ARTICLE IN PRESS
CATENA-01876; No of Pages 9
Catena xxx (2012) xxx–xxx
Contents lists available at SciVerse ScienceDirect
Catena
journal homepage: www.elsevier.com/locate/catena

Sediment accretion and organic carbon burial relative to sea-level rise and storm events in two mangrove forests in Everglades National Park

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ARTICLE INFO

Article history:
Received 6 January 2012
Received in revised form 27 September 2012
Accepted 8 October 2012
Available online xxxx

Keywords:
Mangrove forest
Sediments
Organic carbon
Sea level
Storms
Climate change

ABSTRACT

The goal of this investigation was to examine how sediment accretion and organic carbon (OC) burial rates in mangrove forests respond to climate change. Specifically, will the accretion rates keep pace with sea-level rise, and what is the source and fate of OC in the system? Mass accumulation, accretion and OC burial rates were determined via ^{210}Pb dating (i.e. 100 year time scale) on sediment cores collected from two mangrove forest sites within Everglades National Park, Florida (USA). Enhanced mass accumulation, accretion and OC burial rates were found in an upper layer that corresponded to a well-documented storm surge deposit. Accretion rates were 5.9 and 6.5 mm yr^{-1} within the storm deposit compared to overall rates of 2.5 and 3.6 mm yr^{-1}. These rates were found to be matching or exceeding average sea-level rise reported for Key West, Florida. Organic carbon burial rates were 260 and 393 g m^{-2} yr^{-1} within the storm deposit compared to 151 and 168 g m^{-2} yr^{-1} overall burial rates. The overall rates are similar to global estimates for OC burial in marine wetlands. With tropical storms being a frequent occurrence in this region the resulting storm surge deposits are an important mechanism for maintaining both overall accretion and OC burial rates. Enhanced OC burial rates within the storm deposit could be due to an increase in productivity created from higher concentrations of phosphorus within storm-delivered sediments and/or from the deposition of allochthonous OC. Climate change-amplified storms and sea-level rise could damage mangrove forests, exposing previously buried OC to oxidation and contribute to increasing atmospheric CO_2 concentrations. However, the processes described here provide a mechanism whereby oxidation of OC would be limited and the overall OC reservoir maintained within the mangrove forest sediments.

1. Introduction

Mangrove forests occupy a large areal extent of the world's coastlines between latitudes 25° N and 25° S (Giri et al., 2011) and have long been recognized for the many ecosystem services they provide (Alongi, 2008; Bouillon et al., 2008; and references within). Recently mangrove forests have begun to be examined more for their importance in the global carbon budget (Bouillon et al., 2008; Breithaupt et al., 2012; Chmura et al., 2003; Sanders et al., 2010a). The global estimate for mangrove net primary production is 218 Tg yr^{-1} with approximately 21 Tg fated for particulate organic carbon (OC) export, 24 Tg to dissolved OC export, 42 Tg to CO_2 efflux (Bouillon et al., 2008) and between 26 and 34 Tg to OC burial (Breithaupt et al., 2012; McLeod et al., 2011). The remaining portion is unaccounted for and hypothesized to be largely dissolved inorganic carbon (Bouillon et al., 2008). The burial rate is similar to that of salt marshes and seagrasses, and substantially greater than the rates of freshwater peatlands (Chmura et al., 2003) and upland forests (McLeod et al., 2011). In addition to the high burial rates, mangrove forests contain large stocks of OC which are also estimated to be substantially larger than upland forests (e.g. Donato et al., 2011).

Since these sites not only sequester carbon at a rapid rate, but also contain large quantities of carbon, they have the potential to produce a substantial global climate change feedback. Mangrove forests are sinks for OC and contribute a negative feedback to global warming by sequestering carbon that might otherwise exist as a greenhouse gas. However, many factors associated with climate change have the potential to disrupt this and change mangrove forests from a sink into a carbon source. Climate-induced factors that may influence OC burial in mangrove forests include rise in sea level, rise in atmospheric CO_2, rise in air and water temperature, change in precipitation patterns, and change in frequency and/or magnitude of storms (Alongi, 2008; Gilman et al., 2008). An increase in climate variability may also influence OC burial. In regions prone to frequent and intense storms such as Everglades National Park these events can have contrasting effects. For example, large scale mangrove forest destruction can lead to peat collapse, loss of forest elevation and creation of intertidal flats (Cahoon et al., 2003; Smith et al., 1994). However, Hurricane Wilma

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http://dx.doi.org/10.1016/j.catena.2012.10.009

deposited significant amounts of sediment in the mangroves (up to 10 cm, see Smith et al., 2009).

Because mangroves exist on intertidal sediments with a gentle slope, a small rise in mean sea level can result in a considerable change in the duration of immersion of the mangroves and cause plant mortality (Blasco et al., 1996). For this reason mangrove vegetation can only persist in a fixed location if the sediment accretion rate matches sea-level rise. Because of this, mangrove peat has been used by many investigators to examine Holocene sea-level change (e.g. Scholl and Stuiver, 1967; Scholl et al., 1969; Woodroffe, 1981). On a time scale more appropriate for recent climate change (i.e. 100 years), sediment accretion has been found to match sea-level rise in mangroves of Florida and Mexico (Lynch et al., 1989) and various salt marshes along the east coast of North America (Sharma et al., 1987). Smoak and Patchineelam (1999) and Sanders et al. (2008, 2010a, 2010b) have used sediment accretion rates in mangroves as a proxy for sea-level rise in Brazil where it could be verified that the mangrove forest has not migrated. Sanders et al. (2012) and López-Medellín et al. (2011) also found evidence of mangroves migrating landward where sea-level rise was out-pacing sediment accretion.

