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Elevation and accretion dynamics at historical plots in the Biloxi Marshes, Mississippi Delta

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ABSTRACT

The objectives of this study were to examine changes in accretion and elevation change over periods of up to 15 years for the Biloxi marsh complex (BMC) in southeastern Louisiana, part of the Mississippi Deltaic Plain, identify factors affecting accretionary dynamics, and put these findings in the context of ongoing restoration. We present elevation and accretion data from Surface Elevation Table (SET) and feldspar marker horizon sites first established in 2003. The sites were clustered in two areas (East and West) in the central BMC on the eastern edge of the Mississippi delta. Accretion markers were used in conjunction with elevation measurements to calculate shallow subsidence. These data were analyzed along with similar data from nearby Coastwide Reference Monitoring System (CRMS) sites located around the periphery of the BMC. Elevation decreased at the Western sites by -0.35 ± 0.13 cm/yr, and increased at the Eastern and CRMS sites by 0.40 ± 0.03 cm/yr and 0.72 ± 0.09 cm/yr, respectively. The rate of accretion was similar at the Western (0.49 ± 0.14 cm/yr) and Eastern (0.64 ± 0.07 cm/yr) sites, and over twice as much (1.30 ± 0.11 cm/yr) at the CRMS sites. Shallow subsidence, calculated as the difference between vertical accretion and surface elevation change, was 0.76 ± 0.49 cm/yr at the Western sites, 0.23 ± 0.06 cm/yr at the Eastern sites, and 0.58 ± 0.11 cm/yr at the CRMS sites. These trends are consistent with the observation that sediment is brought in from Chandeleur Sound to the east and is attenuated as deposition occurs across the landscape from east to west, and that levee flank depressions associated with Bayou La Loutre, an abandoned Mississippi River distributary ridge, are causing locally high subsidence in the Western region. Without intervention, these localized areas of the Western region will be submerged within the next several decades at current rates of elevation loss and eustatic sea-level rise, while the Eastern sites and the wetlands on the periphery of the BMC are likely to keep pace with sea level rise well into the second half of this century. These results demonstrate the importance of accurate knowledge of both subsidence and accretionary dynamics in determining coastal wetland sustainability and restoration approaches.

1. Introduction

Wetland soil elevation is directly influenced by a complex relationship between subsidence and accretion, which in turn is affected by organic soil formation, mineral sediment input, and erosion. Accretion is defined as the vertical accumulation of material on the wetland surface, generally as a mixture of organic and mineral fractions (Callaway et al., 1996). Subsidence is defined as all factors, local and regional, that contribute to the lowering of wetland surface elevation, including compaction and consolidation of sediments (both shallow and deep), tectonic activity, isostasy and human impacts such as groundwater and hydrocarbon withdrawal, reduction of sediment input, and reduced wetland productivity (Callaway et al., 1996; Morton et al., 2002; Yuill et al., 2009; Day et al., 2020; Karegar et al., 2015). Erosion is generally limited to the wetland platform edge, where the marsh substrate sloughs off due to wave impacts (Karimpour et al., 2016; Sapkota and White, 2019), rather than the surface of the marsh, which is generally well consolidated (Thomason, 2016). Vegetation on the marsh surface results

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in higher soil strength and acts as a sediment trap, making the marsh surface much less vulnerable to erosion during meteorological events than the edge of the marsh platform. The erosion of the marsh edge is often accompanied by accretion on the nearby marsh surface (Reed, 1988), thus in some cases the marsh platform is maintained at elevation relative to sea level at the expense of the wetland edge.

The frequency, duration, and depth of flooding (i.e., hydroperiod) also directly controls sediment delivery to the wetland surface (Cahoon et al., 1999; Day et al., 2011b). Accumulation of both organic and mineral matter is often significantly related to duration of flooding, implying that allochthonous organic matter as well as mineral matter is delivered to the marsh surface during flooding (Cahoon and Reed, 1994). Although the increased flooding duration enhances sediment deposition, the total amount of flooding may also contribute to lowered marsh productivity through submergence stress on plant vigor (Pezeshki and DeLaune, 1990, 1993, 1996; Mendelssohn and Morris, 2000). Dry periods are also necessary to ensure that introduced sediments consolidate and adhere to the marsh surface (Day et al., 2011b). Hydroperiod controls the oxidative state of the wetland soil, and thereby influences growth of plant shoots and roots as well as soil organic matter decomposition (Bandyopadhyay et al., 1993). There is a feedback between elevation and hydroperiod since elevation directly controls hydroperiod (Reed, 1995).

Meteorological forcing is often a more important regulator of water levels in the microtidal estuaries of the Mississippi Delta than astronomical tidal variability (Perez et al., 2000; Lane et al., 2015; Hiatt et al., 2019). As a result, sedimentation in these microtidal marshes (<0.5 m) is strongly event-related. Accretion is often greater during periods of long and deep flooding events, implying the importance of storm events in increasing the supply of suspended sediment to Louisiana coastal marshes (Cahoon and Reed, 1994; Perez et al., 2000; Day et al., 2011a, b). Mechanisms by which storms affect coastal wetland soil elevation include sediment redistribution by storm surge, and delivery of large quantities of sediment to coastal wetlands by upland runoff or erosion (Cahoon, 2006). Storms elevate water levels and resuspend sediments, which can then be deposited on the marsh surface (Perez et al., 2000). These energy intensive events also result in wave-induced shoreline erosion (Karimpour et al., 2016; Trosclair, 2013).

