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CONSTRUCTED WETLANDS

Seasonal Sediment Dynamics in a Constructed and Natural Tidal Marsh in the Northern Gulf of Mexico

Jacob M. Dybiec[1] · **Morgan Sharbaugh**[1] · **Shelby Rinehart**[1] · **Julia A. Cherry**[1,2]

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Abstract

Reduced sediment loading contributes to tidal marsh loss, making evaluations of sediment dynamics useful in assessing marsh resilience to sea-level rise. Tidal marsh construction can offset these losses, but sediment dynamics are less commonly assessed in these systems. Some studies suggest sediment dynamics should develop over time; however, these studies often focus on accumulation at a single time and/or place, without considering sediment composition (i.e., organic vs. inorganic). We compared seasonal sediment dynamics between a natural and 34-year-old constructed tidal marsh with limited hydrologic connectivity. In July 2021, we established permanent sampling points along one tidal creek in each marsh and made monthly measurements of sedimentation, organic matter accumulation, and surface scour for one year. We found that sedimentation and organic matter accumulation were lower in the constructed marsh, while surface scour was similar between sites. Additionally, the relationship between distance from the tidal creek mouth and sedimentation differed between marshes (positive in natural, negative in constructed), as did organic matter accumulation (no relationship in natural, positive in constructed). However, we found that both marshes followed similar seasonal trends in sediment accumulation (highest in summer, lowest in winter). Observed differences in sedimentation between marshes appear to be marsh-specific (due to limited hydrologic connectivity in the constructed marsh), as sedimentation rates between other natural and restored marshes in the region did not differ. Collectively, these results suggest that consideration of sedimentation rates, including spatial and temporal variation, is critical to develop adequate sedimentary dynamics in restored and constructed marshes.

Keywords Sedimentation · Tidal marsh · Tidal wetland constructed · Ecosystem resilience · Stability

Introduction

Tidal marshes contribute disproportionately to the provisioning of global ecosystem services. Despite this, an estimated 25–50% of tidal wetlands, including substantial area of tidal marsh, have been lost over the course of the last century, with an estimated ~6% loss in the past 20 years (Kirwan and Megonigal 2013; Duarte et al. 2015; Campbell et al. 2022). Recently, coastal stakeholders have increasingly turned to tidal wetland restoration and constructed projects to enhance wetland conservation efforts (Bayraktarov et al. 2016; Liu et al. 2016, 2021; Zhao et al. 2016). While the goal of restoration is to return the structure and functions of a given ecosystem to its original state, constructed projects attempt to offset the loss of one ecosystem by creating an equivalent area elsewhere, where it did not previously exist (Kentula 1996). Regardless of the method, structural and functional equivalency between restored or constructed wetlands and their natural counterparts has been achieved with varying success. Certain structural components, such as plant community composition and aboveground biomass production, recover quickly in some tidal wetlands (Ebbets et al. 2019). However, most hydrologic features, other biological structures, such as macroinvertebrate communities, and biogeochemical processes fail to achieve equivalency after decades to a century post-restoration/construction (Moreno-Mateos et al. 2012), suggesting that the structural and functional

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Jacob M. Dybiec is deceased. This paper is dedicated to his memory.

✉ Julia A. Cherry
cherr002@ua.edu

[1] Department of Biological Sciences, University of Alabama, Tuscaloosa, AL 35487, USA

[2] New College, University of Alabama, Tuscaloosa, AL 35487, USA

recovery of restored/constructed tidal wetlands is not guaranteed.

While there are several causes for the acceleration of tidal wetland loss, one of the primary drivers has been a decline in sediment loading to estuaries (Fagherazzi et al. 2013; Weston 2014). All tidal marshes require a minimum amount of sediment accumulation to maintain vertical (Weston 2014) and horizontal (Mariotti and Fagherazzi 2010; Fagherazzi et al. 2013) stability, with respect to sea level. However, changes in anthropogenic activities and land use in adjacent watersheds, such as the construction of dams and reservoirs, reforestation, and changes in agricultural practices, have drastically reduced the amount of sediment delivered to many tidal marshes (Kirwan and Megonigal 2013; Weston 2014). Declining sediment delivery impairs the capacity for tidal marshes to accrete vertically at a rate equal to or greater than that of local sea-level rise, an issue which will be exacerbated by climate change (Turner et al. 2005). It also accelerates erosion rates, as the expansion of tidal flats in response to reduced sediment loading increases the energy of waves as they reach the marsh edge (Mariotti and Fagherazzi 2013). Given the role of sediment delivery in promoting vertical and horizontal stability, and the general failure of restored/constructed wetlands to reach structural equivalency with natural systems, an understanding of sedimentary dynamics is vital to assess the long-term resilience of restored/constructed tidal marshes.