Despite the acceptance that mangrove ecosystems are important sinks for sediments and OC, relatively few studies have directly examined sediment accretion and OC burial on a time scale relevant to the examination of recent climate change (i.e. 100 years) (Chmura et al., 2003 and references within; Alongi et al., 2001; Sanders et al., 2010b, 2010c). Lead-210 is an ideal tracer for determining sediment accumulation on this 100-year time scale and has proved to be a valuable tracer of sediment accumulation in a variety of environments (Benninger et al., 1979; Carpenter et al., 1984; Crusius and Anderson, 1991; Davis et al., 1984; Koide et al., 1972; Nittrouer and Sternberg, 1981; Nittrouer et al., 1984; Sharma et al., 1987; and many others). However, this approach has been somewhat neglected in mangrove ecosystems with relatively few locations studied (Breithaupt et al., 2012). Lead-210 is a naturally occurring radionuclide of the ^{238}U decay series with a 22.3-year half-life. In shallow water systems unsupported (or excess) ^{210}Pb is mostly supplied from atmospheric fallout. The atmospheric source is produced when gaseous ^{222}Rn, a short-lived ($t_{1/2}=3.8$ days) intermediate daughter of ^{226}Ra, escapes from the earth's crust, decays to ^{210}Pb in the atmosphere, and is removed from the atmosphere by precipitation or dry deposition.

Here we test the hypotheses that sediment accretion is matching sea-level rise at two mangrove forest sites in Everglades National Park and that currently these sites are rapidly burying OC. We measured sediment accretion and OC burial rates by using the ^{210}Pb dating method. To test our hypothesis we compare sediment accretion rates to local sea-level rise to determine the forest's ability to keep pace. To test the second part of the hypothesis we quantify OC burial and consider how this might be influenced by climate change and function as a potential positive or negative feedback mechanism. Storm surge deposits were examined as an important mechanism in maintaining the overall accretion and OC burial rates. Storms might supply allochthonous OC as well as nutrients to stimulate primary production. Organic carbon burial was compared to estimates of global burial rates as well as productivity estimates.

2. Study area

Cores were collected from two sites within the southwest coastal mangrove forests of Everglades National Park (Fig. 1). Site SH3 (Fig. 1c) is a riverine type mangrove forest located in the extensive stands found in the mouth of the Shark River approximately 4 km upstream from the Gulf of Mexico. Red (*Rhizophora mangle*), white (*Laguncalariea racemosa*) and black (*Avicennia germinans*) mangroves are present in almost equal abundance. Stem densities range from 2000–6000 per hectare, with diameters in the 10–50 cm diameter at breast height range. Tree heights approach 20 m. Site SH4 (Fig. 1b) is a tall, fringing type mangrove forest (sensu Lugo and Snedaker, 1974) on the Harney River approximately 10 km upstream from the Gulf of Mexico with the same three species present, with red and white being dominant, and black present in lower numbers. Tree density ranges from 5500–11,300 stems per hectare. Stem diameters range from 2 to 60 cm diameter at breast height and the trees are 14–16 m tall. Hurricane Wilma resulted in the loss of 7% of the forest standing stock biomass at SH3 and 4% at SH4. Stem densities were decreased by 12% and 10% respectively. Deposition of sediment from Wilma was highly variable and depended on distance up river from the Gulf of Mexico and also distance from the riverbank into the forest (Smith et al., 2009). Approximately 8 cm of sediment was deposited at SH3 and 4 cm at SH4 (Smith et al., 2009). A detailed description of Wilma and three other storm's influence on these sites can be found in Smith et al. (2009).

3. Methods

3.1. Mangrove forest structure

Permanent forest plots were established at SH3 and SH4 in the months following Hurricane Andrew (Smith et al., 2009). The plots are circular with a radius of 13 m. All stems of >1.4 m in height have been identified to species, tagged with a numbered aluminum tag, measured for diameter at breast height and mapped. The plots are resampled at regular intervals and the stems remeasured, new recruits recorded, tagged and mapped, and mortalities noted.

3.2. Sediment cores

Two sediment cores were collected from within Everglades National Park (Fig. 1) using a Russian peat corer. This coring device retrieves a half core measuring 5.0 cm in diameter by 50 cm long. The volume of a 1 cm interval is 9.8 cm^3. SH3 was collected on the Shark River (north latitude 25° 21′ 50.74″ and west longitude 81° 04′ 42.53″) and SH4 on the Harney River (north latitude 25° 25′ 24.55″ and west longitude 81° 03′ 37.61″). Each core was collected approximately 10–20 m inland from the respective river and in an area dominated by red mangroves. Cores were sectioned into 1 cm intervals until 10 cm depth and then at 2 cm intervals. A sub-sample of known volume (4.17 cm^3) from each interval was used for gravimetric analyses. Organic C was measured using a Shimadzu SSM 5000A. Samples were acidified with 1 ml of 30% phosphoric acid to remove carbonate material prior to analysis. Percent error is estimated to be less than 1.3% based on sodium bicarbonate standard. The remaining sample material was freeze-dried for ^{210}Pb dating.

It should be noted that we have not removed live roots from sediments prior to analysis. Removal of live roots from samples used for both gravimetric and dating analysis is procedurally difficult and possibly problematic as aliquot structure and consistency would have to be disturbed. While this approach does possibly contain some overlap between living biomass and buried OC, the assumption is that root biomass turnover continually contributes to sediment formation (Castañeda-Moya et al., 2011; Twilley et al., 1992). This approach is consistent with the methods followed in other primary research addressing the question of both OC burial rates and standing stocks in mangrove sediments (e.g. Breithaupt et al., 2012; Chmura et al., 2003; Donato et al., 2011).