The shrink-swell of the marsh surface due to changes in local hydrology and groundwater conditions can cause short-term perturbations to marsh elevation (Cahoon et al., 2011). Cahoon et al. (2011) reported that changes in water storage lead to rapid and large short-term impacts on marsh elevation that can be as much as five times greater than the long-term elevation trend. The implication is that the consequence of taking SET readings during a low water event may cause an over estimate of surface elevation change based on subsequent readings when water levels are higher. This indicates the importance of repetitive measurements to the understanding of long-term patterns (e.g., decadal) on marsh elevation change.

Analyses of elevation change and vertical accretion is important in the context of coastal restoration in general, and specifically for deltas that often have higher relative sea level rise rates due to high rates of geological subsidence (Syvitski et al., 2009). Climate change predictions are that sea level will increase by a meter or more in this century (Hansen et al., 2015; Sweet et al., 2017), thus the ability of wetlands to maintain elevation with respect to local water level rise is critical. Information from the Mississippi delta, and other deltas, provides a context of factors affecting the sustainability of wetlands in a rising water level scenario (Jankowski et al., 2017; Tessler et al., 2018). The State of Louisiana is currently implementing an ambitious 50-year, $50 billion coastal restoration and protection plan (CPRA, 2017). Information on the ability of wetlands in different parts of the delta to maintain elevation with rising water levels is critical to evaluating the success of different restoration approaches.

Here, we discuss decadal patterns of accretion and elevation change in marshes of the BMC on the eastern flank of the Mississippi Delta. In 2018, we re-measured SET and marker horizon sites initially established in 2003. In this paper our objectives are to: 1) examine changes in accretion and elevation change over periods of up to 15 years; 2) compile these findings with data gathered from nearby Coastwide Reference Monitoring System (CRMS) sites located around the periphery of the BMC established in 2007–2008; and 3) discuss factors affecting accretionary dynamics in the BMC especially with respect to sustainable restoration of the area. We hypothesized that accretion and elevation gain would be greater at sites near sediment sources and that areas within BMC with higher subsidence rates would have lower rates of relative elevation gain.

1.1. *Study area*

The Mississippi delta is made up of several interdistributary estuarine basins separated by current and abandoned river distributary channels (Blum and Roberts, 2012). The BMC, located ~50 km southeast of New Orleans, was formed by the St. Bernard delta 2000 to 4000 years ago (Scruton, 1960; Roberts, 1997). Since then, approximately half of the original wetlands have been lost to open water due to shoreline erosion and coastal subsidence (Yuill et al., 2009) primarily on the eastern side of the BMC, which has been exacerbated by human activity (e.g., Day et al., 2000; Thomason, 2016; Twilley et al., 2016). Marsh edge erosion rates associated with significant storm events for the BMC have been reported to be as high as 62.3 m/yr (Trosclair, 2013). Numerous natural crevasses and minor distributaries as well as seasonal overbank flooding of the Mississippi River via Bayou La Loutre sustained the surface elevation of the wetlands prior to Mississippi River levees (Condrey et al., 2014; Saucier, 1963; Welder, 1959). The flooding of Bayou La Loutre created the present day Bayou La Loutre ridge, forming the only uplands in the region that support oak trees, road access, and the limited development. Linear 'lagoons' or 'levee flank depressions' running parallel on either side of Bayou La Loutre are often characterized by higher subsidence rates and lack hydrologic connections to other water bodies (Treadwell, 1955). The BMC currently encompasses approximately 900 km^2 of contiguous wetlands surrounded with an equal area of open water and dispersed wetland islands (Fig. 1).

The construction of the Mississippi River Gulf Outlet (MRGO), a major navigation channel directly connecting the Gulf of Mexico to New Orleans, during the 1960's was a major anthropogenic impact to the BMC. The construction of the channel altered the hydrology of the area by acting as a conduit for more rapid tidal exchange, allowing fresh water to drain quickly during low tide and be quickly replaced by saline waters at high tide, increasing the salinity range of the region (USACE, 2012). Increased salinities killed large swathes of cypress forests to the north and west (Saltus et al., 2012; Shaffer et al., 2009) as well as clams, *Rangia cuneata*, in Lake Borgne that were important for shoreline stabilization (Poirrier and Caputo, 2015). A rock dam was installed below the Bayou La Loutre crossing in 2009 to prevent saltwater from flowing northward through the channel.

The Coastal Protection and Restoration Authority (CPRA) coordinates the implementation of Louisiana's Comprehensive Master Plan for a Sustainable Coast (CPRA, 2017). The master plan identifies and prioritizes projects that build or maintain land and reduce risk to communities. Of the several candidate BMC restoration projects considered for the 2017 master plan, only one (Bayou La Loutre Ridge Restoration) was included in the approved plan. The other projects did not show long-term (i.e., 50 years) benefits in part due to high subsidence rates predicted by BMC models. Understanding how surface elevation changes in this region in response to subsidence is thus a key issue for management and inclusion of the BMC in future master plans (Day et al., 2019).