Sediment dynamics are not frequently assessed as part of post-restoration/construction monitoring programs. A recent systematic review of tidal restoration wetland success indicators found that only 19% of site-specific monitoring protocols included any measure of sediment dynamics, such as sediment elevation, vertical accretion, or sedimentation (Cadier et al. 2020). Studies that have focused on sediment dynamics in restored/constructed marshes have demonstrated that sedimentation is initially very high, as these sites are often low in elevation with respect to sea-level, leading to greater periods of inundation and sediment deposition (Williams and Orr 2002; Brand et al. 2012). As these marshes vegetate and accrete vertically over time, inundation depth and subsequent sediment deposition typically decrease, until an elevation equivalent to reference conditions is eventually reached (Morgan and Short 2002). However, this relationship is dependent on several factors, such as initial site elevation, hydrologic connectivity to the source of the sediment, the sediment trapping potential of established vegetation, and the method and design of the restoration/construction project itself (Bouma et al. 2010; Brand et al. 2012; Ganju 2019). Sediment dynamics may also vary temporally and spatially, yet most studies estimate sedimentation rates from samples collected at a single location and time point (Morgan and Short 2002; Williams and Orr 2002; Brand et al. 2012). Thus, understanding spatial and temporal variability in sedimentation will support more accurate estimations of marsh resistance and resilience to sea-level rise and erosion (Ganju et al. 2017).

To address this gap, we conducted a year-long comparison of sedimentation, surface organic matter accumulation, and surface scour between a natural marsh and a nearby 34-year-old constructed tidal marsh in the northern Gulf of Mexico with limited hydrologic connectivity to sources of suspended sediment. We used this site complex as a case study to highlight how failures to adequately consider hydrologic connectivity and sediment supply in initial design can have lasting impact on sediment quantity and quality, even decades after construction. We hypothesized that sedimentation would decrease and organic matter content would increase with distance from the mouth of the tidal creek in both marshes, as heavier mineral sediments are typically deposited before lighter organic sediments (Bartholdy et al. 2010). Additionally, to contextualize this case study, we conducted a short-term, but spatially robust (across ~ 100 km), survey of sedimentation between natural and restored/constructed marshes in the northern Gulf of Mexico.

Methods

Site Description

We conducted our study at a natural brackish tidal marsh (hereafter, NAT) and a nearby constructed tidal marshes (hereafter, CON-1) along the West Fowl River in Mobile County, Alabama, U.S.A (Fig. 1a). Tides at both marshes are diurnal but strongly meteorologically driven, with a mean tide of 1.49 MASL, mean high tide of 2.20 MASL, and mean low tide of 0.78 MASL during our study period. Mean temperature was 19.5° C, total precipitation was 184.28 cm, and mean discharge from the West Fowl River was 1.1 $m^3 s^{-1}$. The hydroclimatic conditions during our study period are representative of historical ranges for the area (Table 1). NAT is slightly higher in elevation with respect to sea level than CON-1 (NAT: 0.36 ± 0.01 m NAVD88, CON-1: 0.32 ± 0.04 m NAVD88; Ledford et al. 2021).

NAT is located directly adjacent to the West Fowl River, and the marsh platform is dominated primarily by *Juncus roemerianus* (black needlerush) and *Spartina alterniflora* (smooth cordgrass) and characterized by a series of naturally occurring tidal creeks (Fig. 1b). CON-1 was constructed when sections of pine savannah were excavated in parallel strips to an elevation of + 0.3 m mean sea level (MSL) and a single artificial tidal creek (i.e., canal) was dredged through the center of the marsh (Fig. 1c; Vittor et al. 1987). CON-1's artificial creek is connected to the West Fowl River via another narrow creek that was constructed in 1987 in

