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10 authors, including:

Laura C. Feher
United States Geological Survey

Michael J. Osland
United States Geological Survey

Gordon Anderson
United States Geological Survey

William Vervaeke
National Park Service

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The Long-Term Effects of Hurricanes Wilma and Irma on Soil Elevation Change in Everglades Mangrove Forests

Laura C. Feher,[1]* Michael J. Osland,[1] Gordon H. Anderson,[2] William C. Vervaeke,[1] Ken W. Krauss,[1] Kevin R. T. Whelan,[3] Karen M. Balentine,[4] Ginger Tiling-Range,[5] Thomas J. Smith III,[2] and Donald R. Cahoon[6]

[1]U.S. Geological Survey Wetland and Aquatic Research Center, 700 Cajundome Blvd., Lafayette, Louisiana 70506-3152, USA; [2]U.S. Geological Survey Wetland and Aquatic Research Center, Gainesville, Florida 32653, USA; [3]U.S. National Park Service, Miami, Florida 33157, USA; [4]U.S. Fish and Wildlife Service, Suffolk, Virginia 23434, USA; [5]National Marine Fisheries Service (Contracted Through Jamison Professional Services), NOAA Southeast Regional Office, St. Petersburg, Florida 33701, USA; [6]U.S. Geological Survey, Laurel, Maryland 20708, USA

Abstract

Mangrove forests in the Florida Everglades (USA) are frequently affected by hurricanes that produce high-velocity winds, storm surge, and extreme rainfall, but also provide sediment subsidies that help mangroves adjust to sea-level rise. The long-term influence of hurricane sediment inputs on soil elevation dynamics in mangrove forests is not well understood. Here, we assessed the effects of sediment deposition during Hurricanes Wilma (2005) and Irma (2017) on soil elevation change at two mangrove forests located along the Shark and Lostmans Rivers in Everglades National Park. We used surface elevation change data from a 16-year period (2002–2018), measured with the surface elevation table-marker horizon (SET-MH) approach. At the Shark River mangrove forest, we used marker horizons and a combination of deep, shallow, and original SETs to quantify the contributions of four soil zones to net soil elevation change. Rates of elevation change were greatly influenced by storm sediments. Abrupt increases in elevation due to sediment inputs and subsurface expansion during Hurricane Wilma were followed by: (1) an initial post-hurricane period of elevation loss due to erosion of hurricane sediments and subsurface contraction; (2) a secondary period of elevation gain due primarily to accretion; and (3) an abrupt elevation gain due to new sediment inputs during Hurricane Irma. Our findings suggest that elevation change in hurricane-affected mangrove forests can be cyclical or include disjunct phases, which is critical information for advancing the understanding of wetland responses to accelerated sea-level rise given the expectation of increasing storm intensity due to climate change.

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*Corresponding author; e-mail: lfeher@usgs.gov

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Key words: mangrove forest; hurricane; sea-level rise; surface elevation change; accretion; sediment deposition; peat; storm surge; tropical cyclone; Everglades National Park.

Highlights

- Hurricane sediment inputs influence soil elevation change in mangrove forests.
- Elevation change in hurricane-affected mangroves can be disjunct and cyclical.
- Hurricane sediments can help mangroves maintain elevation under rising sea levels.

Introduction

As climate change is expected to alter disturbance regimes and produce novel, extreme disturbances (Emanuel 2005), understanding the factors governing the response of ecosystems to disturbance events is critical information that increases our ability to predict future ecological change (Turner 2010; Johnstone and others 2016). High-magnitude, low-frequency disturbance events such as tropical cyclones can have long-lasting effects on ecosystem processes (Paerl and others 2001). Long-term data regarding ecosystem responses to disturbance events can advance our understanding of ecosystem resilience and the role of disturbances in shaping ecosystem structure and function (Paerl and others 2001; Davis III and others 2004). Here, we assessed the decadal-scale effects of tropical cyclone-derived sediment inputs on processes controlling soil elevation change in mangrove forests.

Mangrove forests are intertidal coastal wetlands that occur along tropical, subtropical, and warm temperate coasts (Tomlinson 1986; Woodroffe and Grindrod 1991). Although a portion of the world's mangrove forests are never affected by tropical cyclones, there are many mangrove forests across the globe that are influenced by the high-velocity winds, storm surge, and extreme rainfall produced by tropical cyclones (Ward and others 2016; Osland and others 2018; Simard and others 2019). The effects of tropical cyclones on mangrove forests operate over varying temporal and spatial scales (Lugo 2008). For example, the immediate effects of cyclones on mangroves can include defoliation, tree mortality, and erosion of surface sediments (Doyle and others 1995; Smith III and others 2009), whereas longer-term effects of cyclones can include large-scale, permanent losses of coastal wetland area, which may ultimately result in peat collapse and substantial decreases in soil elevation (Cahoon and others 2003; Wanless and Vlaswinkel 2005). However, rapid inputs of transported marine sediment from cyclones can also help to sustain soil elevation in response to sea-level rise (Rejmánek and others 1988; Cahoon and others 1995b; Reed 2002; McKee and Cherry 2009; Smith III and others 2009; Smoak and others 2013). Nutrient pulses associated with the large-scale deposition of allochthonous carbonate sediments may also aid in post-storm recovery by stimulating mangrove establishment and productivity (Castañeda-Moya and others 2010; Lovelock and others 2011). Understanding the long-term effects of tropical cyclones on the processes controlling mangrove soil elevations in relation to sea-level rise will be vital for mangrove conservation efforts, especially as the frequency of the most intense storms is expected to increase in response to climate change (Elsner and others 2008; Knutson and others 2010; Kossin and others 2017).

Tropical cyclones have been recognized as important agents of geomorphic change in coastal wetlands as these storms can result in sediment deposition, erosion, compaction or lateral folding of vegetated substrate on an irregular but large-scale basis (Cahoon 2006; Morton and Barras 2011). Previous research has shown that cyclones can deliver significant short-term elevation gains for coastal wetlands (Whelan and others 2009). However, the potential long-term effects on the specific surface and subsurface processes controlling soil elevation in mangrove forests remain largely unexplored. In carbonate settings where there is little mineral sediment input, such as south Florida, sediment deposition from cyclones may be a particularly important soil building mechanism (Cahoon and Lynch 1997). Smoak and others (2013) determined that storm surge deposits from Hurricane Wilma in 2005 had a significant positive net effect on long-term accretion rates in mangroves of the Everglades and that storm deposits represent a potential mechanism by which accretion rates could adjust to sea-level rise in wetland habitats with biogenic soils. Despite the capacity for these high-magnitude disturbances to affect the suite of processes controlling mangrove soil elevation, the long-term effects of tropical cyclones on mangrove soil elevation and stability with respect to sea-level rise have been understudied.

