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Key Points:

- Marsh habitat soils in coastal Louisiana accumulate on average 211–381 g TC m^{-2} $year^{-1}$ over the long term (decades)
- Louisiana marsh soils bury 4.3 Tg TC $year^{-1}$, accounting for 5%–21% of global, 47% of North America, and 65% of Gulf of Mexico rates
- Half of the current soil carbon sink in coastal Louisiana marshes could be lost in the next 50 years with no coastal restoration activity

Supporting Information:

- Supporting Information S1

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Long-Term Carbon Sinks in Marsh Soils of Coastal Louisiana are at Risk to Wetland Loss

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Abstract Coastal marshes are essential habitats for soil carbon accumulation and burial, which can influence the global carbon budget. Coastal Louisiana has extensive marsh habitats (fresh, intermediate, brackish, and saline) where soil cores were collected to a depth of 100 cm at 24 sites to assess long-term carbon accumulation and burial rates. Select soil depth intervals were analyzed for bulk density, total carbon, and radionuclide (^{137}Cs and ^{210}Pb) dating. Marsh habitat maps (years 1949–2013) were also used to determine the most frequently occurring habitat at each field site. Over 5 decades, half of the sites transitioned between marsh habitats at least once. Saline marshes tended to have lower mean total carbon density (0.04 ± 0.002 g cm^{-3}) and lower mean long-term total carbon accumulation rates (211 ± 46 g TC m^{-2} yr^{-1}, $n = 5$, based on ^{210}Pb) compared to the other marsh habitats. Using marsh habitat specific accumulation rates and area, the total carbon burial rate for coastal Louisiana in year 2013 was estimated at 4.3 Tg TC yr^{-1} which accounts for about 5%–21% of the estimated tidal wetland burial rate globally. Historically, about 1.0 Tg TC yr^{-1} was lost due to reduced marsh area from 1949 to 2013. With no coastal restoration activity, the predicted wetland loss over the next 50 years could reduce carbon burial in coastal Louisiana to 2.1 Tg TC yr^{-1}, a reduction of about 50% from the year 2013 rate, with potential to significantly alter the global carbon budget.

1. Introduction

Globally, coastal wetlands play a significant role in producing, accumulating, and storing organic matter (Chmura et al., 2003; Laffoley & Grimsditch, 2009; Ouyang & Lee, 2014). Because of their contribution to the global carbon cycle, societal attention has focused on wetlands and other aquatic ecosystems for their potential to sequester carbon and influence greenhouse gas emissions, climate change, and the "blue carbon" economy (Sutton-Grier et al., 2014). The importance of wetlands to global carbon storage and emission dynamics has only recently been recognized in national inventory efforts (IPCC, 2014). However, global estimates suggest that wetlands store more than one third of the total world pool of soil carbon (Choi & Wang, 2004; Eswaran et al., 1995). Even so, additional information from deep soil cores (1 m) is needed to provide robust estimates of carbon accumulation (g TC m^{-2} yr^{-1}) and burial rates (Tg TC yr^{-1}) in coastal wetlands (Windham-Myers et al., 2018). Throughout this manuscript long-term accumulation rates are defined as the mass of soil carbon (to a depth of 1 meter) per unit area and time with the common units utilized in the literature of g TC m^{-2} yr^{-1}. Burial rates are defined as the mass of soil carbon per unit time with units of Tg TC yr^{-1}, calculated by multiplying the long-term accumulation rate by the area of marsh, in this case for coastal Louisiana.

Carbon accumulation and burial rates may vary among wetland habitats. These habitats are characterized by differences in vegetation community composition and environmental parameters, such as salinity or flood duration and frequency. Herbaceous wetlands of coastal Louisiana have been classified into four marsh habitats: Fresh, intermediate, brackish, and saline based on their vegetation, salinity, and hydrological regimes (Visser et al., 2002). Transition among these habitats results from responses to environmental conditions over time, especially to salinity (Visser et al., 2013). Different marsh habitats often vary in their rates of plant production (Stagg, Schoolmaster et al., 2017; Więski et al., 2010), decomposition, (Janousek et al., 2017; Stagg, Baustian et al., 2017) and ultimately carbon accumulation (Baustian et al, 2017, 2020; Chmura, 2013; Craft, 2007; Hopkinson et al., 2012; Neubauer & Craft, 2009). Investigating the long-term carbon accumulation rates of these four marsh habitats allows estimation of gains or losses of carbon burial under historic and future scenarios of habitat change. Wetland loss can cause soil degradation, exposing previously buried soils to oxidizing conditions that subsequently impacts the global carbon cycle through an increase in atmospheric emissions (Crooks et al., 2018).