Lead-210 and ^{226}Ra measurements were made using an intrinsic germanium detector coupled to a multi-channel analyzer. Freeze dried and ground sediments were packed and sealed in gamma tubes. Lead-210 and ^{226}Ra activities were calculated by multiplying the counts per minute by a factor that includes the gamma-ray intensity and detector efficiency determined from standard calibrations. Identical geometry was used for all samples. Lead-210 activity was determined by the direct measurement of the 46.5 KeV gamma peak. Radium-226 activity was determined via the ^{214}Pb daughter at 351.9 KeV. For ^{226}Ra measurements, the packed samples were set aside for at least 21 days to allow for ^{222}Rn to ingrow and establish secular equilibrium between ^{226}Ra

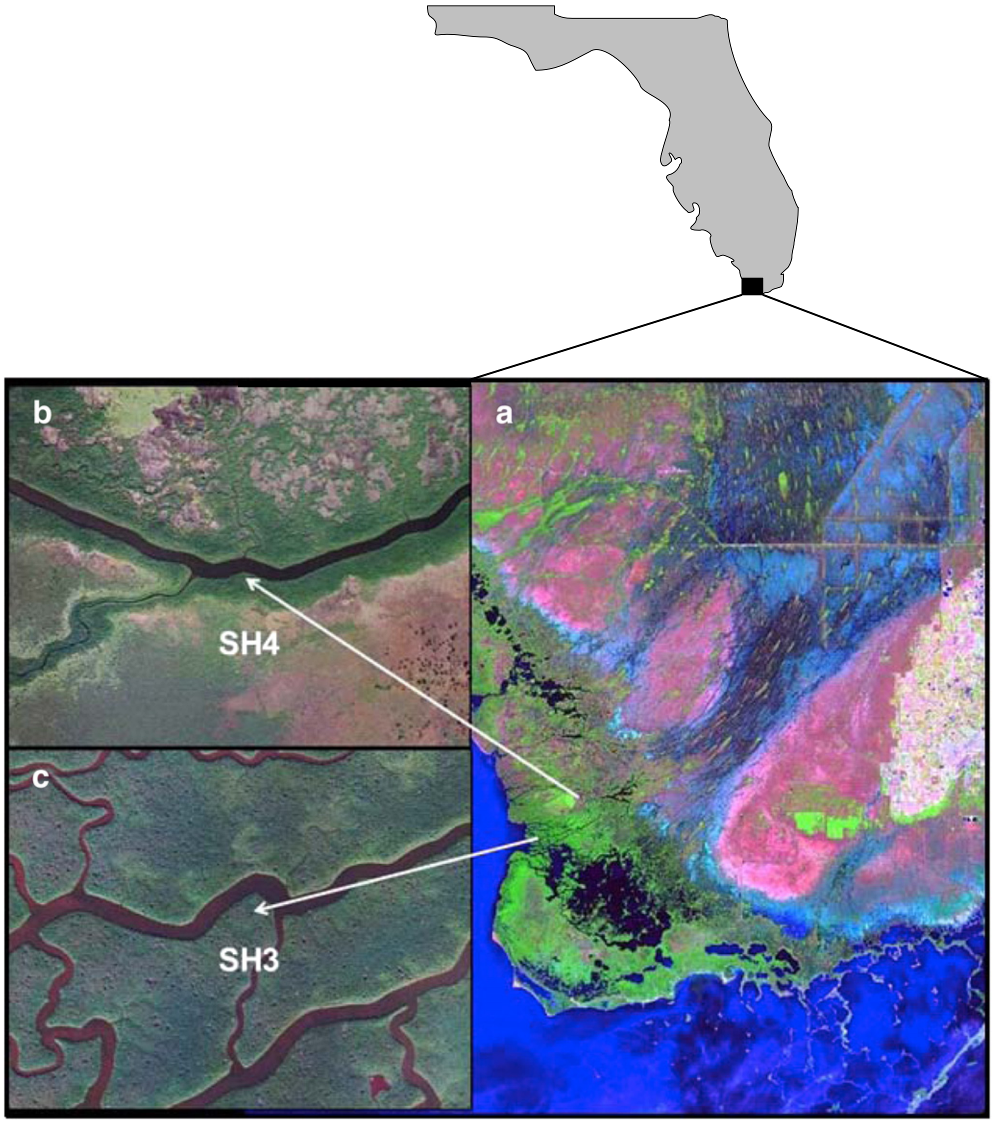

Fig. 1. Panel "a" shows the southern portion of the Florida Peninsula and the southwest coastal Everglades (Scale 1:500,000). Panels b and c are enlargements of the areas around sites SH4 and SH3 (Scale 1:10,000) with arrow indicating core location.

and its granddaughter ^{214}Pb. Excess ^{210}Pb activity was calculated by subtracting the supported ^{210}Pb (i.e., ^{226}Ra activity) from the total ^{210}Pb activity. Excess ^{210}Pb and the sediment mass in each interval were used in the Constant Rate of Supply (CRS) model to determine mass accumulation rates and ages of sediment intervals (Appleby, 2001). The CRS dating model was applied due to expectations that sediment accumulation rates have varied but that the supply rate of ^{210}Pb has been constant over the time period of interest. Often ^{210}Pb dates are confirmed with an independent tracer such as ^{137}Cs; however, in these highly organic sediments lacking clays ^{137}Cs is mobile. Therefore ^{137}Cs was not used to confirm the dates which adds to the uncertainty in the age model.

The age model yields dates for the base of each sectioned interval of the core. For each interval, mass was divided by the accumulation time for that layer in order to calculate the mass accumulation rate. Mass accumulation rates were also calculated for three time periods: the overall dated period (SH3: 1924 to 2009, SH4: 1926 to 2009), the period represented by the occurrence and influence of hurricane Wilma (2000 to 2009), and the period prior to 2000 (SH3: 1924 to 2000, SH4: 1926 to 2000). The slight differences in these time periods are due to the dates derived from each core. Organic carbon burial rates were calculated by dividing the mass of OC in each interval by the time interval, and were calculated for the same time periods as for mass accumulation and sediment accretion rates.

In order to compare with sea-level rise, sediment accumulation rates were calculated in terms of mm yr^{-1}, referred to as accretion rates. Accretion rates must be corrected for compaction within the sediment column. These highly organic sediments typically have very low dry bulk densities at the surface, but will compact at depth due to the overburden. Therefore a given mm yr^{-1} accretion in the upper portion of the core does not translate into that same rate of accretion at depth. Due to this compaction a depth correction was applied prior to calculating the accretion rates. The correction formula of Lynch et al. (1989) was used with a modification for layers with relatively high densities. Intervals with lower dry bulk densities were standardized to the average density of the three intervals from the bottom of the core. When the dry bulk density was greater than the bottom of the core no correction was made.

