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Rapid headward erosion of marsh creeks in response to relative sea level rise

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[1] Tidal creeks in Cape Romain, South Carolina, are extending rapidly onto the established marsh platform producing an unusual morphology, which remains self-similar in time. A time-series of aerial photographs establishes that these channels are headward eroding at an approximate rate of 1.9 m/yr. The rapid rate of headward erosion suggests that the marsh platform is in disequilibrium and unable to keep pace with high local relative sea level rise (RSLR >3.2mm/yr) through accretionary processes. Biological feedbacks play a strong role in the morphological development of the creeks. Dieback of vegetation coupled with intense burrowing by crabs produces a bare and topographically depressed region beyond the channel head toward which the channel head extends. We examine the mechanisms producing this headward extension and pinnate channel morphology, and report a new pattern of creek incision in a regime of rapid RSLR. **Citation:** Hughes, Z. J., D. M. FitzGerald, C. A. Wilson, S. C. Pennings, K. Więski, and A. Mahadevan (2009), Rapid headward erosion of marsh creeks in response to relative sea level rise, *Geophys. Res. Lett.*, *36*, L03602, doi:10.1029/2008GL036000.

1. Introduction

[2] Although there is growing certainty that global sea-level rise (SLR) is accelerating [*Church and White*, 2006; *Jevrejeva et al.*, 2008], there is no consensus on the response of coastal wetland morphology to the changing conditions. The common model of marsh response to SLR predicts increased vertical accretion through enhanced plant productivity and higher rates of inorganic deposition associated with greater water depths [*Redfield*, 1965]. This relationship fails when organic production and inorganic accumulation cannot keep pace with the rate of SLR, culminating in the submergence of the marsh platform [*Redfield*, 1965; *Morris et al.*, 2002].

[3] This paradigm fits observations in regions such as the Louisiana wetlands [*DeLaune et al.*, 1994], but disregards other response scenarios such as expansion of drainage networks, described here and elsewhere in the literature [e.g., *Shi et al.*, 1995]. We report observations of a marsh platform experiencing high RSLR, exhibiting progressive dissection of the vegetated marsh platform by headward extending creeks, where bio-mediation leads to a unique morphology. The inability of marsh surface accretion to keep pace with SLR leads to an increased tidal prism and thus enlargement of the drainage network. This likely has critical effects on marsh hydrology and ecology, because marsh areas proximal to creeks function very differently than uninterrupted areas of marsh platform [*Pennings and Bertness*, 2001].

[4] A number of researchers have looked at creek network development in tidal marshes. Historical analysis of the Dyfi Estuary, Wales, suggests that extension of existing creeks and increase in stream number is attributable to increased tidal prism due to rising sea level [*Shi et al.*, 1995]. A similar line of reasoning has been used to explain expansion of tidal flats and regions of tidal intrusion in both the UK and Australia [*Symonds and Collins*, 2007; *Knighton et al.*, 1991]. However, previous studies do not observe creek initiation and extension in an established marsh system in response to SLR. Observations in Argentine salt marshes indicate that small creeks develop due to the expansion of existing salt pans, and that crab bioturbation and vegetative feedbacks play an important role in this process [*Perillo and Iribarne*, 2003; *Minkoff et al.*, 2006].

[5] Numerical modeling studies aim to improve the understanding of marsh morphological development considering factors such as the rate of RSLR, depth of inundation, inorganic sediment supply, plant productivity and organic accumulation [*Fagherazzi and Sun*, 2004; *D'Alpaos et al.*, 2005; *Kirwan et al.*, 2008]. In the models, morphological changes are based on the balance between erosion (dependent on shear stress criteria) and inorganic accretion, and organic production based on empirical relationships [e.g., *Morris et al.*, 2002]. Thus, marsh and tidal creek evolution are particularly sensitive to critical shear stress values [*Fagherazzi and Sun*, 2004] and empirical relationships for organic and inorganic accretion rates [*Kirwan and Murray*, 2007]. Despite their limitations, models demonstrate that marsh vegetative disturbance becomes particularly important in a regime of SLR. A major conundrum in explaining the headward erosion of creeks on an existing marsh platform is that currents weaken up-channel and do not reach the necessary velocities to exceed critical shear stress to move sediment.