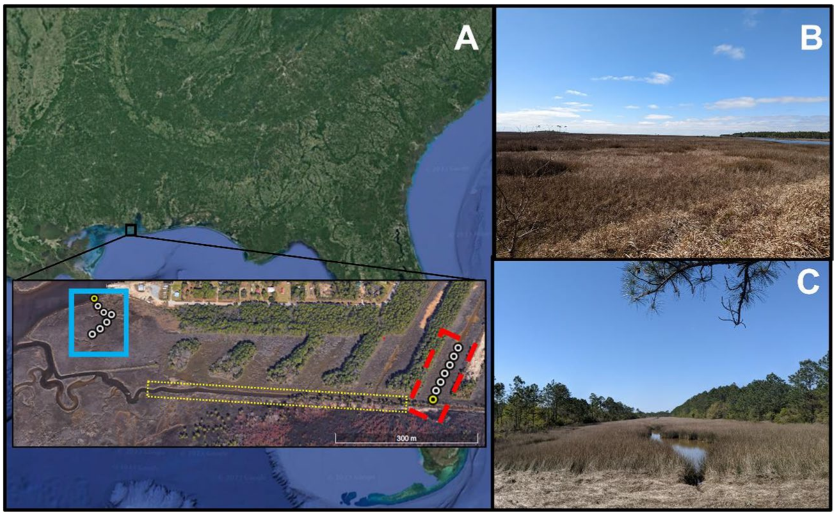

Fig. 1 Map of study site in Coden, AL, USA (A). NAT is directly adjacent to the Fowl River (blue, solid square, **B**), while CON-1 is ~ 0.5 km away (red, dashed square, **C**), located within pine savannah and connected to the Fowl River through a narrow, artificial tidal creek (yellow, dotted square, **A**). Sampling points on each tidal creek are denoted with circles, with the mouth of each tidal creek (0 m) denoted with a yellow circle

Table 1 Summary of hydroclimatic data for the West Fowl River for the years before (July 2020-June 2021), during (July 2021-June 2022), and after (July 2022-April 2023) our study. There were no significant differences in any of these parameters over time

Period	Mean Tide (MASL)[1]	Mean High Tide (MASL)[1]	Mean Low Tide (MASL)[1]	Mean Temperature (°C)[2]	Total Precipitation (cm)[2]	Mean Discharge (cm^3 s^{-1})[3]
2020–2021	1.41	2.14	0.68	19.8	177.67	1.19
2021–2022	1.49	2.20	0.78	19.5	184.28	1.09
2022–2023	1.45	2.19	0.71	19.1	144.48	1.31

[1] Data obtained from NOAA for the tidal gauge at the West Fowl River Bridge, AL (Gauge 8738043)

[2] Data obtained from Weather Underground for nearby Moss Point, MS

[3] Data obtained from USGS for the river gauge on the Fowl River in Laurendine, AL (Gauge 02471078)

accordance with Clean Water Act-mandated mitigation efforts (Fig. 1a). The marsh platform in CON-1 was planted with *J. roemerianus* and *S. alterniflora* in 1988 but is now dominated almost entirely by *J. roemerianus.* Vegetation along the creeks in both NAT and CON-1 is dominated by short-form *Spartina alterniflora* (smooth cordgrass).

Study Design

In July 2021, we set up 7 permanent sampling points at 25 m intervals along the first 150 m of one tidal creek in each marsh (Figure S1). At each sampling point, we installed two PVC poles to a depth of ~ 1 m, one at the edge ("edge") of the marsh and one ~ 0.5 m inland ("interior"; Figure S1). From July 2021-June 2022, we measured the change in height of both poles above the marsh surface each month to determine rates of surface scour (mm scour day^{-1}). The use of poles to monitor scour may alter local hydrology, with consequences for absolute rates of scour. However, these data permit assessment of relative scour rates between NAT and CON-1. We also installed two smaller PVC poles ~ 0.5 m inland of the marsh edge, to which we fastened a sediment trap (diameter = 8.5 cm) using zip ties (Figure S2; Leonard et al. 1995). We collected and replaced the sediment traps at each point monthly. The sediment from each trap was then dried at 60° C to a constant mass to determine total sedimentation, which we used to calculate rates of sedimentation (mg cm^{-2} day^{-1}). We then ashed the dried sediment in a 550° C muffle oven for six hours to determine organic matter content by loss on ignition (OM; %).

In August 2022, to contextualize observed sedimentation at these two sites, we conducted a short-term survey of sedimentation at three natural and seven restored/constructed marshes in the northern Gulf of Mexico (Table S2). At each site, we established three plots on the marsh platform in the dominant vegetation. In each plot, we installed two smaller PVC poles, to which we fastened a sediment trap (diameter = 8.5 cm) using zip ties as described above (Figure S2; Leonard et al. 1995). Traps were left in place for 52 days, at which point they were collected and processed as above to determine the total sedimentation rates at each site.

Statistical Analyses

To assess temporal sedimentary dynamics in both marshes, we first grouped data into seasons: Spring (March-June), Summer (June–September), Fall (September–November), and Winter (November-February). These groupings align with distinct periods of plant growth (emergence in Spring, peak growth in Summer, senescence in Fall, and dormancy in Winter). We used two-way repeated measures analyses of variance (ANOVA) with marsh and season as fixed factors, and distance within marsh as a repeated factor, to understand the seasonal dynamics of sedimentation, organic matter content, and scour (edge and interior). Normality of model residuals were assessed visually with diagnostic plots. To address spatial dynamics across time, we calculated Spearman correlation coefficients between each variable and distance from the mouth of each tidal creek by season. For our region-wide survey, we used a Mann–Whitney U test to assess differences in sedimentation rates between the natural ($n = 3$) and restored/constructed marshes ($n = 7$) due to unequal sample sizes among sites. All analyses were conducted in R 4.1.2 (R Core Team 2022).