In the Atlantic and Eastern Pacific Oceans, tropical cyclones are called hurricanes. Hence, we use the terms hurricane and tropical cyclone synonymously throughout the remainder of this communication. Our study is located in this region, specifically within Everglades National Park (Florida, USA). Mangrove forests in Everglades National Park are frequently affected by hurricanes and tropical storms that deposit storm sediments at considerable distances upstream from the Gulf of Mexico (Smith III and others 2009). Most recently, the passage of Hurricane Wilma in 2005 and Hurricane Irma in 2017 resulted in the deposition of carbonate marine sediments on the mangrove soil surface at depths several times greater than what would normally be accumulated over many years (Smith III and others 2009; Whelan and others 2009). Several studies have examined short-term responses of Everglades mangroves to hurricanes (Smith III and others 2009; Whelan and others 2009; Castañeda-Moya and others 2010; Barr and others 2012). However, the lack of pre-storm benchmark data and long-term storm response data limits the capacity to capture cumulative, long-term effects.

In this study, we investigated the influences of Hurricanes Wilma and Irma on soil surface elevation change over a period of 16 years (2002–2018) in two mangrove forests in Everglades National Park. We used soil elevation data that were measured using the surface elevation table-marker horizon approach (SET-MH) (Cahoon and others 2002a, b; Callaway and others 2013; Lynch and others 2015). The SET-MH approach allows for collection of simultaneous observations of both surface and subsurface processes controlling mangrove soil elevation, with repeated measurements taken over time to determine trends in elevation change. We analyzed our data within the context of the following questions: (1) did hurricane-induced sediment deposits alter patterns of mangrove soil elevation change and are these alterations maintained over time? (2) What are the effects of hurricane sediments on the different depth zones within the soil profile? And (3) how do hurricane sediments affect the ability of mangrove forests to maintain their position within the tidal frame in response to sea-level rise?

Methods

Study Area

This research was conducted along the southwestern coast of Everglades National Park at two mangrove forest sites along the Shark and Lostmans Rivers (Figure 1). The Shark River site is located approximately 4.1 km upstream from the Gulf of Mexico in a mature riverine mangrove forest (25° 21′N, 81° 04′W). The Lostmans River site is located in a similar mature, riverine mangrove forest approximately 2.1 km upstream of the Gulf, along a side creek of the Lostmans River (25° 32′N, 81° 11′W). Both sites contain a mixture of the three most common mangrove species in the region: *Avicennia germinans* (black mangrove), *Laguncularia racemosa* (white mangrove), and *Rhizophora mangle* (red mangrove). The mangrove forests of Everglades National Park cover a large crescent-shaped area (approximately 1400 km^2, Simard and others Simard et al. 2006) across the far southwestern tip of Florida. The mangrove zone is bisected by numerous ponds and rivers that drain the major freshwater sloughs of the Everglades. The hydrologic regime in this area is influenced by mixed tides and river discharge, which can vary substantially between the wet and dry seasons. The daily average tidal range was 1.2 m at the Shark River site and 0.6 m at the Lostmans River site during the period between 2000 and 2010 based on water levels from adjacent tide gages. Soils in the area are composed of a thick layer of mangrove peat up to 5.5 m in depth on top of a limestone platform (Cohen 1968; Whelan and others 2005).

Since soil elevation data collection began at these two sites in the late 1990s, seven tropical cyclones have passed within 90 km of this area of south Florida. Most recently, both sites were heavily affected by Hurricane Wilma in 2005 and Hurricane Irma in 2017. Hurricane Wilma developed in the Gulf of Mexico and struck the southwest Everglades from a westerly direction, making landfall near Cape Romano, Florida (approximately 75 km northwest of the study area) on October 24, 2005, as a Category 3 storm with sustained winds of 190 km/h (Landsea and Franklin 2013). Smith and others (2009) estimated that storm surge depths during Wilma reached approximately 2.5 m at the Shark River site and 5 m at the Lostmans River site. Deposits of suspended sediments left behind by Wilma's surge were measured as 3 to 5 cm thick at both the Shark River and Lostmans River sites (Smith III and others 2009; Whelan and others 2009).

Hurricane Irma's storm path was initially northwest through the middle Florida Keys, making landfall near Marco Island, Florida (approximately 80 km northwest of the study area) on September 10, 2017, as a Category 3 storm with maximum wind speeds of 185 km/h. This was the first major hurricane to strike south Florida since Hurricane Wilma. Storm surge from Hurricane Irma produced

