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Factors influencing blue carbon accumulation across a 32-year chronosequence of created coastal marshes

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Abstract. Saline coastal marshes are blue carbon ecosystems with relatively high soil carbon (C) stocks and high rates of soil C accumulation. Loss of saline wetlands due to relative sea-level rise, land-use change, and hydrologic alterations liberates previously stored C and reduces the capacity for future C sequestration. Widespread wetland loss has prompted marsh restoration and creation projects around the world; however, little is known about the timescale and capacity for created marshes to function as blue C sinks and the role of environmental conditions in mediating soil C accumulation in restoration sites. Using a chronosequence of five created saline marshes ranging in age from 5 to 32 yr and two adjacent natural reference marshes in southwest Louisiana, USA, short- and longer-term C accumulation rates (SCAR and LCAR, respectively) were determined using feldspar marker horizons and peat depth in cores at six locations in each marsh. Created marshes ranged in elevation from −12 to 41 cm (NAVD88) and supported assorted plant community compositions driven by local environmental conditions. SCAR ranged from 75 to 430 g $C \cdot m^{-2} \cdot yr^{-1}$, which were comparable in the two youngest and two oldest marshes. Longer-term CAR ranged from 18 to 99 g $C \cdot m^{-2} \cdot yr^{-1}$ but did not significantly differ among marshes of different ages. Our findings indicate that LCAR in these created marshes were influenced by site-specific environmental conditions (i.e., stem density and mineral sediment) rather than marsh age. Results suggest that conditions appropriate for the establishment of vegetation with high stem densities, such as *Distichlis spicata* and *Spartina patens*, may facilitate higher LCAR in created marshes, which may be useful for restoration project planning and mitigation of climate change.

Key words: autochthonous production; carbon storage; *Distichlis spicata;* Louisiana; *Spartina patens;* stem density; vertical accretion; wetland creation; wetland restoration.

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INTRODUCTION

Wetlands play an important role in the global atmospheric carbon (C) cycle because of their large soil C stocks, ability to sequester C through high rates of sediment accumulation and plant productivity, and low rates of microbial respiration. Coastal wetland macrophytes and algae assimilate carbon dioxide (CO_2), which can be stored over short time periods as biomass and over longer periods as soil organic matter (McLeod et al. 2011). Coastal marshes, in particular, are considered important *blue carbon* ecosystems as they have environmental conditions that promote long-term C storage and high C accumulation rates (CAR), with global estimates in CAR ranging from 4.6 up to 60.4 Tg C/yr (Lovelock and Duarte 2019; Table 1). Additionally,

Table 1. Estimates of global carbon accumulation rates (CAR) in saline marshes.

Global CAR (Tg C/yr)	Source
42.6 ± 4	Chmura et al. (2003)
60.4	Duarte et al. (2005)
5.0	McLeod et al. (2011)
87.0	McLeod et al. (2011)
10.1 ± 1	Ouyang and Lee (2014)
4.6	Bridgham et al. (2006)

saline marsh soils have abundant sulfate that hinders the production of methane (CH_4; DeLaune et al. 1983, Poffenbarger et al. 2011), and gas flux studies suggest that nitrous oxide emissions are negligible (Smith et al. 1983, DeLaune et al. 1990). This allows coastal marshes to function as a net sink for atmospheric greenhouse gases, a critical ecosystem service that can be harnessed for marsh protection and restoration.

Widespread loss and degradation of marshes due to anthropogenic and climatic changes affect their ability to function as blue C sinks, both through the loss of area and through alterations in biogeochemical processes. Dredging and diking, marsh filling, and river channelization have severely altered hydrology, salinity, oxygen availability, productivity, and vegetation community structure (Mitsch and Hernandez 2013). Global warming-driven sea-level rise coupled with subsidence threatens to submerge many coastal marshes, and with development of much of the global coastline, wetlands along the coast may be subject to coastal squeeze (Nicholls 2004). Coastal marsh restoration provides the opportunity to mitigate some of the past and present loss of these systems and their associated functions. Coastal marsh restoration efforts are increasing in North America and globally (Craft et al. 1999, Zedler and Callaway 2000, Edwards and Proffitt 2003, Cornell et al. 2007, Callaway et al. 2012). In Louisiana, marsh creation projects are increasingly prevalent due to large-scale conversion of previous wetland to open water caused by high rates of sea-level rise, subsidence, erosion, and saltwater intrusion. The 2017 Louisiana Coastal Master Plan allocates nearly $18 billion to dredge sediment marsh creation projects over the next 50 yr (CPRA 2017). With such extensive resources devoted to creating marshes, it is necessary to understand and quantify their ecosystem service provision, such as blue C accumulation potential. Additionally, identifying environmental drivers of C sequestration may provide important information for restoration project design and implementation.

Carbon accumulation rates have been shown to vary regionally, and even locally, within the United States (Table 2). Marsh geomorphic setting, elevation, and hydrology, coupled with biological feedbacks, such as vegetation succession and microbial decomposition, may drive differences in CAR (Allen 2000, Reddy and DeLaune 2008, Mudd et al. 2009, Saintilan et al. 2013). Newly created dredge sediment marshes exhibit

Table 2. Estimates of regional carbon accumulation rates (CAR) in saline marshes measured using ^{137}Cs dating.

Regional CAR ($g C \cdot m^{-2} \cdot yr^{-1}$)	Location	Dominant vegetation	Source
39	Upper Bay of Fundy, New Brunswick, Canada – Low	*Spartina alterniflora*	Connor et al. (2001)
194	Upper Bay of Fundy, New Brunswick, Canada – High	*Plantago maritima*	
76	Outer Bay of Fundy, New Brunswick, Canada – Low	*S. alterniflora*	
188	Outer Bay of Fundy, New Brunswick, Canada – High	*P. maritima*	
147 ± 14	Whale’s Tale, San Francisco Bay, Calif., USA – Low	*Spartina foliosa*	Callaway et al. (2012)
103	Whale’s Tale, San Francisco Bay, Calif., USA – High	*Spartina pacifica*	
142 ± 44	China Camp, San Francisco Bay, Calif., USA – Low	*S. foliosa*	
87 ± 5	China Camp, San Francisco Bay, Calif., USA – High	*S. pacifica*	
71–185	Barataria Basin, Louisiana, USA	n/a	*In* Chmura et al. (2003)
76 ± 13	Reedy Creek, Barnegat Bay, New Jersey, USA	*S. alterniflora*	Unger et al. (2016)
250 ± 12	Maurice River, Delaware Estuary, Delaware, USA	*S. alterniflora*	
159	Little Assawoman Bay, Delaware, USA	*S. alterniflora*	Elsey-Quirk et al. (2011)
119	Little Assawoman Bay, Delaware, USA	*Juncus roemerianus*	

Note: n/a, Not applicable.

highly variable abiotic conditions while substrates dewater, stabilize, and become colonized by plants, but there is a paucity of information regarding temporal and spatial drivers of blue C accumulation in created marshes. In natural marshes, longer-term CAR is facilitated by mineral sedimentation through the settling and trapping of allochthonous materials (Mudd et al. 2004) and physical or biochemical stabilization of the C pool (Six et al. 2002, Unger et al. 2016). Vegetation communities with higher stem densities therefore may increase sedimentation rates by reducing flow velocity and increasing sediment trapping, subsequently increasing CAR (Mudd et al. 2004). Additionally, macrophyte species with different above- and belowground biomass stocks and productivities may contribute to variability in the belowground C pool (Elsey-Quirk et al. 2011). Due to tight coupling between marsh hydrology, vegetation type and productivity, and deposition rates (Morris et al. 2002, Stagg and Mendelssohn 2010, Kirwan and Megonigal 2013, Snedden and Steyer 2013), teasing apart direct and indirect drivers of CAR can be challenging.