4. Results

Both cores examined in this study have a typical exponential decrease in specific excess ^{210}Pb activity moving down core with the exception of the low activity in the near-surface (Fig. 2). Over time the mass accumulation rates have varied considerably from the overall average, a notable example being a substantial increase in the 2000 to 2009 period for both cores (Fig. 3). The mass accumulation rate for this period is 4.4 times greater than the 1924–2000 rate for SH3, and 3.3 times greater than the 1926–2000 rate for SH4. This period of enhanced accumulation increased the long-term mass accumulation rates from 677 g m^{-2} yr^{-1} to 903 g m^{-2} yr^{-1} for SH3, and 447 to 545 for SH4 (Table 1). The high accumulation rates in the upper sections of each core are accompanied by relatively low organic carbon content (Fig. 4) indicating anomalous sediment input corresponding to the noted near-surface low in specific excess ^{210}Pb.

The accretion rates for each interval (Fig. 5) are similar to mass accumulation rate trends. The average accretion rates for three distinct time periods are shown in Table 1. The 2000–2009 period accretion rate is 1.8 times greater than the 1924–2000 rate for SH3 and 3.1 times greater than the 1926–2000 rate for SH4.

The OC burial rates are both higher and strikingly different for each core during the 2000–2009 period (260 g m^{-2} yr^{-1} at SH3 and 393 g m^{-2} yr^{-1} at SH4). In contrast to the surface level rate differences between the two cores, overall OC burial rates were similar (151 g m^{-2} yr^{-1} at SH3 and 168 g m^{-2} yr^{-1} at SH4).

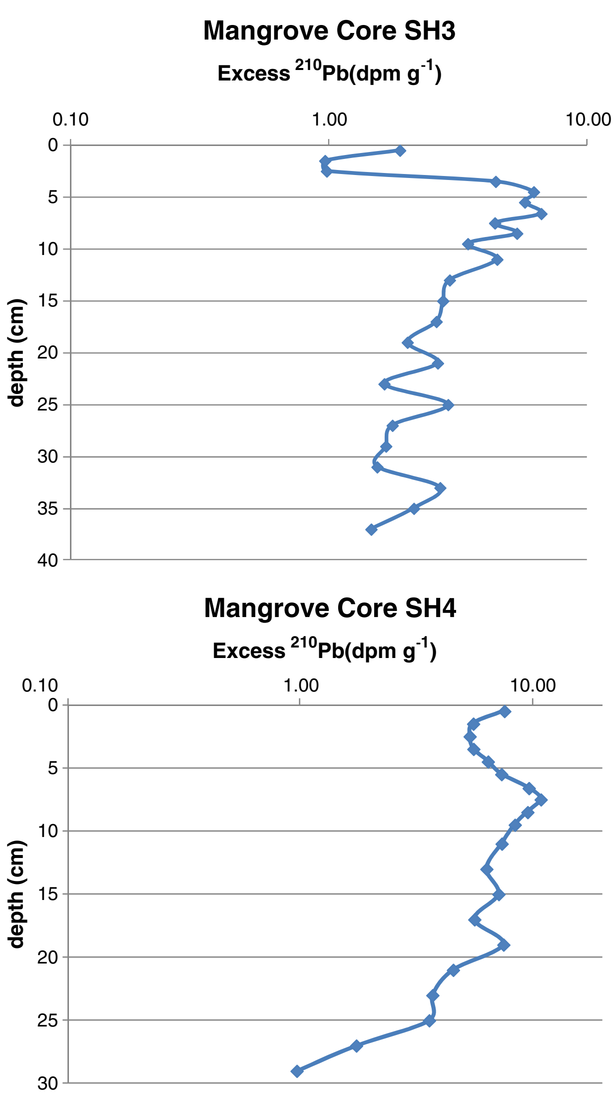

Fig. 2. Excess ^{210}Pb vs. depth profile for SH3 and SH4.

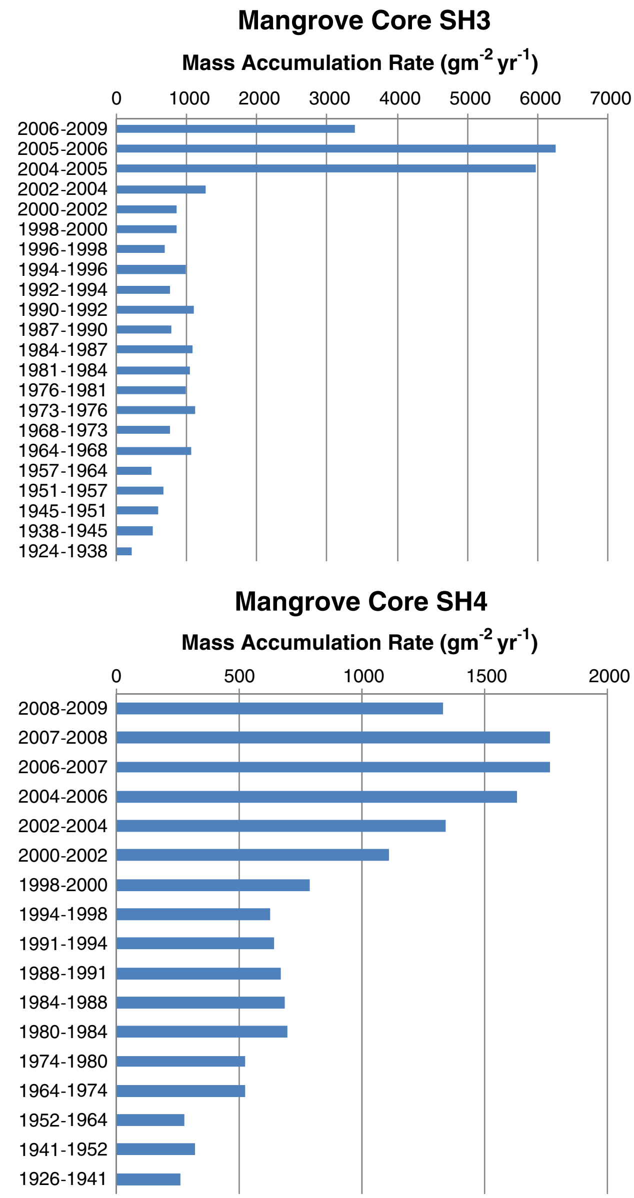

Fig. 3. Mass accumulation rate vs. age profile for SH3 and SH4.