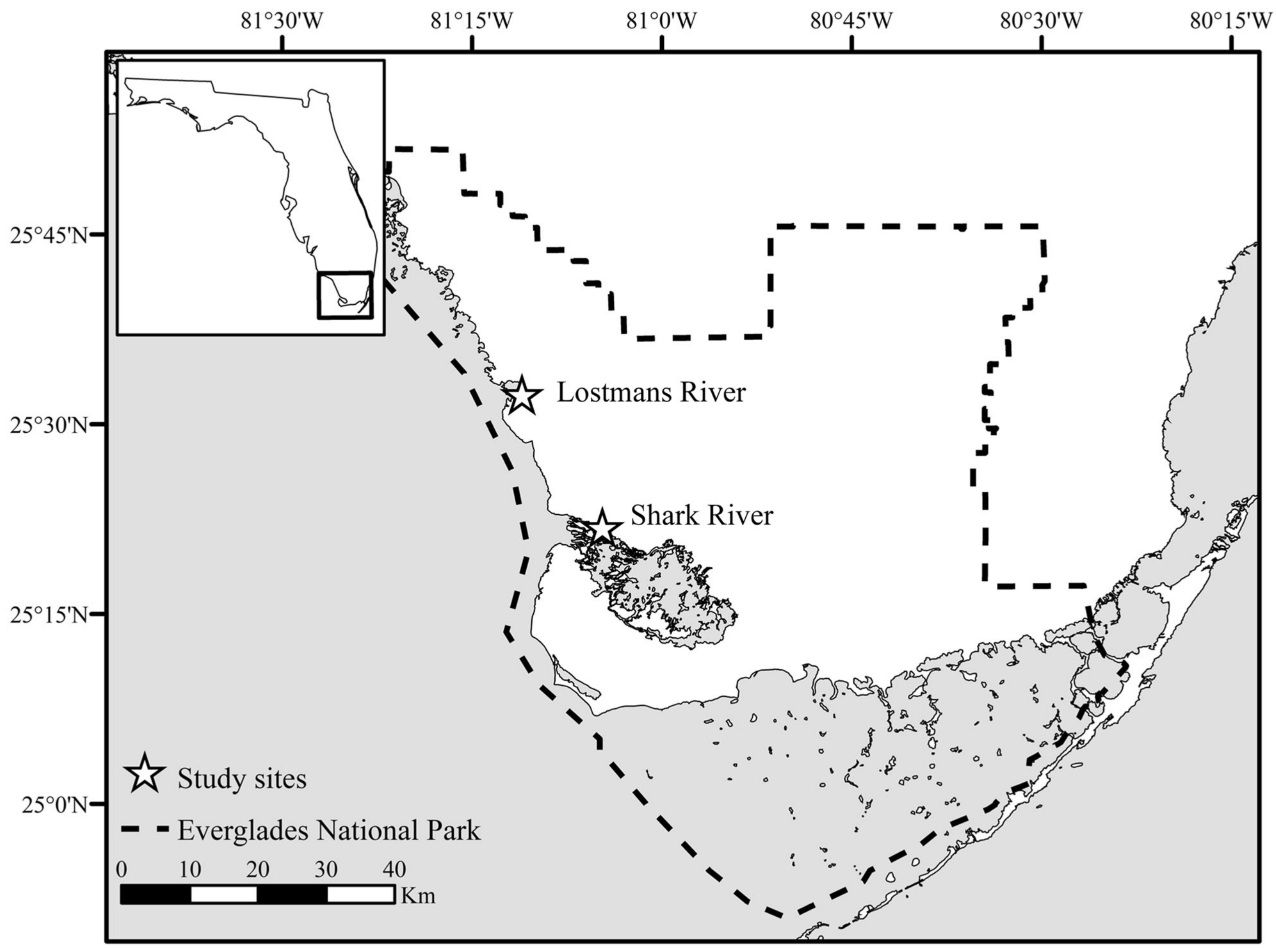

Figure 1. Map showing the location of the study sites in Everglades National Park, Florida, USA.

inundation levels in excess of 2 m at Shark River and 1.7 m at Lostmans River, based on measurements recorded by stream gages located throughout Everglades National Park (Cangialosi and others 2018). Sediment deposits left on the wetland surface following Irma were measured up to 5 cm thick at the Shark River site and 6.5 cm thick at the Lostmans River site (W. Vervaeke, personal observation).

Surface Elevation Table-Marker Horizon Approach

Changes in surface elevation at each site were monitored using the SET-MH approach (Cahoon and others 2002a, b; Callaway and others 2013; Lynch and others 2015). The surface elevation table (SET) device consists of a portable mechanical leveling instrument that is transported into the field and attached to a permanent benchmark pipe that has been installed into the soil at an established depth. The SET instrument is then leveled and positioned in a fixed compass direction, and fiberglass pins are lowered through the instrument plate to the soil surface, such that they reoccupy the same points on the soil surface at repeated sampling events. Changes in the height of the pins above the SET instrument between sampling events therefore provide high-precision measurements of soil surface elevation change over time relative to the stable benchmark (Cahoon and others 2002a). Three types of SET designs were used at each site to monitor changes in different parts of the soil profile. The original SET developed by Boumans and Day (1993) and modified by Cahoon and others (2002a) utilizes a hollow pipe benchmark that is driven to a depth of approximately 4 m. The original SET design was updated to the rod surface elevation table design (RSET) to allow for benchmarks that can be either deeper or shallower than marks used with the original SET (Cahoon and others 2002b; Callaway and others 2013). The deep RSET uses a stainless-steel rod benchmark driven into the ground until refusal, often to depths greater than 10 meters. The shallow RSET design consists of a frame of four support pipes with a measurement rod pipe in the center and was developed to measure changes in the root zone of wetland plants (Cahoon and others 2002b). The original SETs and deep RSETs at these sites were installed to bedrock or near bedrock; hence, they are considered vertically stable (Whelan and others 2005). Marker horizons consist of a feldspar layer placed on top of the wetland soil surface to measure the accumulation of material over time (that is, vertical accretion). When used in conjunction, the SET-MH method provides information about both the surface and subsurface processes that influence elevation dynamics in coastal wetlands (Cahoon and others 1995a, 1999).

Shark River: Data Collection and Analyses

The Shark River site has three replicate SET-MH plots. In each SET-MH plot, there was an original SET, a deep RSET, a shallow RSET, and associated marker horizons. Benchmarks for use with the original SET were installed in July 1998. Three feldspar marker horizon subplots were also installed in each plot in July 1998, for a total of nine marker horizons at the site. Benchmarks for both deep and shallow RSETs were added to each of the three plots in February 2002 (that is, three deep and three shallow RSETs at the site). Installation depths for the original SETs ranged from 4.0 to 4.3 m (Whelan and others 2005). Installation depths for the deep RSET benchmarks ranged from 5.5 to 6.6 m, and shallow RSET benchmarks were installed to a consistent depth of 0.35 m, which represents the root zone of the mangrove forest (Whelan and others 2005).

Surface elevation dynamics from the original SETs at the Shark River site were measured across a 20-year period, from July 1998 to December 2018. Elevations of the deep and shallow RSETs were measured across a 16-year period, from March 2002 to May 2018. On each sampling date, surface elevation measurements were made for nine pins on four fixed measurement positions (that is, compass bearings) around each benchmark, for a total of 36 elevation measurements per benchmark per sampling date. Accretion was determined by coring each marker horizon and measuring the depth to the feldspar layer on each sampling date. In 2009, reference elevations relative to the local vertical datum (North American Vertical Datum of 1988, NAVD 88) were determined for each benchmark using differential optical leveling from a local vertical control benchmark that was previously established using high precision, static-occupied Vertical Global Positioning System (VGPS) methods (Anderson and others 2014). The benchmark elevations were then used to convert the SET-derived relative surface elevation change data to actual elevation in NAVD 88. Earlier elevation surveys at Shark River conducted in 2002 and again in 2005 demonstrated that there was no movement of the SET benchmarks and these benchmarks therefore represent a stable datum (Whelan and others 2005).

As the initial measurements for the deep and shallow RSETs at Shark River were recorded in March 2002, we excluded data from the original SETs and marker horizons that were collected prior to this date so that all SET and marker horizon data from Shark River could be compared across the same time period (that is, March 2002 to December 2018). To determine the elevation change for each individual pin, the elevation reading of each pin on each sampling date was subtracted from its initial value (T_0). The pin-level elevation readings for each measurement date were then averaged across each of the four bearings on each benchmark, then the bearing-level values were averaged to the plot level, and finally the plot-level values were averaged to the site level. For the accretion data from the Shark River site, one to three cores were taken from each marker horizon subplot on each measurement date. The depth to the marker horizon from the cores was then averaged to the subplot level, then the subplot-level values were averaged to the plot level, and finally the plot-level values were averaged to the site level. Because the original feldspar marker horizons have been replaced six times since they were originally installed in July 1998, the plot-level average accretion values from the last sampling date for the older set of accretion plots were added to the plot-level average values from the first sampling date for the new set of accretion plots to produce a continuous time series of vertical accretion. The use of three SET types at the Shark River site allowed us to determine the contribution of four distinct soil depth zones to overall trends in expansion or contraction of the soil profile. We used the formula developed by Whelan and others (2005), where expansion or contraction of the entire soil profile is equal to the sum of surface accretion and changes in the thickness of the active root zone (that is, shallow zone: 0–0.35 m), the middle zone (0.35–4 m), and the bottom zone (4–6 m).