Ultimately, the long-term success and resiliency of created marshes is dependent on the accretion of sediments and soil organic matter (OM), to which C accumulation significantly contributes (Mudd et al. 2009). Many subsiding coastal marshes in Louisiana are subject to low allochthonous sediment availability and are therefore reliant upon autochthonous organic inputs to maintain marsh elevation in the face of high rates of relative sea-level rise (RSLR; Turner and Streever 2002, DeLaune and Pezeshki 2002, Lane et al. 2016). Recently, researchers have shown that vertical accretion rates in the western Chenier Plain are an average of two times lower than in the Mississippi Delta, which may be due to shallow subsidence, distance from a fluvial sediment source, and the effects of Chenier ridges and impoundments (Jankowski et al. 2017). Created marshes in this region may be especially impacted by such factors, and more information is necessary to determine optimal environmental conditions for greater surface accretion and blue C accumulation and storage rates. We hypothesized that total C stocks in created marshes increase with marsh age toward that of natural marshes, facilitated by feedbacks between vegetation productivity and associated particle trapping (productivity + allochthonous inputs > respiration) that serve to increase CAR toward a dynamic equilibrium (productivity + allochthonous inputs ≈ respiration). We also hypothesized that CAR in created marshes will vary due to differences in vegetation and environmental characteristics (e.g., species composition, elevation, hydrology, and porewater chemistry), which are indirectly affected by the age of the marsh through plant colonization and succession.

METHODS

Study area

This study was conducted in Sabine National Wildlife Refuge (SNWR) in the Chenier Plain in southwest Louisiana. Starting as early as the 1800s, the Calcasieu River was successively dredged and deepened, ultimately causing saltwater intrusion and increased flooding in adjacent wetlands (DeLaune et al. 1983). When surveyed in 1949, saw-grass (*Cladium jamaicense*) marsh dominated this area, with abundant fresh to intermediate wetlands and relatively little open water (O'Neil 1949). Subsurface fluid production in the 1950s was associated with minor, yet rapid, land-surface subsidence (Bernier et al. 2011), which, in concert with disturbance from dredging, led to substantial marsh loss and conversion to open water. In 1983, the Army Corps of Engineers and the National Wildlife Refuge system began to create marshes in SNWR by pumping channel dredge material into open water areas bounded by low levees, which were naturally colonized with vegetation. Our study included a 32-yr chronosequence of five created salt marshes representing a range of vegetation communities, and two adjacent natural marshes characterized by high marsh vegetation and dominated by *Distichlis spicata*, *Spartina patens*, and *Bolboschoenus robustus* (Fig. 1). Six sampling locations were selected in each created (5, 8, 13, 20, and 32 yr old) and natural marsh areas. Three created marshes (5, 8, and 13 yr old) and the natural references are located west of Highway 27, where tidal signals are dampened by water control structures at Hog Island Gully. The two eastern created marshes (20 and 32 yr old) have greater influences from tides, barge traffic, and wave action. Space and age are, therefore,

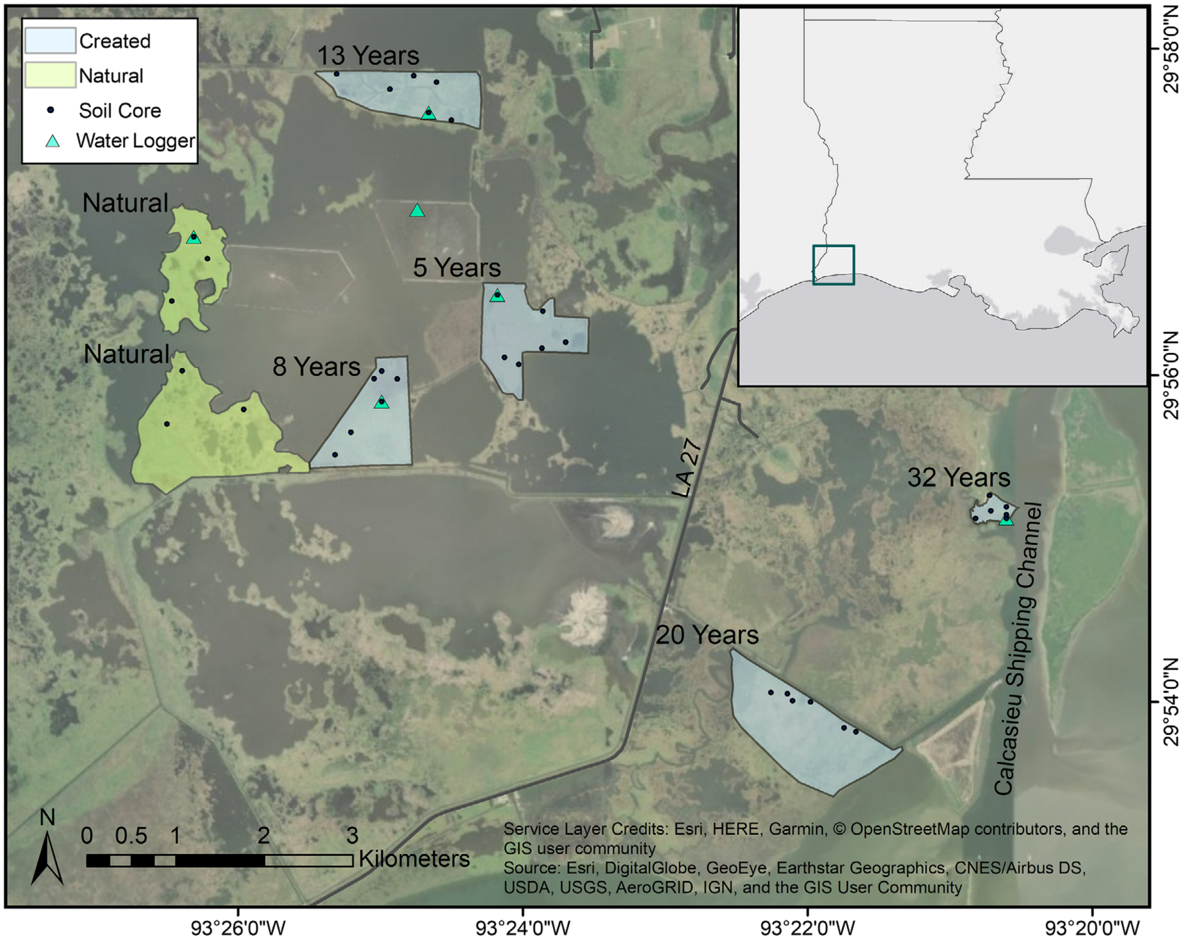

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Fig. 1. Map of created and natural marshes in Sabine National Wildlife Refuge. Points represent core and vegetation plot locations. This map was created using ArcGIS software by Esri. ArcGIS and ArcMap are the intellectual property of Esri and are used herein under license. Copyright Esri. All rights reserved.

confounded due to the spatial separation of the two oldest marshes from the younger and natural marshes. While this was inherent in the layout of marsh locations, it provides an opportunity to evaluate marshes created under a range of within- and among-marsh variability in environmental conditions and to evaluate the relative roles of marsh age and environmental conditions in influencing CARs. Additionally, the reference marshes were selected to represent naturally established marshes within the geographic setting of SNWR in order to facilitate comparisons between created marsh structure and functions; these reference marshes may not represent optimal tidal marsh conditions, as they are subject to similar environmental stressors (e.g., subsidence, saltwater intrusion, climatic shifts) as adjacent created marshes.

Sample collection

Sampling locations were chosen remotely using a 100-m spaced grid overlaid on a land-cover basemap (ESRI 2015) and by randomly selecting intersections which corresponded with specific GPS points in order to capture a range of variability in environmental characteristics within marshes. At each sample location, one PVC soil core was hand-extracted using a 35-cm polycarbonate tube with a diameter of 6.35 cm, and a sharpened bottom edge to minimize compaction, then transported horizontally. A total of 36 cores were collected, six in each created and natural marshes. Next to three randomly selected soil core locations in each created marsh, a 1.0-cm layer of white feldspar clay was deposited within a 0.50-m^2 quadrat to establish a marker horizon with which to measure short-term surface accretion, as described by Cahoon (1994). All plots were established in September and November of 2015, except the 20-yr-old marsh, in which plots were established in September 2016, and therefore only sampled once. In the natural sites, a total of six plots were established.

Soil processing and analyses

PVC soil cores were sectioned in 2 cm depth intervals in the laboratory, with large (>20 mm), rhizomatous tubers of *B. robustus* removed. Tubers occurred infrequently in sites where *B. robustus* occurred (<2 per core). All depth sections were weighed wet and dried to a constant weight at 60°C, and bulk densities (g/cm^3) were obtained by calculating the dry mass per unit volume of each depth section. Subsamples of each 2 cm depth interval were analyzed for percent loss on ignition (LOI), particle size distribution, total organic C (TOC), and for the natural marsh samples, radionuclide analysis. Subsamples were ground and homogenized into a fine powder using a Wiley soil mill. Loss on ignition was determined as the percentage of mass lost following combustion at 550°C for 4 h (Heiri et al. 2001), and particle size distribution was determined using the hydrometer method (Bouyoucos 1962). Total organic C content was determined by weighing ~12 μg of each sample into open Ag-foil capsules, adding 30 μL of deionized water, and fuming with 12 mol/L HCl for 6 h to remove carbonates. The samples were then dried, and the capsules were sealed for analyzing with Costech 1040 CHNOS Elemental Combustion system (Harris et al. 2001).

