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HURRICANE WILMA'S IMPACT ON OVERALL SOIL ELEVATION AND ZONES WITHIN THE SOIL PROFILE IN A MANGROVE FOREST

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Abstract: Soil elevation affects tidal inundation period, inundation frequency, and overall hydroperiod, all of which are important ecological factors affecting species recruitment, composition, and survival in wetlands. Hurricanes can dramatically affect a site's soil elevation. We assessed the impact of Hurricane Wilma (2005) on soil elevation at a mangrove forest location along the Shark River in Everglades National Park, Florida, USA. Using multiple depth surface elevation tables (SETs) and marker horizons we measured soil accretion, erosion, and soil elevation. We partitioned the effect of Hurricane Wilma's storm deposit into four constituent soil zones: surface (accretion) zone, shallow zone (0–0.35 m), middle zone (0.35–4 m), and deep zone (4–6 m). We report expansion and contraction of each soil zone. Hurricane Wilma deposited 37.0 (± 3.0 SE) mm of material; however, the absolute soil elevation change was + 42.8 mm due to expansion in the shallow soil zone. One year post-hurricane, the soil profile had lost 10.0 mm in soil elevation, with 8.5 mm of the loss due to erosion. The remaining soil elevation loss was due to compaction from shallow subsidence. We found prolific growth of new fine rootlets (209 ± 34 SE g m^{-2}) in the storm deposited material suggesting that deposits may become more stable in the near future (i.e., erosion rate will decrease). Surficial erosion and belowground processes both played an important role in determining the overall soil elevation. Expansion and contraction in the shallow soil zone may be due to hydrology, and in the middle and bottom soil zones due to shallow subsidence. Findings thus far indicate that soil elevation has made substantial gains compared to site specific relative sea-level rise, but data trends suggest that belowground processes, which differ by soil zone, may come to dominate the long term ecological impact of storm deposit.

Key Words: contraction, expansion, Florida, peat, soil swell, subsidence, wetland

INTRODUCTION

Changes to soil elevation can have moderate to long-term successional impacts on the ecosystem by modifying the recent geology of an area (Wanless et al. 1994). Changes in soil elevation summarize the balance between elevation gains due to accretion/deposition of material and the losses due to shallow subsidence, compaction, and/or erosion. Changes in soil elevation can affect tidal inundation period, inundation frequency, and overall hydroperiod all of which are important ecological factors that can affect species recruitment, composition, and survival in coastal wetlands (Rabinowitz 1978, Ellison and Fransworth 1993, Cornu and Sadro 2002).

Hurricanes have numerous affects on the ecosystem they impact: increasing canopy openness (Ugarte et al. 2006), providing seed dispersal (Oberbauer et al. 1994), affecting the distribution and ratio of coarse and fine woody debris (Krauss et al. 2005), and favoring some species over others (Smith et al. 1994, Baldwin et al. 2001, Ugarte et al. 2006). However, hurricanes can play an important ecological role in wetlands and coastal ecosystems by affecting soil elevation. Hurricanes can increase soil elevation by depositing material (Cahoon et al. 2003) and folding peat layers, a process in which marsh soils are uplifted and placed on top of other locations within the marsh (Cahoon 2006). Hurricanes can decrease the soil elevation by eroding sediments (Cahoon et al. 1999), compacting marshes even after depositing material at the marsh (Cahoon et al. 1995), and causing catastrophic peat collapse by killing the above ground trees (Cahoon et al. 2003).

In a literature review of how storms affect soil elevation, Cahoon (2006) reported that in 70% (14 of 20) of the studies, subsurface process dominated the long term outcome on soil elevation. However, those studies reviewed lacked the ability to partition the subsurface processes within the soil profile and therefore were unable to measure and distinguish the competing subsurface processes (soil swelling and compaction). It is now possible to partition changes in soil elevation among specific parts of the soil profile and to determine the absolute change for each depth zone.

