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SHORT COMMUNICATION

Evaluating a Steady-State Model of Soil Accretion in Everglades Mangroves (Florida, USA)

Randolph M. Chambers[1] · Adrianna L. Gorsky[1] · Edward Castañeda-Moya[2] · Victor H. Rivera-Monroy[3]

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Abstract
To determine whether mangrove soil accretion can keep up with increasing rates of sea level rise, we modeled the theoretical, steady-state (i.e., excluding hurricane impacts) limits to vertical soil accretion in riverine mangrove forests on the southwest coast of Florida, USA. We measured dry bulk density (BD) and loss on ignition (LOI) from mangrove soils collected over a period of 12 years along an estuarine transect of the Shark River. The plotted relationship between BD and LOI was fit to an idealized mixing model equation that provided estimates of organic and inorganic packing densities in the soils. We used these estimates in combination with measures of root production and mineral deposition to calculate their combined contribution to steady-state, vertical soil accretion. On average, the modeled rates of accretion (0.9 to 2.4 mm year^{-1}) were lower than other measured rates of soil accretion at these sites and far less than a recent estimate of sea level rise in south Florida (7.7 mm year^{-1}). To date, however, no evidence of mangrove "drowning" has been observed in this region of the Everglades, indicating that assumptions of the linear accretion model are invalid and/or other contributions to soil accretion (e.g., additional sources of organic matter; feedbacks between physical sedimentation processes and biological responses to short-term environmental change) make up the accretion deficit. This exercise highlights the potential positive impacts of hurricanes on non-steady-state soil accretion that contribute to the persistence of neotropical mangroves in regions of high disturbance frequency such as the Gulf of Mexico and the Caribbean region.

Keywords Mangroves · Soil accretion · Sea level rise · Hurricanes · Shark River estuary · Florida Coastal Everglades

Introduction

Mangrove forests are the dominant intertidal wetlands in subtropical and tropical coastal regions of the world, covering over 80,000 km^2 (Giri et al. 2011; Hamilton and Casey 2016) and contributing significantly to blue carbon stocks (Breithaupt et al. 2012; Atwood et al. 2017; Rovai et al. 2018; Richards et al. 2020). Although large mangrove wetland areas are continually lost to human impacts (Polidoro et al. 2010; Friess and Webb 2014; Thomas et al. 2017), warming climate is leading to a gradual poleward expansion of mangrove habitat worldwide (Cavanaugh et al. 2014, 2019; Ward et al. 2016; Osland et al. 2017). Additionally, because rising sea level is pushing the mangrove ecotone farther upstream within individual estuaries, mangroves are expanding laterally into formerly freshwater or upland environments (Ross et al. 2000; Rivera-Monroy et al. 2011).

Are the mangrove forests located closer to the coast at greater risk of drowning in rapidly rising seas? To keep pace with sea level rise (SLR), all tidal wetland soils must accrete inorganic and organic matter derived from both allochthonous and autochthonous sources. Sediments brought in by regular tidal flooding or by storm events coupled with the remains of in situ, organic production increase soil elevation, maintaining elevation capital (Kirwan and Megonigal 2013; Cahoon et al. 2020). Especially for karstic wetlands without high sediment input, belowground plant production is the dominant factor

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✉ Randolph M. Chambers
rmcham@wm.edu

[1] Keck Environmental Lab, William & Mary, Williamsburg, VA 23187, USA

[2] Southeast Environmental Research Center, Institute of Environment, Florida International University, Miami, FL 33199, USA

[3] Department of Oceanography and Coastal Sciences, College of the Coast and Environment, Louisiana State University, Baton Rouge, LA 70803, USA

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controlling soil accretion (Nyman et al. 2006; McKee et al. 2007). As a result of SLR, increased flooding of the wetland surface promotes mineral deposition from the tidal water. Higher water levels stimulate plant productivity (Morris et al. 2002); decomposition rates also decrease with increased submergence, leading to increased storage of soil organic matter (OM) and subsequent elevation gain during periods of rapid SLR (Rogers et al. 2019). OM sequestration in flooded soils provides some resilience that keeps tidal wetlands from drowning (Wang et al. 2019). Resilience, however, has its limits. When water level exceeds a threshold, plant respiration is inhibited, the positive feedback between sea level and plant production turns negative, and consequently soil accretion is no longer able to match SLR (Kirwan and Megonigal 2013).