To estimate the depth of marsh above the original surface of dredge sediment when created, dredge sediment was visually identified as a dark gray clay layer and confirmed using bulk densities in each 2-cm segment from the soil surface to 30 cm depth (Fig. 2). This will be hereafter referred to as the dredge horizon, and the

Fig. 2. Examples of soil cores from natural and created marshes in Sabine National Wildlife Refuge. From left to right: Natural marsh, 32-yr-old created marsh, and 13-yr-old created marsh. Blue line indicates dredge horizon.

depth of this horizon was used to calculate longer-term surface accretion and C accumulation rates in created marshes. The known creation dates of the marshes from the Army Corps were used to determine age at time of sampling. Carbon density (g C/cm^3) was calculated by multiplying the respective percent TOC by the total dry bulk density (g/cm^3) of each sample, and CAR was calculated by multiplying the total C density above the dredge horizon by the respective surface accretion rate. Literature values were used for accretion, organic, and mineral accumulation rates in the Chenier Plain region (Table 3; Smith 2012). Carbon densities for natural marsh literature values were calculated using the equation described by Craft et al. (1991; $OC = 0.40^{*}OM + 0.0025^{*}OM^2$) and multiplying by the bulk densities provided (Smith 2012). Longer-term CAR in natural marshes were determined by multiplying calculated C densities by respective accretion rates.

Short-term surface accretion at each feldspar horizon plot was calculated using the change in height of the marsh surface above the top of the feldspar layer along three sides of a square plug over time. Feldspar plots were sampled every 4–6 months. Samples of soil accumulated above marker horizons were collected, dried to a constant weight at 60°C, and processed for LOI as described above. Mineral, organic, and C content of feldspar samples were determined using porewater content, percent LOI, and dry bulk density of the feldspar sample and calculating percent organic C using the equation described by Craft et al. (1991). The product of percent organic, mineral, or C content and bulk density was multiplied by the short-term surface accretion rate at each feldspar plot to obtain short-term accumulation rates.

Table 3. Natural marsh accretion and C accumulation rates (CAR) in Chenier Plain saline marshes.

Location	Accretion rate (cm/yr)	CAR† ($g \cdot m^{-2} \cdot yr^{-1}$)	Source
Rockefeller Wildlife Refuge	0.51	70.31	Smith (2012)
	0.33	56.28	
	0.51	104.95	
	0.69	147.70	
	0.78	146.40	
	0.60	153.46	
	0.42	113.35	
	0.38	99.15	
	0.51	79.83	
Rockefeller Wildlife Refuge	0.90	n/a	DeLaune et al. (1992)
Mermentau River–Grand Lake	0.69	n/a	
Lower Calcasieu Marshes	0.70	n/a	

Notes: n/a, Not applicable.

† CAR calculated after Craft et al. (1999) from bulk density and organic matter values provided in Smith 2012.

Vegetation and environmental measurements

In August 2016, stem densities, average shoot height, and aboveground biomass were obtained within 0.01-, 0.10-, or 0.25-m^2 quadrats at all core sample locations, depending on species density. The 0.01-m^2 quadrats were used for *S. patens* and *D. spicata* dominated plots, and the 0.10- and 0.25-m^2 quadrats were used for *Spartina alterniflora* and *B. robustus* dominated plots, respectively. All were scaled to 1.0 m^2 for calculations. Aboveground biomass was sorted into live and dead standing biomass and dried to a constant weight at 60°C. Shoot height was measured on live herbaceous plants only (*S. patens, D. spicata, S. alterniflora*, and *B. robustus*). Elevation (NAVD88) was surveyed at each core location using Leica GS14, and horizontal and vertical accuracies were 1 and 2 cm, respectively. Water depth relative to the marsh surface was determined from 2 April to 8 July 2016 using continuous water level and salinity monitors (Aqua TROLL 200, In situ) deployed in vented PVC wells ~60 cm deep. Water level data were recorded every 15 min, and salinity data were recorded every 30 min. Average salinity (psu) was determined for each deployment period, with anomalous data removed prior to averaging, as conductivity sensors are easily affected by suspended sediments.

Data analyses

Water depth from 2 April to 8 July 2016 was estimated for each core location ($n = 6$) using the elevation difference (NAVD88) between the marsh surface at the core location and the water level recorder. Mean high water (MHW), mean low water (MLW), and percentage of time flooded were calculated for each core location (MATLAB 9.0.0; The MathWorks, Inc. 2016), and average salinities were determined at each logger location. Aboveground biomass and stem density data were square root-transformed prior to analysis to attain normality and homogeneity of variance. Differences among marshes were tested using one-way ANOVA, and post hoc differences were analyzed with Tukey's honest significant difference test (R Core Team 2017). To examine vegetation community compositions of core locations, we used non-metric multi-dimensional scaling. The *adonis* function in the *vegan* package (Oksanen et al. 2017) was used to test for between-marsh variation. Differences in short- and longer-term surface accretion rates and CARs within and between created salt marshes and natural reference marshes were tested using one-way ANOVA (R Core Team 2017). Rates were log-transformed if assumptions of normality or homogeneity of variances were not met, which were tested using Shapiro-Wilk's method and normality plots of residuals, and Levene's test, respectively.

To elucidate the nature of the relationship between environmental variables and surface accretion and accumulation rates, two statistical approaches were used. The predictor variables were first tested for significant correlations; then, stepwise multiple regressions using minimum Akaike's information criterion corrected for sample sizes were used to identify important explanatory variables on accumulation rates. For the second approach, hierarchical partitioning was used to minimize the influence of multi-collinearity among environmental variables and to assess the independent effects of environmental factors on surface accretion and accumulation rates. Hierarchical partitioning is a regression technique in which all possible linear models are jointly considered to identify the most likely explanatory factors, providing a measure of the effect of each factor that is largely independent from that of others (Walsh and Mac Nally 2013). This analysis was completed using the hier.part package in R (Walsh and Mac Nally 2013, R Core Team 2017). For all statistical analyses, tests of significance were based on $\alpha = 0.05$.

RESULTS

Environmental conditions

From 2 April to 8 July 2016, created marshes were flooded to the soil surface between 68.1% and 99.8% of the time, with the 8-yr-old marsh most frequently inundated. The natural marshes were flooded an average of 85.3% of the time. Because water level recorders were installed only through the spring and early summer, typically a time of seasonally high water, annual flooding of the marsh may be overestimated; however, these data were useful for examining relative differences in flooding dynamics within and among marshes. Mean high water ranged from −9.6 to 42.2 cm in the created marshes and 12.1 to 22.0 cm in the natural marshes. The large range in MHW reflected the range of elevations from −12 to 41 cm, NAVD88 in the created marshes, and 5–15 cm, NAVD88 in the natural marshes (Fig. 3). The 5-yr-old marsh contained highly variable topography, with an elevation range of 27 cm, while the natural site had the most uniform within-marsh elevations, with a range of 10 cm. The natural marsh had the lowest salinity of 10.6 psu, while the highest salinity averaged 22.1 psu in the 32-yr-old marsh adjacent to the shipping channel (Table 4). Mean high water, MLW, percent of time flooded, average water depth, and salinity were highly correlated with elevation ($P < 0.01$), and therefore, we selected elevation as a representative parameter for regression analyses.