2. Methods

Thirty surface elevation/accretion monitoring sites were established

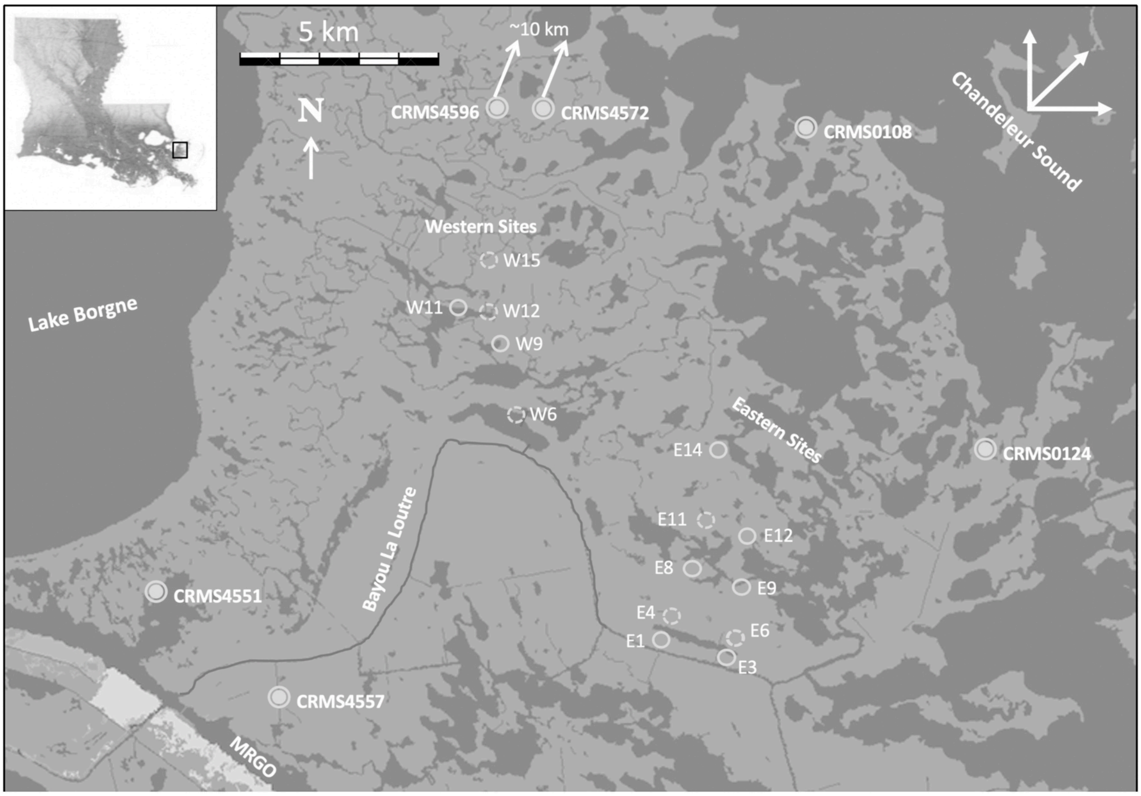

Fig. 1. Study site map indicating locations of Eastern and Western sites as well as CRMS sites. Solid circles indicate where accretion and elevation were measured, while dashed circles indicate where only elevation was measured.

in the BMC in 2003 as part of a research study. The sites were positioned in two areas, near Stump Lagoon to the west and near Blind Lagoon to the east (Fig. 1), referred to as the Western and Eastern sites in this paper. Measurements were made at both areas in 2003, 2004, and 2005, and at the Eastern sites in 2008. A field campaign to revisit the sites was conducted in 2018 to enable estimation of decadal scale changes, and fourteen of the original thirty sites were successfully located. Five SET sites were located at the Western area (W6, W9, W11, W12 and W15), and nine sites were found at the Eastern area (E1, E3, E4, E6, E8, E9, E11, E12 and E14).

Wetland elevation was measured using a surface elevation table (SET; Boumans and Day, 1993; Cahoon et al., 2000; Day et al., 1998, 1999; Lane et al., 2006; Osland et al., 2017) and vertical accretion was measured using feldspar marker horizons (Cahoon and Turner, 1989; Lane et al., 2006, 2017). The rate of shallow subsidence was calculated as the difference between vertical accretion and surface elevation change (Cahoon et al., 1995).

2.1. Wetland surface elevation

Each SET site consists of a supporting base support pipe of a 7.5-cm diameter thin walled aluminum driven vertically into the soil 4–6 m until refusal with a vibracorer (Boumans and Day, 1993; Cahoon et al., 2000, 2002a). The upper end of the base support pipe was fitted with another machined notched pipe designed to receive the upper portable part of the SET. The portable part of the SET is a precisely machined device that can be leveled in two planes and positioned in four directions around the base support pipe. Once leveled, the plate at the end of the SET is in the exact same position during every measurement, providing a constant reference plane in space from which the distance to the sediment surface is measured repetitively through time (Cahoon and Reed, 1994; Cahoon et al., 1999). Nine 3-mm diameter 91-cm-long metal rods (i.e. pins) were used to measure the distance to the wetland surface in four quadrants, providing 36 measurements per sampling effort. The accuracy of this technique is ±1.5 mm (Boumans and Day, 1993; Cahoon et al., 2002a). The rate of elevation change was calculated as the mean difference between individual pin measurements divided by the amount of time since the first measurement. Boards were temporarily placed on the wetland surface during measurements to minimize disturbance of the surrounding surface (as in Lane et al., 2006).

2.2. Wetland vertical accretion

Vertical accretion was measured as the rate of accumulation above feldspar marker horizons placed on the soil surface at the same time as the first SET measurements. Powdered feldspar clay was laid on the wetland surface ~1 cm thick at plots next to each SET platform. The thickness of material deposited on top of the feldspar marker was measured by taking a ~20 cm × 20 cm plug using a shovel or cryogenic coring device, then measuring the thickness of material above the surface of the horizon at 5–10 different locations on cleaned surfaces (Lane et al., 2006, 2017). The rate of vertical accretion was calculated by dividing the thickness of material above the feldspar horizon by the amount of time the horizon had been in the sediment.