[6] In Cape Romain in the Santee River Delta, South Carolina, we examine tidal creeks that are responsible for the dissection of an attendant marsh platform (Figure 1). Straight channels are eroding headward at a significant rate, while interactions of tidal flow, vegetation, and infauna produce unique pinnate features at the heads of straight creeks. We propose that the growth of creeks in this region is a manifestation of RSLR and a direct response to the increased tidal prism. The headward incision of tidal creeks

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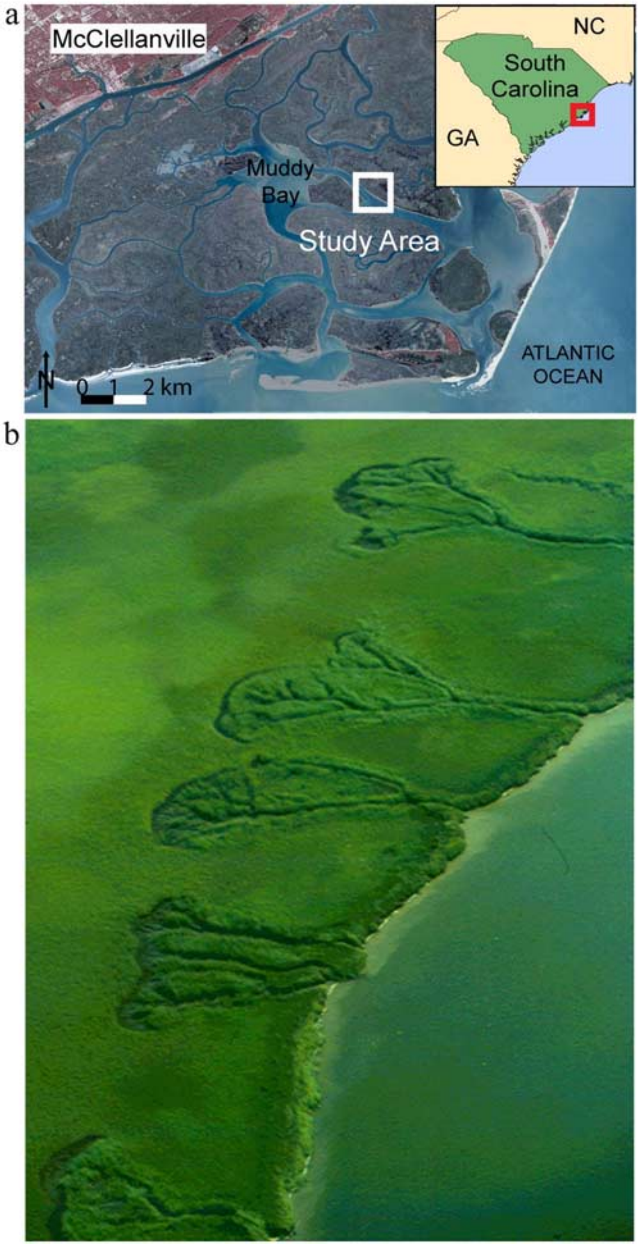

Figure 1. (a) Location of study site south of the Santee River within Cape Romain, South Carolina, USA. (b) Oblique aerial photograph illustrating the straight creeks ending in pinnate structures on the marsh platform; note the bare semi circular depressions at the heads of creeks.

is initiated by subsidence at the creek heads, which is biologically mediated. The formation and rapid extension of creeks in this region represents an alternative scenario to marsh submergence as the morphological response of marshes to future high rates of SLR.

2. Marsh and Tidal Creek Characteristics

[7] The expansive marsh system that backs Cape Romain developed as part of the Santee Delta complex during the Holocene. Marsh sediment was derived through influx from Santee and Pee Dee Rivers. However, this sediment contribution has been substantially diminished during the past century due to dam construction, diverting discharge to Lake Moultrie and the Cooper River. While a small influx of fine sediment was restored to the Santee in 1986, reduction in supply is still significant [*Hughes*, 1994].