Coastal Louisiana is an ideal location to study wetland carbon dynamics because it supports various wetland habitats typical in the northern Gulf of Mexico (Hansen & Nestlerode, 2014; Thorhaug et al., 2018; Windham-Myers et al., 2018). Louisiana is also home to ∼37% of all estuarine herbaceous marshes in the conterminous United States of America (Couvillion et al., 2011) and has experienced some of the greatest wetland loss in the country (Dahl, 2011). In addition, coastal Louisiana is a low lying deltaic plain, where subsidence and high rates of relative sea-level rise will likely continue to threaten wetland persistence and areal extent of a full estuarine gradient that includes these four marsh habitats (Couvillion et al., 2013; Linscombe & Hartley, 2011). Coastal Louisiana has already lost a significant area of wetlands (∼25% of 1932 land area) (Couvillion et al., 2017) with the greatest decline observed in brackish and saline marsh habitats (a decline of 14% and 1%, respectively between 1978 and 2001) (Linscombe & Hartley, 2011). Therefore, future wetland change in coastal Louisiana may have a disproportionate impact on regional, and potentially global, carbon accumulation and burial rates (Couvillion et al., 2013; DeLaune & White, 2012; Hinson et al., 2017; Windham-Myers et al., 2018). This study examined long-term carbon accumulation rates at 24 sites across the four marsh habitats of coastal Louisiana to determine carbon burial rates for the coastal area. Long-term carbon accumulation and burial rates refer to a period spanning multiple decades to a century or more and are often measured with ^{137}Cs and ^{210}Pb dating techniques (Ouyang & Lee, 2014). Short-term carbon accumulation and burial rates (often based on the top 10 cm of soil conditions and utilizing accretion rates measured with feldspar clay marker horizons) refer to a short time scale ranging from months to years (Baustian et al., 2017). The main research questions for this study were (1) what was the most frequently occurring marsh habitat at a field site and did it differ from the current classification? (2) are there differences in long-term soil composition, accretion rates, and total carbon accumulation rates among these marsh habitats in coastal Louisiana? and (3) based on these accumulation rates and estimates of historical and future marsh area, what are the long-term total carbon burial rates for the Louisiana coast and how do they compare to regional and global burial rates?

2. Materials and Methods

2.1. Site Description

Marsh sites were selected based on their salinity and herbaceous vegetation regime and encompassed a broad geographical landscape (∼65 km linear north to south gradient) of Mississippi River Deltaic Plain (Figure 1). Six sites each were located within four current marsh habitats: fresh (0–0.5 psu), intermediate (0.5–5 psu), brackish (5–18 psu), and saline (>18 psu) as defined by Chabreck (1970) and were used to characterize the habitats from historical maps and vegetation surveys in the basins. The dominant marsh habitats known to be associated with specific salinity and hydrological regimes (Visser et al., 2002) consisted of fresh sites dominated by *Panicum hemitomon* and *Typha latifolia*, intermediate sites dominated by *Sagittaria lancifolia* and *Schoenoplectus americanus*, brackish sites dominated by *Spartina patens* and *Schoenoplectus americanus*, and saline sites dominated by *Spartina alterniflora* and *Juncus romerianus*. The 24 sites were located within two hydrologic basins, Terrebonne and Barataria (Figure 1), and co-located with Coastwide Reference Monitoring Systems (CRMS) stations (http://lacoast.gov/crms2/home.aspx), where continuous hydrological and discrete vegetation and soil data have been collected since 2006 (Steyer et al., 2003). Work herein builds upon previous primary productivity, decomposition, and short-term carbon accumulation studies at these same sites (Baustian et al, 2017, 2020; Schoolmaster & Stagg, 2018; Stagg, Baustian et al., 2017; Stagg, Schoolmaster et al., 2017). Data produced from the work described here can be found at USGS ScienceBase Catalog (Baustian et al., 2021).