$$\begin{aligned}&\text{Entire profile expansion and contraction}\\&= \text{Accretion} + (\text{Shallow RSET - Accretion})\\&\quad+(\text{Original SET - Shallow RSET})\\&\quad+(\text{Deep RSET - Original SET})\end{aligned}$$

To account for the effect of Hurricanes Wilma and Irma and to determine time-period specific rates of elevation change, we separated the data into four time periods: (1) Pre-Wilma—a consistent period of elevation gain leading up to the landfall of Hurricane Wilma on October 24, 2005; (2) Post-Wilma #1—a consistent period of linear elevation loss following Wilma (October 25, 2005 to May 22, 2008); (3) Post-Wilma #2—a consistent period of linear elevation gains between May 23, 2008, and landfall of Hurricane Irma on September 10, 2017; and (4) Post-Irma. We used piecewise regression via the R package 'segmented' to estimate the breakpoint date between Post-Wilma #1 and Post-Wilma #2. We used linear regression to determine the rate of elevation change for each time period and for the entire time series. Rates of change for the post-Irma period were not evaluated because this period is still underway and will require additional data collection for accurate rate determination. We compared the long-term rate of elevation change to a regional long-term sea-level rise rate of 2.42 ± 0.14 mm y^{-1} from the Key West tide gage (https://tidesandcurrents.noaa.gov/sltrends) for the period spanning 1913–2017 (hereafter referred to as the long-term Key West sea-level rise rate). We also compared the long-term rate of elevation change to a more local and recent sea-level rise rate of 3.24 ± 1.46 mm y^{-1} calculated from data collected from a tide gage adjacent to the Shark River study site (SFNRC 2018) for the period spanning 1997–2018 (hereafter referred to as the local Shark River sea-level rise rate). One-sample Student's *t* tests were used to determine whether the long-term rate of elevation change from the deep RSETs was greater than the long-term Key West or local Shark River sea-level rise rates. All data analyses were conducted in R (R Core Team 2017).

Lostmans River: Data Collection and Analyses

We established three replicate SET-MH plots at the Lostmans River site. A single benchmark for use with an original SET was installed in each plot in January 1999, for a total of three original SETs at the site. A deep RSET benchmark was added to each plot at Lostmans River in May 2007, for a total of three deep RSETs at the site. Although shallow RSET benchmarks were also installed at Lostmans River in May 2007, these data are not included because measurement of the shallow RSETs at this site has been sporadic as access to the site is limited by tides. Original SET benchmarks were installed to a depth of 3.3 m, whereas installation depths for the deep RSET benchmarks ranged from 4.0 to 5.0 m. Surface elevations of the original SETs at the Lostmans River site were monitored across a 19-year period, from January 1999 to December 2018. Surface elevations of the deep RSETs were monitored across an 11-year period, from May 2007 to December 2018. Although the deep RSETs at Lostmans River were not installed until 2007, there was a significant relationship between surface elevation measurements from the deep RSETs and original SETs (Figure S1, $p < 0.001$, $R^2 = 0.96$); thus, we integrated data from the original SETs and deep RSETs at this site into a single time series of measurements that encompassed the entire 19-year measurement period. We also excluded data that were collected prior to March 2002, to represent changes throughout the same time period used for the Shark River data. Site-level elevation changes were determined using the same method as described for Shark River, including utilizing VGPS benchmarks to reference each SET to NAVD 88. Data from Lostmans River were separated into four similar time periods as for Shark River. We used piecewise regression to determine that the breakpoint date between Post-Wilma #1 and Post-Wilma #2 was September 21, 2007. Linear regression was used to determine rates of elevation change for each time period and for the entire time series. Rates of change for the post-Irma period were not evaluated because this period is still underway and will require additional data collection for accurate rate determination. One-sample Student's *t*-tests were used to determine whether the long-term rate of elevation change was greater than the long-term Key West or local Lostmans River sea-level rise rates. A local recent sea-level rise rate of 3.08 ± 0.84 mm y^{-1} was calculated from data collected from a tide gage adjacent to the site on the Lostmans River (SFNRC 2018) for the period spanning 1998–2018 (hereafter referred to as the local Lostmans River sea-level rise rate). Analyses of elevation change at Lostmans River are used to complement the patterns observed at Shark River, because the data collected from the Lostmans River site were less comprehensive than data collected from the Shark River site.

Results

Shark River

During the Pre-Wilma period, there was no significant change in elevation for the deep RSETs (Figure 2d). However, there were significant positive gains in elevation during the pre-Wilma period for the original SETs (Figure 2c, rate = 5.7 ± 0.9 mm y^{-1}, R^2 = 0.67, $p < 0.001$), shallow RSETs (Figure 2b, rate = 4.6 ± 0.4 mm y^{-1}, R^2 = 0.87, $p < 0.001$), and vertical accretion (Figure 2a, rate = 4.2 ± 0.8 mm y^{-1}, R^2 = 0.61, $p < 0.001$). Hurricane Wilma deposited between 27.6 and 45.9 mm of marine carbonate sediment on top of the peat soil surface at Shark River (mean = 37.5 ± 0.1 mm) and resulted in a mean surface elevation gain of 43.2 ± 1.0 mm across the entire soil profile. During the Post-Wilma #1 period, there were significant decreases in elevation for the deep RSETs (rate = − 9.7 ± 2.1 mm y^{-1}, R^2 = 0.74, p = 0.003), original SETs (rate = − 8.7 ± 1.3 mm y^{-1}, R^2 = 0.87, $p < 0.001$), and shallow RSETs (rate = − 5.3 ± 1.0 mm y^{-1}, R^2 = 0.79, p = 0.002), but there was no significant change in vertical accretion. During the Post-Wilma #2 period, there were significant positive gains in elevation for the deep RSETs (rate = 4.5 ± 0.5 mm y^{-1}, R^2 = 0.84,