2.3. CRMS data

In 2003, the Louisiana Coastal Protection and Restoration Authority (CPRA) and the U.S. Geological Survey (USGS) began implementing the Coastwide Reference Monitoring System (CRMS) as a mechanism to monitor and evaluate the effectiveness of coastal restoration projects (Steyer et al., 2003). Six CRMS sites are located along the periphery of the contiguous BMC (Fig. 1). CRMS4551 and CRMS4557 are located on either side of western Bayou La Loutre, CRMS0108 and CRMS1024 are located to the east, and CRMS4572 and CRMS4596 are located on the northern reaches of the contiguous Biloxi marshes (Fig. 1).

CRMS uses the Rod Surface Elevation Table (RSET) method to estimate surface elevation change rates (Cahoon et al., 2002b). This method is very similar to the SET methodology described above. Accretion at CRMS sites is measured as the thickness of material deposited above a feldspar marker horizon, as described in the methods above. Original marker horizons were established concurrently with baseline RSET measurements, but new feldspar marker horizons were regularly established every two years, providing multiple accretion data sets. Long-term rates of elevation and accretion were estimated from regression fits with the data.

2.4. Statistical analysis

All statistical analyses were carried out using JMP IN Version 12 produced by SAS Institute, Inc (Sall et al., 2017). Analysis of Variance (ANOVA) was used to detect differences between means, and comparison of means with significant ANOVA tests were made using the Tukey-Kramer Honestly Significant Difference (HSD) test. All analyses were conducted using a p-value of 0.05 to determine significance.

3. Results

Nine SET sites were measured at in the Eastern area: E1, E3, E4, E6, E8, E9, E11, E12 and E14 (Fig. 1). All these sites had net positive 2018 elevation change over the entire period ranging from ~4 to 9 cm, and rates of elevation rise ranging from 0.27 to 0.57 cm/yr (Table 1, Fig. 2). Accretion was measured at six of the nine sites in 2018, ranging from 8.50 to 14.74 cm, equivalent to 0.50–0.94 cm/yr (Table 1). Overall, the Eastern sites had a mean rate of elevation change of 0.40 ± 0.03 cm/yr and accretion of 0.64 ± 0.07 cm/yr (Fig. 4).

Five SET sites were measured at the Western area: W6, W9, W11, W12 and W15 at all intervals (Fig. 1). All except site W9 had decreased in elevation ~ -4 to −9 cm by 2018 compared to initial measurements taken in 2003 (Table 1; Fig. 3). W9 maintained elevation with 2018 measurements 1.24 cm higher than initial measurements taken in 2004, indicating a rate of elevation increase of 0.08 cm/yr (note that site W9 was the only site without 2003 data). The other Western sites had deceasing rates of elevation change ranging from −0.27 to −0.62 cm/yr (Table 1). Accretion markers were found in 2018 at sites W9 (5.13 cm) and W11 (9.75 cm), which equates to average rates of 0.35 and 0.63 cm/y, respectively. Overall, the Western sites had a mean rate of elevation change of −0.35 ± 0.13 cm/yr and accretion of 0.49 ± 0.14 cm/yr.

The six CRMS sites had positive rates of elevation change, ranging from 0.41 to 1.03 cm/y. The lowest rates of elevation change were at the three northeastern sites; CRMS4596, CRMS4572 and CRMS0108. Accretion was relatively high, ranging from 0.99 cm/yr at the northernmost site CRMS4572, to 1.70 cm/yr at site CRMS4557 located south of the Mississippi River Gulf Outlet (MRGO) rock berm (Fig. 1; Table 2). Overall, the CRMS sites had a mean rate of elevation change of 0.72 ± 0.09 cm/yr and accretion of 1.30 ± 0.11 cm/yr (Fig. 4).

At all sites, vertical accretion was always greater than surface elevation gain, with the difference due to shallow subsidence caused by compaction and consolidation of the substrate between the wetland surface and the end of the SET pipe (Cahoon et al., 1995). Shallow subsidence, as calculated as the difference between mean elevation change and mean accretion, ranged from 2.07 cm at E3 to 19.27 cm at W11, with average rates of 0.13 and 1.25 cm/y, respectively. Shallow subsidence at the CRMS sites, as calculated as the difference between mean elevation change and mean accretion, ranged from 0.29 cm/yr to 1.07 cm/yr (Table 2). Overall, shallow subsidence averaged 0.76 ± 0.49 cm/yr at the Western sites, 0.23 ± 0.06 cm/yr at the Eastern sites, and 0.58 ± 0.11 cm/yr at the CRMS sites (Fig. 4).

4. Discussion

There was a general pattern of elevation loss at the Western sites (−0.35 ± 0.13 cm/yr) and elevation gain at the Eastern sites (0.40 ± 0.03 cm/yr) and CRMS sites (0.72 ± 0.09 cm/yr; Table 1). Global eustatic sea-level rise (ESLR) is currently approximately 0.3 cm/yr (Sweet et al., 2017). Wetland surface elevation gain was greater than ESLR at the CRMS sites and the Eastern sites with exception of perhaps E11, which had an elevation change rate of 0.27 cm/yr (Table 1), which is near the limit for maintaining relative position in the tidal frame under ESLR. All the sites measured at the Western sites had decreasing elevation, or maintaining as in the case of W9, and thus will not keep pace with sea level rise without intervention with sediment addition and marsh nourishment. At current rates of elevation loss and ESLR, the Western sites will be submerged within the next several decades. In contrast to the Western area, elevation at the Eastern sites increased at a rate of 0.40 cm/yr (Fig. 4). Elevation gain was greater than sea level rise at the Eastern and CRMS sites, suggesting that these wetlands are more likely to keep pace with sea level rise and likely survive into the second half of the 21st century.