Table 1
Mass accumulation rate (MAR), sediment accretion rate, and OC accumulation rate for given time interval.

Period (year)	MAR (g m^{-2} yr^{-1})	Accretion (mm yr^{-1})	Organic C (g m^{-2} yr^{-1})
SH3			
1924 to 2009	903	3.6	151
2000 to 2009	2966	5.9	260
1924 to 2000	677	3.3	139
SH4			
1926 to 2009	545	2.5	168
2000 to 2009	1457	6.5	393
1926 to 2000	447	2.1	144

Please cite this article as: Smoak, J.M., et al., Sediment accretion and organic carbon burial relative to sea-level rise and storm events in two mangrove forests in Everglades National Park, Catena (2012), http://dx.doi.org/10.1016/j.catena.2012.10.009

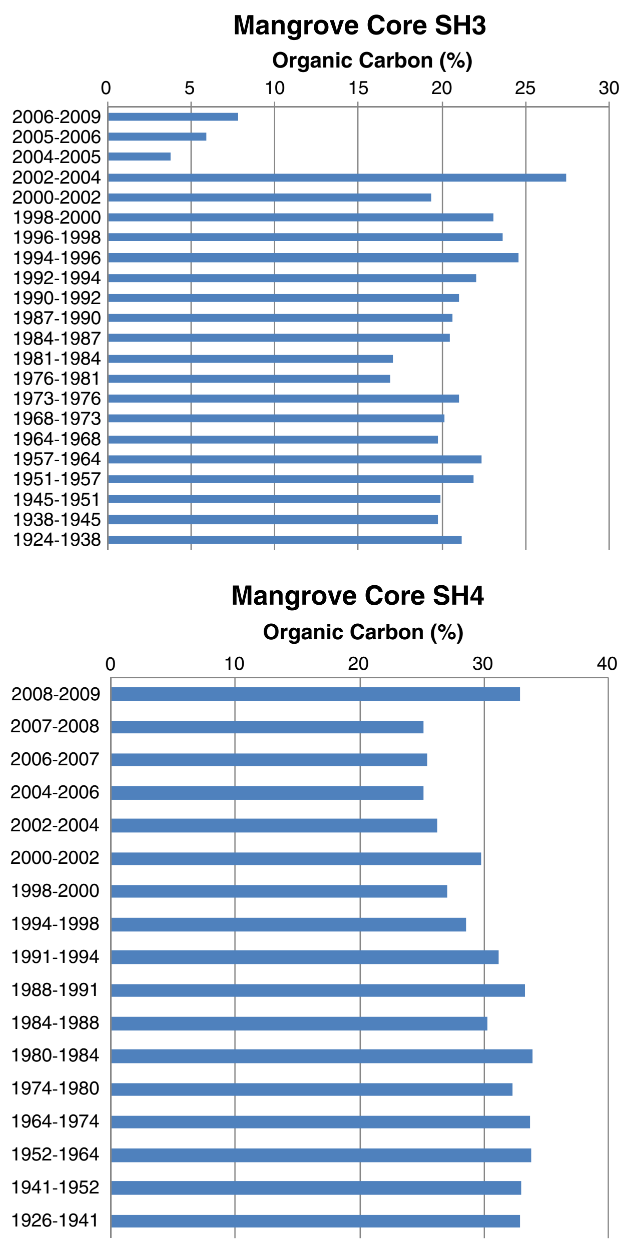

Fig. 4. Percentage organic matter vs. age profile for SH3 and SH4.

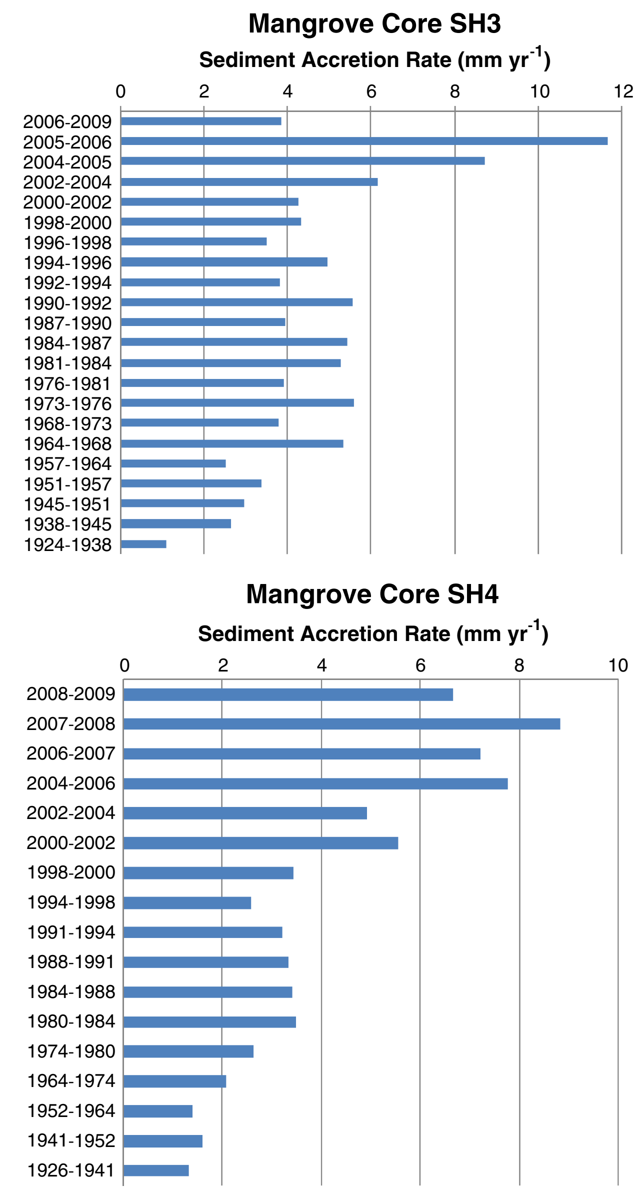

Fig. 5. Sediment accretion rate vs. age profile for SH3 and SH4.