[8] Our study area is part of a large intertidal marsh platform vegetated largely by short-form *Spartina alterniflora* and dissected by broad meandering tidal channels. Along the borders of the major channels, straight tidal creeks have formed at a spacing of 50–100 m. Each creek is 2–4 m wide at the mouth and stretches onto the marsh surface for ~50 m before forming a pinnate pattern, terminating in depressions denuded of vegetation at the creek head (Figures 1 and 2c). This creek pattern can be observed within coastal marshes 30 km to the north and south of the study area.

[9] The mean tidal range in the region is 1.48 m, (1.6 m at springs; NOAA tide gauge 8663618). The marsh platform, which is within ±15 cm of mean high water (MHW; Figure 3a), is at least partially flooded during every tidal cycle. Flood waters initially fill the depressions at creek heads and rise along the border of the major channel before spreading over the marsh surface. During the ebb, water flows off the marsh surface, but continues to funnel through the creeks via the creek heads for several hours thereafter.

[10] The fiddler crab *Uca Pugnax* is the predominant burrowing macro-invertebrate at the site. The region surrounding the bare depressions at the creek heads are heavily burrowed (Figure 2c; >800 burrows/m^2). This region is also preferentially inhabited by herbivorous *Sesarma reticulatum* and predatory mud crabs. Crabs likely aggregate at creek heads because the flooding waters provide increased water oxygen levels and prey delivery. The fringes of these bare depressions exhibit low stem density indicating vegetative die-back. There is a notable correlation between crab burrowing and reduced stem density (Figure 2c), suggesting that crabs may harm plants by eating roots or destroying them during burrowing. Additionally, burrowing creates extensive tunnels within the marsh sediments, potentially impacting drainage and flow. Measured infiltration rates are about three orders of magnitude higher in the creek heads versus control areas on the vegetated marsh platform (1000 ml/min and 0.6 ml/min, respectively).

3. Historical Analyses

[11] An analysis of geo-referenced historical aerial photographs from 1968 to the present (Figures 2a and 2b; using ESRI ArcMap software) reveals that creeks are extending headward into the marsh platform at an average rate of 1.9 ± 0.8 m/yr (n > 100). This rate of extension is supported by field data wherein creek heads staked in July 2007 showed an average extension of 1.91 ± 0.93 m one year later (n = 14). The creeks are visible in photos from 1958, but not measurable due to the image resolution. Extrapolating back assuming a constant incision rate, our observations suggest creek initiation circa 1940 (Figure 2b). This coincides with reduced sediment supply to the Santee and rapid local SLR evident in the Charleston tide curve from 1940–1950 (Figure 3b). During extension, the creeks maintain their morphology, i.e. the pinnate pattern and bare creek heads translate inland. This implies that the denuded creek heads re-vegetate and recover as the channel head migrates. The