Our study used several types of surface elevation table (SET) that permitted partitioning of the soil profile into multiple constituent zones (see also Whelan et al. 2005). We assessed how storm deposits from Hurricane Wilma influenced surface elevation and subsurface soil processes in a mature mangrove forest. We measured direct and short-term (six months and one year post-hurricane) impact on surface accretion, surface erosion, shallow subsidence, and expansion/contraction within four specific zones: the surface (accretion), shallow (active root zone 0–0.35 m), middle (0.35–4 m), and bottom (4–6 m) zones of the entire soil profile.

STUDY SITE

The study site is located 4.1 km upstream from the mouth of the Shark River (25°21′50.3″N 81°4′42.2″W, NGS 84) in Everglades National Park, Florida, USA. A long term U. S. Geological Survey (USGS) vegetation monitoring program with vegetation plots was established at the site in 1994. The study site is in a mature mixed mangrove riverine forest (Lugo and Snedaker 1974) comprised of *Rhizophora mangle* L. (red mangrove), *Laguncularia racemosa* (L.) Gaertn. (white mangrove), and *Avicennia germinans* (L.) Stearn (black mangrove). Tree canopy ranges in height from 13 to 17 m with a sparse understory. Stem density averages 6,470 ha^{-1} with *R. mangle* the dominant followed by *A. germinans* and *L. racemosa* (59, 21, and 19%, respectively). Most stems ($> 77\%$) are < 5 cm dbh with a few stems (1.5%) from all three species $>$ 30 cm dbh. This site was impacted by Hurricane Andrew (1992), sustaining 19.5% stem mortality and 15.8% basal area mortality (Smith et al. 2009).

Hurricane Wilma's Impacts at the Study Site

Hurricane Wilma formed on 15 October 2005 and remained a hurricane until 25 October 2005 during which it set a new record for having the lowest pressure in the North Atlantic Basin at 882 hPA (Shein 2006). Hurricane Wilma made landfall on the southwestern coast of Florida (near Cape Romano) on 24 October 2005, as a category three on the Saffir-Simpson scale with maximum sustained winds estimated at 195 kph (121 mph) and transverses the state on a northeast trajectory exiting south of Jupiter (Pasch et al. 2006). Hurricane Wilma caused 16.4% stem mortality and 12.4% basal area mortality at our study site (Smith et al. 2009).

Storm surge estimated by the National Ocean and Atmospheric Administration was 4.87 m as Hurricane Wilma made landfall at the mouth of the Shark River (NOAA 2005). At the study site, a USGS Hydrology Station constructed 30 m from the Shark River at 1.37 m above local ground elevation (0.32 ft NAVD 88) was overtopped by storm waters. At the study site a 2.5 m storm surge was estimated from the debris/wrack line measured after the storm (Smith et al. 2009). Hurricane Wilma's storm surge of 1.03 m was measured within the mangrove forest at a location 150 m northeast of the site (Krauss et al. 2009, Figure 1 site 4.1 km).

METHODS

We used the surface elevation table (SET) marker horizon (MH) method (SET-MH) in this study (for details on the methodology see Cahoon et al. 1995, 1999, 2002a, b). The SET consists of a mechanical arm that is attached to a benchmark and leveled, establishing a fixed measuring point. Typically each SET has four fixed measurement locations (directions), where nine measuring pins are lowered to the soil surface to obtain a relative soil elevation. The elevation is the mean of 36 measuring pin readings per benchmark. SETs allow for precise measurements of soil surface elevation (± 1.4 mm total error; Cahoon et al. 2002a, b). SETs have been used to monitor vertical accretion (storm sediment deposition and erosion) (review in Cahoon 2006) and subsurface soil processes (subsidence and expansion/contraction) by soil zone (Whelan 2005, Whelan et al. 2005) and for entire soil profile (Cahoon and Lynch 1997, Whelan et al. 2005).