2.2. Most Frequently Occurring Marsh Habitat

Historical vegetation survey maps (1949, 1968, 1978, 1988, 1997, 2001, 2007, and 2013, $n = 8$) were used to estimate the spatial extent of the four marsh habitats in coastal Louisiana through time at the 24 sites.

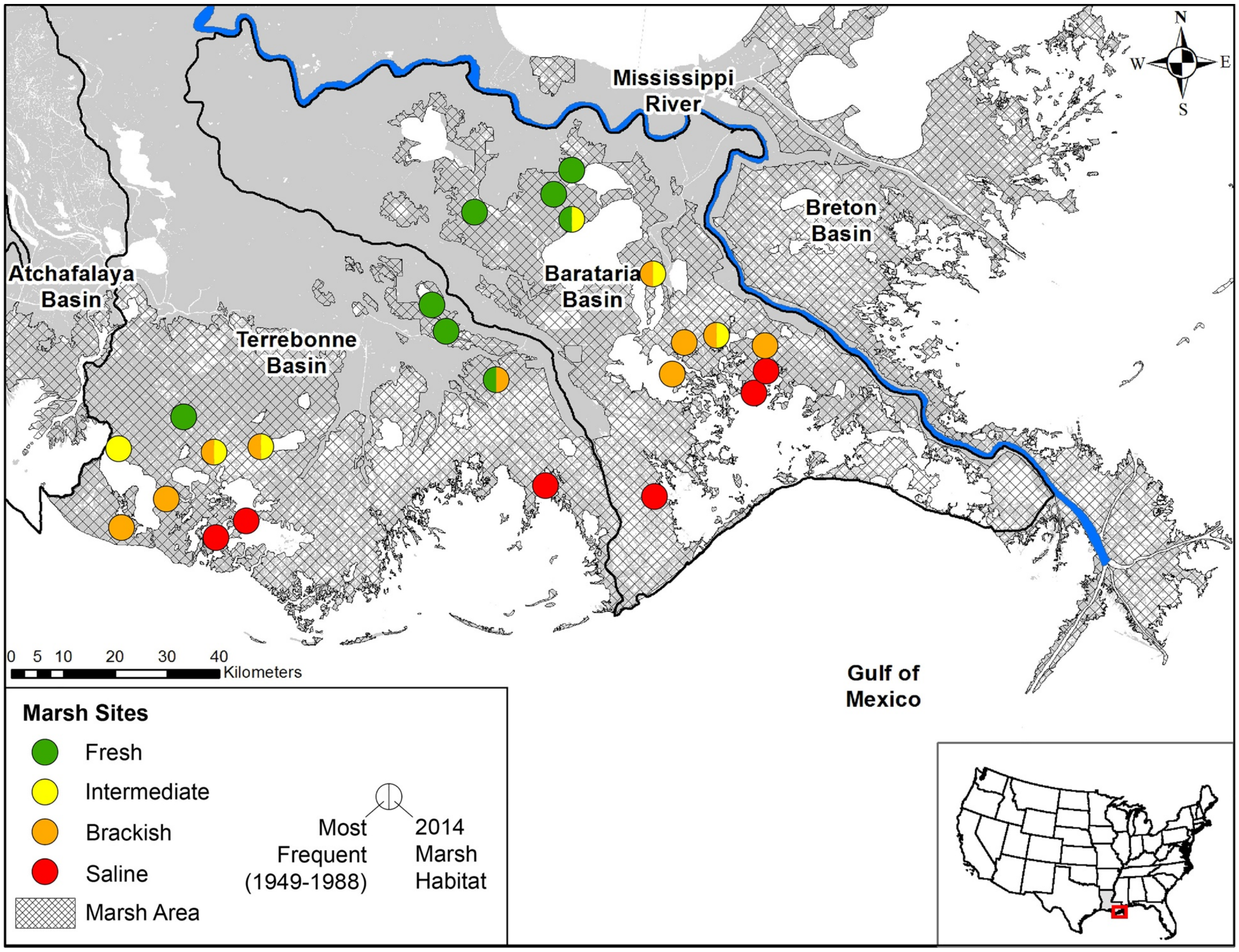

Figure 1. Field site locations color coded by four marsh habitats (fresh, intermediate, brackish, and saline) based on most frequently occurring marsh habitat (left side) and classification in year 2014, right side in Barataria ($n = 12$) and Terrebonne basins ($n = 12$) of coastal Louisiana. Map adapted from Baustian et al. (2017).

These historical vegetation survey maps were downloaded from the CRMS website (CRMS 2015) and were based on previous documented work of ground and helicopter surveys (Chabreck et al., 1968; Chabreck & Linscombe, 1978, 1988, 1997; Linscombe & Chabreck, 2001; O'Neil, 1949; Sasser et al., 2008, 2014). An additional vegetation survey was conducted for this study in 2014 and represents the latest marsh habitat classification. ArcGIS was used to extract the marsh habitat classification at each of the 24 sites for all historical and current vegetation survey maps, and a numerical value was assigned (1 = fresh, 2 = intermediate, 3 = brackish, and 4 = saline) to evaluate the marsh habitat transitions over time and to estimate the most frequently occurring marsh habitat per site (i.e., the mode). Open water (value = 5) was used to characterize the habitat classification for each site but was not included in calculations of most frequently occurring habitat because only marsh habitats were of interest. Therefore, each site included nine observations of marsh habitat classification, except for sites that had open water habitat for certain years, and those sites were: CRMS0337 (1978), CRMS0377 (1978, 1997, 2001, 2007, and 2013) and CRMS3617 (1949 and 1978).

Mean accretion estimates (based on ^{137}Cs and ^{210}Pb from all soil cores) were 0.63 and 0.53 cm yr^{-1}, respectively, and revealed that the available historical observations from 1949 to 1988 correspond most closely with soil depths of 12–100 cm. Therefore, marsh habitat classification observations from 1949 to 1988 were used to identify the most frequently occurring marsh habitat for appropriate representation of the long-term processes.