In southwest Florida, mangroves occur along the estuarine ecotone between the freshwater Everglades and saline waters of the Gulf of Mexico and Florida Bay (Chen and Twilley 1999a; Rivera-Monroy et al. 2011; Castañeda-Moya et al. 2013; Zhao et al. 2020). Unlike mangroves with high alluvial sediment supply (Woodroffe 1992; Lovelock et al. 2015), southwestern Florida mangroves grow in tidal environments where water column suspended sediment is low. Thus, soil accretion is controlled by OM accumulation rather than mineral matter (Chen and Twilley 1999b; McKee et al. 2007; Smoak et al. 2013), especially in the forest interior zone (Breithaupt et al. 2017). Allochthonous sediment input still is critical in south Florida due to the high recurrence of tropical storms (Smith III et al. 2009; Rivera-Monroy et al. 2019) and the rapid increase in SLR during the last decade (Wdowinski et al. 2016). Hurricane-derived sediment inputs composed primarily of minerals may increase the overall elevation of south Florida mangroves, ultimately contributing to long-term net soil elevation gain that reduces their vulnerability to SLR (Castañeda-Moya et al. 2010, 2020; Feher et al. 2020). We hypothesized that without tropical storms, the increasing rate of SLR might not be matched by the hypothetical "background" rate of steady-state sediment accumulation. The current rate of sea level rise may be too high for mangrove wetlands to keep pace in the Shark River estuary, an extensive, mangrove-dominated system characterized by diurnal tides with a mean amplitude of 0.5–1.0 m and frequently impacted by tropical storms (Danielson et al. 2017; He et al. 2020). To test our hypothesis, we employed a steady-state mixing model equation to estimate the theoretical limits to linear, vertical soil accretion rates and compare them with prior accretion rates and against recent and projected values of sea level rise in south Florida.

Methods

The theoretical basis of steady-state soil accretion in tidal wetlands was described by Morris et al. (2016). Their model used the well-established relationship between soil bulk density (BD) and percent organic matter (loss on ignition—LOI), described in this idealized mixing model equation:

$$\mathrm{BD} = 1/[\mathrm{LOI}/k_1 + (1-\mathrm{LOI})/k_2]$$

For a given soil volume, the total dry weight is obtained from the addition of the measured organic and inorganic densities. The resulting bulk density (g cm^{-3}) can also be estimated by first defining the theoretical packing density parameters k_1 (pure organic matter) and k_2 (inorganic matter). For a given soil sample, then, the percent of soil weight contributed by organic matter (LOI) is a fraction of the theoretical packing density k_1, and the percent of soil weight contributed by inorganic matter (1 − LOI) is a fraction of k_2. The reciprocal of the addition of those organic and inorganic fractions of the theoretical packing densities yields the observed soil bulk density.

Estimates of the theoretical packing densities k_1 and k_2 can then be calculated by the relationship between BD and LOI. With knowledge of packing densities, the deposition rates of organic and inorganic matter can be used to calculate the cumulative soil volume over time and determine the rate of vertical soil accretion for given rates of organic and inorganic matter accumulation.