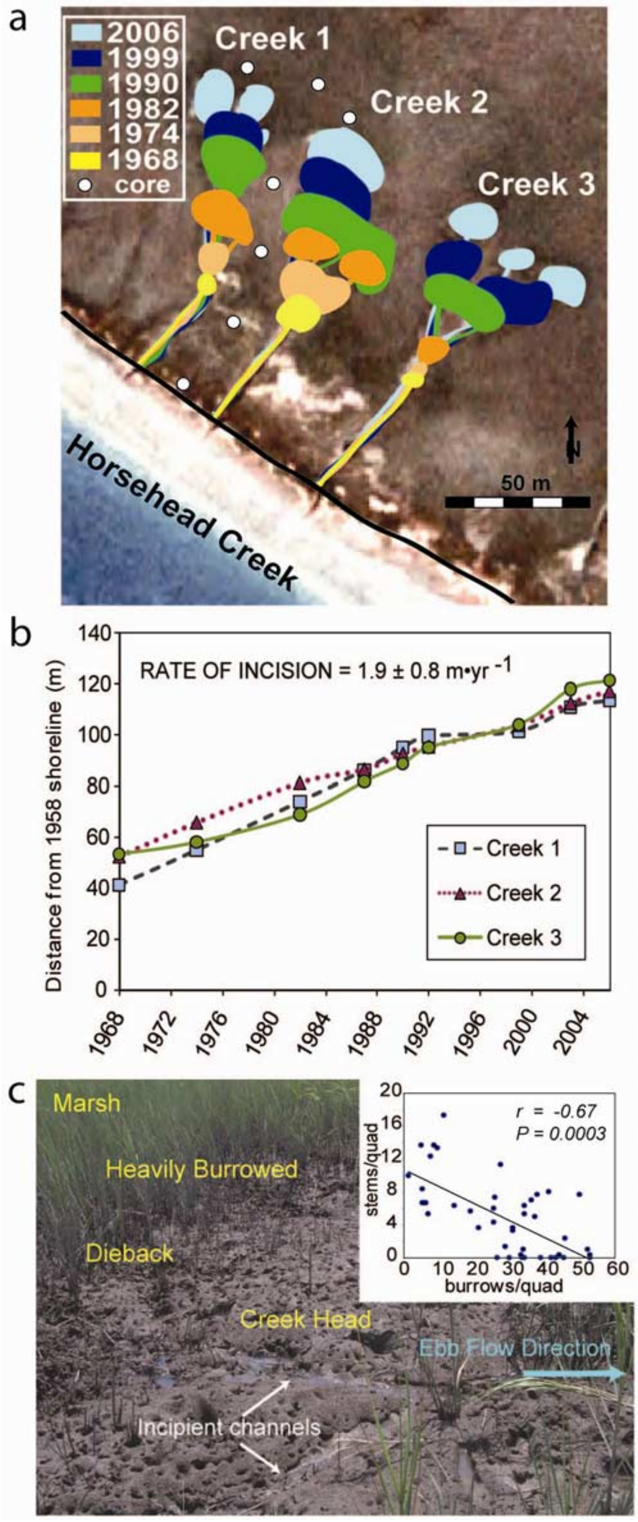

Figure 2. (a) Creek morphology of three representative creeks from 1968 to 2006 mapped using historical aerial photographs and core locations; (b) rates of incision of these creeks based on measurement of creek length in consecutive aerial photographs; (c) creek head showing the dieback region, denuded area and tiny incipient creeks in the bare region; inset shows stem density versus crab burrow density; a clear negative correlation exists (data from four locations on a transect from marsh into bare creek head, n = 12 creeks, quad = 0.0625 m^2).

channel morphology is notably straight and stream order rarely changes or expands. As the channels incise into the marsh, the seaward lower order streams are abandoned and gradually atrophy (e.g., Creek 2; Figures 2a and 3a). This pattern of evolution does not fit with standard models of network pattern, although the basins at creek heads are analogous to the erosional ‘complex’ class of *Pye and French* [1993].

[12] Our analyses demonstrate that short-term trends in sea level exhibit an average RSLR of 4.6 mm/yr over a 20-year tide gauge record from nearby Winyah Bay (1975–1995), identical to the rate in Charleston Harbor for the same time period. However, the long-term 85-year record in Charleston has a rate of 3.2 mm/yr (Figure 3b), indicating sensitivity to the period of averaging. Generally, rates of SLR along the South Carolina coastline are some of the highest along the East Coast (www.tidesandcurrents.noaa.gov/sltrends).

4. Field Observations

[13] In order to investigate mechanisms for creek extension, we examined stratigraphy, current velocities, and topography in the study area. Coring transects taken parallel