2.3. Soil Core Collection

Soil cores (100 cm long) were collected at each site with a McCauley corer (similar to a Russian peat corer, inner diameter = 5.1 cm, one-half volume, to limit compaction) at a consistent distance ~25 m inland from the shoreline (backmarsh area, ~0.14 m elevation, GEOID12A) in February (batch #1) or June/July 2015 (batch #2). Field observations at one site (CRMS4045) indicated some compaction because of a clay layer at a starting depth near 38 cm. Each core was sectioned into 2-cm depth intervals in the field, placed in whirl-paks, and kept on ice until transported to the laboratory and frozen. Soil samples from select depth intervals (e.g., 0–2, 2–4, 4–6, 8–10, 12–14, 16–18, 22–24, 38–40, 58–60, 78–80, and 98–100 cm, $n = 11$) were prioritized for radiochemistry analysis (all selected intervals) and to represent the overall ecological condition (i.e., carbon density) of the deeper or long-term deposited soils (interval depths 12–14 to 98–100 cm).

2.4. Soil Composition Analysis

Soil samples (depth intervals between 12 and 100 cm) collected from batch #1 were used to determine soil properties (bulk density, % organic matter) at each site. The exception is for sites CRMS3166 and CRMS4245 where organic matter analysis was conducted on batch #2 samples (June/July 2015). Soil samples were freeze-dried to a constant weight to determine dry bulk density. Organic matter (OM) content was determined through loss on ignition by combusting material at 550°C for 14 h. To convert percent OM to percent total carbon (%TC), a conversion rate of 0.47 (±0.0081 std. error.) was applied based on an earlier study that used acid fumigation to differentiate soil total carbon and organic carbon (Baustian et al., 2017, 2020). The soil organic carbon fraction on average contributed about 97% of the soil total carbon, therefore organic carbon is a major contributor to the total carbon pool. These parameters (%TC and %TOC) are near identical and both can be used to estimate carbon content. Total carbon density per depth interval was calculated by multiplying the dry bulk density by TC.