We completed this exercise using data from riverine mangrove forests located along the estuarine fringe of the Shark River estuary (SRS) in southwestern Florida (25.353446, −81.116985). As part of the Florida Coastal Everglades Long-Term Ecological Research (FCE-LTER) Program (Childers 2006; https://fcelter.fiu.edu/), three mangrove sites (SRS-4, 5, 6) were established in 2000 and have been sampled extensively for vegetation dynamics, soil analysis, and root biomass and production. Between 2004 and 2018, a total of 172 soil cores were collected in the root zone across all three sites and processed similarly. Soils to 10 cm depth were homogenized except in 2006 and 2018 when surficial storm deposits from Hurricanes Wilma (2005) and Irma (2017), respectively, were sampled separately. From all samples, a 1 cm^3 volume of wet soil was dried and weighed to determine bulk density (BD). The dried soil was then ashed at 450 C for 4 h (Davies 1974) and re-weighed to determine loss on ignition (LOI). We used curve-fitting to estimate the packing densities k_1 and k_2 by plotting soil BD as a function of LOI. LOI, k_1, and k_2 values from the idealized mixing model equation were used to calculate BD for comparison with the measured BD.

Organic matter accretion is derived primarily from autochthonous sources via root production (McKee et al. 2007; Cahoon et al. 2020). We used the assumption from Morris et al. (2016) that 10% of annual, belowground root production is buried as refractory organic matter, primarily as lignin. For each of the three mangrove sites along SRS, measured root production (g m^{-2} year^{-1}) (Castañeda-Moya et al. 2011) was multiplied by 0.1 to obtain an annual rate of organic matter burial, then divided by the organic packing density k_1 to estimate organic accretion rate in mm year^{-1}.

Inorganic matter accretion is derived primarily from allochthonous sources as sediment carried in by the tide. Ignoring the contribution to or removal of mangrove forest sediments from hurricanes (Castañeda-Moya et al. 2010, 2020; Feher et al. 2020), we considered the deposition of inorganic material under steady-state conditions. We assumed that each flooding tide carried suspended sediment onto the soil surface and that 100% of these sediments would settle out of the water column prior to draining off the wetland during tidal ebb. Using an estimate of total suspended solids (TSS) in the Shark River estuary (Romigh et al. 2006), we multiplied TSS by the total number of annual flooding cycles at each mangrove site (Castañeda-Moya et al. 2011) and the mean depth of flooding (Rivera-Monroy and Castañeda-Moya 2018; Zhao et al. 2020) to estimate inorganic sediment deposition. Finally, we divided sediment deposition by the inorganic packing density k_2 to estimate inorganic accretion rate in mm year^{-1}.

With the assumption that organic and mineral accretion rates are additive, their sum provided an estimate of linear, vertical soil accretion in Shark River mangrove forests, for comparison with the current rate of sea level rise in south Florida.

Results

Soil BD and LOI in Shark River mangrove forests varied spatially along the estuarine gradient (Fig. 1a). BD generally was highest and LOI lowest at SRS-6 located near the mouth of the estuary. Soils from SRS-4, located ~18 km upstream, had the lowest BD and highest LOI. Intermediate values of BD and LOI were obtained from SRS-5 (9 km upstream) soils. The inverse relationship between BD and LOI was curve fitted using the idealized mixing equation to obtain estimates of k_1 (0.129 g cm^{-3}) and k_2 (1.024 g cm^{-3}). Linear regression of the modeled BD against actual BD yielded a significant relationship ($P < 0.001$) with an r^2 value of 0.81 (Fig. 1b).

Contributions of organic matter to soil accretion were derived from in situ measures of root production, obtained from soil ingrowth cores installed in the shallow (0–45 cm) and deep (45–90 cm) root zones at each site and then harvested after 1 or 3 years (Castañeda-Moya et al. 2011). Total (0–90 cm depth) root productivity ranged from a low mean of 465 ± 70 g m^{-2} year^{-1} at SRS-4 to a high of 643 ± 93 g m^{-2} year^{-1} at SRS-6 (Table 1). With 10% of root production assumed refractory, we divided this organic soil component by the organic packing density k_1 to obtain the rate of vertical accretion of soil OM (Table 1).