Lane et al. (2006) report a similar range in elevation changes for SET sites surrounding the Violet Canal located approximately 30 km west of the BMC. These sites were decreasing at a rate of −1.10 to −2.34 cm/y, compared to sites in the Breton Sound estuary that were increasing by 0.16–0.42 cm/y. It should be noted that the very high rate of elevation loss (−2.34 cm/y) at Violet Canal was due to a fire deliberately set for wildlife management purposes (Lane et al., 2006). The Violet fire was likely started in the late winter or early spring in order to burn off dead vegetation from the previous year, allowing room for new growth. The

Table 1
Elevation and accretion data using 2018 data compared to initial data (2003 for all sites except W9, which was 2004).

Site	Elevation (cm)	Elevation Change Rate (cm/yr)	Accretion (cm)	Accretion Rate (cm/yr)	Subsidence (cm)	Subsidence Rate (cm/yr)
W6	−8.85	−0.58	.	.	.	.
W9	1.24	0.08	5.13	0.35	3.89	0.26
W11	−9.52	−0.62	9.75	0.63	19.27	1.25
W12	−5.34	−0.35	.	.	.	.
W15	−4.12	−0.27	.	.	.	.
E1	5.30	0.34	7.76	0.50	2.46	0.16
E3	8.90	0.57	10.97	0.70	2.07	0.13
E4	6.99	0.45	.	.	.	.
E6	7.42	0.47	.	.	.	.
E8	5.22	0.33	9.48	0.60	4.26	0.27
E9	7.03	0.45	14.74	0.94	7.71	0.49
E11	4.22	0.27	.	.	.	.
E12	5.90	0.37	8.96	0.57	3.06	0.19
E14	6.16	0.39	8.50	0.54	2.34	0.15

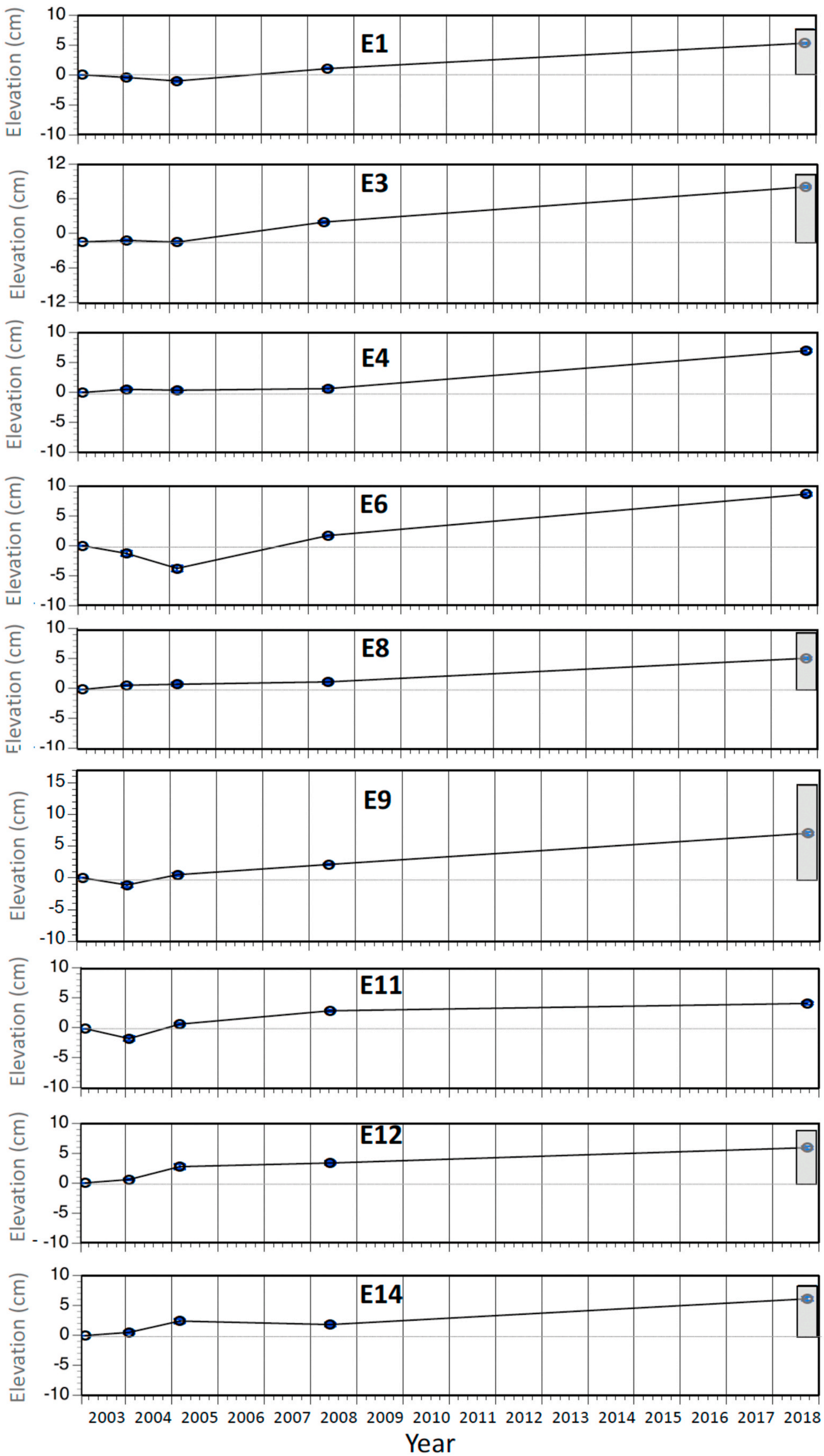

Fig. 2. Elevation (dots connected by lines) and accretion (shaded bars) at the Eastern SET sites from 2003 to 2018. Zero represents initial wetland surface elevation.