2.5. Radionuclide Dating

To determine the carbon accumulation rate (g TC m^{-2} yr^{-1}) at each site, decadal-scale soil accretion was estimated using ^{210}Pb and ^{137}Cs dating (Wilson & Allison, 2008). Lead-210 occurs naturally in the environment and has a half-life of 22.3 years; soil age is estimated by assuming a constant rate of excess ^{210}Pb ($^{210}Pb_{xs}$) input by utilizing the constant initial concentration model (Appleby & Oldfield, 1978; Nittrouer et al., 1979; Shukla & Joshi, 1989). Cesium-137 is a product of thermonuclear weapons testing and does not occur naturally. Atmospheric deposition of ^{137}Cs began in the early 1950s, with peak quantities detected in 1963 (Pennington et al., 1973), and non-steady state inputs starting to decline after the 1972 atmospheric test ban treaty. Thus, the profile of ^{137}Cs with sediment depth peaks at a depth corresponding to 1963 as well as the onset of activity beginning in 1954 can be used as the marker layer above which vertical accretion can be quantified. For this study ^{137}Cs was used to validate ^{210}Pb-based rates to estimate marsh accretion rates (Drexler et al., 2018; Turner et al., 2006) and calculate the long-term carbon accumulation rates.

The soil was combusted to obtain only the mineral sediment (inorganic matter) for the counters to detect the radionuclides. Approximately 2 g was lightly ground and packed into 10-mm diameter vials to a standard height of 37-mm and sealed with epoxy (Du et al., 2012). In some cases, mineral sediment mass from soil samples of a core in batch #1 (collected in February 2015) was insufficient for radionuclide activity detection (see Table 2 and therefore soil samples from batch #2 collected in June/July 2015) of the same depth from other replicate soil cores (cores two, three, and four of batch #2) were pooled together to increase detection. Soil samples from batch #1 and batch #2 were never mixed. Photographs allowed for visual identification of event deposition layers and were used to confirm that the three cores were consistently representing the collection area. Both ^{137}Cs and $^{210}Pb_{xs}$ activity was counted with low-energy germanium detectors, well configuration. Accretion or linear sedimentation rate (cm yr^{-1}) was determined by using the slope of the log-transformed $^{210}Pb_{xs}$ activity. The error rates associated with the ^{210}Pb accretion rates are based on the best fit linear regression of the decay line (Table 2). Accretion rates were also estimated from the depth of the soil layer containing the highest ^{137}Cs activity (since 1963) and the number of years between core collection (DeLaune et al., 1978). The error rates for the ^{137}Cs accretion

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rates are based on the depth of peak activity and derived using the depth difference between the peak interval and the adjacent measured intervals above and below that interval. Hence, the ± error can be different (Table 2).

2.6. Long-Term Total Carbon Accumulation Rate Calculations

Total carbon accumulation rate (g TC m^{-2} yr^{-1}) per soil core was calculated by multiplying the mean carbon density (g C cm^{-3}, calculated from soil intervals between 12 and 100 cm to estimate depth-averaged soil conditions) by the accretion rates (cm yr^{-1}, ^{137}Cs and ^{210}Pb) following Bernal and Mitsch (2008, 2012) and Bianchi et al. (2013). Depth-averaged soil conditions to depths of 100 cm are often used to assess soil carbon stocks such as the Tier 1 approach of IPCC (IPCC, 2014) and others (Holmquist et al., 2018; Windham-Myers et al., 2018).

2.7. Long-Term Total Carbon Burial Calculations

Estimates of long-term total carbon burial rates (Tg TC yr^{-1}) were calculated based on weighted means by utilizing the mean long-term total carbon accumulation rate (from ^{210}Pb) of each marsh habitat and their corresponding marsh habitat area (Figures 6 and 7). Only one accumulation rate from each of the fresh and intermediate habitats existed and therefore a mean (±std. error) was calculated from the two values that equaled 276 ± 123 g TC m^{-2} yr^{-1}, $n = 2$. The mean (±std. error) long-term total carbon accumulation rates for the brackish marsh habitat was 381 ± 40 g TC m^{-2} yr^{-1} ($n = 9$) and for saline marsh habitat was 211 ± 46 g TC m^{-2} yr^{-1} ($n = 5$) (Figure 6).