5. Discussion

5.1. Accretion rates, storm deposits and sea level

The upper section of each core with high mass accumulation and accretion rates corresponds to both a relatively low excess ^{210}Pb activity (Fig. 2) and percent organic carbon layer (Fig. 4). This layer has been well documented as a storm surge deposit from hurricane Wilma in 2005 (Smith et al., 2009). The layer contains marine carbonate as well as organic matter. The storm material has been distributed vertically in the sediment column above and below the sample interval containing the 2005 storm year, likely due to sediment mixing via crab burrowing and/or possible physical sediment mixing. While sediment mixing may add uncertainty to sediment dating the CRS model is relatively insensitive to mixing (Appleby and Oldfield, 1992). In addition, the discussion examines broad time periods to further limit finer scale uncertainty due to sediment mixing. Enhanced rates of mass accumulation and accretion resulted from direct supply of storm surge material and could also be due to increases in production from the higher than normal phosphorous input in the storm surge deposit (Castañeda-Moya et al., 2010). Whelan et al. (2009) observed prolific fine root production in the storm-deposited material and hypothesized that the new rootlets may slow erosion of the deposit. Enhanced root production from phosphorous addition might lead to root growth above and below the interval that includes the year 2005.

Wilma approached Florida from the southwest and the eye of the storm made landfall near Cape Romano, approximately 75 km northwest of the study site, as a Saffir–Simpson category 3 hurricane on 24 October 2005 (Beven et al., 2008). Smith et al. (2009) reported evidence of a 2.5 m storm surge at SH3 and 1 m at SH4. Storm surges in this region have been shown to transport sediments into the mangrove forest (Davis et al., 2004; Risi et al., 1995; Smith et al., 2009). The impact of the storm surge deposit on the long term (~100 year) accumulation and accretion rates can be seen in Table 1. The impact at SH3 was greater compared to SH4 in terms of the mass accumulation rate. This is most likely due to the difference in the storm surge water level, with SH3 being only ~4 km upstream from the Gulf of Mexico and SH4 being ~10 km upstream. The storm deposit had a greater influence on the accretion rate at SH4 compared to SH3 (Table 1). This is due to SH4 receiving relatively more low-density organic debris, and SH3 receiving more high density marine carbonate material (Fig. 4). Sediment deposition was substantial at both sites and this is a potential mechanism by which accretion rates could keep pace with sea-level rise. Smith et al. (2007) calculated that this deposit supplied enough material to allow the sediment elevation to keep pace with approximately 10 years of sea-level rise at the current rate.

For mangroves to survive during this period of global warming, the increases in forest floor elevations due to OC burial and accretion must keep pace with the rate of sea-level rise. Sea-level rise since 1913 has been 2.24 mm yr^{-1} at Key West, Florida (NOAA National Ocean Service, http://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=8724580), approximately 120 km southwest of these study locations. The depth-corrected accretion rate from 1924 to 2009 was 3.6 mm yr^{-1} for SH3 and 2.5 mm yr^{-1} from 1926 to 2009 at SH4. Therefore these two locations are either matching or exceeding sea level rise reported from Key West station. From 2000 to 2009 accretion rates, which include the Wilma storm surge material, are 5.9 mm yr^{-1} and 6.5 mm yr^{-1} respectively for SH3 and SH4. Comparing the long-term accretion rates with the recent rates shows the overall importance of the storm supply to keeping pace with sea-level rise. Whelan et al. (2009) suggest storm deposits should be an important factor in sediment accretion in the mangrove forest. If sea-level rise accelerates and storms increase in magnitude and/or intensity, both possibilities with climate change, these storm deposits potentially provide a mechanism for the mangroves to keep pace with the accelerated sea-level rise. Increase in magnitude and/or intensity might produce more damage and loss of mangrove forest along open water (e.g. Gulf of Mexico) while the supply of material transported from these open water sites could stabilize those inland sites not directly exposed to the storm as in the present study. Loss of mangrove forest along open water in this area has been documented by Smith et al. (2010) in which they observed a shoreline retreat of 500 m between the years 1888 and 2004 along the mouth of the Shark River.

While the Wilma deposit was the only obvious storm surge deposit identified in both cores numerous previous storms have supplied material to these sites as well. The hurricane return period for southern Florida was every 5 years between 1901 and 2005 (Keim et al., 2007). Both hurricanes Donna in 1960 and Andrew in 1992 supplied storm surge material to these sites (Smith et al., 2009). These others storms have supplied material allowing the mangrove forest to keep pace with rising sea level, but the storm deposit layers have been obscured over time. Nevertheless, this as of yet unobscured recent deposit provides evidence of the importance of storms in maintaining the excess sediment supply allowing the forest to keep pace with sea-level rise.

5.2. Organic carbon burial

One of the objectives of this study is the quantification of the OC burial rate in these sediments over the course of a century, examining time-scale resolutions ranging from 2 to 15 years. Measurement of the rate informs comparisons and measurements of ongoing interactions with other components of the local C budget such as production, remineralization, export, and import. From this the ongoing capacity of the system to serve as a sink for atmospheric CO_2 may be calculated. Additionally, understanding the local burial rates enables quantification of potential impacts associated with predicted changes including rising sea level or increased storm frequency. It should be noted that this rate quantification is a different exercise from measuring the standing stock of OC (e.g. Donato et al., 2011) in that standing stock does not involve temporal measurements. Here we have similar overall rates for both cores (Table 1), which are likewise similar to the globally estimated mean rate for mangroves and salt marshes of 163–226 g OC m^{-2} yr^{-1} (Breithaupt et al., 2012; Chmura et al., 2003; McLeod et al., 2011). Two other studies have examined recent historical OC burial in southwest Florida, though in different geophysical settings. In Rookery Bay, FL, a site 2–3 km inland from the Gulf of Mexico, approximately 100 km northwest of SH3 and SH4, the mean burial rate was estimated at 86 g OC m^{-2} yr^{-1} (Lynch, 1989). This value is considerably lower than any long-term means in our cores, but does look similar to the earliest intervals representing the 1920s and 1930s (Fig. 6). The greater burial rates at the Everglades sites are likely due to the greater overall net primary productivity, in addition to being subject to greater depositional influence from both marine and riverine sources. In the Florida Keys, at sites ranging from 65 to 80 km southeast of our sites, Callaway et al. (1997) used ^{137}Cs to calculate organic matter accumulation rates of 318 ± 14 g m^{-2} yr^{-1} for forest-margin sediments dominated by red mangroves, and 211 ± 107 g m^{-2} yr^{-1} for black mangrove-dominant sediments. If organic matter is transformed to OC using the conversion quotient of 1.724 (Schumacher, 2002) these rates equate to 184 ± 7.9 and 122 ± 62 g OC m^{-2} yr^{-1} respectively. Rates at SH3 and SH4 prior to the year 2000 are within the ranges of the Florida Keys sites for the same time period.

