et al.* [2001] estimated losses of about 0.5 m along various drainage canals. *Loveless* [1959] also suggested that lower water tables favored the spread of wildfires and increased rates of aerobic decomposition in the near-surface sediments, whereas *Givnish et al.* [2008] proposed the local transport of sediment from sloughs to the adjacent ridges as an important mechanism for surface patterning. These types of losses should be recorded by stratigraphic markers such as charcoal peaks, truncated age profiles, or distinct changes in bulk density or cumulative mass toward the top of a core. In contrast, no evidence for gaps were apparent in the NESRS core, which instead had a nearly linear age-versus-depth profile and no apparent charcoal layers.

[48] The absence of such evidence is not completely unexpected since sedimentary gaps are insidious and are especially difficult to detect at sites with slow accumulation rates. *Grimm* [2011], for example, needed 53 AMS-$^{14}$C dates to detect erosional facies within a profile of lake sediment that was over 20 m thick, 13,000 years old, and mostly laminated. This scale of resolution is seldom available in wetlands particularly those in the study area where the sedimentary profile is less than a meter. The presence of gaps was therefore analyzed indirectly by a Sadler analysis, which yielded the expected negative power law suggesting a greater loss of sediment from the mostly organic sediments of Units III and IV than from the inorganic silty sediments of Units I and II. Although this approach indicates that gaps may partially account for the thin sedimentary column at the coring site, this method needs to be confirmed by extending it to a greater number of cores within the adjacent area.

#### 5.3.2. Rates of SOM Mineralization

[49] The thin sedimentary profile at the NESRS site may also be a product of high decomposition rates driven by the warm subtropical climate and soil temperatures. This commonly accepted hypothesis [e.g., *Gore*, 1983] is unfortunately difficult to test over long timespans by available methods. Measurements of contemporary carbon fluxes may be unrepresentative of the entire sedimentary record at a site given the probability of a changing environment and the degree to which many wetlands have been altered by human activities. The alternative approach estimates long-term carbon fluxes using mathematical models that estimate decay parameters by first-order reaction kinetics, radiocarbon inventories, or coupled ecosystem-hydrological processes [e.g., *Clymo*, 1984, 1992; *Clymo et al.*, 1998; *Belyea and Malmer*, 2004; *Trumbore and Harden*, 1997; *Frolking et al.*, 2010]. These models are typically calibrated and tested using radiocarbon-dated profiles of dry bulk density and carbon density from representative wetlands.

[50] The reliability of these model calibrations may be limited by conceptual deficiencies in the models that do not conform to the heterogeneities of specific vegetated wetlands. Most carbon accumulation models, for example, assume that organic matter is only added incrementally to the top of a sedimentary profile, whereas wetland plants typically allocate a large fraction of their net primary production to belowground organs [*Chapin et al.*, 2002; *Moore et al.*, 2002; *Chanton et al.*, 2008]. Here we present direct radiocarbon evidence that modern rootlets extend down 60 cm to the middle of the sediment column at the NESRS site at depths that were independently dated to be over 2000 years old. In addition, root biomass represents a significant fraction of the wetland sediment within the study area and elsewhere in the Everglades [e.g., *Gleason and Stone*, 1994; *Cohen and Spackman*, 1974]. Plant roots could therefore compromise model calibrations depending on the magnitude and depth of these carbon transfers.

[51] Model calibrations may be further limited by the low vertical and chronological resolution of many radiocarbon age-models. Both linear and second-order polynomial functions can be fit to the age-versus-cumulative mass profile of the NESRS core with nearly the same degree of statistical significance. A polynomial function may seem preferable since its quadratic format agrees with that of the governing equation for the original *Clymo* [1984, 1992] model. But Clymo's original model and its later derivatives produce a concave curve for the rate of cumulative carbon accumulation indicating that the decay rate declines in time as a function of the organic mass remaining. In contrast, the second-order polynomial fit for the NESRS profile provides a slightly convex curve similar to the predictions of the *Trumbore and Harden* [1997] model and profiles reported for certain northern peatlands [e.g., *Korhola et al.*, 1996; *Trumbore and Harden*, 1997; *Yu et al.*, 2003]. Carbon accumulation models may also overestimate the decay rates for sedimentary profiles with significant sedimentary gaps, which would be expected in subtropical regions with a monsoonal pattern of precipitation interspersed with episodic droughts.