Measures of TSS in Shark River estuary are limited to those obtained by Romigh et al. (2006) at SRS-6. TSS was extremely variable in that study, ranging from 1 to 192 mg l^{-1}. Median TSS varied seasonally from 22 to 25 mg l^{-1} in October and December to ~112 mg l^{-1} in May. We therefore used the seasonal range and median TSS values to estimate sediment load in the water column at all sites. This assumes that all suspended solids in the water column were inorganic and that 100% of TSS would be captured on the mangrove soil surface during each flooding tidal cycle. From long-term data collected from continuous water level recorders installed 50–80 m away from the river channel at each mangrove site, the number of annual flooding tidal cycles ranged from 165 to 395 (Castañeda-Moya et al. 2011; Zhao et al. 2020) and the mean depth of tidal flooding ranged from 3.93 to 8.61 cm (Rivera-Monroy and Castañeda-Moya 2018) (Table 1). Mineral deposition rate was calculated by multiplying TSS by the mean number of tides and flooding depth; this value was then divided by the inorganic packing density k_2

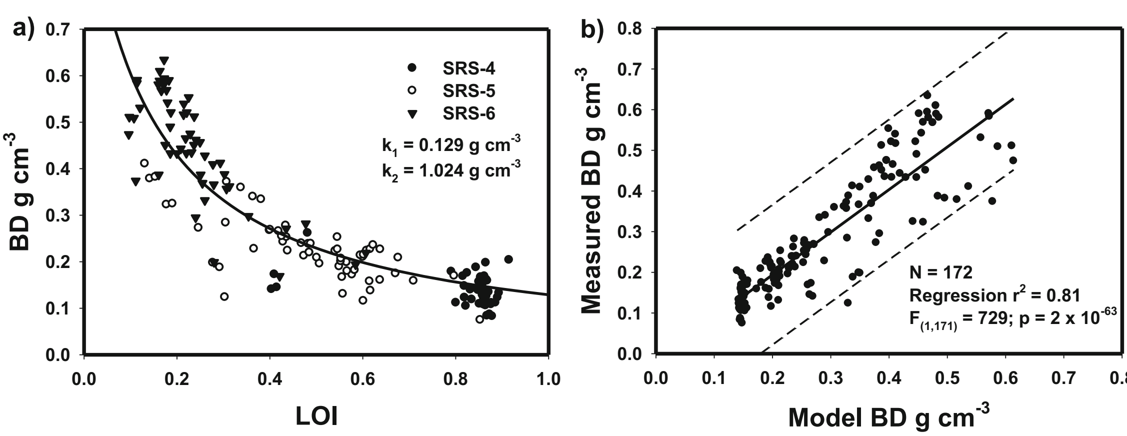

Fig. 1 **a** Variation of soil bulk density (BD) as a function of organic matter content (loss on ignition—LOI), from surface (top 10 cm) mangrove soils collected at Shark River estuary sites (SRS-4-6). Curve-fitting to the idealized mixing model yielded estimates of organic and inorganic packing volumes k_1 and k_2, respectively. **b** Linear regression with 99% prediction interval of modeled and measured BD

Table 1 Calculated organic and inorganic contributions to mangrove soil accretion in the Shark River estuary, southwestern Everglades. Data are means (± 1 SE)

Site	Organic contribution		Inorganic contribution				Soil accretion rate (mm year^{-1})[f]
	Root productivity (g m^{-2} year^{-1})[a]	Organic accretion rate (mm year^{-1})[b]	Total suspended solids (mg l^{-1})[c]	Frequency of inundation (# tides year^{-1})[a]	Average flooding depth (cm)[d]	Mineral accretion rate (mm year^{-1})[e]	
SRS-4	465 (70)	0.36 (0.05)	60 (50)	217 (16)	3.93	0.50 (0.41)	0.86 (0.46)
SRS-5	643 (93)	0.50 (0.08)	60 (50)	165 (7)	6.12	0.59 (0.49)	1.09 (0.57)
SRS-6	469 (80)	0.36 (0.06)	60 (50)	395 (70)	8.61	1.99 (1.38)	2.35 (1.44)