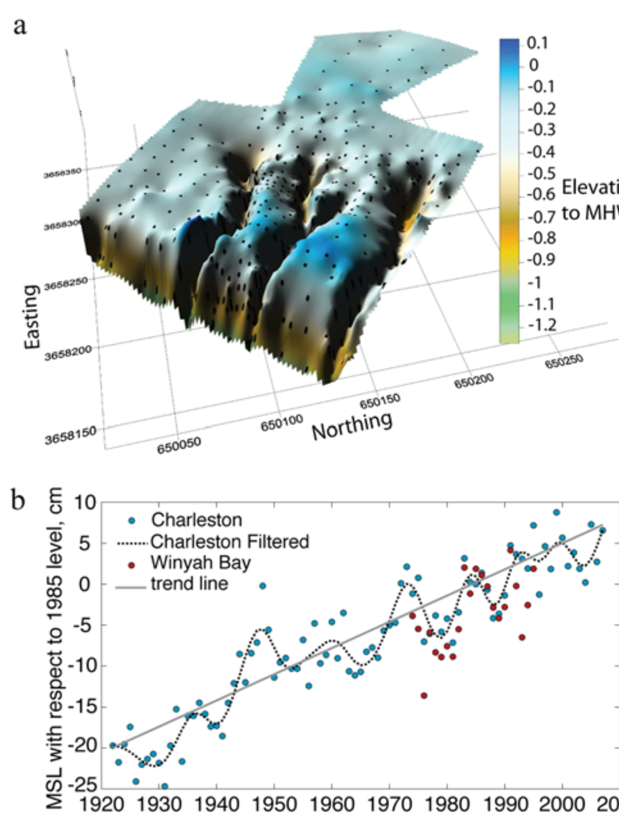

Figure 3. (a) DEM of creeks 1, 2, and 3 (left to right) to MHW based upon 502 data points (shown as black dots). Actively incising creek heads are topographically low regions. (b) Sea level curves for Charleston Harbor and Winyah Bay and the 85 year trend line, showing SLR of 3.2 mm/yr (grey line) and a curve representing the variation of Charleston SL (after applying a low pass filter) [after *Morris et al.*, 2002]; an 11 year cycle can be detected (dashed line).

and perpendicular to the creeks reveal substrata consisting of a massive mud (bulk density 0.67 ± 0.14, organic content 11% ± 2.3) extending to a depth of more than 4 m overlain by a 1.4 m-thick, organic-rich mud (bulk density 0.52 ± 0.11 g/cm^3, organic content 14.7% ± 4.3). The lateral homogeneity of the underlying sediment demonstrates that creek formation is not due to preferential erosion of weaker sedimentary layers. There is reduction in the root biomass towards the bare muddy creek head (on marsh = 4.6 kg/m^3; in head = 0.6 kg/m^3) where the sediment is very soft and highly unconsolidated.

[14] Micro-topography of the marsh was mapped using a Pentax Total Station with vertical and horizontal accuracy of ±0.5 cm. Five hundred data points were collected over an area of 0.2 km^2. The digital elevation map constructed from these data (Figure 3a) shows that the marsh platform has a maximum topographic variation of 0.25 m. The creeks have a depth of 1.2 m (with respect to MHW) close to the mouth and drain entirely at low tide. The creek heads are notably lower than the surrounding marsh platform, forming a circular depression averaging 0.6 m in depth. The depressions are filled for a longer part of the tidal cycle than the surrounding regions and act to funnel water into and out of the creeks.

[15] Flow patterns in the marsh system were investigated over three two-week deployments during large spring tides. Measurements were made using acoustic current profilers (Nortek Aquadopp) at the channel mouth and head (Figure 4) and at two points on the marsh surface. The velocity in the creeks (maximum ~0.8 m/s at the mouth, ~0.1 m/s at the head) is strongly ebb dominated. Velocities on the marsh surface are small (~0.05 m/s) and show no clear dominance in ebb or flood flow direction. Due to restrictions in instrument operation (requiring water depth > 8 cm), the velocity data capture a limited tidal duration, recording when the water is sufficiently deep.

5. Discussion

[16] A progressive channel extension of 1.9 m/yr indicates that the marsh is responding to an increased tidal prism due to high local RSLR. Sediment cores reveal that the marsh is predominantly composed of fine-grained sediment, making it highly susceptible to compaction and subsidence. Loss in elevation is potentially exacerbated by the decreased sediment supply due to damming of the Santee River in 1939. Creek network expansion as a result of increased tidal prism has been observed in several studies [e.g., *Shi et al.*, 1995; *Symonds and Collins*, 2007]; however the initiation of straight creeks in an already established marsh system is previously unreported.

