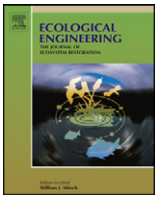
Ecological Engineering 37 (2011) 229–240

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng



Vegetation death and rapid loss of surface elevation in two contrasting Mississippi delta salt marshes: The role of sedimentation, autocompaction and sea-level rise

John W. Day[a,*], G. Paul Kemp[b], Denise J. Reed[c], Donald R. Cahoon[d], Roelof M. Boumans[e], Joseph M. Suhayda[f], Robert Gambrell[a]

[a] *Dept. of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA 70803, United States*
[b] *National Audubon Society, 6160 Perkins Rd., Baton Rouge, LA 70808, United States*
[c] *Dept. of Geology, University of New Orleans, New Orleans, LA 70148, United States*
[d] *USGS Patuxent Wildlife Research Center, 10300 Baltimore Ave, Beltsville, MD 20705, United States*
[e] *Gund Institute for Ecological Economics, University of Vermont, Burlington, VT 05405, United States*
[f] *Hurricane Center, Louisiana State University, Baton Rouge, LA 70803, United States*

ARTICLE INFO

Article history:
Received 19 May 2010
Received in revised form
27 September 2010
Accepted 6 November 2010
Available online 14 December 2010

Keywords:
Peat collapse
Wetland loss
Subsidence
Compaction
Soil strength
Mississippi delta

ABSTRACT

From 1990 to 2004, we carried out a study on accretionary dynamics and wetland loss in salt marshes surrounding two small ponds in the Mississippi delta; Old Oyster Bayou (OB), a sediment-rich area near the mouth of the Atchafalaya River and Bayou Chitigue (BC), a sediment-poor area about 70 km to the east. The OB site was stable, while most of the marsh at BC disappeared within a few years. Measurements were made of short-term sedimentation, vertical accretion, change in marsh surface elevation, pond wave activity, and marsh soil characteristics. The OB marsh was about 10 cm higher than BC; the extremes of the elevation range for *Spartina alterniflora* in Louisiana. Vertical accretion and short-term sedimentation were about twice as high at BC than at OB, but the OB marsh captured nearly all sediments deposited, while the BC marsh captured <30%. The OB and BC sites flooded about 15% and 85% of the time, respectively. Marsh loss at BC was not due to wave erosion. The mineral content of deposited sediments was higher at OB. Exposure and desiccation of the marsh surface at OB increased the efficiency that deposited sediments were incorporated into the marsh soil, and displaced the marsh surface upward by biological processes like root growth, while also reducing shallow compaction. Once vegetation dies, there is a loss of soil volume due to loss of root turgor and oxidation of root organic matter, which leads to elevation collapse. Revegetation cannot occur because of the low elevation and weak soil strength. The changes in elevation at both marsh sites are punctuated, occurring in steps that can either increase or decrease elevation. When a marsh is low as at BC, a step down can result in an irreversible change. At this point, the option is not restoration but creating a new marsh with massive sediment input either from the river or via dredging.

1. Introduction

Coastal scientists and managers are trying to assess the scale of impacts from accelerated sea-level rise due to global warming. Average eustatic sea-level rise (ESLR) for the 20th century was 0.1–0.2 cm year^{-1} (Gornitz et al., 1982) and is currently nearly 0.4 cm year^{-1} (FitzGerald et al., 2008). The IPCC (2007) forecast a mean rise of about 40 cm by 2100, but recent reports suggest that ESLR will be a meter or more by 2100 (Rahmstorf, 2007; Pfeffer et al., 2008; Vermeer and Rahmstorf, 2009).

High rates of relative sea level rise (RSLR) are part of the classic geological model for natural delta evolution developed during the 1950s and 1960s from analysis of the Mississippi River delta (Roberts, 1997; Syvitski et al., 2009). This model considered both ESLR and local subsidence. The Mississippi River deltaic plain expanded in surface area over most of the past 5000 years when ESLR was relatively low as new channels supplied sediment to shallow water bottoms and nourished existing marshes at a rate that more than offset losses (Day et al., 2007). As is true for deltas worldwide, sediment retention by dams and hydrologic alterations within the Mississippi River delta restrict the supply of river sediment to wetland surfaces at the same time that enhanced ESLR is increasing RSLR (Blum and Roberts, 2009; Syvitski et al., 2009). As a result, deltaic wetlands world-wide are threatened as ESLR accel-

---

[*] Corresponding author. Tel.: +1 225 578 6508; fax: +1 225 578 6326.
E-mail address: johnday@lsu.edu (J.W. Day).

0925-8574/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.ecoleng.2010.11.021

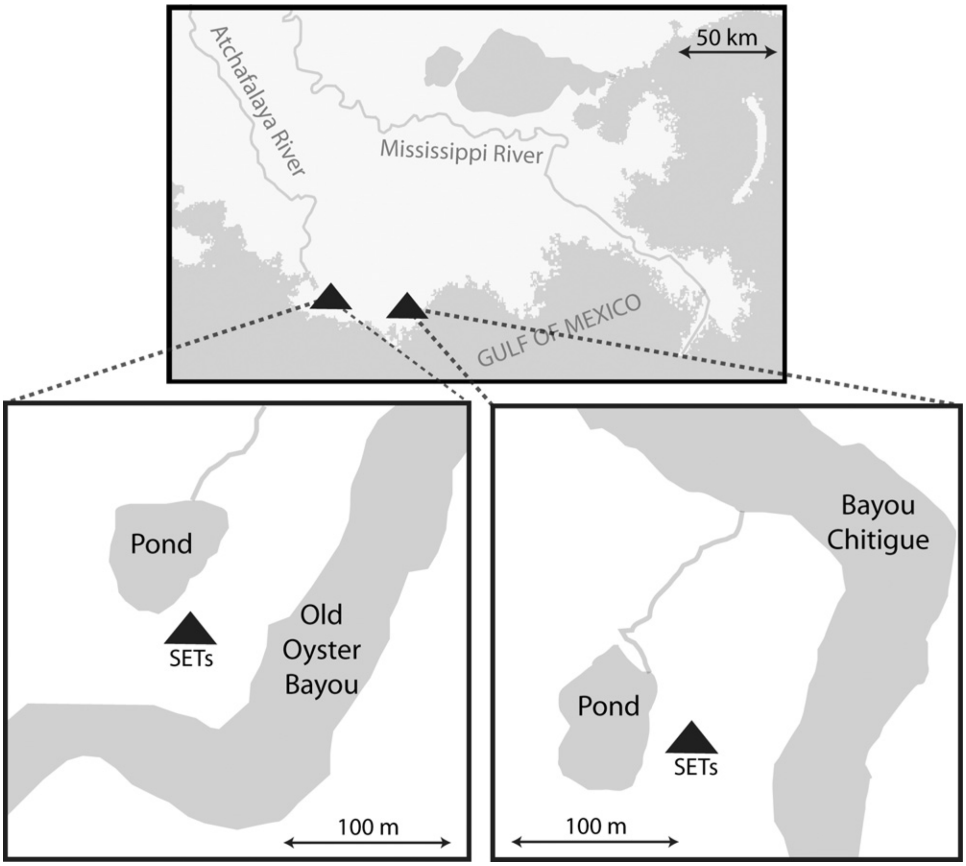


Fig. 1. Site map showing the two study sites at Old Oyster Bayou (OB) and Bayou Chitigue (BC). OB is a stable marsh affected by the discharge of the Atchafalaya River. BC is a deteriorating marsh that receives no direct riverine input. The pond at BC opened up significantly during the study. SETs show locations of the sediment elevation tables and associated measurements in the marsh.

erates (Day and Templet, 1989; Day et al., 2007; Pont et al., 2002; Tornqvist et al., 2008; Vörösmarty et al., 2009).

Coastal wetlands are deteriorating in the Mississippi River delta at a catastrophic rate that is leading to ecosystem collapse (Boesch et al., 2006; Day et al., 2007; Tornqvist et al., 2008; Blum and Roberts, 2009; Shaffer et al., 2009b). On a geological scale, the pattern of land loss is largely consistent with the classic delta evolution model, but the rate of loss is now strongly affected by human alterations. In response, Mississippi River water is currently being reintroduced to the deltaic plain rather than being allowed to flow into deep water of the Gulf of Mexico (Day et al., 2007, 2009).

A number of interrelated impacts cause wetland loss including saltwater intrusion, physical erosion, hydrological disruption due to canals, lack of river input due to levees, and peat collapse (Baumann et al., 1984; Boesch et al., 1994; Turner, 1997; Day et al., 2000, 2007; Shaffer et al., 2009a). Marsh deposition of resuspended sediments plays an important role in countering RSLR (Baumann et al., 1984; Cahoon et al., 1995a; Reed et al., 2006). This contribution to marsh accretion can be greatly reduced by dredged canals, spoil banks and water control structures that are found throughout the delta (Boumans and Day, 1994; Cahoon, 1994; Reed, 1992; Reed et al., 2006). Some have proposed that high concentration of nutrients, particularly dissolved nitrogen, in the river may reduce the capacity of some highly organic marshes to respond to RSLR by increasing the rate of belowground decomposition (Swarzenski et al., 2008).

In the early 1990s, we initiated a multi-disciplinary study to determine the causes of wetland loss in two salt marsh (*Spartina alterniflora*) sites in the Mississippi delta, one with high riverine input and one without (Roberts, 1994; Day et al., 1994). Some observations made during this study were not published or are available only in technical reports or in proceedings no longer readily accessible (Day et al., 1994; Kemp et al., 1999).

We hypothesized that (1) marsh loss remote from river sediment sources was a result of excessive waterlogging caused by a long-term accretion deficit rather than wave shear stress on the edge or surface of the marsh and (2) marshes with adequate supplies of river sediment were not subject to such waterlogging stress. To test these hypotheses, we conducted field measurements and developed a conceptual marsh elevation model that incorporated more detail of below ground dynamics.