Results

Sedimentation was significantly higher in NAT than CON-1 (F = 6.57, df = 146, $p = 0.011$; Fig. 2). Overall, sedimentation was nearly twice as high in NAT (2.25 ± 2.65 mg cm^{-2} day^{-1}) than in CON-1 (1.22 ± 2.46 mg cm^{-2} day^{-1}; Table 2). Additionally, sedimentation differed seasonally. Both marshes displayed similar seasonal dynamics, with sedimentation being highest in the summer, lowest in the winter, and intermediate in the spring and fall (F = 2.53, df = 144, $p = 0.059$; Table 2 and Fig. 2). OM also differed significantly between the two marshes, being slightly higher in NAT compared to CON-1 (16.50 ± 6.71 vs. 14.58 ± 5.60%; F = 4.11, df = 144, $p = 0.046$). However, OM did not differ significantly across seasons (Table 2 and Fig. 2; Table S1).

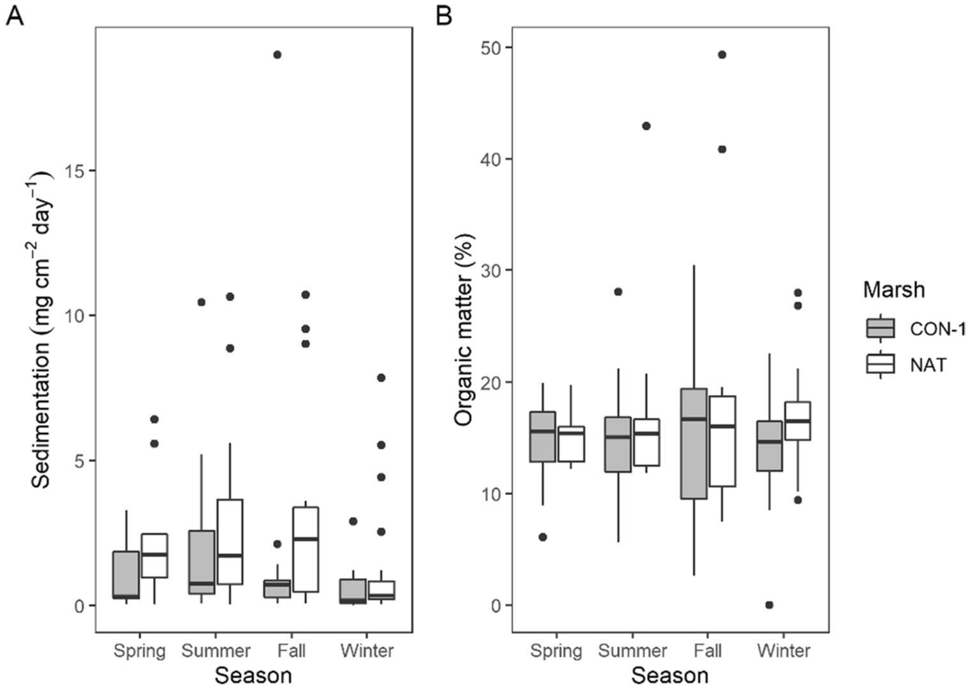

Fig. 2 Comparison of sedimentation rates (**A**) and percent organic matter of deposited sediment (**B**) across seasons and between CON-1 (grey) and NAT (white). Lines inside boxes are median values, box limits are Q1 and Q3, and whiskers represent non-outlier ranges. There were no significant pairwise differences

Table 2 Summary of seasonal sedimentary dynamics by marsh. "*" indicates a significant difference between marshes, and "#" indicates a significant difference between seasons

Marsh	Season	Variable			
		Sedimentation (mg cm^{-2} day $^{-1}$)$^{*,\#}$	Organic Matter (%)*	Edge Scour (mm day^{-1})	Interior Scour (mm day^{-1})
Constructed	Winter	0.51 ± 0.68	13.48 ± 5.48	-0.07 ± 0.43	0.04 ± 0.4
	Spring	0.94 ± 1.06	14.59 ± 3.92	-0.33 ± 1.17	0.02 ± 0.61
	Summer	1.71 ± 2.21	14.64 ± 4.77	0.32 ± 0.86	0.24 ± 0.69
	Fall	1.52 ± 4.03	15.65 ± 7.59	0.23 ± 1.10	0.08 ± 0.39
Natural	Winter	1.28 ± 2.1	17.05 ± 4.49	0.15 ± 0.68	0.07 ± 0.49
	Spring	2.13 ± 1.98	15.11 ± 2.20	0.02 ± 0.82	0.18 ± 0.83
	Summer	2.62 ± 2.71	16.02 ± 5.96	0.16 ± 2.14	0.28 ± 0.61
	Fall	2.90 ± 3.30	17.50 ± 10.91	0.92 ± 2.33	0.02 ± 0.77

Lastly, there was no significant difference in either edge or interior surface scour, either between marshes or across season (Table 2 and Fig. 3; Table S1), nor was there a significant interaction between marsh and season on edge or interior scour (Table S1).