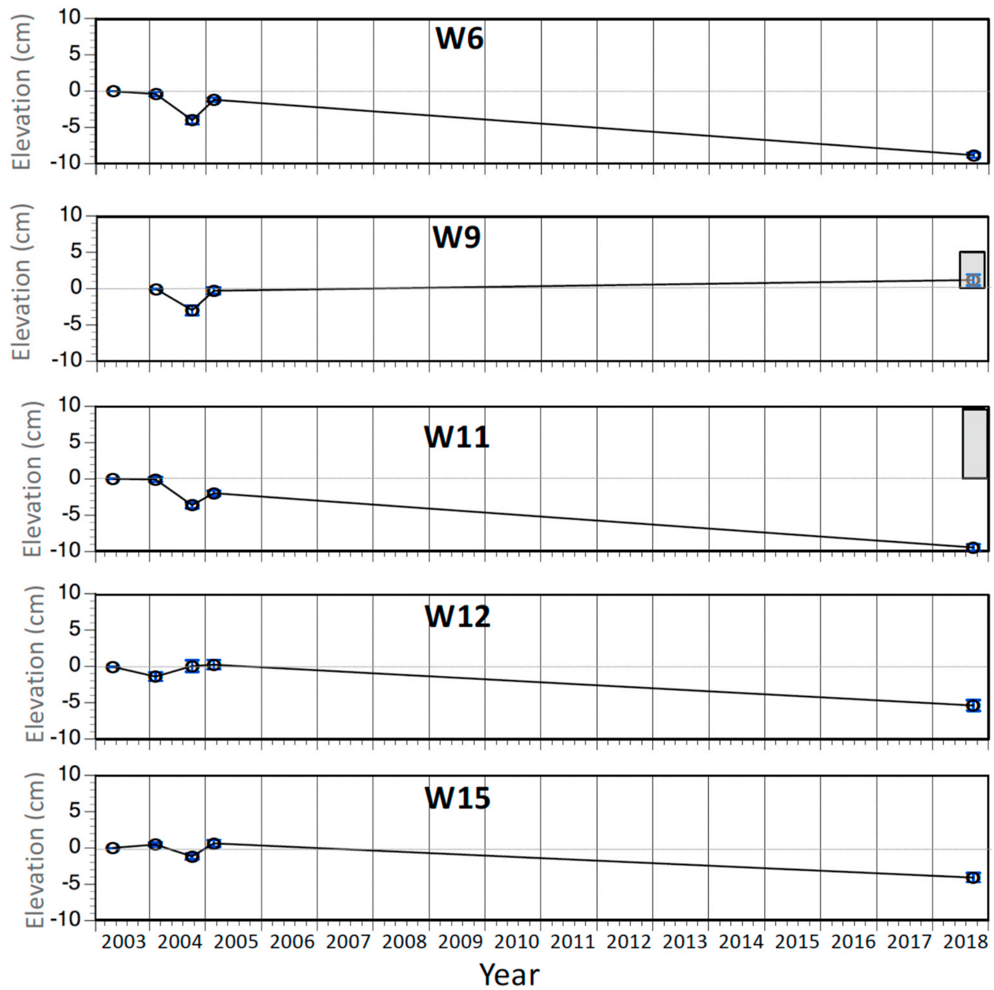

Fig. 3. Elevation (dots connected by lines) and accretion (shaded bars) at the Western SET sites from 2003 to 2018. Zero represents initial wetland surface elevation. Note that 2003 data were not available for site W9.

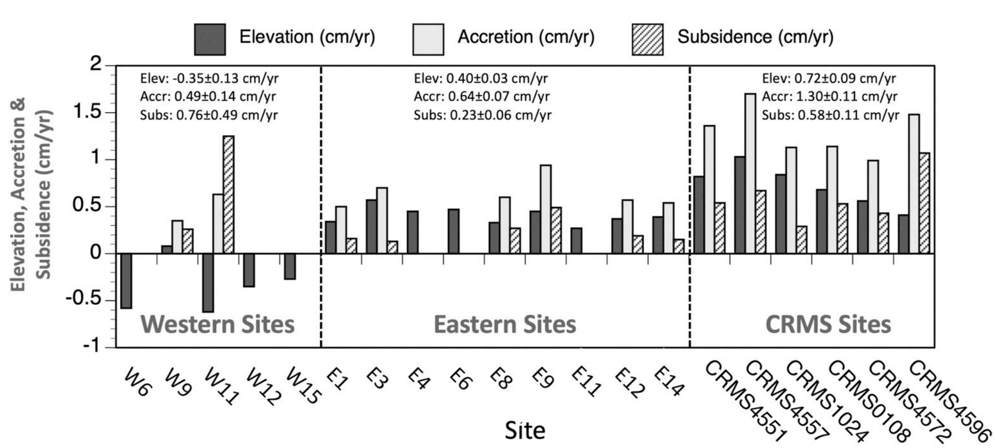

Fig. 4. Elevation change (black bars), accretion (grey bars) and subsidence (cross hatched bars) at the Western (left), Eastern (middle) and CRMS (right) study sites. Mean elevation, accretion and subsidence (±se) are provided above for each site type.

wetland elevation at this site decreased by over 4 cm due to the fire, decreasing the ability of the wetland to maintain elevation in face of relative sea-level rise. There is also evidence that plants regenerating after fire are particularly attractive to herbivores such as nutria, which increases the impacts of herbivores on the vegetation (Ford and Grace, 1998; McFalls et al., 2010).