Vegetation

Vegetation plots contained seven total species: *Batis maritima, B. robustus, Borrichia frutescens, D. spicata, S. alterniflora* (reclassified in 2014 as *Sporobolus alterniflorus*; Peterson et al. 2014), *S. patens*, and *Symphyotrichum tenuifolium*. *S. alterniflora* was present in varying abundances in all marshes. Young created marshes (≤8 yr old) were dominated by *S. alterniflora*, though it was also abundant at lower elevations in the 13- and 32-yr-old marshes. *B. maritima*, *B. frutescens*, and *S. tenuifolium* were only found in the older created marshes east of Highway 27 and dominated the highest elevations. Species richness generally increased with marsh age and elevation. Four species (live and dead) were present in the natural marsh plots, three in the 13- and 5-yr-old plots, and two in the 8-yr-old marsh. In contrast, seven total species were found in both the 20- and 32-yr-old marshes. While total live and dead aboveground biomass was similar among marshes ($P = 0.27$; Fig. 4a), stem densities varied

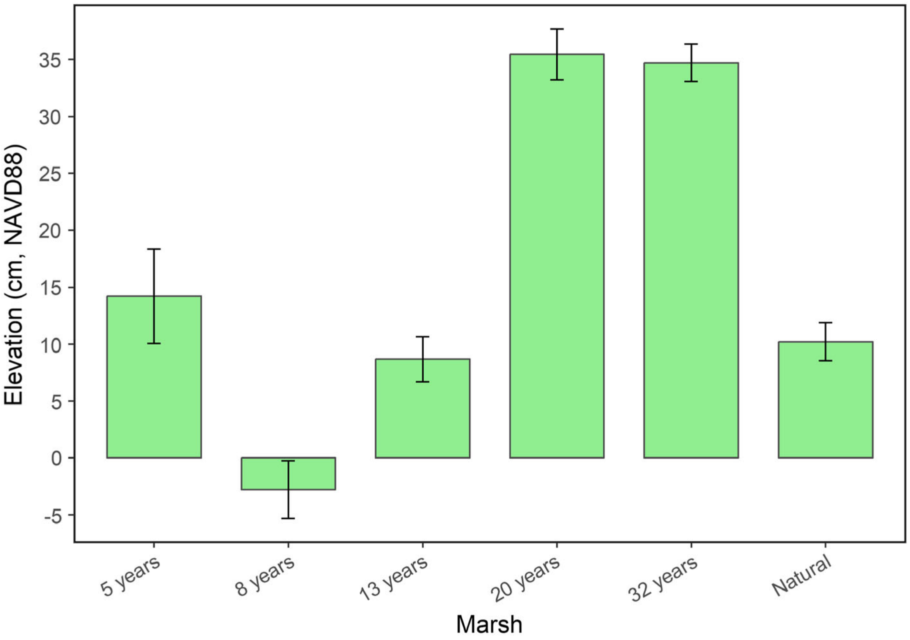

Fig. 3. Average elevations measured within each created and natural marsh of Sabine NWR ($n = 6$). Standard error bars are shown.

Table 4. Environmental characteristics of study marshes (±SE).

Environmental variable	5 yr	8 yr	13 yr	20 yr	32 yr	Natural
MHW (cm)	10 ± 4^{b}	33 ± 3^{s}	9 ± 2^{b}	9 ± 2^{b}	10 ± 2^{b}	17 ± 2^{b}
MLW (cm)	6 ± 4^{b}	29 ± 3^{a}	7 ± 2^{b}	3 ± 2^{b}	3 ± 2^{b}	14 ± 2^{b}
Time flooded (%)	68 ± 11^{b}	100 ± 0^{a}	71 ± 4^{b}	68 ± 10^{b}	81 ± 4^{ab}	85 ± 4^{ab}
Elevation (cm, NAVD88)	14 ± 4^{bc}	-3 ± 3^{d}	9 ± 2^{c}	36 ± 2^{a}	35 ± 2^{a}	10 ± 2^{bc}
Salinity (psu)	14	16	16	n/a	22	11
% Clay	48 ± 3^{ab}	54 ± 5^{a}	38 ± 3^{bcd}	44 ± 2^{abc}	33 ± 2^{cd}	29 ± 3^{d}
% Silt	30 ± 2^{a}	28 ± 2^{ab}	36 ± 1^{a}	29 ± 1^{a}	35 ± 2^{a}	19 ± 3^{b}
% Sand	23 ± 3^{b}	18 ± 4^{b}	26 ± 2^{b}	26 ± 2^{b}	32 ± 4^{b}	52 ± 6^{a}

Notes: Values represent an average of core locations ($n = 6$), except for salinity. Water depth and salinity were measured in one location between 2 April 2016 and 8 July 2016. Mean high water/mean low water (MHW/MLW) is relative to surface. Particle size distribution is average to 10 cm depth. Superscripts of different letters indicate significant differences among marshes. n/a, not applicable.

significantly among marshes ($P = 0.01$; Fig. 4b). The natural and 13-yr-old marshes were dominated by *D. spicata* and *S. patens* and had an average of 2483 and 2866 more stems m^{-2} than the 5-yr-old marsh where *S. alterniflora* was dominant. All marshes contained at least one plot with *S. alterniflora* and *D. spicata* with shoot heights ranging from 25 to 85 cm, though where present, *B. robustus* was the tallest species, up to 95 cm (Table 5). Plant community composition varied significantly among marshes ($P < 0.01$), with distinct groupings of species (Fig. 5). The 5- and 8-yr-old marshes were dominated by *S. alterniflora* and associated with early successional stage, lower elevations, and greater percent of time flooded (Fig. 5). Conversely, the 20-yr-old marsh had high elevations and was dominated by *B. frutescens* and *B. maritima*. Within the 32-yr-old marsh, there were distinct communities of *S. alterniflora* as well as higher-marsh species.

Soil properties

Soil bulk densities were generally lower and organic carbon densities higher in the natural

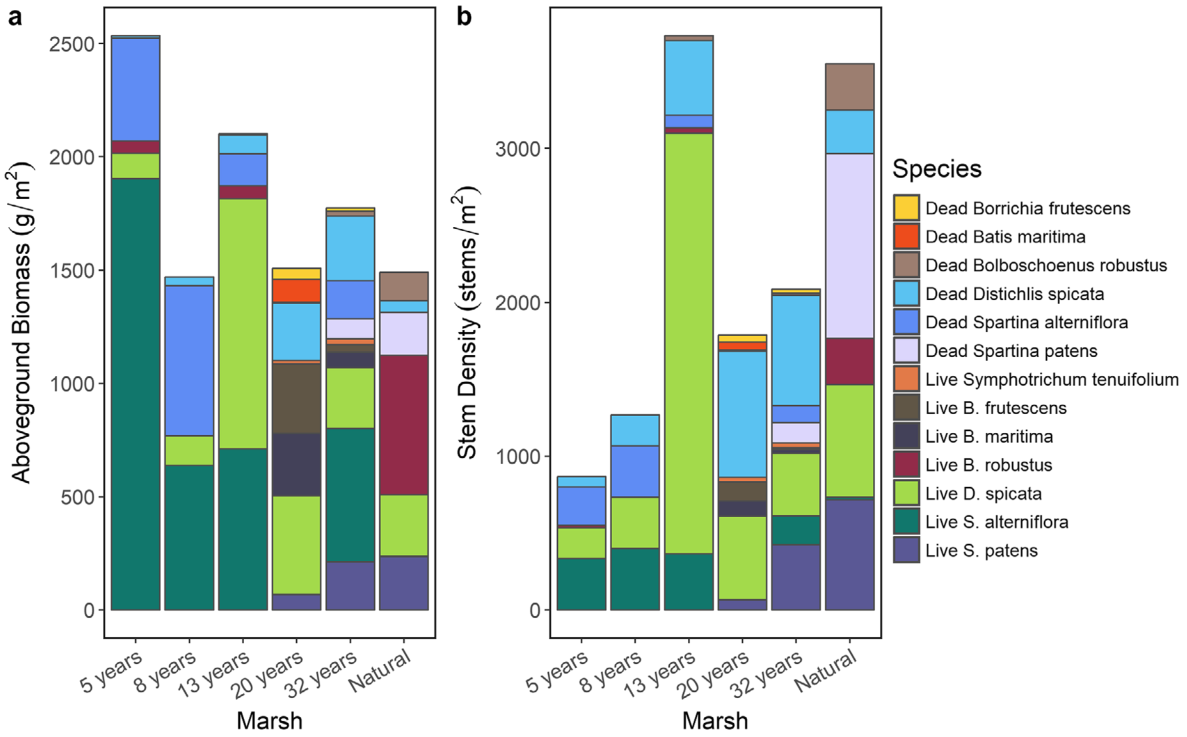

Fig. 4. (a) Average aboveground biomass by species in created and natural marshes in late summer, 2016 ($n = 6$). Standard errors for total biomass were 501, 398, 253, 89, 366, and 371 for the 5-, 8-, 13-, 20-, 32-yr-old, and natural marshes, respectively. (b) Average stem density by species in created and natural marshes in late summer, 2016 ($n = 6$). Standard errors for total stem densities were 176, 528, 963, 293, 891, and 740 for the 5-, 8-, 13-, 20-, 32-yr-old, and natural marshes, respectively.