At this site, we used feldspar as the soil marker horizon to measure vertical accretion (sediment deposition, erosion, and root growth) that occurs at the soil surface. Feldspar was sprinkled on the soil surface; each MH plot was approximately 60 × 25 cm. Three deep-rod surface elevation table (Deep-RSET) benchmarks were driven to bedrock (6.0 m) and thus measured the full soil profile. The three original design SET (Original-SET) benchmarks were driven to ~ 4 m. Three shallow-rod

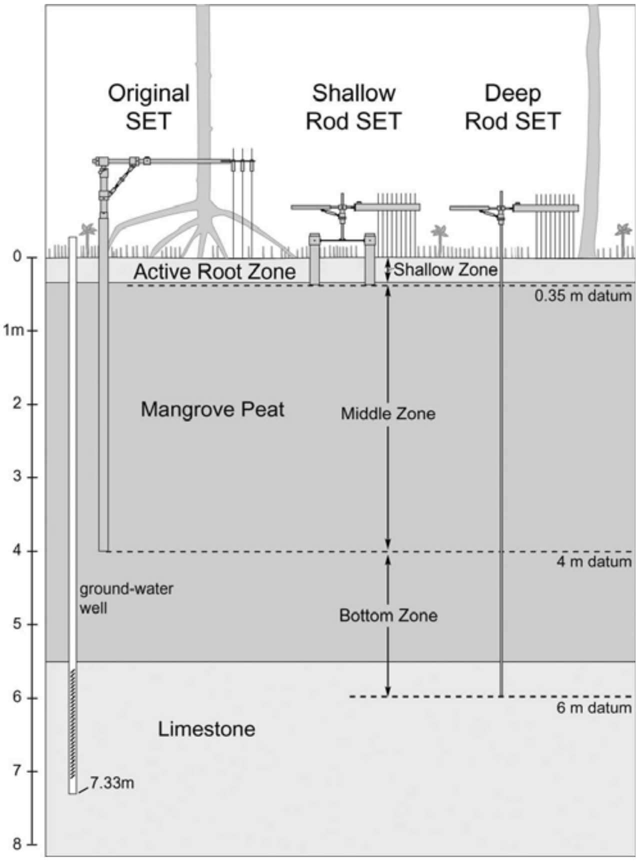

Figure 1. Illustration (1:24 scale) of a Shark River soil profile showing accretion, shallow, middle, and bottom soil zones, and placement depths of Original SETs, Deep, and Shallow-RSETs and a groundwater well (adapted from Whelan et al. 2005, with permission).

surface elevation table (Shallow-RSET) benchmarks were installed to a depth of 0.35 m. The SETs were in three groups; in each group there was one Deep-RSET, one Original-SET, and one Shallow-RSET along with four soil marker horizons. The three SET groups were within 18 m of each other and 45 m of the Shark River. All three SET groups were within the mangrove forest and accessed using boarded cat walks to minimize soil disturbance. Mangrove vegetation was similar at all three group locations. The soil profile was comprised of a mangrove peat layer approximately 6 m deep laid directly over limestone (Whelan et al. 2005). Cohen (1968) reported that the peat types did not have recognizable petrographic constituents and that all of the peat types were marine or brackish and dominated by *R. mangle* for a core taken a nearby site (2.5 km away from current study site).

By using a combination of SET designs at a single study site it is possible to partition changes in soil elevation among the specific parts of the soil profile, such as the shallow root zone and deeper soil zones (Figure 1). By determining the absolute change in width for each depth zone we calculated expansion/contraction for each zone, surface (accretion and/or erosion; above 0 cm), shallow (active root; 0–0.35 m), middle (0.35–4 m), and bottom (4–6 m) of the profile, relative to the expansion/contraction for the entire profile. Interval expansion/contraction was then determined as the change in the width for a particular soil zone between two sample events. (For more information on the relationships between the different SET types and calculation of expansion and contraction within specific soil zones see Equation 2, Whelan et al. 2005). All three SET types and marker horizons have been sampled simultaneously and at low tide since 2002. Specific post Hurricane Wilma storm soil elevation sampling occurred on 9 November 2005 (16 days after Hurricane Wilma), 20 June 2006, and 14 November 2006.