2. Site description

Two *S. alterniflora* marshes with differing riverine influence were selected (Figs. 1 and 2). Old Oyster Bayou (OB), which is 20 km from the mouth of the Atchafalaya River, receives large direct inputs of suspended clays from the river. Frontal passages regularly increase total suspended solids (TSS) levels in adjacent bays to 500 mg l^{-1} or more (Perez et al., 2000). The area is characterized by delta formation at the river mouths and low rates of wetland loss in nearby marshes (Britsch and Dunbar, 1993). Bayou Chitigue (BC) about 70 km to the east receives no direct fluvial sediment input and the BC region has high wetland loss (Britsch and Dunbar, 1993). Both study sites are micro-tidal with an astronomical tide of about 30 cm, though wind-forced excursions of two to three times this range commonly occur during cold front passage (Perez et al., 2000). Areas with altered hydrology due to canal construction

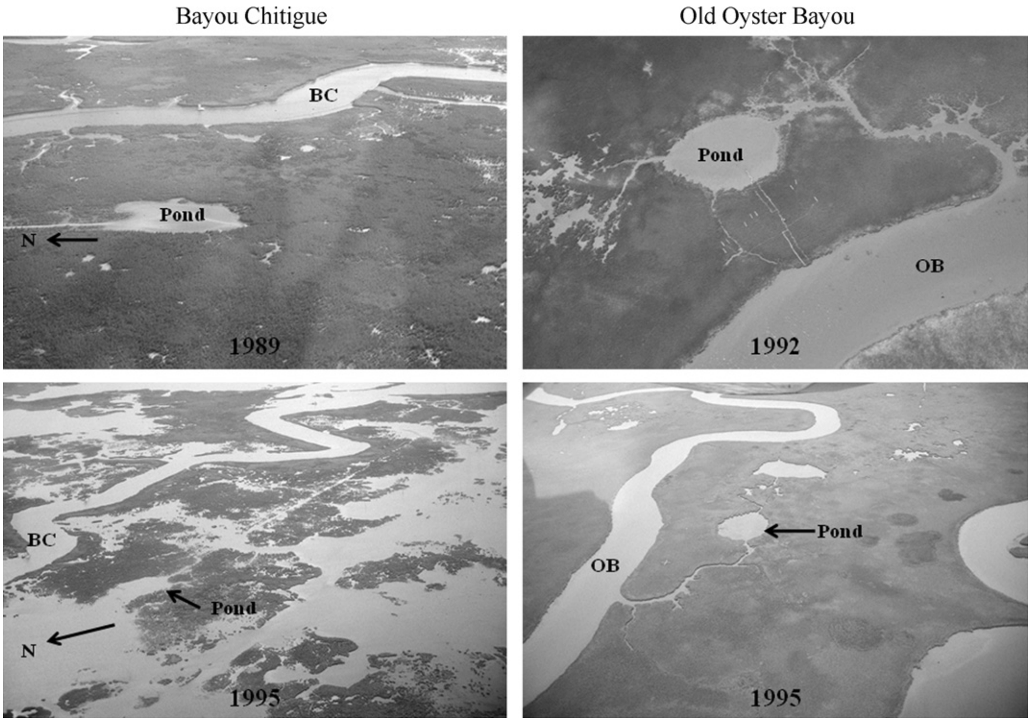


Fig. 2. Photos of the two study sites. The Old Oyster Bayou (OB) pond was stable during the study and remained a landscape feature in 2008. The Bayou Chitigue (BC) pond opened up considerably by 1995 and the pond and surrounding marsh had disappeared by 2008. *Note*: Orientations differ in the photos. The location of board walks is visible in the 1992 photo of OB.

and spoil placement can affect sedimentation dynamics (Swenson and Turner, 1987). However, there were no canals at either site, so that altered hydrology did not affect marsh surface dynamics and wetland loss during the study.

OB is a firm, healthy marsh with a continuous vegetation cover and almost no exposed mud surface. The pond has been a stable landscape feature since the 1940s (Britsch and Dunbar, 1993) and continues to be so. The BC area had rapid wetland loss in the second half of the 20th century (Britsch and Dunbar, 1993) and most of the marsh at the study site deteriorated early in the study. Additional information on wetland loss at the sites is given by Morton et al. (2002, 2003, 2005). The BC marsh is hummocky with considerable exposed mud. Digital Global Position System (DGPS) measurements showed that the OB marsh was about 10 cm higher than the BC marsh, which was near mean sea level (Day et al., 1994). The BC and OB marshes were flooded for about 85% and 15% of the time, respectively (Wang, 1994; Wang et al., 1993) and current velocities in the marsh were never sufficient to resuspend surface sediments (Wang, 1994). On August 25, 1992, Hurricane Andrew, with sustained winds of 200 km h^{-1}, passed over the two sites (Cahoon et al., 1995a).

Each site was located between a small pond about 50 m in diameter (<1.0 ha) and a tidal channel (bayou) about 30–40 m wide. Each pond was connected by a small creek to the bayou that was in turn connected to a nearby large, shallow bay. The depth of the ponds was 30–40 cm. The hydrology of these sites is described by Wang et al. (1993) and Wang (1994). At each site, boardwalks were constructed from bayou to pond to allow access while minimizing marsh disturbance. Boardwalks were also constructed in the marsh for 30–40 m parallel to and about 3 m from the pond edge.

3. Methods

Measurements were made of hydrodynamics, vegetation, sedimentation dynamics, and soil geotechnical characteristics. Observations of the marsh edge and vegetation were made during field sampling.

3.1. Water level, wave, and suspended sediment measurements

Arrays of instruments were placed in the ponds to assess differences in the concentration and organic matter composition of fine-grained sediments reaching each site, and to determine the relative importance of local wave energy in driving marsh loss associated with pond expansion. Each array consisted of a wind sensor placed 1 m above marsh elevation and atmospherically compensated pressure sensors located in the pond linked to a Campbell Scientific CR-10 data-logger. These arrays were used to obtain wind, wave and water level data (Day et al., 1994). The pressure sensors were each placed at the sediment water interface about 8 m apart, one located within a meter of the pond margin, while the other was closer to the center of the pond where the water depth was about 20 cm greater. During each experiment, data were obtained in 4.26 min bursts at a sampling rate of 4 Hz. Autosamplers collected water samples in the ponds about 3 m from the marsh edge for up to 48 h before the start of wave data collection. Each water sample was filtered through pre-combusted, pre-weighed Whatman 2.5 cm glass fiber filters that were dried for 24 h at 55 °C for gravimetric determination of TSS concentration (Banse et al., 1963). The filters were combusted for 3 h at 550 °C and reweighed to obtain the organic matter content. Synoptic wind, wave, water level and suspended sediment data were acquired in 1992, 1993 and 1994 from the BC pond on 13 days and at the OB pond on 15 other days for a total of 191 datasets. Total wave energy and frequency were extracted from spectra generated from each de-trended pressure record to provide an analog of bed shear stress. Wave height was not measured directly, but waves with amplitude greater than 5 cm were never observed in the ponds. Paired *t*-tests were used to compare TSS and percent organics from the marsh and pond margin at both sites. Additionally, regression analyses were performed to determine relationships between water level and TSS at the pond margin, and TSS and percent organic matter in suspended sediment (SAS Institute Inc., 1991).

3.2. Sediment deposition, vertical accretion and elevation change

Surface sediment traps were used to measure short-term sediment deposition (STD) to assess the role of short-term flooding events in delivering sediment to the marsh surface (Reed, 1989, 1992). The sediment traps were placed along the boardwalks between the bayou and the pond and collected approximately bi-weekly from February 1992 to September 1993 at both BC and OB. Seasonal marsh surface sediment accretion was determined using feldspar marker horizons (Cahoon and Turner, 1989) placed at BC in September 1990 and at OB in August 1991. The markers were sampled approximately semi-annually until August 1993. Changes in the elevation of marsh and pond sediment surfaces were determined using a surface elevation table or SET, which is capable of measuring elevation changes of 1–2 mm (Cahoon et al., 2002). SET stations were installed at BC in September 1990 and at OB in August 1991, and elevation change was measured at the same times as accretion over the marker horizons. Two replicate SET stations were placed in three locations, in the marsh about midway between the pond and bayou, about 2 m from the pond edge, and in the center of the pond. Three marker horizons were placed randomly in the vicinity of each marsh SET station. Paired *t*-tests were used to compare marsh elevation, STD and elevation change at SET station from the two sites. Regression analyses were performed to determine relationships between elevation and sediment deposition, and mean water level and sediment deposition (SAS Institute Inc., 1991). Following the intensive measurements in 1990–1993, the SETs were re-measured periodically over the next decade to detect longer-term changes in marsh elevation. Regression analyses produced a linear fit of change in elevation over time that yielded the rate of elevation change. Two periods were analyzed: short term (December 1990–July 1993 for BC and October 1991–July 1993 for OB) and long term (December 1990–April 2004 for BC and October 1991–July 2004 for OB).

3.3. Soil geotechnical measurements

Two types of measurements were made at each site. A portable, electrically-driven Dutch cone penetrometer (PEP, Are et al., 2002) was used mid-way between the pond and the bayou to obtain a profile of cone resistance and percent moisture content of the upper 2 m of the substrate. Then, to characterize the upper 25 cm of the rooted zone, 8-cm diameter cores, 30 cm long, were collected from the marsh between the bayou and the pond along transects parallel to the boardwalk. Four cores were collected from the BC site at 10, 20, 60 and 80 m from the bayou, and five from OB at 5, 10, 20, 40 and 45 m from the bayou. Cores were slowly pushed into the soil by hand, while roots were cut along the outside to reduce compaction. The top and bottom were capped prior to withdrawal. The cores were sliced longitudinally and one half was tested for fall cone strength (Mullins and Fraser, 2006). The remaining half was cut into 5 cm slices, weighed to establish moisture content, then dried at 55 °C, weighed again to determine bulk density, and finally combusted at 550 °C for 24 h for the percent organic matter. Specific gravity was calculated assuming specific gravities for inorganic and organic components of 2.61 and 1.14, respectively (Callaway, 1994; DeLaune et al., 1983). The void ratio, which is dimensionless, is calculated as:

$$e = \frac{V_\mathrm{v}}{V_\mathrm{s}} = \left(\frac{G_\mathrm{s} g_\mathrm{w}}{W_\mathrm{s}}\right) - 1 \qquad (1)$$

where V_v and V_s are the volumes of the soil voids and solids, respectively, G_s is specific gravity, g_w is the unit weight of water (1 g cm^{-1}) and W_s is the dry unit weight or bulk density of the soil (g cm^{-3}) (Dunn et al., 1981). More details of these measurements are given in Day et al. (1994). Paired *t*-tests were used to compare bulk density, percent organic matter, specific gravity, and void ratio measurements from the two sites (SAS Institute Inc., 1991).