[17] Based on field measurements we propose a conceptual model for the evolution of these tidal creeks. Since water velocities on the marsh platform are insufficient to initiate erosion of the cohesive muds, other processes must be invoked to explain the channel extension. The creek heads that are denuded of vegetation and densely burrowed by crabs show a significantly lower elevation than the surrounding marsh platform. This disparity suggests a removal and collapse of the sediment due to feedbacks between bioturbation, vegetation dieback, and drainage. Water funneling into the depressions at the creek head

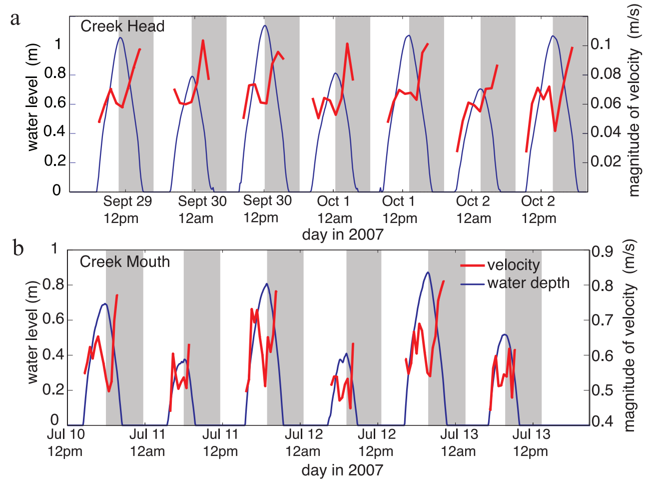

Figure 4. Examples of typical currents at (a) the head and (b) the mouth of the creek. The period of the ebb is shaded; the period of the flood un-shaded. Both head and mouth exhibit ebb dominance.

forms incipient channels that merge to form an extension of the creek. With time, regions of crab colonization and vegetative dieback transgress further onto the marsh platform. As the bare region migrates headward onto the marsh, the creek extends into the denuded area, improving drainage and promoting plant recolonization.

[18] Conceivably, a number of processes are interacting synergistically to produce the observed channel extension, the key being the topographic depression of creek heads, which precedes channel progression onto the marsh platform. Possible contributing factors include physical removal of sediment by crab burrowing, collapse of sediments due to crab burrowing, destabilization of sediments due to the removal of vegetation and rooting, and increased decomposition of organic matter due to infiltration of oxygenated water in burrowed regions. These processes have been reported in other wetland studies [*May*, 2002; *Paramor and Hughes*, 2004].

[19] Despite low velocity measurements in the creek heads, direct erosion must be a process contributing to the extension of the creeks, demonstrated by the formation of small incipient channels in the creek head. It is possible that the substrate in the creek head experiences higher velocities towards the end of the ebb, when water is focused into the creek head due to the lower elevation. Furthermore, as the water recedes during the ebb, water held in the marsh sediment is observed to percolate through heavily burrowed soil into incipient channels within the bare creek heads, extending the period of ebb flow and potential erosion in this area.

[20] It is interesting to note that the pinnate structure of the creek heads with denuded depressions at the channel ends has been maintained throughout the headward migration since 1968. No sign of sinuosity is evident in the channels, indicative of their immaturity [*Allen*, 2000]. Hence, we suggest that these structures are a prototype for tidal creeks developing in a regime of rapid RSLR.

[21] The control on the lateral spacing and stable stream number of the expanding tidal network requires further

investigation; however, atrophy of certain creeks implies reduced flow and preferential drainage toward lower topography. The relative importance of biologically driven versus physically driven erosion of sediment is also a topic for further research.

6. Conclusions

[22] Atypical tidal creeks with straight channels ending in a pinnate pattern are observed in the Santee River Delta. The analysis of historical aerial photographs reveals a constant rate of headward incision of ~1.9 m/yr. We believe the increased dissection of the marsh platform is due to the high rates of RSLR in the region. At the creek heads, intense crab burrowing and loss of vegetation leads to increased drainage and collapse of the substrate. The formation of these depressions, followed by channelization and a recovery of vegetation, results in the observed pattern of creek extension and morphology. Future surface process models need to account for bio-physical feedbacks, and substrate collapse and drainage in order to simulate the development of the tidal creeks described here. These observations elucidate a mechanism for headward incising tidal creeks and highlight the importance of biological interactions with physical processes.

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References

Allen, J. R. (2000), Morphodynamics of Holocene salt marshes: A review sketch from the Atlantic and southern North Sea coasts of Europe, *Quat. Sci. Rev.*, *19*, 1155–1231.