We also sampled the roots within the storm deposit layer by taking six soil cores, 5 m from the river bank, using a Russian "D" style peat corer (20–21 December 2006). Each core sample was 5 cm in diameter and 50 cm in length. The corer penetrated through the surficial storm sediment layer (20–70 mm thick) into the underlying mangrove peat. Care was taken to extract uncompressed core samples. The cores were separated at the line of demarcation between the storm deposited sediment layer and the underlying mangrove peat. A 2 cm segment was excised from the storm deposit layer at the interface with the peat. The samples were washed and sieved using a 500 μm sieve. The clean roots were carefully sorted for roots ≤ 1 mm that were air dried and weighed. We did not differentiate between live and dead roots.

RESULTS

Storm Deposition

Hurricane Wilma deposited 37.0 (± 0.5 SE) mm of material within the marker horizon plots (45 m from the Shark River). However, this material was not deposited evenly throughout the forest. Storm deposition 3 to 5 m from the river bank was 56.0 (± 11.0 SE) mm ($N = 3$) in depth. Storm sediments were a grey-colored marine carbonate material and easily differentiated from the dark brown mangrove peat below. Deposited material at this site tended to be greater near the river and decreased with greater distance inland, albeit at the site micro scale (5 to 45 m from the Shark River).

Deposits had a bulk density of 0.8 g cm^{-3} and were 91% carbonate material (G. Tiling unpublished

Table 1. Mean (± SE, mm yr^{-1}) accretion, elevation change, and shallow subsidence (vertical accretion - elevation change) rates for a mangrove study site (Shark River, Everglades National Park, Florida) before Hurricane Wilma and including Hurricane Wilma.

Period of record	Accretion	Change in elevation as recorded by Deep RSET	Shallow subsidence
Before Hurricane Wilma (March 2002 to June 2005)	6.5 (1.2)	1.4 (3.9)	5.1
Including Hurricane Wilma (March 2002 to November 2006)	11.5 (3.9)	6.2 (4.9)	5.2

data cited in Anderson et al. 2007). Hurricane Wilma deposited significant amounts of marine sediment into the mangrove forest along the Shark River, between 296 to 448 metric ton (MT) ha^{-1} according to our measurements.

At 14 months post hurricane, surface soil cores taken 5 m from the river bank had a gray marine storm deposit to 59.0 ± 7.2 SE mm in depth and the presence of fine rootlets were observed in the storm deposit material. Total fine rootlet ($\leq$ 1 mm dia. live and dead) in the storm deposit was 209 ± 34 SE g m^{-2}.

Soil accretion, Elevation and Shallow Subsidence and Contraction/expansion in Soil Zones

Hurricane Wilma deposited a substantial amount of material within the marker horizon plots at our study site and increased the long term accretion rate (March 2002 to November 2006) from 6.5 to 11.5 mm yr^{-1}. The long term rate of soil elevation increased from 1.4 to 6.2 mm yr^{-1} due to hurricane deposits. However, shallow subsidence (post depositional compaction) rates remained essentially unchanged (Table 1).

The soil elevation change for the entire profile, as recorded by the Deep-RSET, from the sampling event prior to the Hurricane Wilma (June 13, 2005) to the sampling event immediately after the storm (November 9, 2005) was +42.8 mm (Figure 2, Table 2), which represents a gain of 5.8 mm in excess of measured accretion (i.e., the storm deposited material of +37.0 mm). This 5.8 mm gain in elevation for the entire profile resulted from a +8.1 mm expansion in the shallow soil zone, −2.7 mm contraction in the middle soil zone, and a +0.4 mm expansion in the deep soil zone (Table 2, Figure 3).

Six months after Hurricane Wilma (20 June 2006) the soil elevation recorded a loss of −10.5 mm for the entire soil profile compared to the elevation recorded immediately after the storm. The majority of loss occurred in the accretion part of the soil column (−4.9 mm) and the shallow soil zone (−4.7 mm). The middle zone contracted −1.6 mm and the deep soil zone expanded +0.8 mm (Table 1).