The Integrated Compartment Model output about future (after 50 years) marsh area from the 2017 Louisiana Coastal Master Plan (Coastal Protection & Restoration Authority of Louisiana, 2017) was used to estimate future burial rates. This landscape model simulates long-term hydrology, vegetation, and morphology for the entire Louisiana coastal wetland system by using associated subroutines written in Fortran 90 (White et al., 2017, 2019). The landscape model relies on bathymetry, topography, and land use/land cover data. It is driven by boundary conditions that represent tidal water levels and salinities; tributary inflows (suspended sediments, salinity) and rainfall; winds, temperature, and evapotranspiration (White et al., 2019). The model was calibrated/validated with over 200 field observations collected from 2006 to 2013. Calibration first started with the hydrology subroutine because it is the primary driver of the other subroutines (vegetation and morphology) (Brown et al., 2017; White et al., 2019). These modeling efforts considered future subsidence and sea-level rise rate scenarios as well as proposed restoration projects (e.g., marsh creation, sediment diversion, barrier island nourishment) in coastal Louisiana (Alymov et al., 2017). The landscape was updated annually based on the feedback among hydrology, morphology, and vegetation subroutines (Cobell et al., 2017). Output from the hydrology and morphology subroutines are used as inputs to the vegetation subroutine (Visser & Duke-Sylvester, 2017). Annual wetland vegetation species distribution is calculated based on the ecological niche that uses annual mean salinity and standard deviation of water level from mortality and establishment tables. The wetland vegetation species output is then classified into a marsh habitat for each of the vegetation cells (500 × 500 m) (Visser & Duke-Sylvester, 2017). Two simulations of future conditions were compared, including with no coastal restoration activity (simulation G300) and with full implementation of coastal restoration (simulation G400). In both simulations, a medium sea-level rise scenario (S04) was used with a non-linear eustatic sea-level rise of 0.63 m over 50 years (see Figure 2 in White et al., 2019) and a spatially varying subsidence rate represented by the lowest quantile value for each zone (Alymov et al., 2017; Meselhe

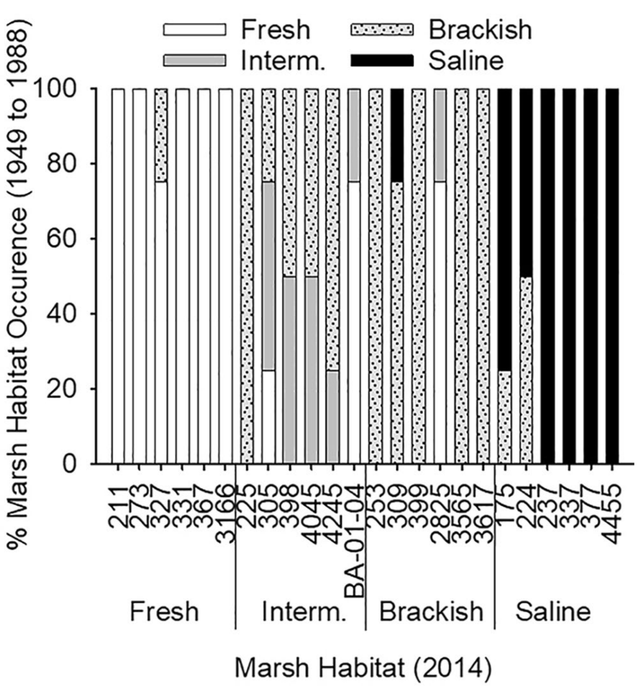

Figure 2. Relative frequency of marsh habitat occurrence (with no open water category) for each field CRMS site from 1949 to 1988, an estimated time that best corresponds to the soil core intervals from 12 to 100 cm. Individual sites are grouped according to marsh habitat classifications in year 2014. CRMS, Coastwide Reference Monitoring Systems.

et al., 2017). The magnitude of subsidence rates therefore varied from a minimum value of 0 mm year^{-1} in the north shore area of Lake Pontchartrain to a maximum value of 19 mm yr^{-1} in the Bird's Foot Delta; salt domes had an assumed uplift of 2 mm yr^{-1} (Reed & Yuill, 2017). The output used from this landscape model was the total area per marsh habitat after 50 years.