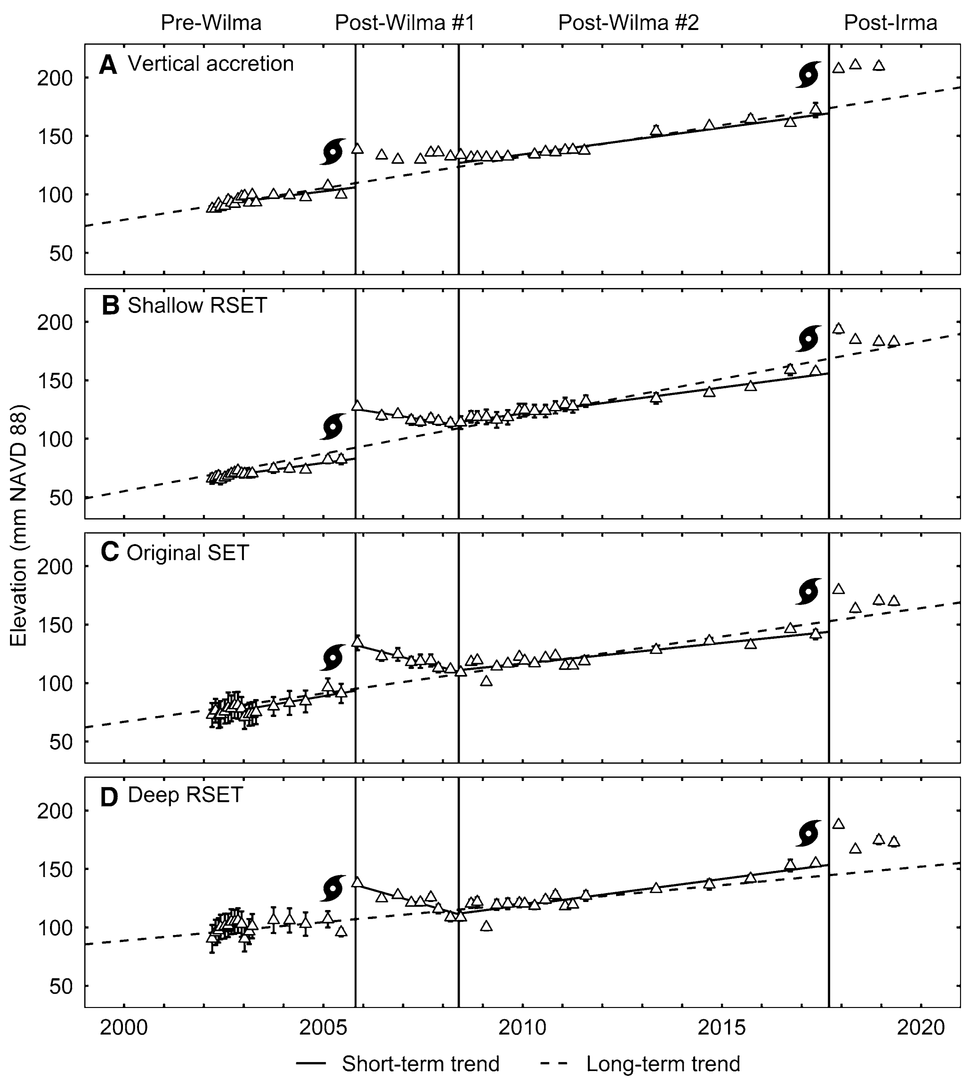

Figure 2. Vertical accretion (**a**) and surface elevation change (NAVD 88: North American Vertical Datum of 1988) from the shallow RSETs (rod surface elevation table) (**b**), original SETs (surface elevation table) (**c**), and deep RSETs (**d**) in the Shark River mangrove forest (2002–2018). Hurricanes Wilma (2005) and Irma (2017) are denoted with the hurricane symbols. The vertical lines denote four periods: (1) Pre-Wilma; (2) Post-Wilma #1; (3) Post-Wilma #2; and (4) Post-Irma. Points represent the soil surface elevation on each sampling date (mean ± SE). Significant regression lines are shown for short-term trends with solid lines and for long-term trends with dashed lines.

$p < 0.001$), original SETs (rate = 3.5 ± 0.4 mm y^{-1}, $R^2 = 0.78$, $p < 0.001$), shallow RSETs (rate = 4.5 ± 0.3 mm y^{-1}, $R^2 = 0.94$, $p < 0.001$), and vertical accretion (rate = 4.6 ± 0.3 mm y^{-1}, $R^2 = 0.94$, $p < 0.001$). Hurricane Irma deposited between 23 and 48 mm of sediment on top of the soil surface at Shark River (mean = 35.1 ± 1.9 mm) and resulted in a mean surface elevation gain of 35.8 ± 1.4 mm across the entire soil profile (Figure 3a). Across the entire period of record (that is, the long-term trend), there were significant positive gains in elevation (Figure 2a–d) for the deep RSETs (rate = 3.2 ± 0.3 mm y^{-1}, $R^2 = 0.74$, $p < 0.001$), original SETs (rate = 4.9 ± 0.4 mm y^{-1}, $R^2 = 0.79$, $p < 0.001$), shallow RSETs (rate = 6.4 ± 0.3 mm y^{-1}, $R^2 = 0.89$, $p < 0.001$), and vertical accretion (rate = 5.4 ± 0.3 mm y^{-1}, $R^2 = 0.91$, $p < 0.001$). The long-term rate of soil elevation change from the deep RSETs was not significantly higher than either the long-term Key West ($t = 0.6$, $p = 0.6$) or local Shark River sea-level rise rates ($t = -0.04$, $p = 0.9$).

By incorporating the surface elevation and vertical accretion data into the equation developed by Whelan and others (2005), we determined the contributions of the different soil zones to the overall expansion or contraction in the entire soil profile at Shark River (Figure 3). Positive rates of vertical change represent soil expansion, whereas