We calculated the void volume due to different soil components using an equation derived from Rybczyk and Cahoon (2002) by treating near-surface expansion and contraction of void space as a proxy for biological activity in the rooting zone including below-ground plant root production and decomposition. Any increase in marsh surface elevation with respect to mean sea level, $\mathrm{EL_{MSL}}$, is then a function of the addition of mineral (S_m), organic (S_o) and void (S_v) components of the annual accretion, and any expansion of void space caused by rooting and other biological processes (S_r) in the upper 25 cm of the marsh. These terms are in cm year^{-1}.

$$\frac{\mathrm{dEL_{MSL}}}{\mathrm{d}t} = S_\mathrm{m} + S_\mathrm{o} + S_\mathrm{v} + S_\mathrm{r} + C_{0-25} + C_{25-300} + D + \mathrm{ESLR} \qquad (2)$$

The last four terms of Eq. (2) have a negative sign and cause the marsh surface to sink or subside relative to sea level. Consolidation is divided into three depth intervals; loss of void space in the upper 25 cm rooting zone (C_{0-25}), consolidation between the root zone and the 3 m deep base of the SET (C_{25-300}) that was profiled by the PEP, and finally sinking caused by deep geological subsidence (D). Results of calculations based on this equation are given in Table 3 and more details can be found in Kemp et al. (1999).

4. Results

4.1. Marsh morphology and surface elevation

Vegetated marsh cover at BC decreased dramatically during the study while the OB marsh remained stable. During the winter of 1991–1992, the eastern shore of the BC pond retreated by 2–3 m. After Hurricane Andrew transited the study area in August 1992, the pond at BC was gradually engulfed by a larger water body to the north (Fig. 2). This expansion followed vegetation death not only around the pond edge but also along the margins of the small channel connecting the pond with the bayou and between the bayou and the pond. At OB, however, little change was recorded in pond depth, shore position, and vegetation cover in the same period. Aerial imagery from 2008 showed that the pond at OB has remained stable but at the BC site, the pond has disappeared into open water while all that remains of the marsh is a thin strip along the bank of the bayou.

Marsh surface elevation changes were consistent with observed changes in marsh morphology. All SET stations at BC except that monitoring the pond bottom, which was stable, showed fluctuations in excess of 6 cm during the 3 years of intense monitoring (Fig. 3a). Elevation at the interior marsh station rose more than 6 cm in the interval that included Hurricane Andrew, but all of this gain was gone a year later. The BC pond edge site, originally established 1 m from the edge of the pond lost nearly 8 cm over the winter of 1991–1992, and by March 1992 was no longer vegetated and was part of the bottom of the expanded pond, about 2 m from the retreating marsh edge. SET stations at OB for the same period showed a slight deepening of the pond, an initial 2 cm increase in marsh surface elevation associated with Hurricane Andrew that was reduced by half in the following year but still resulted in an overall increase that persisted for the remainder of the study. The pond margin did not retreat at OB but the pond edge marsh site experienced an overall loss in elevation of 2 cm (Fig. 3b).

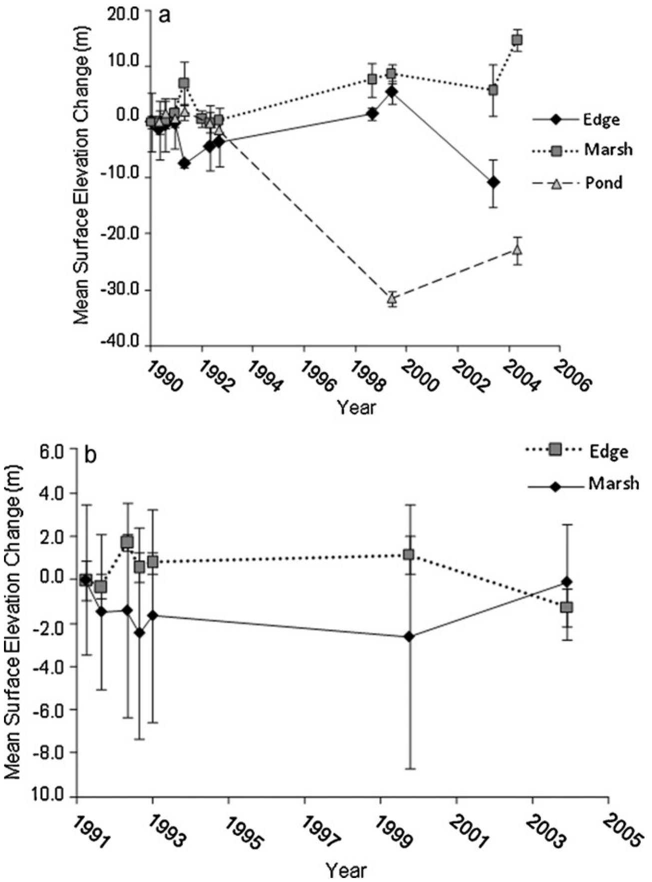


Fig. 3. Mean marsh surface elevation change (±St. Dev.). (a) Bayou Chitigue. (b) Old Oyster Bayou.

4.2. *Marsh flooding patterns*

The OB and BC sites were flooded about 15% and 85% of the time, respectively, suggesting that the BC marsh is near local sea level (Fig. 4). The BC marsh had 187 flooding events in 1993 (some up to 40 cm) and was never dry for more than 10 days. The OB marsh had less than half the flooding events, rarely was inundated to a depth of greater than 25 cm, and was exposed at times for more than 30 days. The OB marsh was regularly inundated only during spring tides during the two Gulf high stands of sea level from April to June and September through October, and was flooded in the winter only during cold fronts. The spring water level maximum overlaps maximum water and sediment discharge of the nearby Atchafalaya River and provided an opportunity for deposition of river sediments at OB. The BC marsh drained on only one occasion to more than 10 cm below the marsh surface, while the OB marsh commonly drained this low and at one point drained to nearly 20 cm below the surface.

4.3. *Short-term sediment deposition and vertical accretion*

Both short-term sediment deposition (STD) and accretion were high at both sites with higher values at BC (Fig. 5, Table 1). Vertical accretion, *H*, measured above the marker layers was greater than 2 cm year^{-1} at both sites but was nearly twice as high at BC than at OB, though this did not represent a significant difference. This indicates that the BC marsh breakup was not caused by lack of sediment input or an accretion deficit. Feldspar horizons became more difficult to locate in BC plots where death of individual marsh plants resulted in the appearance of bare mud between living culms. Where horizons could be found, the white clay was scattered through the upper 10–15 cm of the soil column suggesting that a mixing of the upper soil column accompanied marsh breakup.

Short-term sediment deposition (STD) was 2.5 times greater at BC than OB (1.83 $\mathrm{g\,m^{-2}\,day^{-1}}$ vs 0.73 $\mathrm{g\,m^{-2}\,day^{-1}}$ at BC and OB). STD was highly variable with peak rates over two orders of magnitude greater than the lowest rates (Fig. 5). The highest rates of STD during the study were observed at both sites during the fall following Hurricane Andrew and during the spring high sea level stand the next year. Although sediment collection pads were lost at BC during Hurricane Andrew, the highest STD rates found at any time during the study at OB occurred in the interval that included the hurricane. Distance from pond margin had no influence on the rate of sediment deposition, but deposition was positively and significantly correlated with mean water level during collection intervals at both sites (Fig. 6). Deposition was also positively and significantly correlated with elevation at OB ($p = 0.05$, $R^2 = 0.40$), though there was no correlation at BC.

4.4. *Waves and sediment concentrations*

Water depths in the ponds ranged from 0 to 50 cm at the pond margin sensor, and from 9 to 64 cm at the sensor located closer to the center. The highest wind speed recorded at 1 m above the marsh surface at either site during intensive sampling was 5 $\mathrm{m\,s^{-1}}$, which corresponds to an estimated speed of 8 $\mathrm{m\,s^{-1}}$ at the standard 10 m level. The 50 m fetch limited the frequency and size of waves to small ripples that were essentially deep-water waves. The wave

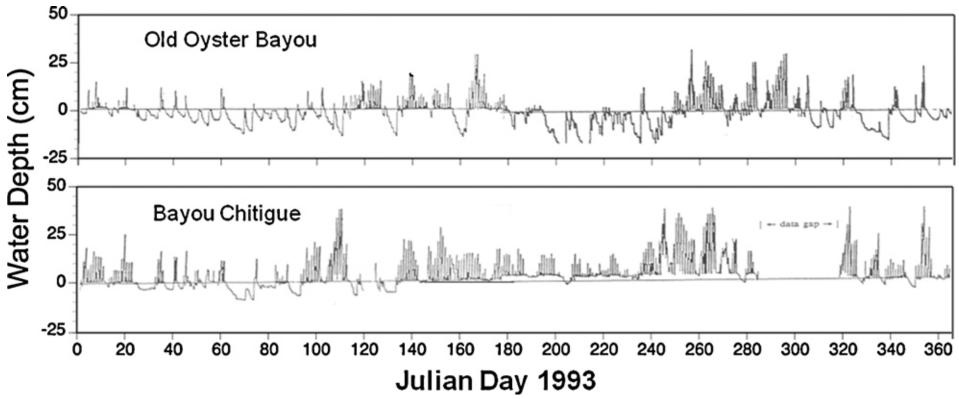


Fig. 4. Water levels at the two sites during 1993. Upper graph is Old Oyster Bayou (OB), lower graph is Bayou Chitigue (BC). BC was flooded about 85% of the time and OB was flooded about 15% of the time (from Wang, 1994).