Table 5. Average shoot height for dominant plant species (cm ± SE).

Marsh age (yr)	*Spartina alterniflora*	*Distichlis spicata*	*Spartina patens*	*Bolboschoenus robustus*
5	85 ± 7	35	n/a	95
8	58 ± 10	59	n/a	n/a
13	73 ± 37	40 ± 7	n/a	85 ± 30
20	25	46 ± 3	49	n/a
32	59 ± 3	54 ± 6	62 ± 4	n/a
Natural	25	37 ± 8	43 ± 12	85 ± 5

marsh as compared to the created marshes, particularly at depth (Fig. 6a). Carbon densities from 0 to 30 cm were relatively uniform in created marshes (Fig. 6b) with a slight increase with marsh age (Fig. 6b). Age since creation, however, was not the only factor influencing bulk soil and organic C densities. For example, the 8- and 13-yr-old marshes had lower bulk densities than the 20-yr-old marsh, reflecting higher organic matter accumulation.

Longer-term accretion and accumulation rates

Total C stocks above the dredge horizons increased linearly with created marsh age within the observed range of values, as hypothesized (Fig. 7). Longer-term surface accretion rates ranged from 0.2 to 0.8 cm/yr. Accretion rates in the 20-yr-old marsh were significantly lower than rates found in the 8-yr-old marsh ($P < 0.01$; Fig. 8a, Table 6), likely due to its high elevation (Fig. 3). Marsh elevation explained approximately 33% of the variation in longer-term accretion rate in created marshes, with higher accretion rates at lower elevations ($R^2 = 0.33$; $P < 0.01$). Organic matter accumulation rates were similar among created and

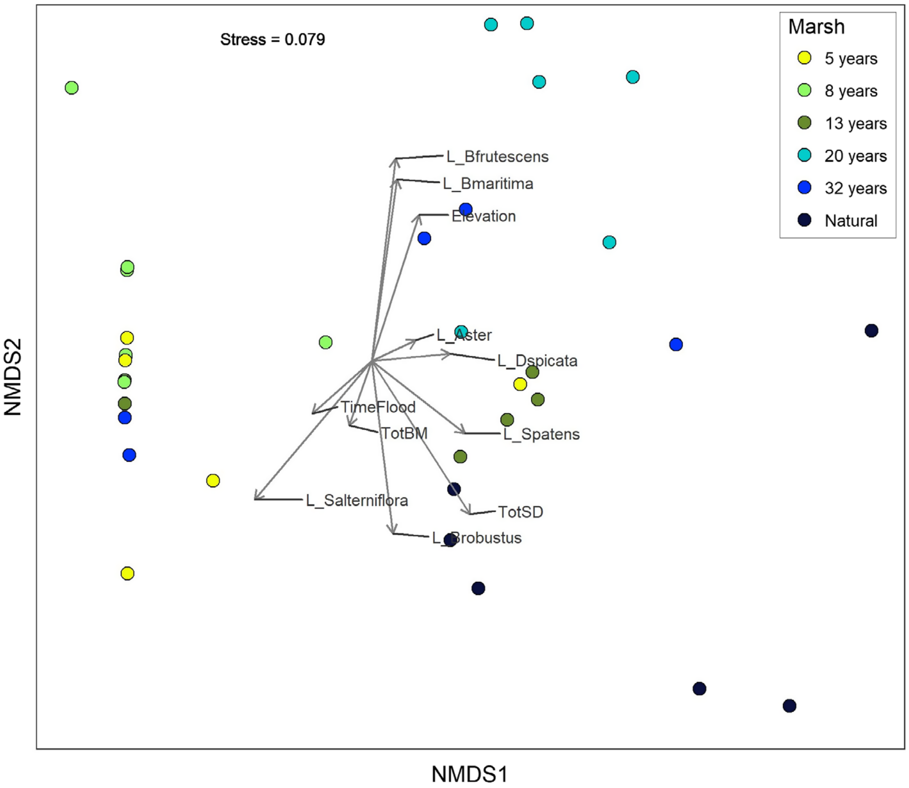

Fig. 5. Vegetation community compositions in created and natural marshes as determined by non-metric multi-dimensional scaling using Bray distance. Vectors indicate dominant plant species and associated environmental variables.

natural marshes ($P = 0.94$), while mineral accumulation rates in the 5-yr-old marsh were significantly higher than in the natural marshes ($P < 0.01$; Table 6). Despite differences in longer-term accretion rates among marshes, LCAR did not significantly differ among created marshes of different ages (Fig. 8b). Natural marshes, however, had LCAR which were significantly higher than those in the 20- and 5-yr-old created marshes ($P < 0.05$).

Across created marshes, stem density was the most important contributor to LCAR ($I = 62.4\%$), with mineral sediment density, age, elevation, and vegetation biomass having smaller contributions ($I = 27.8\%$; $I = 4.2\%$; $I = 3.6\%$, $I = 2.1\%$). These findings were supported by stepwise multiple regression, where stem density was also identified as the most important overall predictor of LCAR in created marshes ($R^2 = 0.24$; $P < 0.01$; Fig. 9). Contrary to hypothesized relationships between stem density and sediment deposition, LCAR was positively associated with OM accumulation rates ($R^2 = 0.51$; $P < 0.01$), but not mineral sedimentation rates ($R^2 < 0.01$; $P = 0.95$). Within created marshes, environmental contributors to LCAR were variable (Table 7). In the 13- and 32-yr-old marshes, stem density remained the most important predictor, but in the 8-yr-old low-elevation marsh, LCAR was strongly and positively related to marsh elevation ($R^2 = 0.92$; $P < 0.01$). Within the oldest and youngest marshes, mineral sediment density was found to contribute to LCAR, with stem density and biomass secondary contributors.

Short-term surface accretion and accumulation rates

Short-term surface accretion rates measured using feldspar marker horizons ranged from an average of 0.4–1.6 cm/yr in created marshes,