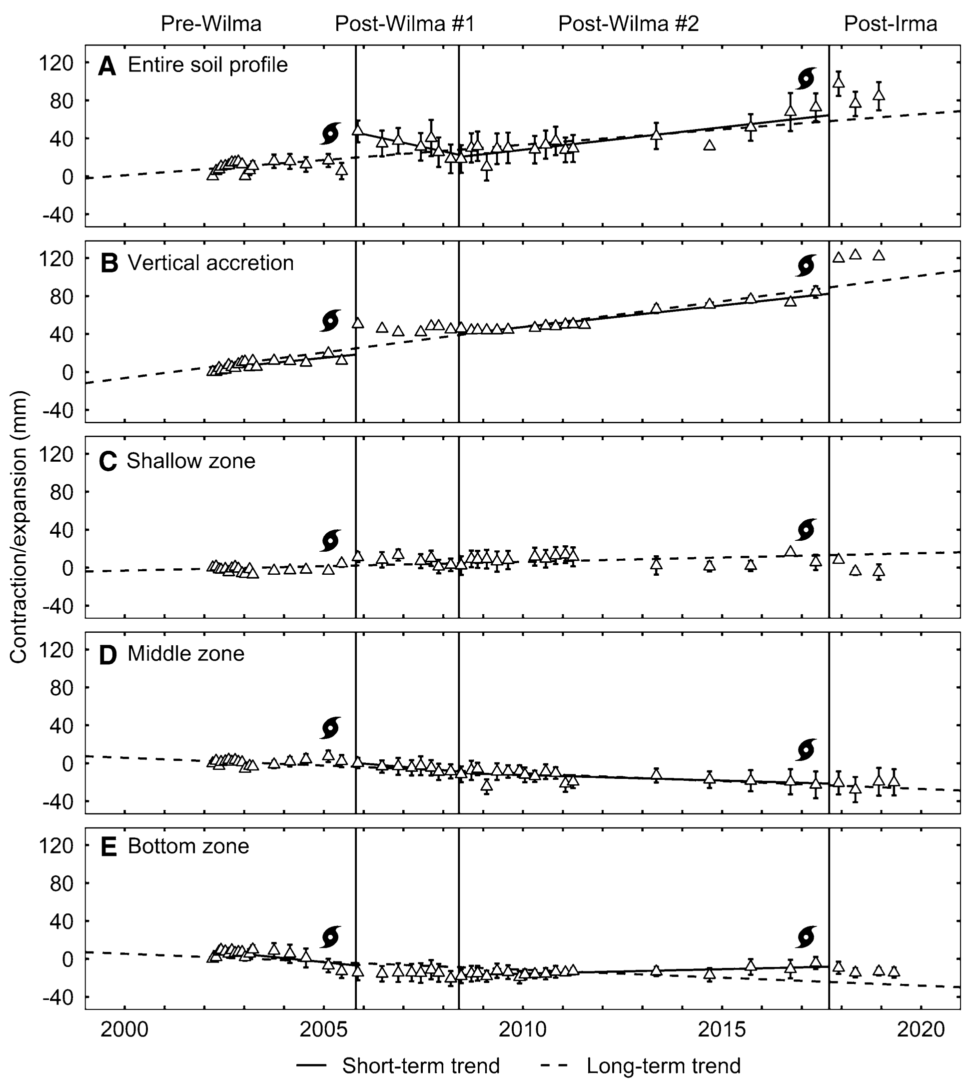

Figure 3. Contraction/expansion of the entire soil profile (**a**), accretion zone (**b**), shallow zone (**c**), middle zone (**d**), and bottom zone (**e**) in the Shark River mangrove forest (2002–2018). Hurricanes Wilma (2005) and Irma (2017) are denoted with the hurricane symbols. The vertical lines denote four periods: (1) Pre-Wilma; (2) Post-Wilma #1; (3) Post-Wilma #2; and (4) Post-Irma. Points represent vertical change on each sampling date (mean ± SE). Significant regression lines are shown for short-term trends with solid lines and for long-term trends with dashed lines.

negative rates of vertical change represent soil contraction (that is, elevation gains and losses, respectively). Rates of vertical change differed among different portions of the soil profile and among different time periods. During the Pre-Wilma period, there was no significant ($p > 0.05$) vertical change across the entire soil profile (Figure 3a), the shallow soil zone (Figure 3c), or the middle soil zone (Figure 3d). However, there was a significant decrease in vertical change during the Pre-Wilma period for the bottom soil zone (Figure 3e, rate = -4.3 ± 1.1 mm y^{-1}, $R^2 = 0.45$, $p = 0.001$). Hurricane Wilma resulted in a mean expansion of 6.7 ± 4.7 mm in the shallow soil zone, mean contraction of − 2.0 ± 1.6 mm in the middle soil zone, and mean contraction of − 1.3 ± 0.9 mm in the bottom soil zone. During the Post-Wilma #1 period, there was a significant decrease in vertical change across the entire soil profile (rate = − 9.1 ± 3.1 mm y^{-1}, $R^2 = 0.56$, $p = 0.03$), no significant change in the shallow soil zone, a significant decrease in vertical change in the middle soil zone (rate = − 3.4 ± 0.8 mm y^{-1}, $R^2 = 0.70$, $p = 0.006$), and no significant change in the bottom soil zone. During the Post-Wilma #2 period, there was a significant increase in vertical change across the entire soil profile (rate = 4.7 ± 0.7 mm y^{-1}, $R^2 = 0.73$, $p < 0.001$), no significant change in the shallow soil zone, a significant decrease in vertical change in the middle soil zone (rate = −1.2 ± 0.4 mm y^{-1}, $R^2 = 0.29$, $p = 0.01$), and a significant increase in vertical change in the bottom soil zone (rate = 1.0 ± 0.2 mm y^{-1}, $R^2 = 0.52$, $p < 0.001$). Hurricane Irma resulted in a mean expansion of 1.5 ± 5.5 mm in the shallow soil zone, mean expansion of 1.9 ± 2.6 mm in the middle soil zone, and mean contraction of − 5.1 ± 1.0 mm in the bottom soil zone. Across the entire period of record, there were significant increases in vertical change across the entire soil profile (rate = 3.2 ± 0.3 mm y^{-1}, $R^2 = 0.69$, $p < 0.001$) and in the shallow soil zone (rate = 0.9 ± 0.2 mm y^{-1}, $R^2 = 0.38$, $p < 0.001$) and significant decreases in vertical change in the middle soil zone (rate = − 1.6 ± 0.2 mm y^{-1}, $R^2 = 0.72$, $p < 0.001$) and bottom soil zone (rate = − 1.6 ± 0.3 mm y^{-1}, $R^2 = 0.46$, $p < 0.001$).

Lostmans River

The patterns of elevation change measured by the combined deep RSETs and original SETs at Lostmans River were similar to Shark River (Figure 4). During the Pre-Wilma period, the rate of elevation change at Lostmans River was not significant ($p > 0.05$). Hurricane Wilma deposited between 26.8 to 46.3 mm of sediment on top of the soil surface at Lostmans River (mean = 34.3 ± 2.5 mm) and resulted in a mean surface elevation gain of 42.9 ± 6.6 mm. During the Post-Wilma #1 period, there was a significant decrease in elevation (rate = − 18.3 ± 3.4 mm y^{-1}, $R^2 = 0.88$, $p = 0.01$). For the Post-Wilma #2 period, there was a significant increase in elevation (rate = 5.1 ± 0.5 mm y^{-1}, $R^2 = 0.86$, $p < 0.001$). Hurricane Irma deposited between 14.0 to 65.0 mm of sediment on top of the soil surface at Lostmans River (mean = 33.4 ± 7.4 mm) and resulted in a mean surface elevation gain of 34.4 ± 3.0 mm. Across the entire period of record (that is, the long-term trend), there was a significant increase in elevation at Lostmans River (rate = 4.9 ± 0.4 mm y^{-1}, $R^2 = 0.78$, $p < 0.001$). The long-term elevation change rate at the Lostmans River site was significantly greater than the long-term Key West sea-level rise rate ($t = 17.1$, $p = 0.003$), as well as the local Lostmans River sea-level rise rate ($t = 13.0$, $p = 0.006$).

Discussion

Mangrove forests in the greater Everglades are particularly prone to repeated hurricane and tropical storm disturbances due to their position at the land–sea interface on low latitude coastlines with high cyclonic activity. Mangroves have several adaptations to persist in dynamic environments, including high rates of primary production, short regeneration times, prolific propagule production, and extensive belowground biomass and nutrient reserves (Alongi 2008). However, the long-term resilience of mangrove ecosystems to these repeated disturbances can be difficult to predict because storm effects are highly dependent upon storm characteristics (for example, wind speed, storm surge, storm path), position of the site within the greater landscape, and initial site conditions (Doyle and others 2009). Additionally, there can be substantial variability in mangrove soil elevation responses to storms as the processes contributing to elevation change are highly site-specific and may change over time (Krauss and others 2010; Webb and others 2013; Woodroffe and others 2016).