Distance from the mouth of the tidal creek had a significant effect on sedimentation in both marshes, which was consistent across seasons. However, the nature of that relationship differed between sites, with sedimentation decreasing with increasing distance at CON-1 and increasing with increasing distance at NAT (Table 3). Distance from the mouth of the tidal creek was also associated with a significant increase in proportion of organic matter deposited at CON-1 in all seasons except winter, but not in NAT (Table 3). Interior and edge scour did not show any relationship with distance from tidal creek mouth, in either marsh or in any season (Table 3).

Across the northern Gulf of Mexico, we observed no difference in sedimentation between the three natural and seven restored/constructed marshes ($U = 68.0$, $p = 0.672$; Fig. 4), suggesting that CON-1 is unique regarding sedimentation relative to other restored/constructed marshes in the region.

Discussion

Declines in sediment loading coupled with pervasive sea-level rise threaten the long-term stability of tidal marshes. While tidal marsh construction and restoration projects have increasingly been used to offset recent losses, the ability of these systems to develop natural sedimentary dynamics over time has not been well established. Through a

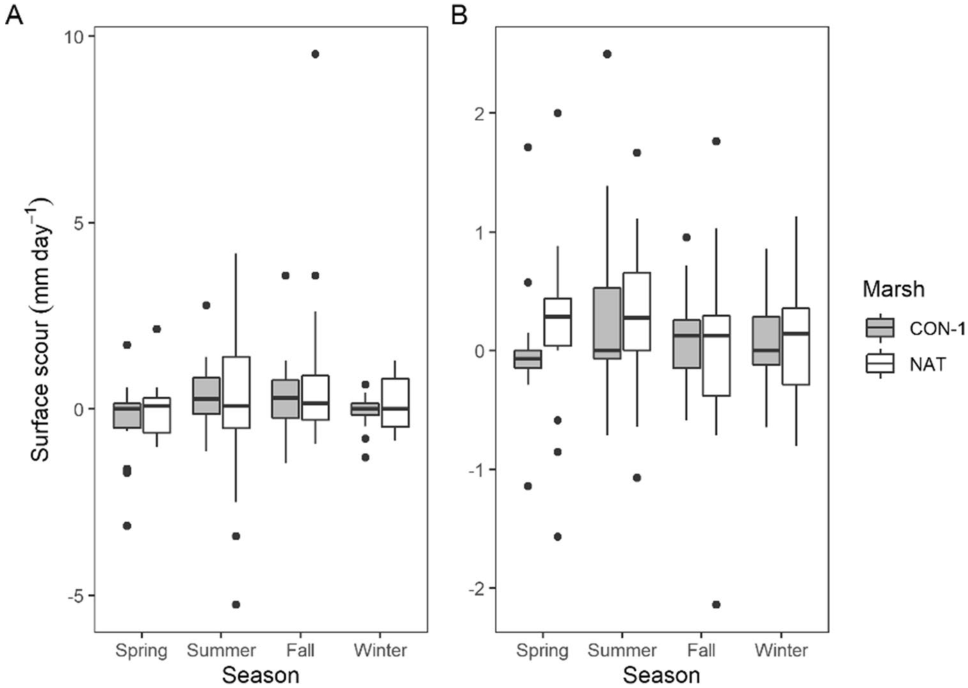

Fig. 3 Comparison of edge (**A**) and interior (**B**) surface scour rates across seasons between CON-1 and NAT. Lines inside boxes are median values, box limits are Q1 and Q3, and whiskers represent non-outlier ranges. There were no significant pairwise differences

Table 3 Spearman rank correlation coefficients between sedimentary dynamics and distance from tidal creek mouth by marsh

Marsh	Season	Variable			
		Sedimentation	Organic Matter	Edge Scour	Interior Scour
Constructed	Winter	–0.55**	–0.16	-0.38	0.06
	Spring	–0.70**	0.82***	0.36	–0.03
	Summer	–0.59**	0.69**	-0.06	–0.05
	Fall	–0.64**	0.54*	-0.38	–0.039
Natural	Winter	0.60**	–0.03	-0.19	0.0004
	Spring	0.84***	0.11	-0.34	0.15
	Summer	0.64**	0.27	0.11	–0.22
	Fall	0.47*	–0.25	-0.03	–0.19