[52] The NESRS core provides an alternative approach for determining the degree to which decay rates govern long-term rates of carbon storage and sediment accretion in warm-climate wetlands. The decay hypothesis predicts that these rates should change markedly at the organic/inorganic boundary given the differing degrees of reactivity of inorganic silt and organic matter to microbial metabolism. However, there was only a slight difference in the accretion rate from the largely organic sediment in Units III and IV (0.21 mm yr$^{-1}$) to that of the largely silty layers of Units I and II (0.18 mm yr$^{-1}$). The nearly linear but slow rate of sediment accretion and carbon accumulation throughout the profile strongly suggests that some external agent governs the long-term rate of sediment accumulation at this site.

#### 5.3.3. Hydrogeologic Setting

[53] The elevation of the water table imposes a dual set of controls on sedimentation processes in the Everglades since decomposition proceeds much more slowly below the oxic/anoxic boundary of sediment profiles and the deposition of marl is generally restricted to shallow, illuminated, water depths. Prior to the drainage era, water levels in the Everglades were ultimately constrained by the morphometry of its bedrock basin and the hydraulic gradient extending from Lake Okeechobee to the sea. Precipitation and surplus recharge from Lake Okeechobee largely flows across the Everglades as overland flow because of the orientation of the bedrock trough and the fine-scale impermeability of the underlying bedrock. Unlike many wetlands the Everglades has a direct natural outlet to the sea through the Shark River Slough (Figures 1a and 1b) so that water levels throughout the wetland were probably closely

adjusted to the rising sea levels of South Florida since the Mid-Holocene. Such a relationship is supported by the long-term rate of sediment accretion at the NESRS site of 0.2 mm $yr^{-1}$, which tracked the slow and steady rise of sea level of 0.35 mm $yr^{-1}$ over the past 4000 years [*Scholl and Stuiver*, 1967; *Scholl et al.*, 1969; *Wanless et al.*, 1994]. The elevation of this drainage outlet, which was initially less than a meter above modern sea level (Figure 1b) further suggests a sensitive linkage between sea level and water levels across the Everglades.

[54] Within any flooded wetland, a drainage outlet will create a hydraulic regime similar to that of a river, because any transient rise in the water level following a storm event will readjust to the elevation of the outlet. In the Everglades this drainage outlet is directly connected to the sea, which sets the lower constant-head boundary for the entire watershed. Rising sea levels should therefore impose an upper limit to sedimentation rates because 1) sea level set the base level for the hydraulic gradient within the pre-drainage Everglades, 2) neither organic matter nor marl can accumulate above the prevailing water levels, and 3) the hydrogeologic setting is not conducive for the formation of water table mounds. Water table mounds preferentially form under drainage divides or within the interfluvial divides between rivers in large peat basins [cf. *Glaser et al.*, 1997, 2004] and these geomorphic features are not present in the Everglades. Sediment accumulation rates are further limited by the shallow depth of the Everglades basin, which is less than 1–2 m within large portions of the south-central and southern Everglades (Figure 1b) [*Parker and Cooke*, 1944]. Although short-term rates of sediment accumulation in the Everglades may be limited by the low primary productivity of the vegetation [*Davis and Ogden*, 1994] or by carbon losses through decomposition [*DeBusk and Reddy*, 1998; *Qualls and Richardson*, 2008] or wildfires [*Loveless*, 1959], the ultimate control on accumulation rates in the Everglades over long timespans may be the shallow depth of the bedrock basin and the slow rise in sea levels since the Mid-Holocene.

### 5.4. Regional Comparisons

[55] Regional comparisons of carbon storage are subject to multiple sources of error related to methodology and the variable preservation of organic matter in wetland sediments. Spatial control is usually limited by the rarity of profiles that are documented by both multiple radiocarbon dates and also direct measurements of bulk density and carbon content [*Clymo et al.*, 1998; *Dommain et al.*, 2011]. Alternatively rates of carbon storage have been estimated from short cores dated by $^{137}$Cs or $^{210}$Pb or by modern ecosystem measurements. Unfortunately, these short-term rates are typically ill-suited for extrapolating to longer timescales because they fail to incorporate carbon losses related to rapid diagenetic processes in the near-surface sediments and continual decomposition in the deeper peat. Sadler-type effects and changing conditions are also likely to drive different rates of carbon accumulation over long timespans.