Previous investigations of storm effects on wetland elevation dynamics have noted that several different surface or subsurface processes control soil elevation responses, including sediment deposition, erosion, compaction, peat decomposition, root growth, lateral folding of vegetated substrate, or

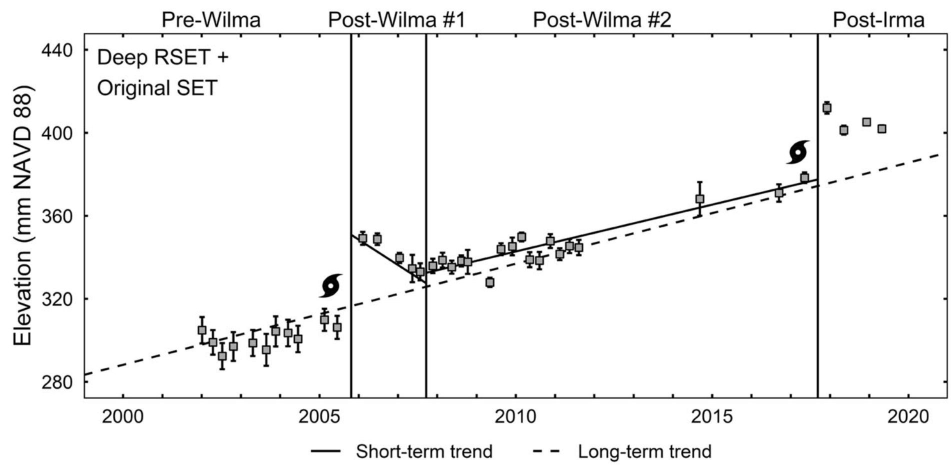

Figure 4. Surface elevation change (NAVD 88: North American Vertical Datum of 1988) from the combined deep RSETs (rod surface elevation table) and original SETs (surface elevation table) in the Lostmans River mangrove forest (2002–2018). Hurricanes Wilma (2005) and Irma (2017) are denoted with the hurricane symbols. The vertical lines denote four periods: (1) Pre-Wilma; (2) Post-Wilma #1; (3) Post-Wilma #2; and (4) Post-Irma. Points represent the soil surface elevation on each sampling date (mean ± SE). Significant regression lines are shown for short-term trends with solid lines and for the long-term trend with a dashed line.

soil shrink or swell with groundwater flux (Cahoon 2003, 2006; Toscano and others 2018). Based on previous research of hurricane sediment effects on coastal wetlands throughout the Gulf of Mexico (Cahoon and others 1995a; Cahoon 2003, 2006; McKee and Cherry 2009; Whelan and others 2009) and Australia (Woodroffe and Grime 1999; Rogers and others 2013), we expected that the soil elevation responses generated by these processes would follow one of two generalized patterns where either (a) the post-storm trajectory of soil elevation change remains elevated over time (Figure 5a), or (b) the post-storm trajectory of soil elevation change returns to a level of equilibrium following sediment deposition and a slight loss of elevation (Figure 5b). Soil elevation change at the Shark River and Lostmans River sites is best illustrated by a combination of these nonlinear cyclical patterns. Although some parts of the soil profile show a return back to equilibrium following a short-term loss in elevation (for example, the data from the shallow and original SETs at Shark River), there was ultimately a long-term net gain in elevation of the full soil profile at both sites. Rapid sediment deposition on the mangrove surface therefore increased the elevation capital of these sites and potentially reduced their vulnerability to submergence by sea-level rise (Cahoon and Guntenspergen 2010). Although storm deposits are known to be critical for maintaining elevations in deltaic salt marshes where the supply of mineral sediments has been severely limited by human modification of

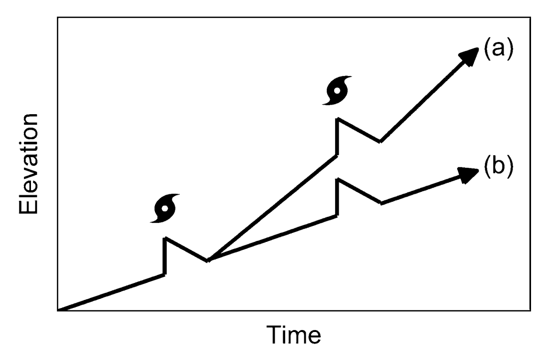

Figure 5. Hypothesized effects of hurricanes on soil elevation change in mangrove ecosystems: **a** an increase in the rate of elevation change following hurricane sediment deposition, or **b** the rate of elevation change returns to equilibrium following hurricane sediment deposition.

the coastal landscape (Rejmánek and others 1988; Cahoon and others 1995b; Reed 2002), our study is one of the few examples that demonstrates ecological enhancement of the processes controlling soil elevation by storm deposition in a mangrove ecosystem with naturally limited mineral sediment inputs (Smith III and others 2009; Whelan and others 2009; Smoak and others 2013). In fact, a meta-analysis of globally distributed mangrove monitoring sites by Sasmito and others (2016) indicated that storm-affected mangroves have some of the highest short-term surface elevation change and surface accretion rates among a variety of hydrogeomorphic settings. While other coastal wetlands in different hydrogeomorphic settings have shown variable responses to storm sedimentation (Cahoon and others 1995a, 1996; Woodroffe and Grime 1999; Rogers and others 2013), our results suggest that the storm-induced deposition of marine sediments may be critical to the establishment and continued persistence of mangrove ecosystems in non-deltaic areas that receive minimal terrigenous sediment inputs and also have a disturbance regime of reoccurring storms.

Beyond the effects of rapid sediment deposition on surface processes (that is, vertical accretion), hurricanes can also have significant effects on the subsurface processes controlling soil elevation dynamics such as root growth, decomposition, sediment compaction, and soil shrink and swell from groundwater flux. Although the majority of the previous studies on soil elevation dynamics before and after storms indicated that subsurface processes dominated the long-term changes in soil elevation (Cahoon 2006), few studies have attempted to compare storm effects among subsurface processes (Cahoon and Lynch 1997; Cahoon and others 2003; McKee and Cherry 2009; Whelan and others 2009). The use of multiple SET types in the current study allowed us to differentiate and quantify the effect of different subsurface processes on net elevation change (Whelan and others 2005, 2009). Before Hurricane Wilma, vertical accretion of sediment at the surface was completely negated by contraction (either through compaction or soil shrink due to groundwater flux) in the bottom soil zone, ultimately resulting in no net vertical change across the entire soil profile for the Pre-Wilma period (Figure 3). During the initial Post-Wilma #1 period, a net decrease in the vertical change of the entire soil profile resulted from erosion or compaction of the storm-deposited sediments (that is, the vertical accretion rate was zero or negative) combined with compaction of the middle soil zone. A study of soil elevation and groundwater changes conducted at the Shark River site by Whelan and others (2005) demonstrated that short-term patterns of soil elevation change at this site are strongly influenced by groundwater fluctuations. Thus, the 5.7 cm deficit between the depth of the sediment deposited by Wilma (37.5 mm) and the surface elevation change recorded immediately after Wilma (43.2 mm) could be attributed to swelling of the shallow soil zone as a result of water being trapped under the deposited storm sediments, whereas subsequent decreases in the soil profile during the continued Post-Wilma #1 period could be attributed to dewatering of the shallow soil zone (Whelan and others 2009). Following this period of erosion and compaction, the vertical change of the entire soil profile experienced a net increase owing to vertical accretion at the surface (that is, the vertical accretion rate was greater than zero), which, when combined with a slight expansion in the bottom soil zone, outweighed minor compaction in the middle soil zone. In other words, prior to Wilma, subsurface processes were the dominant force controlling soil elevation, but after Wilma, surface accretion processes (that is, sediment deposition or erosion) were dominant and subsurface processes played a more minor role. Therefore, although the pulse of sedimentation from the storm itself was important, we also document a facilitated shift in what controls surface elevation in the years after the storm.