The dramatic increase in OC burial during the 2000–2009 period relative to the long-term rates at each site shows the importance of storm deposits in maintaining the long term OC burial rates, just as was observed for accretion rates (Table 1). Overall, the burial rates for the entire period are similar at both sites, with the rate at SH4 being slightly greater than that at SH3. This slight difference is reversed from findings in Terminos Lagoon (Mexico) (Lynch, 1989) and Cananeia and Tamandare (Brazil) (Sanders et al., 2010a, 2010b) in which OC burial rates and mass accumulation rates are diminished with distance along transects from open water. This pattern is the same for OC concentration, with the greater percentage of sedimentary OC being found farther inland (Fig. 4) (Chen and Twilley, 1999). The reversal in expected burial rates is most notable in the 2000–2009 period when SH4 accumulated 51% more OC annually than SH3. However, the relationship for mass burial rates during each of the three periods remained as expected, and SH4 accumulated only 50% as much mass as SH3 did during the 2000–2009 period. How one location can accumulate only half the mass, but nearly one third more OC, can be explained, in part, by the organic carbon profiles (Fig. 4). While both sites show a decline in percent organic carbon during this time period, the difference is much more prominent at SH3. This suggests that a greater proportion of the mass at SH3 can be attributed to the storm-derived inorganic shelf sediment identified by Castañeda-Moya et al. (2010), and a greater proportion of lower density OM contributes to the mass at SH4. This is further supported by the findings of Castañeda-Moya et al. (2010) at their SRS-5 site, where it was noted that only a slight film of marine sediment deposition was visible. Located upriver from SH3 on the Shark River, SRS-5 is approximately the same distance inland as SH4 is on the Harney River, and provides indirect evidence of reduced marine deposition there as well. On a much smaller scale, in the immediate aftermath of Hurricane Wilma a gradient of storm deposition was recorded with a decrease in material with increased distance inland (Whelan et al., 2009). However, it is important to note that the decline in OC concentration in the surface intervals at SH4 does indicate that it received inorganic material, simply not of the same magnitude as that supplied to the SH3 site.

Compared to the Hurricane Wilma interval at SH3, the higher OC burial rate and lower overall dry bulk densities in the same interval at SH4 lead to questions regarding whether the source of the organic material, as well as the mechanism for its delivery, are different in the two locations. A possible hypothesis is that the increase of OC burial at SH3 is driven by an increase in belowground productivity due to the enhanced P availability (Castañeda-Moya et al., 2010), while the sharp increase at SH4 is the result of storm-derived organic debris removed and transported from less protected locations near open water. However, increased belowground productivity does not appear to account for the increase at SH3. Whelan et al. (2009) note that root growth in the layer of the Wilma deposit at SH3 was 179.6 g dry weight m^{-2} yr^{-1}, and the amount of total fine rootlets in the storm deposit was well within the error margins of pre-hurricane measurements at the same

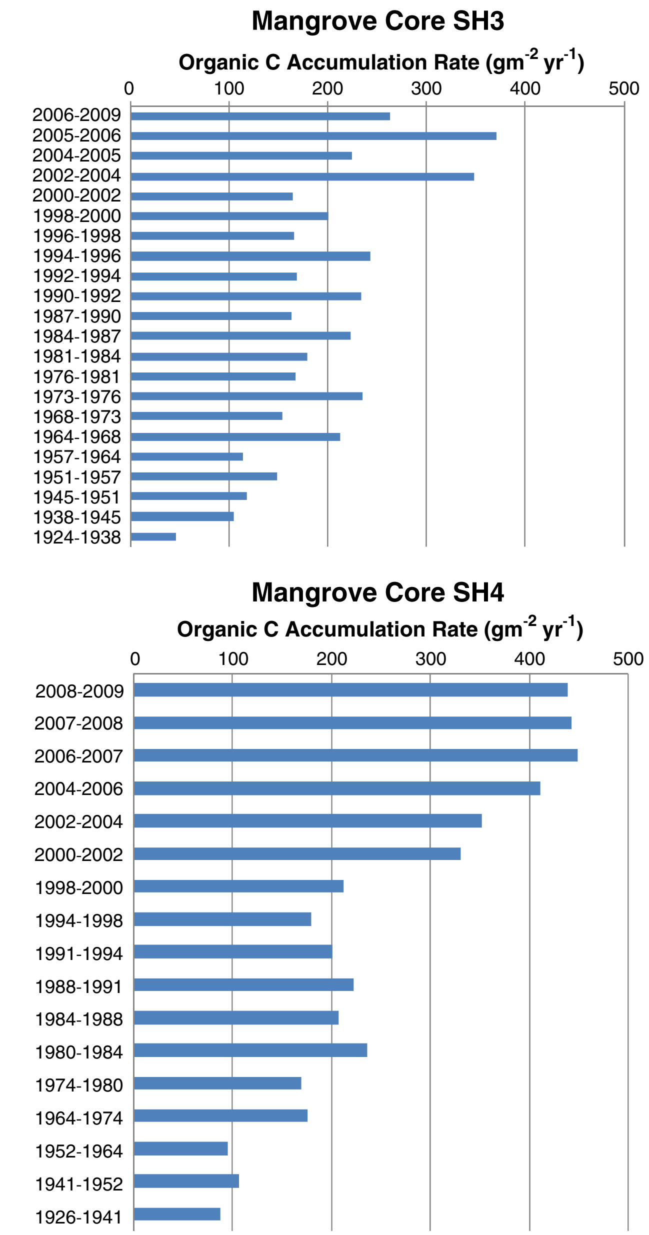

Fig. 6. Organic carbon accumulation rate vs. age profile for SH3 and SH4.