[56] Past studies in the Everglades generally support an expectation that rates of carbon storage will decline over longer timespans of averaging. Sediment, accumulated very slowly over the past 4600 years at the NESRS site whether measured in terms of sediment accretion (0.2 mm $yr^{-1}$) or total carbon accumulation (12.1 g $m^{-2}$ $yr^{-1}$). In contrast, much higher rates were reported for shorter timescales in the Everglades, particularly from sites that have been altered by nutrient enrichment or lengthened hydroperiods. *Davis* [1991], for example, reported carbon accumulation rates as high as 221–522 g C $m^{-2}$ $yr^{-1}$ based on multi-year incubations of *Cladium* shoots in litterbags, whereas *Craft and Richardson* [1993, 2008] analyzed short cores from altered sites that recorded significantly lower rates of 86–192 g C $m^{-2}$ $yr^{-1}$ and 54–161 g C $m^{-2}$ $yr^{-1}$ over timespans of 26 and 100 years, respectively. They also reported still lower rates of 28 $\pm$ 9 g C $m^{-2}$ $yr^{-1}$ in short cores from less disturbed areas, whereas the rate of sediment accretion declined from 5.6 mm $yr^{-1}$ in highly altered sites to 0.8 mm $yr^{-1}$ in less disturbed settings. However, these short-term rates could not be sustained for long periods of time since they would completely fill in most areas of the shallow bedrock basin of the Everglades in 1000–2000 years.

[57] Relatively few long-term records of carbon accumulation are available for other tropical and subtropical wetlands (Table 3). *Dommain et al.* [2011], recently reported that only four long-term profiles from Southeast Asia are supported by both multiple radiocarbon dates and also direct measurements of carbon density. They therefore used assumed average values for carbon density to compile 20 long-term records for their regional survey of the extensive peatlands of the Malay Peninsula and the islands of Sumatra and Borneo. The high fraction of wood in these peat profiles would imply relatively similar rates of carbon accumulation across this region because woody tissue is essentially resistant to decay in anaerobic environments. However, *Dommain et al.* [2011] reported much higher rates of peat accretion and carbon accumulation from coastal sites (1.8 mm $yr^{-1}$ and 77 g C $m^{-2}$ $yr^{-1}$, respectively) than those from lowland sites farther inland on Borneo (0.5 mm $yr^{-1}$ and 31.3 g $m^{-2}$ $yr^{-1}$, respectively).

[58] The four detailed profiles also showed that these rates varied significantly through time in response to changes in sea level, climate, and the local geomorphic processes [*Page et al.*, 2004; *Dommain et al.*, 2011]. Peat growth, for example, was essentially stagnant in the interior of Borneo during the Last Glacial Maximum when sea level was 100 m lower, which steepened the hydraulic gradient across Borneo and also led to a drier regional climate. The rapid rise in sea level during the early Holocene subsequently lowered the regional hydraulic gradient across the lowlands of Borneo, and spurred the most rapid rates of peat accretion (≈1 mm $yr^{-1}$) and carbon accumulation (≈60 g C $m^{-2}$ $yr^{-1}$) of the Holocene. As the rate of rising sea level slowed to about 0.25 cm $yr^{-1}$ after the mid-Holocene, the rates of peat accretion and carbon accumulation stabilized to about 0.3 mm $yr^{-1}$ and 20 g C m-2 $yr^{-1}$, respectively, which is similar to the rates recorded by the NESRS core. More recently rates of peat accretion on several inland peat domes on Borneo have been arrested by more intense El Niño-drought cycles [*Dommain et al.*, 2011].

[59] Few long-term records are available for rates of peat accretion and carbon accumulation from other lowland wetlands in the tropics and subtropics. High rates of peat accretion were reported of about 1 mm $yr^{-1}$ for a

**Table 3.** Long-Term (>1000 Years) Rates of Peat Accretion and Carbon Accumulation in Wetlands From the Northern and Southern Hemispheres