$^{*}p = 0.05$, $^{**}p = 0.01$, $^{***}p < 0.01$

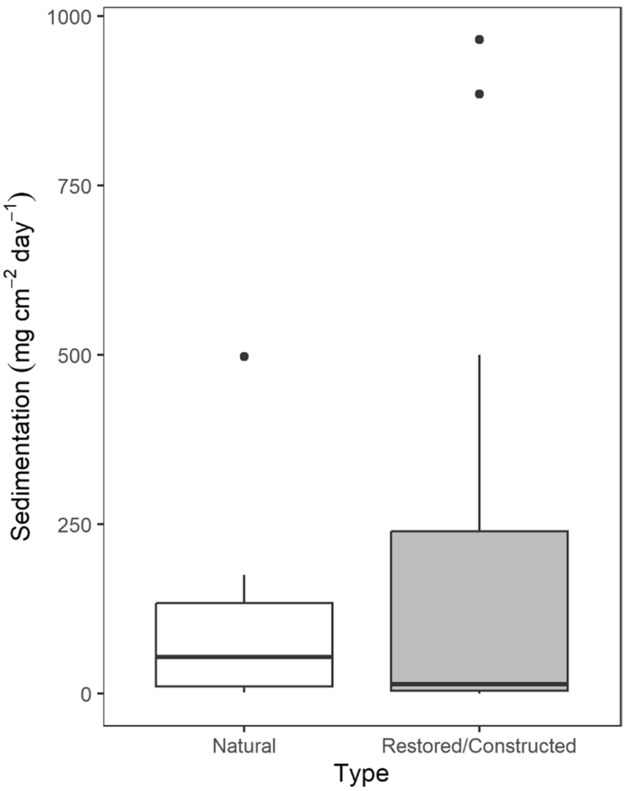

Fig. 4 Comparison of sedimentation rates between three natural and seven restored/constructed tidal marshes along the northern Gulf of Mexico. Lines inside boxes are median values, box limits are Q1 and Q3, and whiskers represent non-outlier ranges. There was no significant difference

year-long comparison of sedimentation, surface organic matter accumulation, and surface scour between a natural and constructed tidal marsh, we sought to address this gap in our understanding of marsh stability using a natural and constructed marsh with limited hydrological connectivity as a case study. As we expected, both sedimentation and organic matter accumulation were lower in the constructed marsh than in the natural marsh (Fig. 2). This difference was not the case for sedimentation in other restored/constructed marshes relative to natural marshes in the region (Fig. 4). Despite expecting surface scour to be greater in the natural marsh due to increased hydrological connectivity to the nearby Fowl River, we found no difference between the two marshes (Fig. 3; Table S1). Additionally, while the expected relationship between tidal creek distance and sedimentation/organic matter accumulation was present in the constructed marsh, it was not in the natural marsh (sedimentation increased with distance instead of decreased, while there was no spatial relationship with organic matter accumulation; Table 3). Collectively, these results suggest that the method of marsh construction at this study site failed to achieve adequate hydrologic connectivity to facilitate sedimentation at similar levels to the natural marsh, with implications for marsh resilience to sea-level rise.

Contrary to some past studies which have assessed sedimentary dynamics in restored/constructed tidal marshes, our results suggest that sedimentation rates in CON-1 have not reached equivalency with NAT, even 34 years-post construction. This result is despite CON-1 still being lower in elevation with respect to sea-level than NAT, which should promote higher rates of sedimentation through increased frequency and depth of inundation (Morgan and Short 2002; Williams and Orr 2002). CON-1 likely failed to achieve equivalent sediment dynamics to NAT because of two key shortcomings of its design. First, CON-1 has inadequate hydrologic connectivity to the West Fowl River, due in part to the distance from the river and its position relative to NAT. Hydrologic connectivity between a restored/constructed tidal wetland and its adjacent estuary is necessary to establish naturally equivalent tidal regimes (Callaway et al. 2007). Naturally equivalent tidal regimes would likely be associated with a greater sediment supply, which is necessary for vegetation to initially establish, and critical to the ability of these systems to build vertically at a rate greater than or equal to sea-level rise (Wolters et al. 2005; Weston 2014).