[a] Total belowground productivity (0–90 cm) (Castañeda-Moya et al. 2011)

[b] Morris et al. (2016); 10% of belowground productivity divided by k_1

[c] Romigh et al. (2006)

[d] Rivera-Monroy and Castañeda-Moya (2018)

[e] Morris et al. (2016); mineral deposition divided by k_2

[f] Organic accretion plus mineral accretion

to obtain the rate of vertical accretion of soil inorganic matter (Table 1).

Mangrove soil accretion rates, calculated by summing the organic and inorganic contributions, ranged from 0.86 to 2.35 mm year^{-1} (Table 1). Autochthonous inputs of organic matter from root production comprised only 15–46% of the total modeled accretion. In south Florida, sea level rise (measured at Key West) averaged 7.7 ± 4.3 mm year^{-1} between 2001 and 2016 (Dessu et al. 2018).

Discussion

Our modeling exercise using organic and inorganic data from riverine mangrove forests along the Shark River estuary yielded mean, steady-state soil accretion rates (0.9 to 2.4 mm year^{-1}) far lower than the current SLR rate (7.7 mm year^{-1}; Dessu et al. 2018) and also lower than recently measured soil accretion rates in this coastal region. (3–4 mm year^{-1}; Whelan et al. 2009; Breithaupt et al. 2017; Osland et al. 2020). The idealized steady-state mixing model used for our calculations is fraught with many assumptions, however, some of which are untested and others that might be wrong. The notion of "steady-state" is itself problematic, since most wetlands are always responding in a non-linear fashion to environmental change over timescales ranging from hours (e.g., storms) to centuries (Breithaupt et al. 2018) to millennia (e.g., relative sea level rise; Rogers et al. 2019). This is a critical consideration given that in sub-tropical and tropical regions where mangroves inhabit diverse geomorphic settings (Simard et al. 2019), tropical cyclones can disrupt steady-state conditions by uprooting and defoliating trees and eroding or depositing sediment. Diverse impacts like these can cause temporal shifts in the rates and composition of sediment accreted (Feher et al. 2020; Krauss and Osland 2020). Florida, for example, has experienced 35 major hurricanes (category 3–5 on the Saffir-Simpson scale) in the last 150 years (https://www.aoml.noaa.gov/hrd/hurdat/UShurrs_detailed.html); two of those hurricanes directly impacted the Shark River mangrove forests during our soil sampling period (i.e., Wilma in 2005; Irma in 2017). Although the theoretical organic and inorganic matter packing densities may not have been altered by hurricanes, mangrove soil accretion in this coastal region dramatically changed post-hurricane disturbance (Feher et al. 2020).

Prior investigations have documented the spatially explicit gradient of higher coastal to lower upstream impacts of these two recent hurricanes on Shark River mangrove vegetation and soils, which over time have led to different periods of wetland elevation gain and loss (Smith III et al. 2009; Whelan et al. 2009; Castañeda-Moya et al. 2010; Danielson et al. 2017; Rivera-Monroy et al. 2019; Feher et al. 2020). Recently, Castañeda-Moya et al. (2020) showed that phosphorus-enriched storm-surge deposits of sediment derived from the Gulf of Mexico could fertilize near-coast mangroves in the southwestern Everglades, including the Shark River estuary. These mineral inputs increased soil elevation via direct sediment deposition and stimulation of primary productivity, including root growth. Sediment deposits from hurricanes Wilma and Irma, however, were only evident up to 10 km from the Gulf of Mexico, with no deposition in upstream mangrove sites on Shark River (18 km upstream) and Harney River (14 km upstream) (Castañeda-Moya et al. 2010, 2020). Although the response to short-term disturbance from hurricanes of different magnitudes can range from ecosystem resistance to regime change (Osland et al. 2020), tropical cyclones in some instances can provide a critical, longer-term subsidy to soil accretion in mangrove wetlands where autochthonous organic matter is the main contributor to wetland elevation gain (Smoak et al. 2013; Feher et al. 2020). This is the case for south Florida mangroves thriving in a karstic environmental setting generally deprived of large terrestrial sediment supply and nutrients compared with mangroves in minerogenic, alluvial environments that receive a larger allochthonous sediment supply contributing to net elevation gain (Woodroffe 1992; Lovelock et al. 2015).