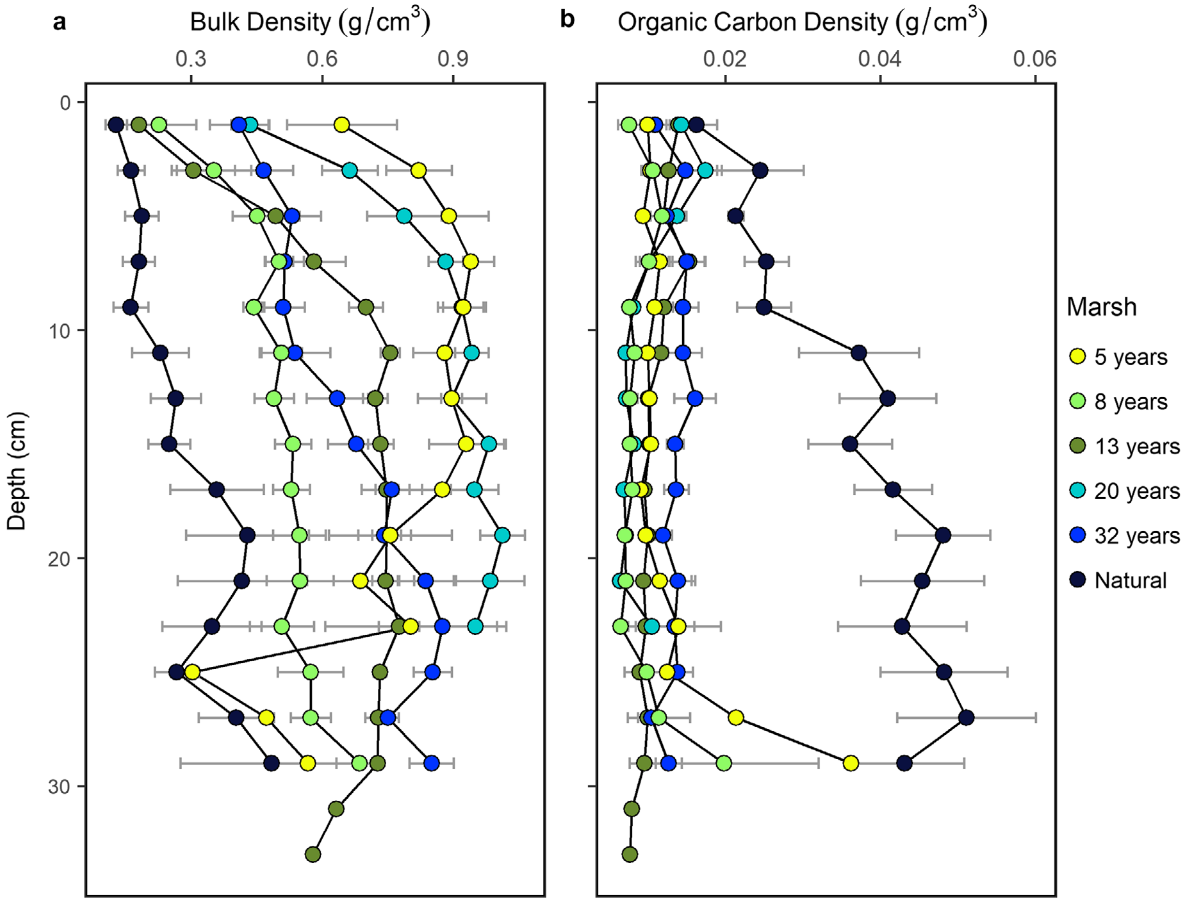

Fig. 6. (a) Average bulk densities in created and natural marsh cores. (b) Average organic carbon densities in created and natural marsh cores. Standard error bars indicated in gray.

averaged 0.9 ± 0.2 cm/yr in natural marshes, and did not significantly differ among marshes ($P = 0.16$; Fig. 8a, Table 6). Accretion rates above feldspar horizons were not associated with any measured vegetation or environmental variable ($P > 0.05$), and no significant relationship between short- and longer-term surface accretion rates was found ($P > 0.05$). Although short-term accretion rates were similar among marshes, OM, mineral sediment, and SCAR varied significantly (Table 6), with both OM and mineral contributions significantly related to SCAR ($P < 0.01$). The 13-yr-old marsh had OM and short-term C accumulation rates from 3.3 to 5.7 times higher than those found in the 5-, 8-, and 20-yr-old marshes ($P < 0.05$; Fig. 8b). Higher SCAR was positively but weakly associated with plant stem densities ($P = 0.07$). Mineral accumulation rates were over 7 times lower in the 8-yr-old marsh than those found in the 32-, 20-, and 13-yr-old marshes, with the 8-yr-old marsh being the lowest in elevation and dominated by low-density *S. alterniflora*.

Discussion

Influence of marsh age on C stocks, accretion, and accumulation rates

As hypothesized, C stocks increased with created marsh age, to a maximum of 1973 g C/m^2 in the 32-yr-old marsh but remained less than the natural marsh average of 2246 g C/m^2, a trend also found in other created wetlands (Osland et al. 2012, Radabaugh et al. 2018). While it is not possible to have negative C stocks, or positive stocks with no sediment present, the linear

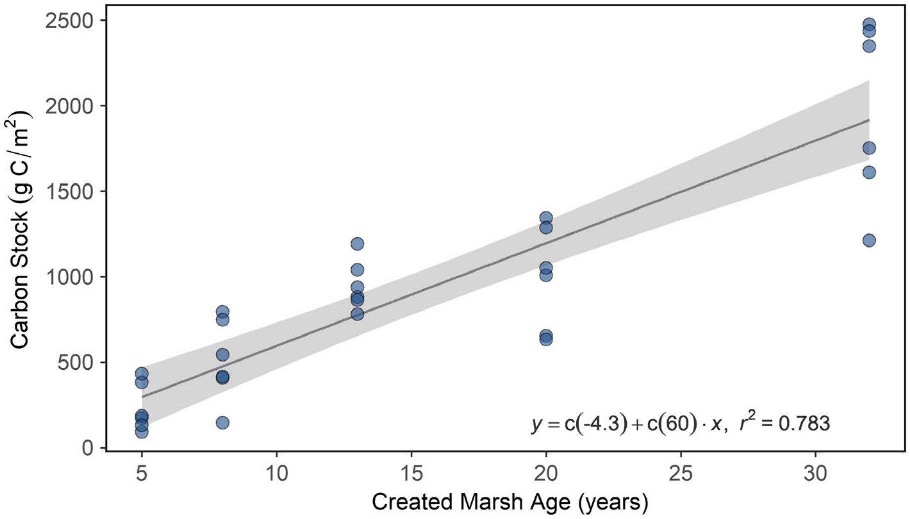

Fig. 7. Relationship between carbon stock above dredge horizon and created marsh age. 95% confidence interval indicated in gray.

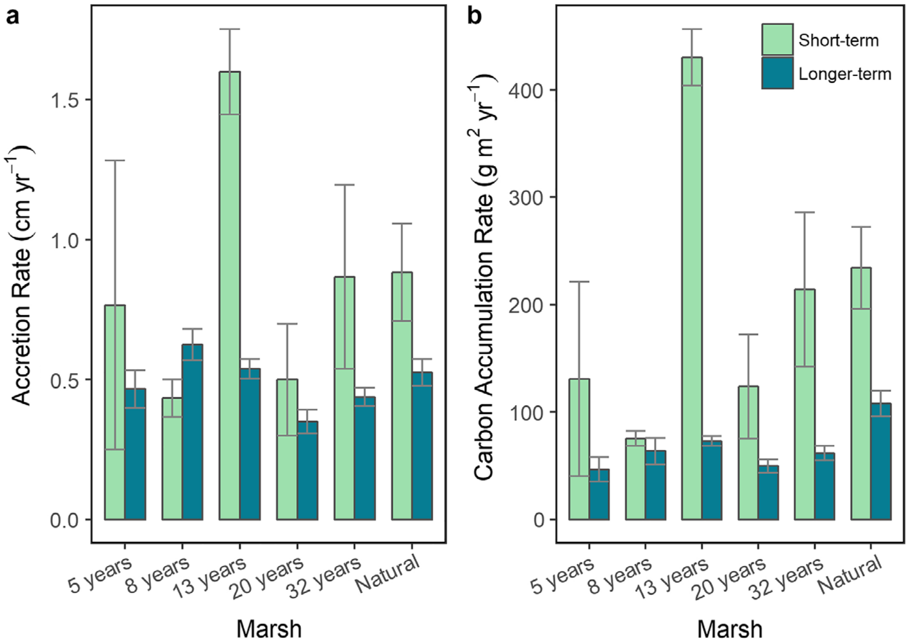

Fig. 8. (a) Short- and longer-term accretion rates in created and natural marshes in Sabine NWR. (b) Short- and longer-term carbon accumulation rates in created marshes and natural marshes. Standard error bars are shown. Letters indicate significant differences. [†]Short-term rates for natural marshes were obtained from this study, and longer-term rates for natural marshes were obtained from Smith (2012).

prediction is based on our observed range of values in created marshes. The true relationship between C stocks and marsh age is likely nonlinear near the origin, which may be due to initial rapid accretion as newly created marshes (<5 yr) colonize. Similarly, rapid increases in soil OM content as created marshes age (Zedler and Callaway 1999, Edwards and Proffitt 2003) suggest

Table 6. Short- and longer-term accretion and accumulation rate averages (±SE) in created and natural marshes.

Marsh age	Accretion rate (cm yr^{-1})	Organic matter accumulation (g m^{-2} yr^{-1})	Mineral accumulation (g m^{-2} yr^{-1})	OC accumulation (g m^{-2} yr^{-1})
Short-term				
5	0.77 ± 0.5^{a}	327 ± 226^{b}	2748 ± 1524^{ab}	131 ± 91^{b}
8	0.43 ± 0.1^{a}	188 ± 18^{b}	377 ± 44^{b}	75 ± 7^{b}
13	1.60 ± 0.2^{a}	1073 ± 66^{a}	3649 ± 1183^{a}	430 ± 26^{a}
20	0.48 ± 0.2^{a}	310 ± 121^{b}	2832 ± 311^{a}	124 ± 48^{b}
32	0.85 ± 0.3^{a}	534 ± 179^{ab}	3407 ± 1616^{a}	214 ± 72^{ab}
Natural	0.89 ± 0.2^{a}	584 ± 95^{ab}	1071 ± 216^{ab}	234 ± 38^{ab}
Longer-term				
5	0.47 ± 0.1^{ab}	222 ± 33^{a}	2741 ± 471^{a}	47 ± 12^{a}
8	0.63 ± 0.1^{a}	222 ± 32^{a}	1698 ± 341^{ab}	64 ± 12^{ab}
13	0.54 ± 0.0^{ab}	253 ± 16^{a}	1586 ± 206^{ab}	73 ± 5^{ab}
20	0.35 ± 0.0^{b}	219 ± 25^{a}	2038 ± 236^{ab}	50 ± 6^{a}
32	0.44 ± 0.0^{ab}	245 ± 19^{a}	1933 ± 267^{ab}	62 ± 7^{ab}
Natural†	$0.53 \pm .05^{ab}$	239 ± 28^{a}	984 ± 213^{b}	108 ± 12^{b}

Notes: Superscript letters indicate significant differences between marshes. Short-term natural marsh rates were obtained from this study.