At the one year post Hurricane Wilma sampling (14 November 2006), the entire soil profile elevation remained relatively the same (0.4 mm, Figure 2). However, there was erosion at the surface (accretion) zone and contraction of the deep soil zones (−3.6 and −2.3 mm, respectively), but this was offset by an expansion in the shallow soil zone (+6.8 mm). The middle soil zone remained relatively unchanged −0.4 (Figure 3, Table 2).

DISCUSSION

Storm Deposition

It would take 18–27 standard dump trucks (16.3 MT capacity) to deposit between 37 to 56 mm of material per hectare (at a bulk density of 0.8 g cm^{-3}). Expanding this calculation to the area immediately downstream of the site and the nearby surrounding area (approximately 10 km^2 - a very conservative estimate, see Smith et al. 2009) there would need to be between 18,126 to 27,243 dump truck loads to deposit this amount of material. Although this is a large amount of material,

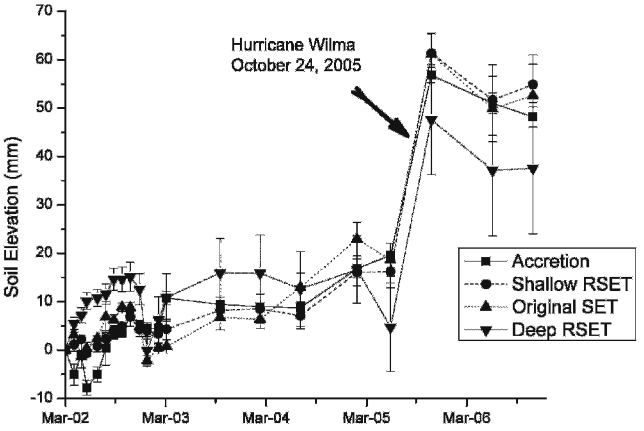

Figure 2. Long term mean (± 1 SD) absolute soil surface elevations for Accretion, Shallow-RSET, Original-SET, and Deep-RSET at a mangrove forest on the Shark River capturing the impact of Hurricane Wilma.

Table 2. Mean interval change (± SE, mm) in the expansion/contraction for each of the four constituent soil zones and the entire soil profile.

Sample Date	Accretion	Shallow	Middle	Bottom	Entire soil profile
11/9/2005	37.0 (0.5)	8.1 (4.1)	−2.7 (2.0)	0.4 (1.8)	42.8 (3.3)
6/20/2006	−4.9 (3.8)	−4.7 (7.2)	−1.6 (2.7)	0.8 (1.2)	−10.5 (3.1)
11/14/2006	−3.6 (4.8)	6.8 (6.9)	−0.4 (3.0)	−2.3 (2.9)	0.4 (0.8)

Hurricane Wilma's deposition at this site was lower than soil deposition estimates from Hurricanes Rita and Katrina along the Louisiana coast line (51.8 ± 7.7 mm, Turner et al. 2006) and Hurricane Andrew along the Florida coast line (up to 20 cm, Risi et al. 1995). Our results, however, were higher than carbonate sediment deposited along the Buttonwood ridge in Everglades National Park after Hurricane Irene (12 ± 10 mm calculated from Figure 6, Davis et al. 2004). We found a decrease in deposited material with greater distance inland, which follows the patterns described by others (Risi et al. 1995, Turner et al. 2006). The bulk density of our material was higher that what was found for Hurricanes Katrina and Rita in Louisiana (0.37 ± 0.35 g cm^{-3}, Turner et al. 2006). The Hurricane Wilma storm material also had a higher proportion of carbonate material (91%) compared to Hurricane Andrews deposits along the southwestern coastline of Everglades National Park (3–55%, Risi et al. 1995).