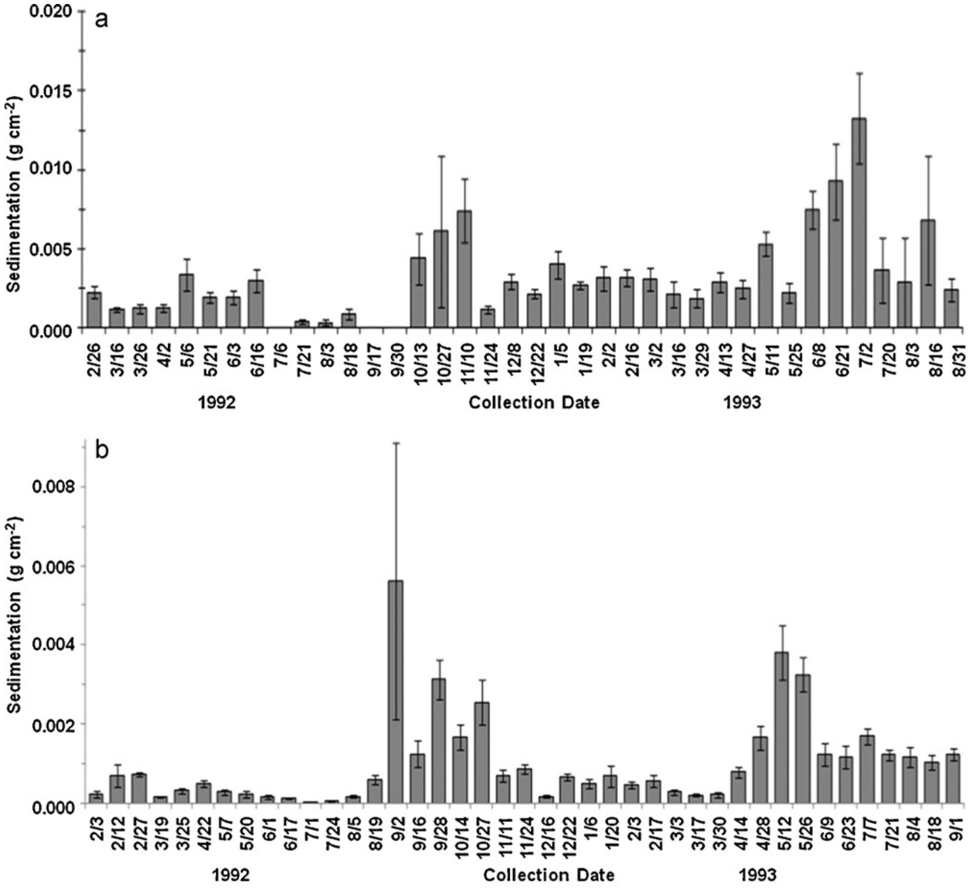


Fig. 5. Short-term sedimentation patterns at Bayou Chitigue (a) and Old Oyster Bayou (b).

records were examined to see whether an intrusion of lower frequency and perhaps larger waves from outside the pond system occurred when the marsh surface was flooded. We did not observe such intrusion on high tides. After Hurricane Andrew, however, when the BC pond opened up rapidly along the north side, waves with frequencies between 1 and 2 Hz were recorded, providing the highest energy conditions monitored. Total suspended sediment (TSS) concentrations in the ponds ranged from 10 to 200 $\mathrm{mg\,l^{-1}}$ at BC and from 20 to 400 $\mathrm{mg\,l^{-1}}$ at OB. Mean TSS concentration in the OB pond (107 $\mathrm{mg\,l^{-1}}$) was higher than at BC (67 $\mathrm{mg\,l^{-1}}$) (Table 1, Fig. 7). A background level of about 30 $\mathrm{mg\,l^{-1}}$ of organic suspended material was present in all TSS samples from both ponds, but any increase in concentration above this threshold was attributable to mineral sediments. Predominantly mineral TSS concentrations above 150 $\mathrm{mg\,l^{-1}}$ were frequently observed in samples from the OB pond but not at BC (Fig. 7). Additionally, a significant positive interaction was found between water level and TSS concentration, with 51% of the variation being explained. At OB, TSS was significantly negatively correlated with the percentage of organic matter in the suspended sediment. This is because when TSS levels are

Table 1
Summary results for Bayou Chitigue and Oyster Bayou. See text for additional information on sampling periods and techniques.

	Bayou Chitigue	Old Oyster Bayou
Marsh elevation, *E* (cm, msl)*	3.5 (5.0)	12.4 (2.0)
Short-term sediment deposition, STD ($\mathrm{g\,cm^{-2}\,year^{-1}}$)*	1.83	0.73
Suspended sediment in pond		
Mean TSS conc. ($\mathrm{mg\,l^{-1}}$)	67 (33)	107 (75)
Percent organic*	34 (11)	30 (11)
Rates of elevation change from SET, E_{SET} ($\mathrm{cm\,year^{-1}}$)		
Short term*		
Marsh	0.1	0.6
Edge	−2.0	−1.3
Pond	−0.7	
Long term		
Marsh	0.8	0.0
Edge	−0.3	−0.1
Pond	−2.1	
Marker layer accretion, *H* ($\mathrm{cm\,year^{-1}}$)	3.44 (1.54)	2.06 (0.83)

Values in parentheses are ±1SE.
* Significant difference between sites ($p < 0.01$).

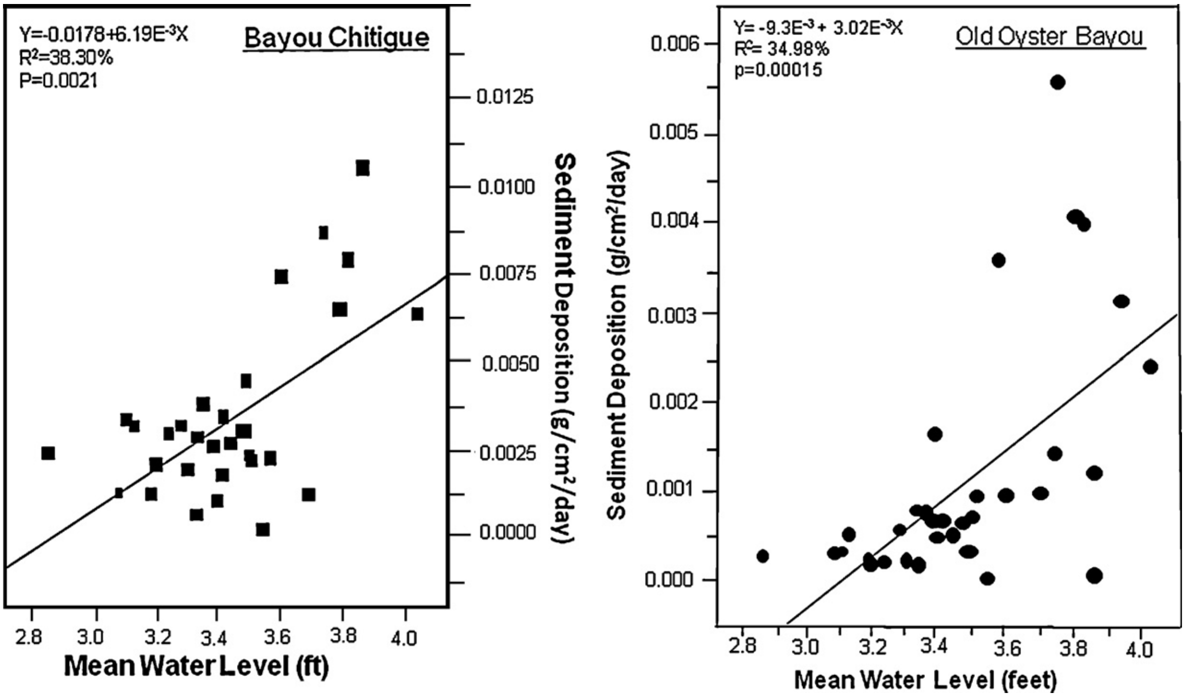


Fig. 6. Relationship between sediment deposition and water levels at the two sites.

very high, they have a much higher mineral content reflecting the riverine source.

4.5. Soil geotechnical properties

Dutch cone penetrometer (PEP) resistance, a measure of soil strength, was lowest at the surface at BC (100–300 g cm^{-2}) than at any other depth, while the opposite was true at OB (Fig. 8), where resistance at the surface was much higher (1000–1400 g cm^{-2}). Right below the zone of active root growth sampled in the cores, at a depth of approximately 35 cm, resistance dropped to its lowest value in profiles from each site, 200 and 400 g cm^{-2} at OB and BC, respectively. Below the rooted sod, resistance increased with depth at about the same rate to the maximum depth (1.8 m) penetrated, indicating that similar sediments with similar loading histories underlie both marsh sites, and that they are normally consolidated. Moisture content at BC was highest in the upper 60 cm of the profile, where it averaged 450% of the dry solids, but, again, this pattern was reversed at OB, increasing from 300% in the upper 60 cm to more than 600% below this point. Soil strength as measured by the fall cone penetrometer was more than an order of magnitude greater at OB than BC (Table 2).

Surface sediment in the upper 5 cm at OB was significantly higher in bulk density ($p < 0.01$) and lower in organic matter ($p < 0.05$) than at BC, and was significantly higher in this respect from samples collected at greater depths through the rooting zone

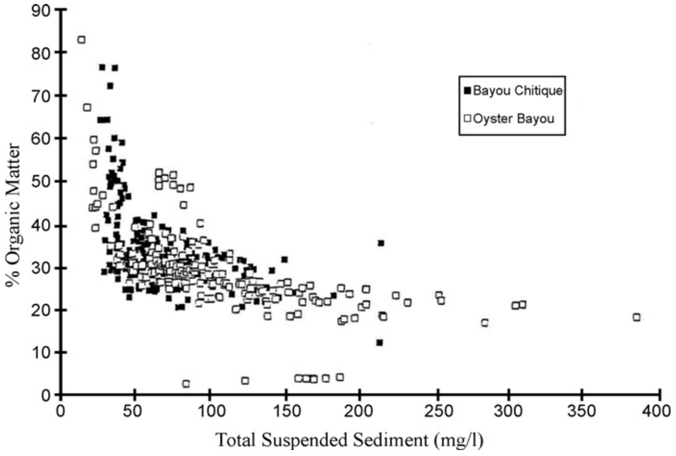


Fig. 7. Organic matter content of suspended sediments in the two salt marsh ponds as a function of total suspended sediment (TSS) concentration.