Model Caveats

We derived our estimates of the packing densities k_1 and k_2 from the observed relationship between BD and LOI from mangrove soils collected in the upper 10 cm of the soil profile. The estimate of k_1 was 51% higher and k_2 was 49% lower than constants obtained by Morris et al. (2016) for marsh and mangrove soils collected from 33 coastal wetland sites throughout the USA. We may have adequately described the relationship between BD and LOI for recently deposited soils, and our estimated steady-state accretion rates may be specific for shallow soils deposited over the last few decades (Breithaupt et al. 2018). Our steady-state rates, however, are closer to the mean accretion of ~2.5 mm year^{-1} measured over centennial time scales (summarized by Breithaupt et al. 2018). Rates of sea level rise and soil accretion have fluctuated over even longer timescales as reflected in deeper, older peat soils that were not part of our study. Indeed, mangrove encroachment and colonization at the mouth of Shark River date to 3800 y BP, indicating their persistence and adjustment to SLR in this coastal landscape (Yao and Liu 2017). Wetland accretion and elevation changes measured by combining different methods targeting different soil depths and spatial scales (e.g., surface elevation tables, marker horizons, radiometric dating) are required to evaluate longer-term responses to SLR (McKee et al. 2007; Breithaupt et al. 2018).

To calculate organic accretion rates, we used a published estimate of organic matter preservation in salt marshes (10% of root production; Morris et al. 2016). OM preservation could be higher in these Shark River mangrove soils where refractory organic matter in roots is greater than 20% (Poret et al. 2007). Alternately, OM preservation could be enhanced if soils are buried by storm sediments (Breithaupt et al. 2020) or are more frequently flooded by SLR (Rogers et al. 2019; Wang et al. 2019). For example, root decomposition rates in tidal-dominated Shark River mangroves (0.0012 to 0.0018 day^{-1}) are slow but 1.6–1.9 times higher compared with permanently flooded scrub mangroves in the southeastern Everglades (Poret et al. 2007). Differences in environmental conditions (e.g., soil P fertility, hydroperiod) across the Everglades landscape may have a significant effect on organic matter preservation at different soil depths. Further, the ingrowth method for measuring root production does not capture the production of roots > 20 mm diameter (Castañeda-Moya et al. 2011), thus underestimating total belowground root production. We also acknowledge that different amounts of organic matter are deposited annually on the soil surface, either as direct deposition of aboveground leaves (Danielson et al. 2017) and other biomass (e.g., algal turf: McKee 2011) or as allochthonous inputs from regular tidal flooding. Because most of this surficial material input that is not associated with storms typically oxidizes prior to incorporation into deeper soil layers (Charles et al. 2020) or gets washed away by tidal action (Twilley et al. 1986; Castañeda-Moya et al. 2013), we did not include these contributions to organic deposition and thus may have underestimated organic soil accretion. A theoretical doubling of organic matter accumulation derived from allochthonous or autochthonous sources could increase steady-state accretion by up to 0.5 mm year^{-1} (Table 1).

One key source of inorganic sediment influencing net soil accretion via tidal exchange is TSS. For this analysis, we used TSS data available from only one site (SRS-6), and those data were not collected over an annual cycle. Thus, we used a range of TSS estimates, noting that TSS is likely highest nearest the Gulf of Mexico at SRS-6 and probably decreases with distance upstream at the SRS-4 site. In the absence of additional data, we used the available TSS estimates at all sites, then multiplied these values by the average annual frequency and depth of tidal inundation to determine the mass of sediment transported to the mangrove soil surface. As a first-order approximation per Morris et al. (2016), we assumed that all suspended solids were composed of inorganic minerals and that all TSS was removed from the water column and deposited on the mangrove soil every tidal cycle. These assumptions may have led to an overestimation of steady-state inorganic soil accretion.