† Longer-term rates for Chenier Plain natural marshes were calculated from Smith (2012).

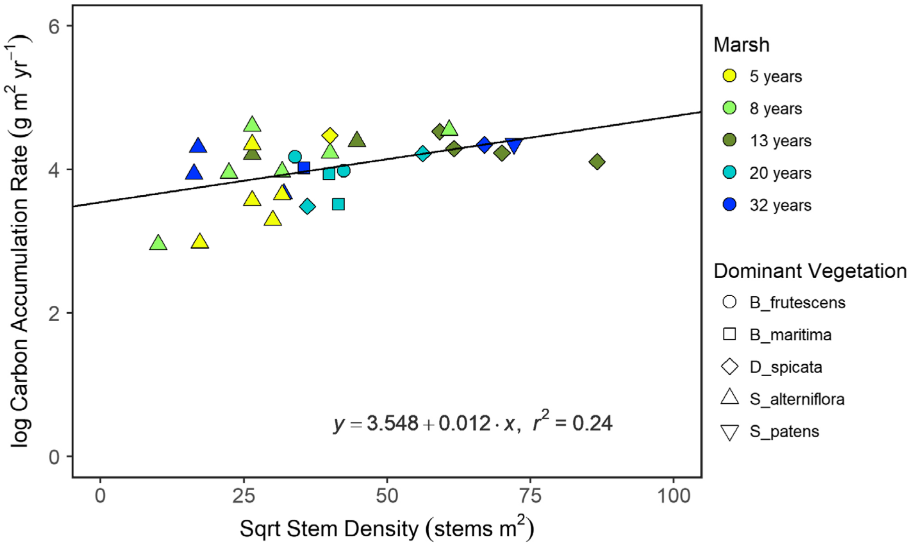

Fig. 9. Relationship between stem densities and carbon accumulation rates in created marshes, with marsh age indicated by color and dominant vegetation communities indicated by shape.

the potential for created marshes to sequester carbon at relatively high rates before stabilizing at a rate that is dependent on site-specific conditions. Contrary to the first hypothesis, however, short-term surface accretion rates and LCAR in SNWR did not vary among created marshes of different ages, owing to high within-marsh variability. While the 20-yr-old marsh had significantly lower longer-term accretion rates than other created marshes, and the 13-yr-old marsh had the highest SCAR, there was no clear trend in accretion or C accumulation rates due to marsh age. Additionally, the range of longer-term accretion rates in created marshes (0.2–

Table 7. Environmental variables contributing to C accumulation rates within created marshes.

Environmental variable	5 yr	8 yr	13 yr	20 yr	32 yr
Elevation	12.6	3.9	10.7	19.1	5.3
Total biomass	10.0	**57.7**	3.1	21.7	23.1
Total stem density	24.0	25.3	**76.9**	20.2	**68.2**
Mineral sediment density	**53.4**	13.1	9.3	**39.1**	3.5

Notes: Value (%I) indicates percent independent contribution based on hierarchical partitioning. Dominant variables are in bold.

0.8 cm/yr) were similar to those reported for nearby natural marshes (0.3–0.8 cm/yr; Smith 2012), suggesting that all marshes in this area are responding similarly to environmental, climatic, and geomorphic conditions, regardless of age. In a study of created marshes planted with *S. alterniflora*, Davis et al. (2015) found CAR to decline with marsh age; however, high estimates in younger marshes may reflect the planting of this carbon-rich species. In SNWR marshes, both young marshes and low-elevation areas in older marshes are dominated with *S. alterniflora*; thus, a similar declining trend in CAR may be complicated by variable initial elevations and the subsequent succession of diverse plant communities.

Short- vs. longer-term accretion rates

We anticipated longer-term surface accretion rates to be lower than short-term accretion rates due to compaction and decomposition over time (Neubauer et al. 2002). We found this trend to hold true in all marshes except the 8-yr-old marsh, which contained the highest longer-term accretion rates, but the lowest short-term rates. Because soil cores represent an integration of marsh conditions over time, longer-term accretion rates may not represent current accretion rates, especially in created marshes. Dredge sediment marshes can decrease in elevation from a few centimeters to meters after creation, as the sediment consolidates and dewaters (Turner and Streever 2002). The 8-yr-old marsh may have been created at an initial elevation that supported rapid vegetation colonization and growth of *S. alterniflora*, but later settled to a sub-optimal elevation for high rates of marsh accretion; this marsh now experiences prolonged inundation such that productivity is reduced, reducing vegetation contributions to surface elevation and increasing the potential for erosion (Watson et al. 2017, Feher and Hester 2018). Thus, short-term settling and long-term subsidence in created marshes may have dramatic impacts on productivity and ultimately, soil accretion. In SNWR, the low short-term accretion rates estimated in the 20- and 8-yr-old marshes suggest a similar trend as detailed by Stagg and Mendelssohn (2010), in which above- and belowground production of *S. alterniflora* at intermediate elevations was greater than productivity measured at very low or high elevations within marshes restored through sediment addition.

Role of vegetation and environmental factors in accretion and CAR dynamics

Site-specific environmental conditions influenced LCAR and surface accretion rates across created marshes to a greater extent than marsh age, which supported the second hypothesis, to an extent. Successional trajectories of created marshes varied at the site level and thus obscured effects of marsh age on accretion and CAR. Longer-term surface accretion rates in created marshes were inversely related to elevation, likely associated with greater inundation, and greater sedimentation deposition, as well as colonization by more productive, flood tolerant plant species, such as *S. alterniflora* (Morris et al. 2002, Kirwan and Megonigal 2013). Within-marsh variability in environmental conditions is likely driven by microtopography, as younger marshes had the greatest ranges in elevations and may exhibit more abiotic variability than older marshes because of the timescale of settlement and consolidation of dredge sediment. It is these abiotic conditions that subsequently drive plant community compositions and accretion processes, as has been found in other restored marshes (Shafer and Streever 2000, Stagg and Mendelssohn 2011, Kongchum et al. 2017). On average, we found the lowest short-term accretion rates in both the lowest and highest elevation marshes. These sites may represent the lower and upper boundaries in the parabolic model of inundation developed by Morris et al. (2002), in which aboveground production is reduced at both high and low water depths, coupled with changes in species composition. In SNWR, the overall low accretion rates compared to RSLR suggest that this parabola will shift over time, with increasing accretion in high-elevation areas as subsidence and compaction occur, and mid- to low-elevation marshes ultimately submerging.

In a natural marsh, elevations tend to increase in response to sea-level rise as the marsh ages and vertically accrete, reaching a dynamic equilibrium controlled by tidal maxima (Pethick 1981). However, variable initial conditions of each created marsh may obscure typical patterns of natural marsh evolution, and it is coincidental that the oldest sites in this area were also highest in elevation. Due to their high elevations and locations near the shipping channel, the 20- and 32-yr-old marsh edges were subject to higher salinities as well as storm and wave impacts that may promote the growth of more resilient, but lower stem density, shrub and forb species such as *B. maritima*, *B. frutescens*, and *S. tenuifolium* (Lonard et al. 2011). Increased wave action due to barge wakes may cause increased erosion rates near the marsh edges, but random selection of core locations should capture a representative accretion rate that includes erosion. We attribute the relatively low LCAR to low overall accretion rates and the paradoxical interactions of elevation and high-density plant species. Lower accretion rates were found at higher elevations, and higher LCAR were found within in older, higher elevation marshes with high stem densities. Therefore, interactions between the differential drivers of surface accretion and accumulation rates counteract major differences in LCAR among marshes. Thus, we suggest that marsh elevation, coupled with vegetation successional processes and tidal flushing, is biologically important factors that indirectly influence rates.