Church, J. A., and N. J. White (2006), A 20th century acceleration in global sea-level rise, *Geophys. Res. Lett.*, *33*, L01602, doi:10.1029/2005GL024826.

D'Alpaos, A., S. Lanzoni, M. Marani, S. Fagherazzi, and A. Rinaldo (2005), Tidal network ontogeny: Channel initiation and early development, *J. Geophys. Res.*, *110*, F02001, doi:10.1029/2004JF000182.

DeLaune, R. D., J. A. Nyman, and W. H. Patrick Jr. (1994), Peat collapse, ponding and wetland loss in a rapidly submerging coastal marsh, *J. Coastal Res.*, *10*, 1021–1030.

Fagherazzi, S., and T. Sun (2004), A stochastic model for the formation of channel networks in tidal marshes, *Geophys. Res. Lett.*, *31*, L21503, doi:10.1029/2004GL020965.

Hughes, W. B. (1994), National water-quality assessment program: The Santee River Basin and coastal drainages, N. C. and S. C., *U.S. Geol. Surv. Fact Sheet, FS-010–94*.

Jevrejeva, S., J. C. Moore, A. Grinsted, and P. L. Woodworth (2008), Recent global sea level acceleration started over 200 years ago?, *Geophys. Res. Lett.*, *35*, L08715, doi:10.1029/2008GL033611.

Kirwan, M. L., and A. B. Murray (2007), A coupled geomorphic and ecological model of tidal marsh evolution, *Proc. Natl. Acad. Sci.*, *104*, 6118–6122.

Kirwan, M. L., A. B. Murray, and W. S. Boyd (2008), Temporary vegetation disturbance as an explanation for permanent loss of tidal wetlands, *Geophys. Res. Lett.*, *35*, L05403, doi:10.1029/2007GL032681.

Knighton, A. D., K. Mills, and C. D. Woodroffe (1991), Tidal creek extension and saltwater intrusion in northern Australia, *Geology*, *19*, 831–834.

May, M. K. (2002), Pattern and process of headward erosion in salt marsh tidal creeks, M.S. thesis, East Carolina Univ, Greenville, N.C.

Minkoff, D. R., M. Escapa, F. E. Ferramola, S. D. Maraschin, J. O. Pierini, G. M. E. Perillo, and C. Delrieux (2006), Effects of crabe-halophytic plant interactions on creek growth in a S. W. Atlantic salt marsh: A Cellular Automata model, *Estuarine Coastal Shelf Sci.*, *69*, 403–413.

Morris, J. T., P. V. Sundareshwar, C. T. Nietch, B. Kjerfve, and D. R. Cahoon (2002), Responses of coastal wetlands to rising sea level, *Ecology*, *83*, 2869–2877.

Paramor, O. A. L., and R. G. Hughes (2004), The effects of bioturbation and herbivory by the polychaete *Nereis diversicolor* on loss of saltmarsh in south-east England, *J. Appl. Ecol.*, *41*, 449–463.

Pennings, S. C., and M. D. Bertness (2001), Salt marsh communities, in *Marine Community Ecology*, edited by M. D. Bertness, S. D. Gaines, and M. E. Hay, pp. 289–316, Sinauer Assoc., Sunderland, Mass.

Perillo, G. M. E., and O. O. Iribarne (2003), Processes of tidal channel development in salt and freshwater marshes, *Earth Surf. Processes Landforms*, *28*, 1473–1482.

Pye, K., and P. W. French (1993), *Erosion and Accretion Processes on British Salt Marshes*, vol. 1, *Introduction: Saltmarsh Processes and Morphology*, Cambridge Environ. Res. Consult., Cambridge, U.K.

Redfield, A. C. (1965), Ontogeny of a salt marsh estuary, *Science*, *147*, 50–55.

Shi, Z., H. F. Lamb, and R. L. Collin (1995), Geomorphic change of salt marsh tidal creek networks in the Dyfi Estuary, *Wales, Mar. Geol.*, *128*, 73–83.

Symonds, A. M., and M. B. Collins (2007), The establishment and degeneration of a temporary creek system in response to managed coastal realignment: The Wash UK, *Earth Surf. Processes Landforms*, *32*, 1783–1796.

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