location (Whelan et al., 2005) suggesting no change in belowground productivity following the storm. Transformed to OC (after Schumacher, 2002) the production rate in this layer only accounts for 104.2 g OC m^{-2} yr^{-1}, or 40% of our recorded mean OC burial, leaving 60% of the OC unaccounted for at SH3. This limited data suggests that something other than belowground production, possibly litterfall and/or transported OC, makes a major contribution to the increased burial rate at both sites. The difference at the two sites may be explained by the less dense organic matter being transported a greater distance (SH4) while the higher density marine carbonate material falls out of suspension sooner (SH3) during the hurricane storm surge.

Knowledge of burial rates can contribute to budgeting the system's ongoing sink capacity, and is especially useful in relation to measurements of ecosystem production. An eddy covariance flux tower, capable of measuring ecosystem production, is situated near SH3 as part of the Florida Coastal Everglades Long Term Ecological Research station (Barr et al., 2010). The flux tower began collecting data in January 2004 and gathered a year and a half of measurements before being temporarily disabled by Hurricane Wilma. Based on that initial period of data collection, the tower provided an annual ecosystem production value of 1170 ± 127 g OC m^{-2} yr^{-1} (Barr et al., 2010). Our measurement of the mean burial rate prior to the influence of Wilma (139 g OC m^{-2} yr^{-1}) (Table 1) yields an estimate of centennial-scale OC burial as 12% of net ecosystem production at SH3. This percentage is identical to the most recent global assessment of the OC burial fraction of mangrove production (Breithaupt et al., 2012). However, this percentage assumes that all of the buried OC is produced locally. This is unlikely because of regular tidal and riverine import and export. Additionally, our analysis of Wilma's influence has identified elevated rates of OC burial that are hypothesized to occur, in part, due to the delivery of allochthonous OC. Future studies in this area ought to consider the origins of the buried OC, possibly characterizing its origination within the estuarine gradient.

6. Conclusion

Enhanced mass accumulation and accretion rates were observed corresponding to a storm deposit layer associated with hurricane Wilma in 2005. Rates resulting from this event were dramatically greater than the long-term averages and showed the importance of these storm events in maintaining the long-term rates. When comparing both locations the site closest to the Gulf of Mexico (SH3) had the greatest mass accumulation associated with the storm deposit. The site farther inland (SH4) experienced the greatest impact in terms of accretion rate. This was due to SH3 having a higher concentration of marine carbonate material and SH4 having a higher concentration of low density organic material in the deposit. When comparing the accretion rates with the Key West sea-level data since 1913 it was found that both these sites were matching or exceeding sea-level rise. These storm deposits provide a mechanism for the mangroves to keep pace, and an increase in storm magnitude and/or intensity with climate change may amplify this mechanism and offset acceleration in sea-level rise. Increase in magnitude and/or intensity might produce more damage and loss of mangrove forest along open water (e.g. Gulf of Mexico) while the transfer of material stabilizes those sites not directly exposed to the storm.

Organic C burial rates were 1.3 to 2 times greater within the Wilma storm layer than the long term rate. As with the accretion rates, the storm influence was important in maintaining the long term OC burial rate as well. The long term rates are similar to the globally estimated mean rate for mangroves, salt marshes, and seagrasses (Breithaupt et al., 2012; Chmura et al., 2003; McLeod et al., 2011). Overall the OC burial rate was slightly lower at the site nearest the Gulf of Mexico (SH3) compared to the site farther inland (SH4). The same trend, but with a higher magnitude of difference, was observed within the storm layer. Farther inland, the storm deposit had a higher concentration of OC than compared to the deposit at SH3, which had a greater concentration of marine carbonate. The enhanced OC burial within the storm deposit could have been due to increased production from phosphorus supplied in the marine carbonate and/or allochthonous OC removed from other sites. The storm surge has the capacity to transport low density organic matter a greater distance inland while the higher density marine carbonate material will not be transport as far accounting for the higher OC burial at the more inland site.

Understanding the local burial rate of OC may include consideration of the impacts that are predicted to accompany changing climate conditions including the threats of rising sea level and increased frequency and intensity of storms (Gilman et al., 2008). Our results demonstrate the mixed responses that may occur to these threat conditions. While enhanced mangrove mortality was documented (Smith et al., 2009), here we note a simultaneous and considerable enhancement of OC burial both during and subsequent to the storm itself.

The fate of OC is an important consideration as the total OC burial within mangrove systems is substantial despite the fact that global

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area of mangrove forest is small. An increase in storm activity or sea level rise that outpaces the mangrove forest accretion may produce a substantial remobilization of buried OC. Some of this OC may be oxidized and function as a positive feedback mechanism in climate change. However, our findings suggest that some of the remobilized OC will be transferred inland and subsequently buried, therefore limiting oxidation.

Acknowledgments

The authors thank Tom Harmon, Luciana Sanders, Gordon Anderson, Karen Balentine, Ginger Tiling-Range and Paul Nelson for assistance with field sampling and laboratory processing. We thank Renato Campello Cordeiro for organic carbon analysis. The authors are grateful for the constructive comments of two anonymous reviewers. T.J. Smith III was funded by the U.S. Geological Survey and Army Corps of Engineers. J.M. Smoak received funding from U.S. Geological Survey, Southeast Ecological Science Center. Discussions with faculty and students involved in the Florida Coastal Everglades Longterm Ecological Research program (supported by the National Science Foundation under grant no. DBI-0620409) are gratefully acknowledged. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. government.

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