CON-1's limited hydrologic connectivity to the West Fowl River likely greatly reduced its sediment supply by constricting tidal exchange with the river and the Gulf of Mexico. Additionally, because the two marshes are separated by forest, the tides that inundate CON-1 must first pass-through NAT and the artificial tidal creek connecting the two (Fig. 1a); as such, much of the sediment which would be available to CON-1 is deposited in NAT. For these reasons, the potential supply of sediment in CON-1 should be lower than the potential in NAT. Preliminary sampling of suspended sediments in both marshes confirmed this difference, as the suspended sediment concentration in tidal creeks was three times greater at NAT than at CON-1 (NAT: 0.4 ± 0.5 mg/mL; CON-1: 0.1 ± 0.2 mg/mL; Appendix S2; Table S3). Similar reductions in sediment loading have been noted in restored/constructed tidal marshes with restricted tidal exchange, with unrestricted sites having upwards of 25 times more sediment accumulation than restricted sites (Oosterlee et al. 2020). These observations, in combination with ours, suggest that restored/constructed marshes with restricted tidal ranges and connectivity may struggle to achieve and maintain naturally equivalent sedimentary dynamics, regardless of time.

Second, the tidal creek at CON-1 lacks the morphological complexity observed in most natural tidal creeks. Tidal creeks facilitate the movement of materials like sediment throughout a marsh and can develop quickly in restored and constructed tidal marshes, assuming necessary hydrologic conditions for channel bottom erosion are present (D'Alpaos et al. 2007). However, after 34 years, the only tidal creek in CON-1 is the artificial one that was dredged through the center of the marsh in 1987, which has sustained a low sinuosity (i.e., straight) for 30 + years (Fig. 1). The persistence of this creek in its original form is likely due to the reduction in hydrological connectivity to the West Fowl River, which greatly reduces the wave energy needed for bottom channel erosion and formation of the tidal creek sinuosity typical of natural systems (Voulgaris and Meyers 2004). Further, sediment deposition across the marsh surface from sheet flow decreases exponentially as distance from the marsh edge increases (Leonard et al. 1995; Temmerman et al. 2005). Our spatial data indicate that areas further into the marsh platform along the CON-1 tidal creek had lower sedimentation rates than areas nearer the mouth of the creek (i.e., at 0 m; 25–150 m: 0.7 ± 0.8 mg cm^{-2} day^{-1}; 0 m: 4.1 ± 5.5 mg cm^{-2} day^{-1}). Increased tidal creek sinuosity could potentially increase the supply of sediments to areas further into the marsh platform, by promoting bottom channel erosion and surface sediment resuspension (D'Alpaos et al. 2007). As such, the development of morphologically complex tidal creeks may be an essential component of restoration efforts to facilitate sedimentation further into the marsh platform (Reed et al. 1999).

While sediment dynamics at CON-1 have not reached equivalency with NAT, this result does not appear to be representative of sedimentation for restored/constructed marshes in the region (Fig. 4), despite all these sites being considerably younger than CON-1 (7–19 vs. 34 years; Table S2). Contrary to CON-1, these other sites having a greater degree of hydrologic connectivity to the Gulf of Mexico or smaller waterbodies directly adjacent to the Gulf of Mexico (e.g., Weeks Bay; Table S2). Thus, the fact that the development of sedimentation dynamics at CON-1 lags other restored/constructed marshes in the region is not surprising and highlights the importance of considering hydrologic connectivity and sediment supply in the design phases of restoration/construction projects. Additionally, as is demonstrated by CON-1, time since restoration/construction alone may not overcome inadequate restoration or construction design.

We found variable relationships between tidal creek distance from the mouth and sedimentation/organic matter accumulation in both marshes. Sedimentation increased with increasing distance at NAT and decreased with increasing distance at CON-1. Likewise, while organic matter accumulation increased with increasing distance at CON-1, there was no relationship with distance at NAT (Table 3). As with the general differences in overall sedimentation and organic matter accumulation, variable relationships between tidal creek distance and sediment dynamics may be a result of differences in hydrology and tidal creek morphology. Patterns of sedimentation across tidal wetland surfaces are affected by several factors, such as elevation, distance from the nearest tidal creek or marsh edge, and tidal creek density (Temmerman et al. 2003; Voulgaris and Meyers 2004). As mentioned above, tidal creeks are more sinuous and denser at NAT than at CON-1. At smaller scales like those evaluated in this study (i.e., tens of meters), increased channel sinuosity has been correlated with increased rates of erosion (Priestas et al. 2015). Increased rates of erosion can lead to the resuspension of sediments on the marsh surface, potentially increasing supplies of sediment further into the marsh platform (Leonardi et al. 2018). Decreased sinuosity may also explain why there was a clear relationship between organic matter accumulation at CON-1 and not NAT; there are variable sources of sediment to the interior of the marsh platform at NAT (both from tides and resuspension) but not CON (only from the tides), making the relationship between sediment type and distance less predictable. Regardless of the reason, these results suggest that samples collected at a single site and time point are inadequate for fully characterizing the sediment dynamics of restored/constructed marshes. For example, had we focused only on points at the mouth of each tidal creek, we would have concluded that sedimentation was significantly greater at CON-1 than at NAT (4.1 ± 5.5 vs. 0.23 ± 0.41 mg cm^{-2} day^{-1}). As such, any post-project monitoring program aiming to assess the development of sedimentary dynamics must take these spatial differences into account.