Hurricanes Andrew, Rita, and Katrina were major storms (Categories 5, 3, and 3 on the Saffir-Simpson scale, respectively) and Hurricane Irene was a minor storm (Cat. 1), and each of these storms varied in size. Both intensity and size influence storm surge and deposition (Resio and Westerink 2008). In addition, each of these storms approached/exited the coastline from different angles, had different forward momentums, and the bathymetry of the water bodies from which the storm surge and deposition came from were different. All of these factors help explain the variaiton in depositional characteristics observed among storms (Turner et al. 2006, Resio and Westerink 2008).

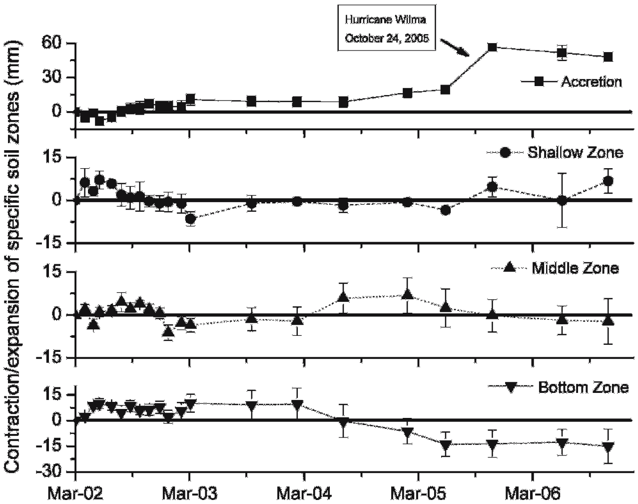

Figure 3. Absolute mean (± 1 SD) contraction/expansion of the four constituent soil zones: accretion zone, shallow zone, middle zone, and bottom zone relative to the contraction/expansion of the entire soil profile as measured by the Deep RSET (calculations are based on Equation 2, Whelan et al. 2005).

The amount of total fine rootlet in the storm deposit (209 g m^{-2} ± 34 SE) was similar to values reported for live rootlets in this same mangrove forest at undisturbed (186 g m^{-2} ± 85 SE) and new canopy gap (152 g m^{-2} ± 69 SE) sites (Whelan 2005). Rootlet ages were not determined. However, fine rootlets found in the Hurricane Wilma storm deposition layer probably grew into this material in the 14 months after it was deposited. Essentially the root growth rate within the storm deposited material was 179.6 g m^{-2} yr^{-1}. Roots can increase soil strength (Micheli and Kirchner 2002), and thus these new roots should help stabilize the storm deposit and slow soil surface erosion.

Soil Accretion, Elevation, and Understanding the Contraction and Expansion of Soil Zones

Traditional hurricane sediment impact studies using SET-MH methodology report the rate of accretion, elevation change, and shallow subsidence with and without the hurricane inputs as a way to determine the role of hurricanes on a particular wetland and to understand which wetland soil process (i.e., accretion, shallow subsidence, hydrological swelling) is determining the outcome. Because we used multiple SETs type in this study, we are able to report how the Hurricane Wilma storm material deposited at our study site affected the various soil zone differently, essentially partitioning the shallow subsidence and other belowground processes (Figures 2, 3). Hurricane Wilma deposited material at our study site doubled the accretion rate, and the rate of soil elevation change increased 4.4 times. However, shallow subsidence rates remained largely unchanged (Table 1). Hurricane deposited material at our study site had a net affect of increasing the soil elevation.