There was evidence of fire at many of the SET sites at both the Eastern and Western areas. Fire is a widely used management tool to improve habitat quality for wildlife in coastal Louisiana (Nyman and Chabreck, 1995) and may have occurred spontaneously prior to human intervention (Viosca, 1931). There has been little research into the effect of burning on wetland elevation or accretion, but 'root burns' and 'deep

Table 2
Summary table of CRMS data from sites in the Biloxi marshes.

site	Accretion Est.2008 (cm/yr)	Accretion Est.2010 (cm/yr)	Accretion Est.2012 (cm/yr)	Accretion Est.2014 (cm/yr)	Accretion Est.2016 (cm/yr)	Mean Accretion (cm/yr)	Elevation (cm/yr)	Subsidence (cm/yr)
CRMS0108	0.61	0.92	1.37	0.88	1.94	1.14	0.68	0.53
CRMS1024	1.66	0.96	0.57	1.20	1.24	1.13	0.84	0.29
CRMS4551	1.44	1.25	0.78	1.32	2.03	1.36	0.82	0.54
CRMS4557	1.61	1.55	1.17	2.38	1.79	1.70	1.03	0.67
CRMS4572	0.86	0.69	0.54	0.79	2.05	0.99	0.56	0.43
CRMS4596	1.08	0.90	1.66	1.70	2.06	1.48	0.41	1.07

peat burns' that in some cases have burned the wetland down to the underlying clay subsoil have been documented in coastal Louisiana (Lynch, 1941). Some studies have found increases in above ground productivity associated with burns along the Gulf coast (Whipple and White, 1977; Hackney and de la Cruz, 1983), while others reported substantial decreases (Ford and Grace, 1998). Cahoon et al. (2010) examined sites subject to burning at Blackwater NWR in Maryland, and found significant increases in above- and below-ground plant production. Annually burned marshes were found to have the lowest surface accretion, root zone subsidence, shallow subsidence, and elevation deficit (i.e., lagged behind the relative sea-level rise rate) compared to other treatments but the effects were not significant. The impact of fire on long-term elevation trends in the BMC is difficult to quantify, but evidence of burning, such as melted marker poles, were found at most of the sites, and fire undoubtedly impacted elevation. The prevalence of fire could explain why we were unable locate many of the sites since marker poles had melted to the ground in many locations making finding decade old sites in tall vegetation nearly impossible.

Accretion was lower at the Western sites, with an average of 0.49 ± 0.14 cm/yr compared to 0.64 ± 0.07 cm/yr at the Eastern sites, though they were not statistically different. These trends are consistent with the observation that sediment is brought in from Chandeleur Sound to the east or Lake Borgne to the west and is attenuated as deposition occurs across the landscape from east to west. Accretion at the CRMS sites was much higher (1.30 ± 0.11 cm/yr) likely due to proximity to open bay waters where re-suspended sediments are present as well as the erosion of the marsh edge (Reed, 2002). These accretion measurements are comparable with accretion reported at the Violet Canal ranging from 0.34 to 0.44 cm/y, and at the Breton Sound estuary ranging from 0.75 to 1.57 cm/yr (Lane et al., 2006).

This study calculated mean shallow subsidence rates of 0.76 ± 0.49 cm/yr at the Western sites, 0.23 ± 0.06 cm/yr at the Eastern sites, and 0.58 ± 0.11 cm/yr at the CRMS sites, with and overall mean for all BMC sites of 0.46 cm/yr. We note that the 0.76 cm/yr given here for the Western area should be used with caution as it is derived from only two values, a low rate of 0.26 cm/yr, and 1.25 cm/yr, the highest calculated rate. In general, the range of shallow subsidence rates reported here trend lower than the ~0.54 cm/yr deep subsidence rate estimated by Applied Coastal Research and Engineering in their recent study of subsidence rates for this part of the Mississippi Delta Plain (ACRE, 2019), and are also lower than others reported rates from Louisiana and other deltas (Day et al., 1999, 2011a; Hensel et al., 1999; Ibanez et al., 1997; Lane et al., 2006). Jankowski et al., (2017) reported peak subsidence of ~1.5 cm/yr using data from 185 CRMS sites in the Mississippi delta. Lane et al. (2006) reported rates of subsidence in the Breton Sound estuary southwest of the BMC ranged from 0.59 to 1.21 cm/y, and from 1.52 to 2.78 cm/yr along the Violet Canal. Cahoon et al. (1995, 1999) reported shallow subsidence of 0.5 and 1.5 cm/yr for Old Oyster Bayou and Bayou Chitigue, respectively, located in coastal Louisiana. Shallow subsidence in the Rhone, Po, and Venice wetlands of the Mediterranean ranged from 0.1 to 0.9 cm/yr (Ibanez et al., 1997; Day et al., 1999, 2011a; Hensel et al., 1999).

The Western sites are located adjacent to and within ponds north of a meander of the old Bayou La Loutre distributary channel. These elongated ponds on either side of the Bayou La Loutre ridge are also described as levee flank lagoons (Treadwell, 1955), and form in back swamp positions adjacent to distributary channels. They are evidence of a localized component of subsidence that occurs parallel to the partially buried natural levee flanks of abandoned distributary channels. Locally distributed lithologic differences between the 50–100 ft thick sandy channel system of Bayou La Loutre and the clay- and organic-rich bays and swamps adjacent on either side of distributary channels are responsible for pond development. Clays and peat deposited in interfluve areas are highly compactible while sandy channels are relatively non-compactible (Meckel et al., 2007). The lack of hydrologic connections to other water bodies (Treadwell, 1955) further emphasizes the typical isolation of these interior ponds and local influence of levee flank subsidence patterns. In general, shallow subsidence is low in the BMC, but is greater in pond areas near the Bayou La Loutre ridge.