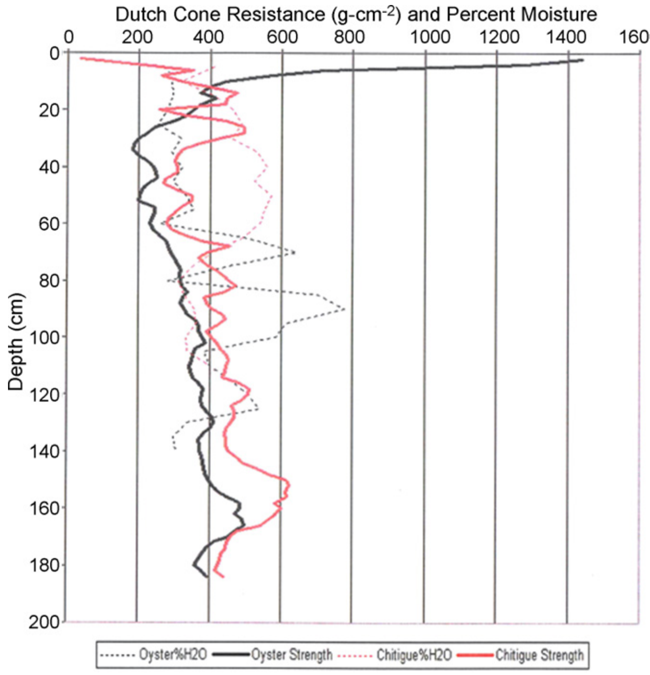


Fig. 8. Dutch cone penetrometer resistance and percent moisture at BC and OB for upper 1.8 m.

Table 2
Soil properties at Bayou Chitigue and Oyster Bayou.

	Bayou Chitigue	Oyster Bayou
Bulk density ($g\,cm^{-3}$)	4 cores	5 cores
0–5 cm**	0.23 (0.05)	0.38 (0.09)
5–10	0.24 (0.07)	0.25 (0.03)
10–15	0.20 (0.05)	0.22 (0.06)
15–20	0.21 (0.07)	0.27 (0.04)
20–25	0.23 (0.05)	0.23 (0.06)
Avg.**	0.22 (0.06)	0.27 (0.06)
Void ratio	4 cores	5 cores
0–5 cm*	9.53 (2.12)	5.54 (1.56)
5–10	8.88 (2.04)	7.71 (0.89)
10–15	10.45 (2.18)	10.04 (2.98)
15–20	10.09 (2.79)	7.49 (1.16)
20–25	9.03 (1.56)	9.06 (2.15)
Avg.**	9.60 (2.14)	7.97 (1.75)
Percent organic	4 cores	5 cores
0–5 cm*	18.15 (2.00)	13.68 (2.70)
5–10	21.40 (4.59)	24.70 (3.85)
10–15	23.83 (5.65)	18.40 (4.01)
15–20	23.03 (5.26)	19.62 (4.74)
20–25	22.03 (4.72)	21.42 (7.24)
Avg.*	21.69 (4.45)	19.56 (4.51)
Percent water, PW	2 cores	2 cores
0–5 cm	472 (90)	242 (84)
5–25	323 (149)	170 (86)
Fall cone strength of upper	2 cores	2 cores
50 cm (kPa)**	0.55 (0.54)	9.63 (1.11)
H_2S, $mg\,l^{-1}$	37–82	12–13
Eh, mv upper 25 cm	−120	−85

Data presented as mean (±SE).
* Significant differences between sites indicated by $p < 0.05$.
** Significant differences between sites indicated by $p < 0.01$.

at both sites (Table 2). Differences between the sites at depths below the upper 5 cm were not significant. The dried soil weight contributed by organic matter averaged about 20% at both sites, which is typical of Mississippi River delta salt marsh soils. Water content determined gravimetrically was consistent with values from the PEP profile, ranging from 150 to 300% of dry weight at OB and twice this at BC. The moisture content can be greater than 100%, when the water trapped in the wet soil is greater than the weight of the dry solids.

Small differences in specific gravity and bulk density translate into larger differences in the void ratio, e. Void ratios ranged from 4 to 15 at OB and from 6 to 13 at BC (Table 2). The mean void ratio for sediments from the upper 5 cm at BC was nearly twice that at OB ($p < 0.05$), and was 1.2 times greater for the upper 25 cm. Void ratio increased from the surface to about 15 cm at OB in the zone of active root growth and then dropped off, while BC showed less variation with depth. However, the mean void ratio, 9, at a depth of 20–25 cm, was the same at both sites. Voids, whether within or outside of roots, in a marsh soil with a void ratio of 9, contribute 90% of total soil volume. Total void volume was greater at BC than OB, but the volume due to roots was higher at OB (Table 3). Shear strength at OB was stronger by a factor of 10 than at BC (Table 2).

The bulk density, W_s, of the upper 5 cm at both sites can be used to assess whether the short-term sediment deposition rate (STS, Table 1) summed over a year provides a reliable predictor of both measured accretion (H) and of the composition of the uppermost portion of the marsh soil deposit. A vertical accretion rate can be predicted from the mean annual STS input using the bulk density (W_s) of the upper 5 cm, as:

$$H = \frac{\mathrm{STS}}{W_s \quad (0\text{–}5\ \mathrm{cm})} \tag{3}$$

H calculated at BC using Eq. (3) was 8 cm $year^{-1}$ while measured accretion amounted to only 43% of this value (3.44 cm $year^{-1}$). In contrast, the STS based value at OB was almost identical to the mean measured accretion rate of 2.06 cm $year^{-1}$ (Tables 1 and 2). This indicates that more than half of the sediment volume deposited at BC did not get incorporated into the marsh deposit, while the OB marsh captured nearly all of this material.

5. Discussion

Since the initial study in 1991–1993, the OB marsh has remained stable, while the BC marsh and pond have mostly disappeared. Thus, we reanalyzed the original data in an effort to understand the differences between the sites.

We chose the BC site because it was close to the lower limit of its elevation range (McKee and Patrick, 1988) and early in the study we observed the beginning stages of marsh breakup. Marsh surface elevation at BC hardly increased at a sufficient rate to offset any relative sea level rise rate greater than zero, even though it received sediment at more than twice the rate at OB because of higher frequency and duration of flooding at BC. This was true even though the mean TSS concentration at BC was less than 70% of OB. While accretion over the marker layer was nearly twice that at OB, the BC marsh permanently retained less than half of the sediment available to it. The OB marsh retained virtually all of the smaller sediment input and elevation gain is about equal to RSLR. In the following paragraphs, we develop these ideas in more detail.

5.1. Marsh surface elevation change

Our values for surface elevation change (Table 1) are similar to rates at OB and BC measured independently at nearby stations between 1992 and 1994 (Rybczyk and Cahoon, 2002). Nyman et al. (1993) and DeLaune et al. (1994) also reported about 10 cm elevation loss in the interior of the marsh at BC in 1992–1993 using leveling and ^{137}Cs dating, which was similar to our findings. Nyman et al. (1995) killed marsh clumps with an herbicide and measured a loss in elevation over 2 years. They also reported that physical removal or erosion in the months following collapse of sediments was not significant as the entire ^{137}Cs inventory in the upper 50 cm of the initial soil column was retained after the collapse. Over the longer term, with the loss of vegetation that is critical in holding the marsh together and the opening up of the area, waves and currents lead to export of soil material as has been noted by Wilson and Allison (2008).

Other characteristics at BC suggested that a rapid drop in elevation plays an important role in marsh loss. The marsh substrate at BC was extremely fluid and much of the vegetation occurred as clumps floating on a base of fluid, muddy soil. Isolated clumps could be picked up out of the mud. The clumps had a dense root mat 15–20 cm wide and 20–30 cm deep. After vegetation death and loss of elevation, remnants of the clumps were still present floating in the surface of the mud, as smaller masses with roots and shoots only a few cm in length, indicating decomposition of the root mass.

The widespread presence of a white film of *Beggiatoa* spp. on the surface of the marsh and exposed mud areas was observed at BC but not at OB. *Beggiatoa* is a chemoautotrophic bacterium that uses the oxidation of reduced sulfur as an energy source. The widespread presence of *Beggiatoa* indicates a high level of anaerobic decomposition via sulfate reduction. Roques (1996) reported that the upper 25 cm of soils at BC were more reduced and had higher levels of H_2S than soils at OB. At BC, Eh averaged −120 mv with H_2S ranging from 38 to 72 ppm. Values at OB averaged −85 mv for Eh, and H_2S ranged from 12 to 13 ppm. The level of H_2S at BC exceeded that which causes stress and growth reduction in *S. alterniflora*, while

Table 3
Effects of void volume changes with depth on thickness of accreted layer for a constant rate of mineral sediment input (H is the measured change in surface elevation; S_m, S_o, S_v, and S_r are the calculated contributions to elevation change due to dry mineral, organic material, void space, and root growth in each soil layer). C_{0-25} is the calculated compaction in the upper 25 cm.