Post hurricane we observed erosion of deposited material during a summer rainstorm at low tide, when no standing water was present in the forest (Figure 4). The shallow soil zone expanded immediately following the hurricane (Figure 3), which may be due to water being trapped in this layer while storm material was deposited. Unfortunately, USGS hydrological measurement equipment was destroyed during the hurricane and critical hydrology data to support this hypothesis were unavailable. However, similar soil swelling was reported over the entire soil profile in a *Juncus* salt marsh following Tropical Storm Alberto (Cahoon et al. 1999). Continued post hurricane samplings found that the shallow zone contracted and then expanded. The contraction of the shallow zone after post storm sampling may be due to dewatering of the hypothesized trapped water (Figure 3). Earlier work at our mangrove study site indicated that ground-water head pressure changes drive short-term expansion and contraction cycles and changes in soil elevation of the entire soil profile, as well as in specific zones within the profile (Whelan et al. 2005). Pre-hurricane, long term expansion and contraction of the shallow soil zone has varied from −6.4 to +7.1 cm since measurement began in 2002, and these maximal interval changes are probably related to seasonal hydrological patterns (contraction during the dry season and expansion during the wet season, Figure 3). Hurricane Wilma's deposition did not appreciably change the long term expansion and contraction pattern within the shallow soil zone.

The middle soil zone contracted due to hurricane deposition and after the hurricane continued to contract (Table 2). The bottom soil zone had some minor interval expansion ($\leq$ 1 mm), but the longer term trend was for continued subsidence (Figure 3). Patterns in both the middle and bottom soil zones suggest shallow subsidence. Compaction/shallow subsidence after storm deposition was reported in 7 of the 20 studies reviewed by Cahoon (2006).

CONCLUSION

We found that Hurricane Wilma increased the soil elevation 42.8 mm at our study site. Even one year post-hurricane there was still a net increase of 32.8 mm in soil elevation compared to pre-storm elevation. This increase in the mangrove forest soil elevation is especially important at counter balancing the effect of relative sea-level rise from eustatic sea-level rise (1.9 ± 0.1 mm yr^{-1}, Maul and Martin 1993) and belowground subsidence. Since the hurricane return interval for South Florida is approximately every 5 years and every 3 years for all tropical storms (Keim et al. 2007), this type of increase in soil elevation should be an important factor in the mangrove forest of South Florida. While collecting sediment cores and pore water samples, we observed an extensive area of marine carbonate soil deposit at ~25 cm depth in a mangrove forest impacted by Hurricane Donna in 1960 (Craighead and Gilbert 1962). Increases in soil elevation from Hurricane Andrew persisted for five years at the Old Oyster Bayou, Louisiana (Cahoon et al. 1999). Storm deposits apparently can persist for some time in the soil column.

Figure 4. Storm deposit material washing out the Shark River mangrove forest at the study location (20 June 2006).

Here we were able to measure both surface processes and belowground changes immediately after the storm to one year post hurricane. We detected post hurricane erosion of the upper soil layer. However, processes belowground varied by soil zone and over time. After six months, soil elevation loss occurred from both erosional (47%) and subsurface (53%) processes. After one year, surface erosion decreased, but still was the principle factor controlling the decrease in elevation. Subsurface processes mitigated erosional losses. Additionally, with rootlets invading the storm deposits, the new roots may slow soil surface erosion of storm deposits.

This study moves forward the fundamental research in understanding wetland soil processes. We build upon the observations of Kaye and Barghoon (1964) that accretion deposition amounts and soil surface elevation are not in a one to one relationship which generated the understanding for the need to measure and report shallow subsidence (Cahoon 1995). As a standard now, the rates of accretion, soil elevation, and shallow subsidence are reported for long term soil elevation studies. Here in, we are suggesting that belowground processes are complex, but by partitioning the soil profile it is possible to identify different processes affecting soil zones (hydrological shrink and swell in the shallow zone, compaction in the middle and bottom zone).

The larger ecological impact of Hurricane Wilma's storm deposit at this site will be determined by both gains in soil elevation and the extensive tree damage that occurred (Smith et al. this issue). High tree mortality may lead to substantial subsidence in mangrove forest (i.e., Hurricane Mitch, Cahoon et al. 2003) and at a smaller scale, in canopy gaps (Whelan 2005)). Understanding where the soil zone is changing is important to help explain what processes are forcing the long-term outcome in soil elevation. Understanding soil elevations change is important because of an expected increase in storm activities in this region and an increase in sea level (Goldenburg et al. 2001).

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