| Region | n | Peat Accretion (mm $yr^{-1}$) | C Accumulation (g C $m^{-2}$ $yr^{-1}$) | Reference |
|---|---|---|---|---|
| | | *Subtropical* | | |
| Everglades, Florida | 1 | 0.21 | 12.1 | This study |
| | | *Tropical Lowland* | | |
| Indonesia | | | | |
| Central Kalimantan | 11 | 0.54 | 31.3 (23–76) | *Dommain et al.* [2011] |
| Coastal Kalimantan | 14 | 1.77 | 77 (55–107) | *Dommain et al.* [2011] |
| Peru | | | | |
| Amazonia | 5 | 1.69 (1.66–1.72) | 39 (29–39) | *Lähteenoja et al.* [2009] |
| Amazonia | 5–13 | 2.56 (2.44–2.68) | 85 (55–115) | *Lähteenoja et al.* [2012] |
| Venezuela | | | | |
| Oronoco River Delta | ? | 2.7 | | *Aslan et al.* [2003] |
| Belize | 1 | 0.98 | | *Wooller et al.* [2007] |
| Panama | 3 | 2.5–2.7 | | *Phillips and Bustin* [1996] |
| | | *Tropical Highlands* | | |
| Ecuador | | | | |
| Altiplano | 1 | 1.3 | 46 | *Chimner and Karberg* [2008] |
| Venezuela | | | | |
| Guayana Highlands | 14 | 0.65–0.33 | | *Zinck et al.* [2011] |
| | | *Northern Peatlands Regional Surveys* | | |
| Eastern Canada, Minnesota, and Maine | 32 | 0.55 | 50 (32–98) | *Gorham et al.* [2003] |
| Russia | ? | 0.34 | 38.1 | *Botch et al.* [1995] |
| a) Polygonal mires | ? | | 12 | |
| b) Fens and marshes | ? | | 72–80 | |
| Finland | 1028 | | 22.5 (2.8–88.6) | *Tolonen and Turunen* [1996] |
| a) Bogs | 548 | | 24.0 (6.6–85.8) | |
| b) Fens | 373 | | 15.1(2.8–49.1) | |
| Finland | >500 | | 20.3 | *Turunen et al.* [2002] |

coastal mangrove peatland in Belize, Central America [*Wooller et al.*, 2007], 2.5–2.7 mm $yr^{-1}$ for a coastal peat dome in Panama [*Phillips and Bustin*, 1996] and 2.7 mm $yr^{-1}$ for peatlands on the Orinioco River Delta of Venezuela, South America [*Aslan et al.*, 2003]. These values are about five times to an order of magnitude higher than those recorded at the NESRS site. They are probably related to peatland development on a tectonically subsiding coastline (Panama) or an aggrading coastline in which the buildup of coastal and deltaic sediment, lowers local hydraulic gradients leading to rising water tables (Belize and Venezuela). Farther inland *Lähteenoja et al.* [2009, 2012] also reported high long-term rates of accretion of 0.46–9.3 mm $yr^{-1}$ and carbon accumulation rates of 28–108 g C $m^{-2}$ $yr^{-1}$, from the extensive peatlands on the subsiding Pastaza-Marañon foreland basin of Peruvian Amazonia. The upper range of these rates is quite high relative to those from other areas and may be driven by high local rainfall, flood pulses from nearby rivers, and also fluvial and tectonic processes that lower the local hydraulic gradient. The other South American records for peat accretion (1.3 mm $yr^{-1}$ and 0.65–0.33 mm $yr^{-1}$) and carbon accumulation (to 46 g C $m^{-2}$ $yr^{-1}$) are restricted to higher elevations with cooler alpine climates [*Chimner and Karberg*, 2008; *Zinck et al.*, 2011]. A similar range of values (0.3–4.9 mm $yr^{-1}$) for peat accretion rate was reported by *Drexler et al.* [2009] for temperate marshes on the west coast of North America.

[60] In contrast, several regional surveys have summarized the more extensive data sets available for LORCA in peatlands above 45°N latitude. Overall, these surveys yield a surprisingly similar range of values for long-term rates of carbon accumulation, although only the *Gorham et al.* [2003] survey in Table 3 was based on profiles with multiple radiocarbon dates and direct measurements of carbon density. The highest average value of 50 g C $m^{-2}$ $yr^{-1}$ was reported for eastern Canada and adjacent parts of the United States [*Gorham et al.*, 2003], whereas similar but lower average values were reported for Russia (38.1 g C $m^{-2}$ $yr^{-1}$; [*Botch et al.*, 1995], and Finland (20.3 and 22.5 g C $m^{-2}$ $yr^{-1}$) [*Tolonen and Turunen*, 1996; *Turunen et al.*, 2002]. In addition, these surveys identified geographic patterns in LORCA that are related to climatic gradients (southern > northern in Finland and Russia, but continental > maritime in eastern Canada, Minnesota, and Maine), peatland type (bogs > fens in Finland and Russia), and age (younger > older in NE Canada/United States and Finland). The lower carbon accumulation rates characteristic of older sites and those in northerly permafrost regions are also documented by the compilation of *Yu et al.* [2009]. However, the entire range of LORCA values for each of the profiles included in these surveys varied between about 10–90 g C $m^{-2}$ $yr^{-1}$.