Depth	%Org	Bulk density (g cm^{-3})	Void ratio	S_m (cm year^{-1})	S_o (cm year^{-1})	S_v (cm year^{-1})	Change (+) = S_r (−) = C_{0-25} (cm year^{-1})	H (cm year^{-1})
Oyster Bayou ($H_{surface}$ = 2.06 cm year^{-1}, S_m = 0.259 cm year^{-1})								
0–5	13.68	0.38	5.54	0.259	0.094	1.707	0.000	2.060
5–10	24.70	0.25	7.71	0.259	0.170	2.376	0.744	2.804
10–15	18.40	0.22	10.04	0.259	0.126	3.094	0.675	3.479
15–20	19.62	0.27	7.49	0.259	0.135	2.308	−0.777	2.702
20–25	21.42	0.23	9.06	0.259	0.147	2.792	0.496	3.198
Mean	19.56	0.27	7.97	0.259	0.134	2.455	0.228	2.849
Bayou Chitigue ($H_{surface}$ = 3.44 cm year^{-1}, S_m = 0.410 cm year^{-1})								
0–5	18.15	0.23	9.53	0.410	0.208	2.822	0.000	3.440
5–10	21.40	0.24	8.88	0.410	0.245	2.629	−0.155	3.285
10–15	23.83	0.20	10.45	0.410	0.273	3.094	0.493	3.778
15–20	23.03	0.21	10.09	0.410	0.264	2.988	−0.116	3.662
20–25	22.03	0.23	9.03	0.410	0.253	2.674	−0.325	3.336
Mean	21.69	0.22	9.60	0.410	0.249	2.841	−0.021	3.500

the lower levels at OB are generally below that threshold (Webb and Mendelssohn, 1996; McKee et al., 2004).

About 90% of accretion during the study period at OB occurred during the passage of Hurricane Andrew while the hurricane accounted for 38% at BC (Cahoon et al., 1995a). Cahoon et al. (1995a) reported 98% recovery of marker horizons from intact marsh at both sites, indicating that physical erosion of the vegetated surface does not generally occur, even during hurricanes. Where marsh breakup occurred, however, the horizons were lost suggesting that mixing of the upper soil column was occurring.

5.2. Short-term deposition

Rates of STD found in our study were highly variable but are within the range of values reported by Wang (1994) for sedimentation during individual tidal cycles from both sites and by Reed (1992) for other sites in coastal Louisiana. Wang also reported that inorganic sediments deposited at OB consisted of more than 50% sand and silt (>2 μm), while those at BC contained less than 30%. The sands and silts were deposited mostly near the bayou bank, while more clay was deposited inland. The high variability in rates of STD reflects both concentrations of total suspended sediments in the water column and the degree to which the marsh is flooded. This high variability reflects the high variability of the processes that affect the concentration. The highest concentrations of TSS occur during energetic events, mainly frontal passages and hurricanes (Baumann et al., 1984; Reed, 1989, 1992; Cahoon, 1994). For example, Perez et al. (2000) reported that TSS concentrations in Fourleague Bay (about 2 km from the OB site and the main source of water and sediments to the site) during frontal passages was commonly greater than 500 mg l^{-1} and sometimes nearly 2000 mg l^{-1}. These storms also lead to increased flooding of marshes.

These results indicate that sediment deposited on the marsh surface comes from the bayou rather than from the pond bottom. Cahoon et al. (1995b) found, like us, that surface elevation gain closely followed vertical accretion at OB, while the higher rate of vertical accretion at BC resulted in relatively little elevation gain. The high variability of STD was associated with high water level events such as hurricanes, frontal passages and river floods as reported by others (Baumann et al., 1984; Reed, 1992; Cahoon et al., 1995a). This indicates the importance of sediments mobilized co-incident with high water levels. At OB, the influence of both Hurricane Andrew and the Atchafalaya River are apparent in this sediment-rich basin, showing that proximity to a fluvial sediment source influences marsh surface sediment deposition.

5.3. Soil geotechnical properties

Bulk density and percent organic matter at the two sites were similar to those measured by Nyman et al. (1993). The main difference between the sites was in the upper 5 cm (Table 2). Salt marsh soils consolidate and gain strength through desiccation at the surface, and at greater depths in response to loading. Sediments settling out of the water column are thus transformed from a mobile fluid mud with the potential to flow off of the marsh surface into a soil layer that bonds with that pre-existing surface. These processes decrease void space, which contributes up to 90% of the volume of the marsh soils. However, biological activities taking place immediately below the surface, especially root growth and burrowing by organisms, provide a new structure or matrix that can then increase void volume without diminishing strength (Tables 2 and 3). Thus, the decrease in void volume at the surface is countered by increase in void volume below the surface due to root growth and other biological processes (Table 3). At BC, root growth below the surface merely invades water filled voids, while at OB these biological activities create new void space.

Desiccation and drainage depend, like sedimentation, on the position of the marsh surface in the tidal range. Surface soils in a higher marsh like OB experience drying to greater depths as was apparent in the penetrometer profiles (Fig. 8). Deeper drainage increases the load on soils below the tidal frame in two ways. First, the thickness of the drained soil column uncompensated by buoyancy is increased, but second, tidal drainage is incomplete so the weight of water trapped above the saturated zone contributes significantly to the load that must be supported. Drainage and desiccation act to reduce void space and so contribute to settlement. But they also build strength, which is the ability to resist subsequent loads without deformation or settlement.

Autocompaction is a function of position within the tidal frame and the loading history (Pizzuto and Schwendt, 1997). If soils are normally consolidated, they support without settling only those loads to which they have already been subjected. In this way, a soil layer becomes stronger as it is subjected to greater loads, which generally occurs with age and depth of burial. Marsh soils in the Mississippi delta grow upward as a response to relative water level rise, so that the upper few centimeters represent only a few years of accumulation. Numerous authors have reported on this upward growth which leads to elevation gain and the ability to withstand relative sea-level rise (DeLaune et al., 1983; Hatton et al., 1983; Baumann et al., 1984; Cahoon, 1994; Cahoon et al., 1995a,b; Day et al., 1999; Rybczyk and Cahoon, 2002). Desiccation can cause overconsolidation at the surface, which gives the

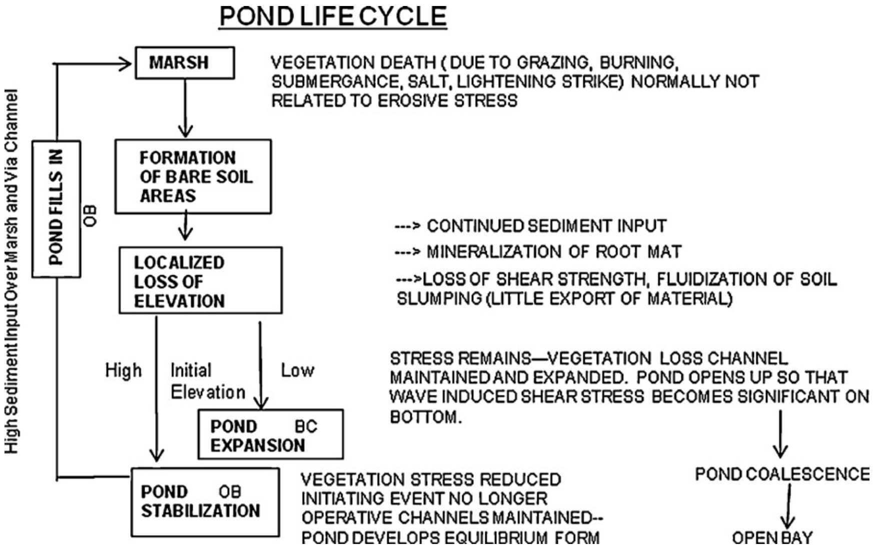


Fig. 9. Conceptual diagram of the process of pond formation and expansion. The initial elevation of the marsh surface is critical as to whether the pond expands or is stable.

new soil greater strength than the loading history would suggest. Howes et al. (2010) reported soil strength at high salinity wetlands in the Breton Sound estuary was much higher than low salinity wetlands near the Caernarvon river diversion. The low salinity wetlands likely drain less frequently than the high salinity marshes. The soils at OB dried out much more frequently than those at BC. If there were no sediment input, the marsh surface elevation would decline (Cahoon et al., 2010). As sediment continues to be introduced at the surface, however, a layer that started at the surface is found later at a lower point in the sediment profile while the surface continues to grow upward. Such a layer, described as a sediment 'cohort' by Day et al. (1999), is operated on by different processes as it ages and is displaced from the surface. A cohort is a sediment layer that is deposited over a period of time such that it can be considered as a homogeneous layer in terms of soil diagenetic processes. Sediment deposition and desiccation are active at the soil water interface, while biologically mediated introduction of voids and organic matter predominate in the rooted zone. At greater depths, consolidation and dewatering induced by progressive loading lead to deformation and loss of voids. This consolidation contributes to what Cahoon et al. (1995b) call shallow subsidence. Eventually, as the soil layer is buried to greater depths, the deposit experiences less thinning even though it is exposed to greater loading, and the contribution of any single layer to settlement approaches zero.

5.4. Summary and conceptual model

We developed a conceptual model of marsh deterioration (Fig. 9). There has been long-term relative sea-level rise at both sites. The BC marsh is at the lower end of its vertical elevation range. Despite high sediment input, there is a low rate of sediment capture and soils do not drain and consolidate. OB sediment input is lower but is more mineral than BC reflecting river input, and most sediments are retained. Thus, sediment capture, consolidation and soil strength, organic matter content are dependent on position in the tidal frame and mineral sediment is related to river input. Because BC elevation is low, collapse took place due to metabolic effects of prolonged inundation. This collapse is not the same as soil removal by waves and currents. Once collapse occurs, low elevation and poor soil strength prevent revegetation. The accretion deficit for interior marshes in the delta is similar to those at BC (2–3 mm year^{-1}, Baumann et al., 1984; Hatton et al., 1983; DeLaune et al., 1994).

Accretion deficit is not the same as sediment deficit. As elevation drops, the efficiency of incorporation of deposited sediments diminishes while the void volume increases. In the rooting zone, added void volume reduces upward displacement of the marsh surface by rooting and other biogenic processes, while increasing shallow autocompaction below this zone. At OB, this expansion contributed almost half of the total aggradation potential, compared to 12% at BC (Table 3).