The validity of using the surface elevation table–marker horizon (SET-MH) has come into question. Although the SET-MH method has been used world-wide, Byrnes et al. (2019) argued that SET-MH measures should not be included in determining subsidence measures because subsidence is a purely geologic process, separate from biophysical processes occurring in the active marsh zone. Byrnes et al. (2019) contend that shallow subsidence measured by the SET-MH method in deep Holocene sediments are not valid because of down-drag on the rod, and that the high spatial variability of wetland surface processes precludes the ability to make meaningful estimates of subsidence using the SET-MH method. In reply, Cahoon et al. (2020) demonstrated that it is not only reasonable but also essential to apply the SET-MH method to obtain a complete as possible assessment of surface elevation dynamics to inform coastal wetland restoration and management planning in coastal Louisiana and other coastal wetlands worldwide.

The information from this study has implications for sustainable restoration of the BMC, the Louisiana Coastal Master Plan, and for coastal regions in general in a rising sea level scenario. In the development of the Coastal Master Plan, the Louisiana Coastal Protection and Restoration Authority (CPRA) used comprehensive modeling to project wetland sustainability given future climate projections. Estimates of subsidence are important inputs to the modeling and until recently, estimates of shallow subsidence for periods of more than just a few years have not been available. For the 2017 Coastal Master Plan, CPRA used a subsidence polygon map depicting geographic areas to which estimated ranges of subsidence rates were assigned based on best professional judgement due to lack of comprehensive data sets (Reed and Yuill, 2017; CPRA, 2017). The subsidence rates for the polygon that included the BMC were 0.3–1.0 cm/yr and the rate used in the modeling prediction to select projects was 0.65 cm/yr, greater than subsidence rates for most SET and CRMS sites in the BMC (Tables 1 and 2). In addition, results of this study show that accretion and surface elevation change rates at many of the Eastern and Western sites as well as the CRMS sites are higher than subsidence rates used by the 2017 Coastal Master Plan. Decadal scale data sets, such as those examined in this study should be of value during the next iteration of Coastal Master Plan development.

The variations in accretionary dynamics, the role of sediment supply patterns, and their consideration is restoration planning applies to the rest of the Mississippi delta and coastal systems world-wide. Day et al. (2011a) showed that an area receiving regular riverine input from the Atchafalaya River was more sustainable than a similar marsh area that was isolated from riverine input. The emerging Atchafalaya delta complex is one of the most sustainable area of coastal Louisiana because of high riverine input (Twilley et al., 2016). Globally, areas with high riverine input are more sustainable. Day et al. (2011b) reported northwestern Mediterranean deltas with strong riverine input had accretion and surface elevation change rates almost an order of magnitude greater than areas without riverine input. Anthony et al. (2010) reported that rapid and sustained fluid-mud concentration and trapping are associated with fresh water–salt water interaction and estuarine front activity on the continental shelf between the Amazon and Orinoco rivers due to the enormous Amazon water and sediment discharge. The dynamics of sedimentation processes at the landscape scale is an important factor in restoration planning, and measurements across large systems and over decadal time scales, as described, here can provide important insights not available from local short-term studies.

5. Conclusions

This study examined changes in accretion and elevation change over periods of up to 15 years in the BMC. Generally, there was elevation gain at the Eastern and CRMS sites and elevation loss at the Western sites. The Western sites, noted to be associated with local areas of more rapid subsidence, are in danger of submergence without intervention due to ESLR. In contrast, the increase in elevation at Eastern sites suggests that elevation kept up with ESLR and that the eastern sites are within an effective sediment transport and retention system. The results of the study suggest that both accretion and subsidence can vary significantly across a marsh landscape that otherwise appears relatively homogenous.

Western region sites in levee flank depressions associated with Bayou La Loutre are experiencing locally high subsidence and are also isolated from mineral sediment sources. All of the Western SET sites had decreased elevation (with exception of W9) in 2018 compared to 2003, and thus will not keep pace with sea level rise without intervention, such as marsh sediment nourishment. In contrast, wetland surface elevation gain from 2003 to 2018 was greater than sea level rise at the Eastern SET sites (with exception of E11), suggesting that the northeastern interior wetlands of the BMC will keep pace with sea level rise, as will the wetlands on the periphery of the BMC, as indicated by data from the CRMS stations. These trends are consistent with the concept that sediment is resuspended and brought in from Chandeleur Sound to the east and deposition is attenuated across the landscape from east to west.

In general, our study provides insights for discussions of coastal wetland sustainability with rising sea levels. Eustatic sea-level rise, subsidence and accretionary dynamics must be considered in determining wetland sustainability. For the BMC, we showed that both subsidence and accretionary dynamics varied significantly and produced different conclusions about wetland sustainability and restoration approaches. For example, the stations adjacent to the abandoned Bayou La Loutre distributary are less sustainable because of sinking of flanking lagoons results in higher subsidence rates. Thus, sediment nourishment may be needed in these areas for marshes to survive.

Credit author statement

Robert R. Lane: Conceptualization, Investigation, Formal analysis, Writing - original draft, Denise J. Reed: Conceptualization, Writing - review & editing, Data curation, John W. Day: Writing - review & editing, G. Paul Kemp: Writing - review & editing, Elizabeth C. McDade: Writing - review & editing, William B. Rudolf: Funding acquisition

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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