We also noted significant differences in sedimentation through time for both marshes, which highlights the importance of considering seasonal variation in assessments of sediment dynamics. If we had only conducted our sampling during the spring or fall, we would have excluded the maximum and minimum periods of sedimentation in both marshes. Likewise, had we only conducted our study during the summer and extrapolated these data across time, we would have vastly overestimated total sedimentation (Table 2). As with space, sedimentation varies seasonally in tidal wetlands, depending on factors such as wave energy, sediment loading from adjacent estuaries, and seasonal patterns in plant growth (Lacy et al. 2020). While the seasonal patterns noted herein are common, they are not ubiquitous. For example, a similar study conducted in the Scheldt estuary in Belgium found that sedimentation was highest in winter and lowest in summer (Temmerman et al. 2003). Thus, it is important to fully consider space and time in assessments of restored/constructed wetland sedimentary dynamics, especially given that these dynamics may be region- or site-specific.

Our results also highlight the necessity of incorporating other factors, such as sediment type, into assessments of restored/constructed marsh stability. Due to its lower bulk density, organic matter has a more pronounced effect on elevation maintenance than mineral sediment (Turner et al. 2005; Morris et al. 2016). However, because it is more labile and can compact more easily over time, these contributions are often short-lived when compared to mineral sedimentation (McKee and Cherry 2009). Therefore, focusing on bulk sediment accumulation, instead of differentiating between the two, may result in inaccurate conclusions regarding marsh resilience to sea-level rise. We found only a slight difference in OM content of the sediment deposited between NAT and CON-1 (Fig. 2). Because overall rates of sedimentation between sites were so different, though, CON-1 is receiving significantly less organic matter, overall. A reduction in sediment scour (i.e., removal of surface sediment) in CON-1 may offset this reduction in organic matter accumulation. However, despite CON-1 being more protected from the impacts of waves, we found no difference in sediment scour between the two marshes (Fig. 3). The design of CON-1 is unusual, in that it was constructed inland, away from its source of water and sediment. However, our results highlight the necessity of considering sedimentary dynamics in the design phase of coastal restoration projects, as time alone may not be sufficient for more natural dynamics to develop.

In conclusion, our study demonstrates the importance of considering sediment supply in the design and monitoring phases of tidal marsh restoration and construction projects. While some restored/constructed tidal marshes do develop naturally equivalent sedimentary dynamics over time (Fig. 4; Williams and Orr 2002; Brand et al. 2012), others like CON-1 do not, even after decades, owing either to a lack of sediment supply (Weston 2014) or barriers to sediment delivery (Oosterlee et al. 2020). Effort should be made during the planning and implementation of tidal wetland restoration/construction to overcome these limitations as much as possible. However, reduced sediment supply is itself a major driver of tidal wetland loss (Fagherazzi et al. 2013; Weston 2014). As such, restoration/construction efforts will be needed in coastal areas where natural sources of sediment are in short supply. In these cases, additional management efforts that artificially increase sediment loading, such as thin-layer dredge disposal or sediment slurry addition, may overcome these deficits (Stagg and Mendelssohn 2011; Thorne et al. 2019). In cases where physical barriers to sediment loading exist, such as dikes or levees, breaching or removing barriers has been shown to readily increase rates of sedimentation (Gerwing et al. 2020). Considering these factors during the design, implementation, and monitoring of restoration/construction projects will promote the resilience of these wetlands to climate change.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s13157-023-01719-x.

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Author Contributions All authors contributed to the study conception and design. Material preparation and data collection were performed by Jacob Dybiec, Morgan Sharbaugh, and Shelby Rinehart. Data analysis and writing of all versions of this manuscript were performed by Jacob Dybiec, Morgan Sharbaugh, and Shelby Rinehart. Julia Cherry provided funding to conduct the study from her research overhead account in the Department of Biological Sciences at the University of Alabama. All authors have read and approved the final manuscript.

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Data Availability The datasets generated and analyzed during the current study are available in the "Fowl-River-Sedimentation-Project" repository (https://github.com/dybie1jm/Fowl-River-Sedimentation-Project).

Declarations

Competing Interests The authors have no relevant financial or non-financial interests to disclose.

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