Our results also highlight the importance of considering multiple temporal scales when assessing hurricane effects on mangrove soil elevation dynamics. Many of the previous studies of hurricane effects on soil elevation dynamics monitored elevation for only one to two years after the storm. For instance, monitoring at the Shark River site by Whelan and others (2009) indicated that soil elevation rapidly increased as a result of the sediment deposition from Hurricane Wilma, followed by a small decline in elevation one year after the storm. Our continued monitoring of this site and the Lostmans River site over a 16-year period showed that this initial decline in elevation immediately after sediment deposition from Wilma was then followed by a multi-year period of increasing elevation due to accretion prior to the deposition of new sediment during Hurricane Irma. A similar initial decline in elevation one year following sediment deposition by Hurricane Irma indicates that the long-term trend of soil elevation change at these sites likely follows a cyclical trajectory of alternating periods of elevation loss and elevation gain punctuated by repeated hurricane events. Therefore, long-term data may be needed to develop a complete understanding of the cumulative effects of hurricane-induced sediment deposition on mangrove soil elevations to discern whether storm deposits are compensatory or additive to long-term soil surface trajectories relative to rising seas.

Mangroves and other coastal wetlands are highly vulnerable to submergence under predicted scenarios of sea-level rise. For mangrove ecosystems to maintain their stability in response to global climate change, the long-term rate of change in soil elevation from vertical accretion and subsurface change must be equal to or greater than long-term local rates of sea-level rise. In sediment-poor, oligotrophic settings such as mangroves of the Everglades, the maintenance of soil elevation is dependent upon biotic production, as the main soil building mechanism in these settings is the accumulation of mangrove peats that are largely composed of root matter (McKee 2011). The pulses of phosphorus from storm sediments can therefore contribute to enhanced resilience to sea-level rise by stimulating primary production and subsequently increasing the subsurface development of mangrove peat (McKee and others 2007; Castañeda-Moya and others 2010; Baustian and Mendelssohn 2015, 2018; Danielson and others 2017). As long as mangrove forest vegetation is minimally affected by wind and flood damage, these nutrient pulses can advance forest recovery following a storm through rapid regrowth of aboveground biomass and enhanced dispersal of propagules needed to recolonize more heavily affected areas (Lovelock and others 2011). Although there is the potential that additional phosphorus inputs could result in a net reduction in belowground biomass allocation due to alleviation of phosphorus limitation or enhanced decomposition, nutrient pulses can promote the production of fine roots that stabilize newly deposited sediments and thereby help to maintain the elevation gains from these rapid sedimentation events (Smith III and others 1994; Whelan and others 2009). Similarly, hurricane sediments may stimulate plant production not only by adding nutrients, but also by ameliorating flooding and associated growth-limiting factors such as sulfide (Baustian and Mendelssohn 2015, 2018). For instance, prolific growth of new fine rootlets have been observed in cores of storm deposit material collected at Shark River in the months immediately following both Hurricanes Wilma (Whelan and others 2009) and Irma (W. Vervaeke, personal observation). While the sites discussed here are less nutrient limited as compared to other parts of the Everglades, large inputs of phosphorus-rich storm sediments in more nutrient-limited areas may have even greater biological effects (Davis III and others 2004; Castañeda-Moya and others 2011).

Although the ability of mangroves to actively modify the elevation of the soil surface confers a degree of resilience to future disturbances, mangrove ecosystem responses to hurricanes can vary significantly between sites within the same ecosystem. In many cases, mangroves that fringe coastlines are more directly exposed to storms and therefore experience significantly greater erosion of surface sediments and tree mortality leading to peat collapse and declines in elevation (Duever and others 1994; Cahoon and others 2003; Smith III and others 2009). Thus, the beneficial effects of storm sediments on mangrove soil elevations at the Shark River and Lostmans River sites may be unique to the specific landscape position of these two sites—close enough to the Gulf of Mexico to receive sediments from storms and tides, yet far enough inland to avoid erosion and widespread mangrove mortality from storms leading to peat collapse. Consequently, while future increases in hurricane activity could result in increased mangrove mortality and peat collapse along open water areas (Wanless and Vlaswinkel 2005; Smith III and others 2009), a subsequent increase in sediment transport from these areas could stabilize more inland forests not directly exposed to the storm (Smoak and others 2013). Thus, rapid sedimentation from storm events may become increasingly important for the persistence of mangrove ecosystems as sea-level rise rates are expected to accelerate substantially in the coming decades (Nerem and others 2018). Therefore, monitoring conducted at landscape-level spatial resolutions will be critical to inform ecosystem-wide predictions of mangrove responses to sea-level rise given the expectation of increased storm intensity due to climate change.

Conclusions

Although the potential synergistic effects of accelerated sea-level rise and increasing hurricane activity due to climate change likely will have significant effects on mangrove ecosystems, the long-term influences of hurricanes on soil elevation dynamics in mangrove forests are not well understood. Whereas other studies from around the world have also noted the importance of infrequent, pulsing events such as storms to the long-term resilience of coastal wetlands in deltaic or riverine settings (Day and others 1995; Woodroffe and others 2016), ours is one of the few studies to demonstrate the importance of storm sediment inputs for mangrove ecosystems in a carbonate setting where the accumulation of autochthonous peat is the major mechanism of soil building (McKee and others 2007). Similarly, although storm sediments had varying effects on different parts of the soil profile, we show that large deposits of storm sediments can ultimately enhance long-term rates of elevation change across the entire soil profile. Finally, although we found that long-term rates of elevation change were often equal to or greater than the rate of local sea-level rise, long-term monitoring of soil elevation dynamics in other coastal wetland habitats will be needed to develop a more complete understanding of the implications of storm effects on coastal wetland sustainability relative to future acceleration in rates of sea-level rise.

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DATA ACCESSIBILITY

https://www.sciencebase.gov/catalog/item/58f65df4e4b0bd52222f7818.

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