Finally, for theoretical soil accretion rates, we simply added the estimates of the organic and inorganic components. Organic and inorganic contributions are additive for soil bulk density, but they are not for soil volume (Breithaupt et al. 2017). Organic matter is a key driver of soil volume but not density: accretion volume is directly related to organic matter, whereas bulk density is directly related to inorganic matter (McKee et al. 2007; Breithaupt et al. 2014, 2017). The non-organic space taken up by an organic soil volume can be filled by water, by gas, or by inorganic matter, in which case the inorganic volume is incorporated into the organic volume. Thus, our calculations may have overestimated soil accretion by adding the organic and mineral contributions, thereby underestimating the susceptibility of these mangrove forests to SLR.

Can Steady-State Mangrove Forests Keep Up with SLR?

The average sea level rise measured at Key West, FL between 2001 and 2016, was 7.7 ± 4.3 mm year^{-1} (Dessu et al. 2018), and our estimates for average, steady-state mangrove soil accretion ranged between 0.9 and 2.4 mm year^{-1} among sites (Table 1). For comparison, Breithaupt et al. (2014) used ^{210}Pb core dating from SRS-6 to estimate the recent short-term (10 years) rate of soil accretion at 4.8 ± 1.0 mm year^{-1}, which is still less than SLR. Further, Osland et al. (2020) used soil elevation tables in combination with marker horizons to estimate longer-term accretion (1998-2018) at 3–4 mm year^{-1} in the Big Sable Creek area, south of Shark River estuary. Because the modeled level of steady-state soil accretion does not match the observed rates, mangrove forests in Shark River estuary may be reliant on non-steady-state processes to keep up with sea level rise, or they may be losing ground. In this sense, the model may provide a background level of steady-state accretion that is supplemented or reduced by hurricanes. For example, Smoak et al. (2013) calculated a soil accretion rate of 5.9 mm year^{-1} in the SRS-6 mangrove forest for the period of 2000–2009, during which a large storm deposit of inorganic sediment and organic matter occurred (Hurricane Wilma 2005). The frequency and size of recent storm subsidies create legacies and appear to help mangrove forests of the southwest Florida coast to continue accreting soil even as the water rises. Results of our modeling exercise suggest that these mangrove forests eventually may drown without these non-steady-state storm subsidies. Hurricane impacts on elevation change can be negative, however, with storm-derived soil erosion, compaction and subsurface contraction (Feher et al. 2020; Osland et al. 2020). The cumulative impact of tropical storms needs to be considered in the long term when assessing net changes in soil elevation, particularly as the frequency of strong hurricanes increases as a result of climate change (Webster et al. 2005; Walsh et al. 2016; Benedetto and Trepanier 2020).

Finally, a geologic analysis of mangrove forest growth and expansion over the past 10,000 years found that accretion in mangrove wetlands in the Caribbean and Gulf of Mexico was interrupted when SLR exceeded 5.7 mm year^{-1} (Saintilan et al. 2020). The ongoing rate of sea level rise globally has approached and at times exceeded this geologic rate, leading the authors to suggest that some mangrove ecosystems have reached the threshold of submergence, beyond which they cannot survive. Recent soil accretion estimates in Shark River mangrove forests (Smoak et al. 2013; Breithaupt et al. 2014) would concur that the threshold has been reached or even passed. The coming decade may see the continuing, lateral expansion of mangroves into current freshwater wetlands of south Florida as a result of marine transgression, even as the existing, more seaward mangrove locations may be losing the vertical race to keep up with increasing sea level.

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