The BC marsh initially formed near the active Lafourche Mississippi River distributary. Although that channel was largely abandoned about 300 years BP, there was some input until the late 19th century. At that time, elevation of the BC marsh was similar to that of the marsh at OB but since then it has lost elevation. This elevation loss was initially slow because of efficient incorporation of sediments introduced when the marsh is flooded. With increased flood duration and decreased drying and consolidation, sediment retention efficiency decreased and the degradation of the interior marsh accelerated.

The accretion deficit and elevation loss is decades long and could likely be stabilized by increased sediment input as suggested by streamside salt marsh accretion rates (Hatton et al., 1983). But it ultimately leads to a point where several years without significant storm input results in rapid loss of elevation. During this last stage, the marsh experiences high sediment input. Just before collapse the marsh is reduced to individual clumps of stressed vegetation floating in a fluid mud substrate. The stage is then set for rapid marsh deterioration and loss over a matter of months.

The increased duration of flooding leads to the collapse of the marsh. Plants are stressed due to excessive waterlogging, anoxia, low Eh, and elevated sulfides and have lower below ground production and organic soil formation (e.g., Mendelssohn and Morris, 2000; Roques, 1996). That worsens the accretion deficit. When stress becomes too extreme, plants die (Mendelssohn and Morris, 2000) leading to rapid loss of root volume and mass due to loss of root turgor and root decomposition (DeLaune et al., 1994). Aerenchyma tissue filled with gas can occupy up to 30% of the volume of living *S. alterniflora* (Arenovski and Howes, 1992). Following death, root decomposition is rapid (Padgett and Celio, 1990; Padgett et al., 1989; Benner et al., 1991). After decomposition, the root mass at BC was reduced to a stubble on the remnants of individual culms on the fluid mud substrate. Plant death also reduces soil strength so that marsh scarps become unstable and fail.

After vegetation death, soils can be removed by low energy waves and currents that once posed no threat. Export of liquefied soil material can then occur, especially as the pond opens up to merge into adjacent water bodies. At this point, restoration of the existing marsh is no longer possible with normal sediment input. The only option is to rebuild the substrate high enough in the tidal frame with massive amounts of sediment introduced either from the river or through placement of dredged sediments.

Our original hypothesis that marsh deterioration was due to waterlogging stress resulting from a lack of sediment input is only partially correct. The long duration of flooding of the BC marsh clearly stresses the plants. The low elevation is not due to lack of sediment input but to low capture efficiency. By 2009, the OB marsh remained stable while the BC marsh site had largely disappeared more than a decade earlier.

These findings have important implications for wetland management with sea-level rise (IPCC, 2007). High sediment input will be necessary on a large scale if Louisiana marshes are to survive high rates of sea-level rise. Our findings support the use of river diversions for regional-scale wetland restoration (Boesch et al., 1994; Day et al., 2007, 2009). The OB marsh with long-term riverine influence is in an area with low land loss and results of our study provide insights into how loss of elevation occurs and how and where it might be reversed. Others have also concluded that river input is important to maintain the delta (Roberts, 1997; Day et al., 2007; Tornqvist et al., 2008; Blum and Roberts, 2009). Another way to provide sediment input is via dredged sediments (Mendelssohn and Kuhn, 2003).

Our results also provide insight into natural vs human caused wetland loss. Altered hydrology due to canals or impoundments can result in reductions in sediment input and accretion deficits (Swenson and Turner, 1987; Cahoon, 1994; Reed, 1992; Boumans and Day, 1994). The accretion deficit, lack of consolidation, and wetland loss at BC occurred in the absence of alterations in local hydrology. Physical erosion was not the primary cause for marsh loss but soil can be removed by waves and currents after vegetation death and marsh loss. These mechanisms likely play a role in wetland loss throughout the delta. Although the study sites were interior marshes, we believe that our general findings about accretionary dynamics are generally applicable to deltaic marshes.

Acknowledgments

Funding for this study was provided by the United States Geological Survey (grants number 14-08-0001-23411 and 04ERAG0068). Additional funding came from the Louisiana Sea Grant Program. Assistance in the project was provided by Robert Lane, Numair Latif, David Roques, Nina de Luca, Derral Dupre, Wendy Morrison, Laura Dancer, and Jill Rooth.

References

Are, D., Kemp, P., Guistina, G., Day, J., Scarton, F., 2002. A portable, electrically-driven Dutch cone penetrometer for geotechnical measurements in soft estuarine sediments. J. Coastal Res. 18, 372–378.

Arenovski, A, Howes, B., 1992. Lacunal allocation and gas transport capacity in the salt marsh grass *Spartina alterniflora*. Oecologia 90, 316–322.

Banse, K., Falls, C., Hobson, L., 1963. A gravimetric method for determining suspended matter in seawater using Millipore filters. Deep Sea Res. 10, 639–642.

Baumann, R., Day, J., Miller, C., 1984. Mississippi deltaic wetland survival: sedimentation vs. coastal submergence. Science 224, 1093.

Benner, R., Fogel, M., Sprague, E.K., 1991. Diagenesis of belowground biomass of *Spartina alterniflora* in salt-marsh sediments. Limnol. Oceanogr. 36, 1358–1374.

Blum, M., Roberts, H., 2009. Drowning of the Mississippi delta due to insufficient sediment supply and global sea-level rise. Nat. Geosci. 2, 488–491.

Boesch, D.F., Josselyn, M.N., Mehta, A.J., Morris, J.T., Nuttle, W.K., Simenstad, C.A., Swift, D.J.P., 1994. Scientific assessment of coastal wetland loss, restoration, and management in Louisiana. J. Coastal Res., Special Issue Number 20.

Boesch, D., Shabman, L., Antle, L., Day, J., Dean, R., Galloway, G., Groat, C., Laska, S., Luettich, R., Mitsch, W., Rabalais, N., Reed, D., Simenstad, C., Streever, B., Taylor, R., Twilley, R., Watson, C., Wells, J., Whigham, D., 2006. A New Framework for Planning the Future of Coastal Louisiana after the Hurricanes of 2005. University of Maryland Center for Environmental Science, p. 48 http://www.umces.edu.

Boumans, R., Day, J., 1994. Effects of two marsh management plans in the Mississippi delta on water and materials flux and short-term sedimentation. Wetlands 14 (2), 247–261.

Britsch, L., Dunbar, J., 1993. Land loss rates: Louisiana coastal plain. J. Coastal Res. 9, 324–338.

Cahoon, D., 1994. Recent accretion in two managed marsh impoundments in coastal Louisiana. Ecol. Appl. 4, 166–176.

Cahoon, D., Turner, R.E., 1989. Accretion and canal impacts in a rapidly subsiding wetland. II. Feldsparmarker horizon technique. Estuaries 12, 260–268.

Cahoon, D., Reed, D., Day, J., Steyer, G., Boumans, R., Lynch, J., McNally, D., Latif, N., 1995a. The influence of Hurricane Andrew on sediment distribution in Louisiana coastal marshes. J. Coastal Res. 18 (Special Issue), 280–294.

Cahoon, D., Reed, D., Day, J., 1995b. Estimating shallow subsidence in microtidal salt marshes of the southeastern United States: Kaye and Barghoorn revisited. Mar. Geol. 128, 1–9.

Cahoon, D., Lynch, J., Hensel, P., Boumans, R., Perez, B., Segura, B., Day, J., 2002. High precision measurements of wetland sediment elevation: I. Recent improvements to the sedimentation-erosion table. J. Sediment. Res. 72 (5), 730–733.

Cahoon, D.R., Perez, B.C., Segura, B.D., Lynch, J.C., 2010. Elevation trends and shrink-swell response of wetland soils to flooding and drying. Estuarine Coastal Shelf Sci., doi:10.1016/j.ecss.2010.03.022.

Callaway, J.C., 1994. Sedimentation Processes in Selected Coastal Wetlands from the Gulf of Mexico and Northern Europe. Ph.D. Dissertation. Louisiana State University, p. 209.

Day, J., Reed, D., Suhayda, J., Kemp, P., Cahoon, D., Boumans, R., Latif, N., 1994. Physical processes of marsh deterioration: the role of pond formation and enlargement. In: Roberts, H.H. (Ed.), Critical Physical Processes of Wetland Loss 1988–1994. Final Report Submitted to the U.S. Geological Survey, November 1994. Louisiana State University, Baton Rouge, 1994, pp. 5.0–5.40.

Day, J., Rybczyk, J., Scarton, F., Rismondo, A., Are, D., Cecconi, G., 1999. Soil accretionary dynamics, sea-level rise and the survival of wetlands in Venice Lagoon: a field and modeling approach. Estuarine Coastal Shelf Sci. 49, 607–628.

Day Jr., J.W., Britsch, L.D., Hawes, S.R., Shaffer, G.P., Reed, D.J., Cahoon, D., 2000. Pattern and process of land loss in the Mississippi Delta: a spatial and temporal analysis of wetland habitat change. Estuaries 23, 425–438.

Day, J., Boesch, D., Clairain, E., Kemp, P., Laska, S., Mitsch, W., Orth, K., Mashriqui, H., Reed, D., Shabman, L., Simenstad, C., Streever, B., Twilley, R., Watson, C., Wells, J., Whigham, D., 2007. Restoration of the Mississippi Delta: lessons from Hurricanes Katrina and Rita. Science 315, 1679–1684.

Day Jr., J.W., Templet, P.H., 1989. Consequences of sea-level rise: implications from the Mississippi Delta. Coast. Manage. 17, 241–257.

Day, J., Cable, J., Cowan, J., DeLaune, R., de Mutsert, K., Fry, B., Mashriqui, H., Justic, D., Kemp, P., Lane, R., Rick, J., Rick, S., Rosas, L., Snedden, G., Swenson, E., Twilley, R., Wissel, B., 2009. The impacts of pulsed reintroduction of river water on a Mississippi delta coastal basin. J. Coastal Res. 54, 225–243.

DeLaune, R., Baumann, R., Gosselink, J., 1983. Relationships among vertical accretion, coastal submergence, and erosion in a Louisiana Gulf coast marsh. J. Sediment. Petrol. 53, 147–157.