[61] The similar range in LORCA values in both northern and tropical wetlands (except for a few Amazonian outliers) is surprising given the relatively small sample size of these surveys, large degree of spatial and temporal variability of wetlands, and multiple measurement uncertainties (e.g., dating and bulk density). LORCA values do not seem to be biased by the averaging procedures used by many studies to estimate carbon density because these estimates fall within the same range as those derived from more detailed analyses. A possible exception would be profiles containing complex mixtures of organic and inorganic sediment such

as those at many Everglades sites. The limited range of LORCA values may be a reflection of the high water content (wet mass usually >85% water), low carbon density (dry mass ≈ 45%–55% carbon), and relatively young age (usually <12,000 years) of most wetland sediments. However, the lack of any pronounced difference in LORCA values between northern and tropical wetlands suggests that rates of carbon storage are not limited by the warm soil temperatures of the tropics but by other factors that maintain a waterlogged profile.

[62] This interpretation is supported by the maximum peat depths reported for these regions, which are closely adjusted to the hydrogeologic setting of a site rather than climate alone. In Southeast Asia, for example, a maximum peat depth of 9.5 m was reported for the Sebangau peat dome, which is located within a broad 26–40 km interfluve between the Katingan and Kahayan Rivers on the island of Borneo [*Page et al.*, 1999, 2004]. In contrast the maximum depth of a peat dome along the Canadian transect of *Gorham et al.* [2003] was 7.4 m on the 7-km-wide island of Miscou, New Brunswick, where the coastline has been subsiding for the past 7000 years [*Glaser and Janssens*, 1986, Figure 7]. The depth of these peat domes conforms to the prediction relating the maximum potential height of a water table mound under a bog to the distance between the water bodies that bound a wetland watershed and also the relative elevations of these water bodies [cf. *Glaser et al.*, 2004]. Sea level would therefore set an upper limit to the height of a peat dome in lowland sites close to the coast in addition to climate.

[63] In contrast the 97 cm profile at the NESRS site probably represents an adjustment to the shallow depth of the tectonically stable Everglades basin and the low hydraulic gradient extending from Lake Okeechobee to the sea. The long-term rate for carbon accumulation at the NESRS site is over 4 times lower than the average values reported for peatlands in eastern North America [*Gorham et al.*, 2003] and those in the lowland tropics [e.g., *Dommain et al.*, 2011; *Lähteenoja et al.*, 2009, 2012]. The carbon accumulation rate at the NESRS site is also about 3 times lower than the average value for peatlands across Russia [*Botch et al.*, 1995] and 2 times lower than those in Finland and Europe [e.g., *Belyea and Malmer*, 2004; *Tolonen and Turunen*, 1996]. As one of the longest sediment cores from our survey (Figure 3), the sedimentation rate at the NESRS site may be near the upper limit possible for this shallow portion of the Everglades basin. These data indicate that the geologic setting and local hydraulic gradients may impose important contraints on long-term rates of carbon storage in the Everglades and other warm-climate wetlands.

## 6. Conclusions

[64] The Everglades represents a problematic setting for determining long-term accumulation rates for dry mass and carbon. Here radiocarbon dating is subject to both open system and hard water effects, whereas sedimentary models must also account for erosion and transfers of primary production by deeply penetrating root systems. Although a chronology based on gastropod shells seems to provide a reliable means for estimating long-term rates of sediment accumulation, the statistical uncertainty associated with each datapoint generally precludes any attempt to find a unique curve-fitting model for the mass accumulation data. Therefore an element of uncertainty will always be associated with models based on age-versus-mass data alone unless independent means can be found to test the underlying assumptions of these models such as those of *Clymo* [1984] and *Sadler* [1981]. Nevertheless, the long-term estimates for both dry mass and carbon accumulation at the NESRS site provide important insights on the processes that govern sedimentation in portions of this vast subtropical wetland and its role as a sink for carbon.

[65] The very slow long-term rate of carbon accumulation at the NESRS site is significantly lower than that reported for northern peatlands and tropical wetlands by a factor of more than 2–4. These slow rates are probably influenced by the low productivity of the wetland vegetation in the Everglades, high rates of decomposition driven by the subtropical climate, and also the loss of organic sediment by wildfires and erosion [e.g., *Loveless*, 1959; *Richardson*, 2008; *Givnish et al.*, 2008]. However, the absence of any significant change in the rate of sediment accretion throughout a stratigraphic profile that contains both organic and inorganic strata suggests that accumulation rates may be ultimately governed by external hydrogeologic controls over long, millennial, time-spans. The close similarity between rates of sediment accretion at the NESRS site and the rise in sea level in South Florida over the past 4000 years further suggest that changes in sea level may have been an important driver for the long-term dynamics of the Everglades prior to the drainage era. Models of wetland carbon storage should therefore be expanded to incorporate the effects of the local hydrogeologic setting on fluxes of carbon and water in these important ecosystems.

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