In this system, stem density was determined to be the most important predictor of both short- and longer-term CAR across created marshes, while the within-marsh predictors varied. Both the highest short- and longer-term CAR were found in the 13-yr-old marsh, which was comparable to surrounding natural marshes. The 13-yr-old marsh had abundant *D. spicata*, which, along with *S. patens*, exhibit high stem densities, and may be more resistant to decomposition due to high lignin content (Lonard et al. 2010, 2013). Aboveground litter from these species may therefore remain in the substrate for longer periods than *S. alterniflora* litter, which is readily decomposed (Lonard et al. 2010, 2013). In contrast, the 8-yr-old marsh, with a low SCAR of 75.3 $\mathrm{g \cdot m^{-2} \cdot yr^{-1}}$, may be sub-optimal in the elevation-growth range for *S. alterniflora*. That is, it floods at a depth and frequency that suppresses vegetative growth and decreases overall vertical accretion and organic C accumulation rates, which were 3.7 and 5.7 times lower than rates found in the 13-yr-old marsh. Field observations support this suggestion, as we noted large patches of vegetative die-off in the 8-yr-old marsh over the duration of this study. Within the 8-yr-old marsh dominated by low-density *S. alterniflora*, vegetative biomass was found to have the greatest percent contribution to LCAR. Marsh areas with bare sediment and very low stem density may be subject to higher turbulence and sediment erosion, further reducing measured short-term surface accretion and CAR (Reed and Cahoon 1992, Greiner et al. 2013). Although previous studies have demonstrated the ability of dense vegetation to trap sediment and slow water velocity to increase particle settling (Mudd et al. 2004, Fagherazzi et al. 2012), we found that overall, mineral sediment accumulation rate was not correlated with LCAR in these created marshes. Mineral sediment contributed to CAR to a greater extent than other variables within the 5- and 20-yr-old marshes, suggesting a greater dependency on mineral inputs. In the youngest marsh, this may be due to reworking of mineral-dense dredge material in sparsely vegetated areas. In the 20-yr-old marsh, which contained woody, high-elevation species, allochthonous inputs from infrequent flooding and storm surges may be contributing more to accretion and CAR than productivity. Within the 13- and 32-yr-old marshes, however, stem density remained the most important predictor of LCAR, suggesting these marshes remain dependent upon autochthonous, rather than allochthonous contributions to sustain soil C accumulation rates (Jankowski et al. 2017). This variability in factors that contribute to C accumulation points to complex and site-specific feedbacks between marsh elevation, mineral sediment availability, and vegetation type and structure, even within a limited geomorphic setting such as the Chenier Plain (Fig. 10).

Created marsh persistence

LCAR in SNWR created marshes averaged 59.0 g $C{\cdot}m^{-2}{\cdot}yr^{-1}$, less than the 107.9 g $C{\cdot}m^{-2}{\cdot}yr^{-1}$ natural marsh average calculated from Smith (2012). In Cameron Parish, CARs ranged from 41 to 115 g $C{\cdot}m^{-2}{\cdot}yr^{-1}$ (Chmura et al. 2003); in contrast, rates in the Mississippi Delta were found between 131 and 265 g $C{\cdot}m^{-2}{\cdot}yr^{-1}$ (Markewich et al. 2007). In this setting, vegetation contributes to overall accretion more than mineral sedimentation, and despite relatively high short-term surface accretion rates, created marshes may not persist over time without additional mineral sediment sources (Morris et al. 2016). Rogers et al. (2019) recently suggested that an increase in vertical accommodation space driven by RSLR may lead to increasing sedimentation and C sequestration; however, the limited tidal exchange and reduced sediment availability in this region may contradict this trend. Mean observed RSLR in this area is 9.5 mm/yr (±6.33 mm/yr, $n = 89$; Jankowski et al. 2017), which is 1.5 times higher than even the highest longer-term accretion rate we measured in this study, suggesting both created and natural marshes are at risk of drowning in SNWR. Our results support and augment these findings by demonstrating a substantial accretion deficit in created marshes in the western Chenier Plain, irrespective of environmental conditions or age. Additionally, SNWR marshes have relatively low short- and longer-term CAR as compared with other regions in Louisiana but were maximized in the 13-yr-old marsh. This site may serve as a useful model for future dredge sediment creation projects that seek to both sequester blue C and maintain elevation in the face of RSLR, though we note the potential need for future sediment amendments to maintain marsh stability over a long period (Stagg and Mendelssohn 2011).

Implications for marsh creation and restoration

Our results point to complex and dynamic feedbacks between created marsh age, elevation, and vegetation stem density, with stem density ultimately the most important factor influencing CAR in SNWR. Our results suggest that investing greater resources in refining project design and implementation may prove invaluable; if high stem density species are targeted based on the geomorphic setting, vertical accretion and CAR may be optimized, ultimately increasing the beneficial lifespan of the marsh. In assessing post-creation progress, relying solely upon the age of a created marsh to infer rates of blue C accumulation may prove inappropriate (Zedler and Callaway 1999). This study, among others, points to the necessity for long-term marsh monitoring and modeling under potential sea-level, sediment availability, and climate scenarios

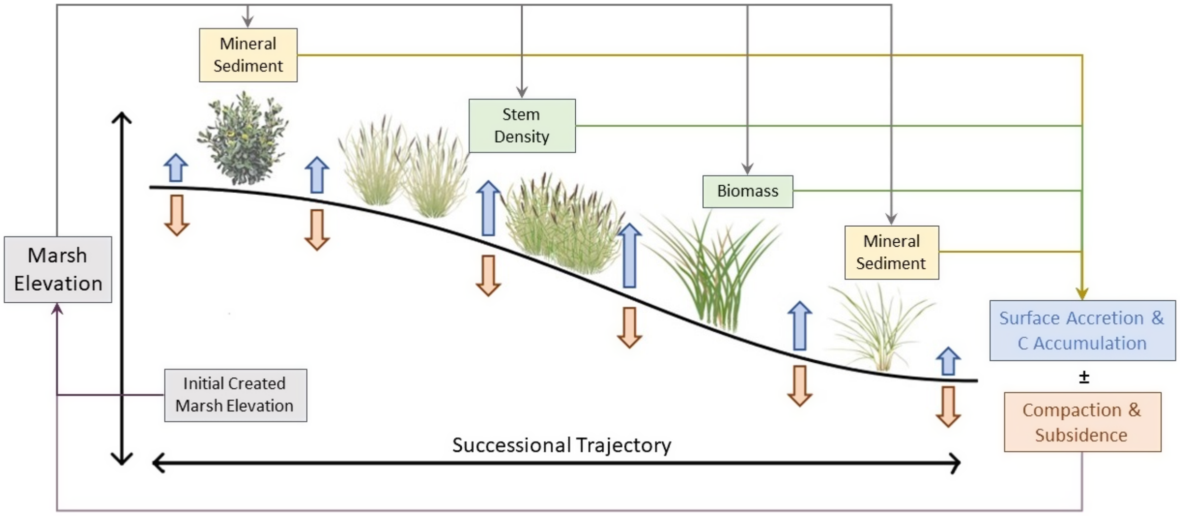

Fig. 10. Conceptual diagram illustrating site-specific feedback processes influencing accretion and carbon accumulation in created dredge sediment wetlands.

(Kulawardhana et al. 2015, Propato et al. 2018). Several questions remain to be resolved; in particular, whether the influence of stem density on LCAR extends to created marshes in different geomorphic settings or with greater sediment availabilities. Longer-term studies are required to evaluate created marsh development over time in order to quantify feedbacks of elevation and vegetation species on CAR.

Conclusions

Across the 32-yr chronosequence of created marshes, CARs were most influenced by plant stem densities, maximized in *S. patens* and *D. spicata* communities. This has implications for the planning and design of dredge sediment marshes, and points to the importance of creating marshes at optimal elevations for the establishment and growth of high-density species such as *D. spicata* and *S. patens,* particularly in settings where allochthonous sediment inputs may be low or variable. Designing marshes to promote high-density species may have multiple benefits, as the higher elevations that support these species may also increase project longevity in the face of RSLR and serve to increase C accumulation. Further research on the ecological development of created marshes will provide critical insights on marsh restoration in the context of a high projected RSLR that will likely be experienced globally in the future.

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