DeLaune, R, Nyman, J., Patrick, W., 1994. Peat collapse, ponding and wetland loss in a rapidly submerging coastal marsh. J. Coastal Res. 10, 1021–1030.

Dunn, I., Anderson, L., Keifer, F., 1981. Fundamentals of Geotechnical Analysis. John Wiley & Sons, New York, p. 430.

FitzGerald, D., Fenster, M., Argow, B., Buynevich, I., 2008. Coastal impacts due to sea-level rise. Annu. Rev. Earth Planet. Sci. 36, 601–647.

Gornitz, V., Lebedeff, S., Hansen, J.E., 1982. Global sea-level trends in the past century. Science 215, 1611–1614.

Hatton, R.S., DeLaune, R.D., Patrick Jr., W.H., 1983. Sedimentation, accretion and subsidence in marshes of Barataria Basin, Louisiana. Limnol. Oceanogr. 28, 494–502.

Howes, N., FitzGerald, D., Hughes, Z., Georgiou, I., Kulp, M., Miner, M., Smity, J., Barras, J., 2010. Hurricane-induced failure of low salinity wetlands. Proc. Nat. Acad. Sci. 107, 14014–14019.

IPCC (Intergovernmental Panel on Climate Change), 2007. In: Watson, R.T., Zinvowera, M.C., Moss, R.H. (Eds.), Climate Change: Adaptation and Mitigation of Climate Change: Scientific-Technical Analysis. Contribution of Working Group II to the IPCC. Cambridge Univ. Press, New York, p. 880.

Kemp, G.P., Day, J., Reed, D., Cahoon, D., Wang, M., 1999. Sedimentation consolidation and surface elevation change in two salt marshes of the Mississippi deltaic plain: geotechnical aspects of wetland loss. In: Rozas, L., Nyman, J., Proffitt, C., Rabalais, N., Reed, D., Turner, E. (Eds.), Recent Research in Coastal Louisiana: Response to Human Influences. Louisiana Sea Grant College Program, Louisiana State University, Baton Rouge, LA, pp. 15–34.

McKee, K., Patrick, W., 1988. The relationship of smooth cordgrass (*Spartina alterniflora*) to tidal datums: a review. Estuaries 11, 143–151.

McKee, K.L., Mendelssohn, I.A., Materne, M.D., 2004. Acute salt marsh dieback in the Mississippi River deltaic plain: a drought-induced phenomenon? Global Ecol. Biogeogr. 13, 65–73.

Mendelssohn, I.A., Morris, J.T., 2000. Eco-physiological controls on the productivity of *Spartina alterniflora* loisel. In: Weinstein, M.P., Kreeger, D.A. (Eds.), Concepts and Controversies in Tidal Marsh Ecology. Kluwer Academic Publishers, Boston, MA, pp. 59–80.

Mendelssohn, I.A., Kuhn, N., 2003. Sediment subsidy: effects on soil–plant responses in a rapidly submerging coastal salt marsh. Ecol. Eng. 21, 115–128.

Morton, R.A., Buster, N., Krohn, M.D., 2002. Subsurface controls on historical subsidence rates and associated wetland loss in southcentral Louisiana. Gulf Coast Assoc. Geol. Soc. 52, 767–778.

Morton, R.A., Tiling, G., Ferina, N.F., 2003. Causes of hot-spot wetland loss in the Mississippi delta plain. Environ. Geosci. 10, 71–80.

Morton, R.A., Bernier, J.C., Barras, J.A., Ferina, N.F., 2005. Rapid subsidence and historical wetland loss in the Mississippi Delta Plain: likely causes and future implications. USGS Open-File Rep., 1216–2005.

Mullins, C., Fraser, A., 2006. Use of the drop-cone penetrometer on undisturbed and remoulded soils at a range of soil–water tension. Eur. J. Soil Sci. 31, 25–32.

Nyman, J., DeLaune, R., Roberts, H., Patrick, W., 1993. Relationship between vegetation and soil formation in a rapidly submerging coastal marsh. Mar. Ecol. Prog. Ser. 96, 269–279.

Nyman, J., DeLaune, R., Pezeshki, R., Patrick, W., 1995. Organic matter fluxes and marsh stability in a rapidly submerging estuarine marsh. Estuaries 18, 207–217.

Padgett, D., Celio, D., 1990. A newly discovered role for aerobic fungi in anaerobic salt marsh soils. Mycologia 82, 791–794.

Padgett, D., Celio, D., Hearth, J., Hackney, C., 1989. Growth of filamentous fungi in a surface-sealed woody substratum buried in salt marsh sediments. Estuaries 12, 142–144.

Perez, B., Day, J., Rouse, L., Shaw, R., Wang, M., 2000. Influence of Atchafalaya River discharge and winter frontal passage on suspended sediment concentration and flux in Fourleague Bay, Louisiana. Estuarine Coastal Shelf Sci. 50, 271–290.

Pfeffer, W., Harper, J., O'Neel, S., 2008. Kinematic constraints on glacier contributions to 21st-century sea-level rise. Science 321, 1340–1343.

Pizzuto, J., Schwendt, A., 1997. Mathematical modeling of autocompaction of a Holocene transgressive valley-fill deposit, Wolfe Glade, Deleware. Geology 25, 57–60.

Pont, D., Day, J., Hensel, P., Franquet, E., Torre, F., Rioual, P., Ibanez, C., Coulet, E., 2002. Response scenarios for the deltaic plain of the Rhône in the face of an acceleration in the rate of sea level rise, with a special attention for Salicornia-type environments. Estuaries 25, 337–358.

Rahmstorf, S., 2007. A semi-empirical approach to predicting sea-level rise. Science 315, 368–370.

Reed, D.J., 1989. Patterns of sediment deposition in subsiding coastal marshes. Terrebonne Bay, Louisiana: the role of winter storms. Estuaries 12, 222–227.

Reed, D.J., 1992. Effect of weirs on sediment deposition in Louisiana coastal marshes. Environ. Manage. 16 (1), 55–65.

Reed, D.J., Peterson, M.S., Lezina, B.J., 2006. Reducing the effects of dredged material levees on coastal marsh function: sediment deposition and nekton utilization. Environ. Manage. 37, 671–685.

Roberts, H.H., 1994. Critical Physical Processes of Wetland Loss 1988–1994. Final Report Submitted to the U.S. Geological Survey, November 1994. Louisiana State University, Baton Rouge.

Roberts, H.H., 1997. Dynamic changes of the holocene Mississippi River delta plain: the delta cycle. J. Coastal Res. 13, 605–627.

Roques, D., 1996. Factors Affecting Mobilization and Speciation of Sulfur in Two Louisiana Salt Marshes. M.S. Thesis. Louisian State University, Baton Rouge, p. 74.

Rybczyk, J., Cahoon, D., 2002. Estimating the potential for submergence for two wetlands in the Mississippi River delta. Estuaries 25, 985–998.

S.A.S. Institute, Inc., 1991. SAS System for Linear Models, 3rd edition. SAS Institute, Inc., Cary, NC.

Shaffer, G., Day, J., Mack, S., Kemp, P., van Heerden, I., Poirrier, M., Westphal, K., FitzGerald, D., Milanes, A., Morris, C., Bea, R., Penland, S., 2009a. The MRGO navigation project: a massive human-induced environmental, economic, and storm disaster. J. Coastal Res. 54 (SI), 206–224.

Shaffer, G., Wood, W., Hoeppner, S., Perkins, T., Zoller, J., Kandalepas, D., 2009b. Degradation of Balcypess-Water Tupelo swamp to marsh and open water in southeastern Louisiana, U.S.A.: an irreversible trajectory? J. Coastal Res. 54, 152–165.

Swarzenski, C., Doyle, T., Fry, B., Hargis, T., 2008. Biogeochemical response of organic-rich freshwater marshes in the Louisiana delta plain to chronic river water influx. Biogeochemistry 90, 49–63.

Swenson, E., Turner, R., 1987. Spoil banks: effects on a coastal marsh water level regime. Estuarine Coastal Shelf Sci. 24, 599–609.

Syvitski, J., Kettner, A., Overeem, I., Hutton, E., Hannon, M., Brakenridge, R., Day, J., Vorosmarty, C., Saito, Y., Giosan, L., Nichols, R., 2009. Sinking deltas due to human activities. Nat. Geosci., doi:10.1038/NGE0629.

Tornqvist, T., Wallace, D., Storms, J., Wallinga, J., van Dam, R., Blaauw, M., Derksen, M., Klerks, C., Meijneken, C., Snijders, E., 2008. Mississippi delta subsidence primarily caused by compaction of Holocene strata. Nat. Geosci. 1, 173–176.

Turner, R.E., 1997. Wetland loss in the northern Gulf of Mexico: multiple working hypothesis. Estuaries 20, 1–13.

Vermeer, M., Rahmstorf, S., 2009. Global sea level linked to global temperature. Proc. Nat. Acad. Sci. 106, 21527–21532.

Vörösmarty, C., Syvitski, J., Day, J., de Sherbinin, A., Giosan, L., Paola, C., 2009. Battling to save the world's river deltas. Bull. At. Sci. 65 (March/April), 31–43.

Wang, F., 1994. Dynamics of intertidal marshes. In: H. Roberts (Ed.), Critical Physical Processes of Wetland Loss. Final Report to the USGS. Dept. of Oceanography and Coastal Sciences, Louisiana State University, pp. 8.1–8.26.

Wang, F., Lu, T.S., Skora, W., 1993. Intertidal marsh suspended sediment transport processes, Terrebonne Bay, Louisiana, U.S.A. J. Coastal Res. 9, 209–220.

Webb, E.C., Mendelssohn, I.A., 1996. Factors affecting vegetation dieback of an oligohaline marsh in coastal Louisiana: field manipulation of salinity and submergence. Am. J. Bot. 83, 1429–1434.

Wilson, C.A., Allison, M.A., 2008. An equilibrium profile model for retreating marsh shorelines in southeast Louisiana. Estuarine Coastal Shelf Sci. 80, 483–494.