2.8. Statistical Analysis

Statistical analyses and data manipulations were performed in Statistical Analysis System (SAS) 9.4. The null hypothesis for all tests was that there was no difference in soil properties (bulk density, total carbon percentage, total carbon density), accretion rates, and long-term total carbon accumulation rates among marsh habitats with $\alpha = 0.05$. All study sites were re-categorized according to the most frequently occurring marsh habitat (from maps dated between 1949 and 1988) and thus all subsequent statistical analyses for the long-term carbon accumulation rates used the most frequently occurring marsh habitat as the categorical variable. Differences among soil properties (log-transformed for bulk density and TC density) from marsh habitats were evaluated with an analysis of variance using generalized linear mixed models (PROC

Table 1
Coastal Louisiana Field Sites From Various Marsh Habitats Where Soil Cores Were Collected and Analyzed (Interval Depths of 12–100 cm) for Mean (±std. Error) of Bulk Density, Total Carbon (TC, %), and Total Carbon Density

Most Freq. Occ. Habitat from 1949 to 1988	Site ID	Basin	2014 marsh habitat	Floating type	Mean soil bulk density (g cm^{-3})[a]	Std. err. bulk density (g cm^{-3})[a]	Mean soil TC (%)[a]	Std. err. TC (%)[a]	Mean soil TC density (g cm^{-3})[a]	Std. err. TC density (g cm^{-3})[a]
Fresh	BA-01-04	BA	Intermediate	Floating	0.17	0.01	37.77	2.84	0.06	0.003
Fresh	CRMS0211	BA	Fresh	Floating	0.17	0.01	30.74	4.20	0.05	0.007
Fresh	CRMS0273	BA	Fresh	Floating	0.13	0.01	41.33	1.12	0.06	0.005
Fresh	CRMS0327	TE	Fresh	Floating	0.15	0.01	31.41	1.49	0.05	0.003
Fresh	CRMS0331	TE	Fresh	Floating	0.25	0.08	31.62	2.98	0.07	0.012
Fresh	CRMS0367	TE	Fresh	Floating	0.18	0.02	27.14	4.32	0.05	0.003
Fresh	CRMS2825	TE	Brackish	Non-Floating	0.19	0.01	34.26	1.64	0.06	0.004
Fresh	CRMS3166	BA	Fresh	Floating	0.46	0.16	27.05	4.74	0.07	0.007
Intermediate	CRMS0305	TE	Intermediate	Non-Floating	0.51	0.06	8.36	1.49	0.04	0.006
Brackish	CRMS0225	BA	Intermediate	Non-Floating	0.22	0.01	30.09	2.66	0.07	0.006
Brackish	CRMS0253	BA	Brackish	Non-Floating	0.33	0.03	16.41	2.15	0.05	0.004
Brackish	CRMS0309	TE	Brackish	Non-Floating	0.45	0.04	9.79	1.37	0.04	0.005
Brackish	CRMS0398	TE	Intermediate	Non-Floating	0.31	0.02	17.55	3.02	0.05	0.006
Brackish	CRMS0399	TE	Brackish	Non-Floating	0.24	0.02	20.66	2.65	0.05	0.007
Brackish	CRMS3565	BA	Brackish	Non-Floating	0.25	0.02	23.04	4.09	0.06	0.007
Brackish	CRMS3617	BA	Brackish	Non-Floating	0.31	0.08	23.12	3.43	0.06	0.004
Brackish	CRMS4045	TE	Intermediate	Non-Floating	0.48	0.13	12.42	3.90	0.05	0.005
Brackish	CRMS4245	BA	Intermediate	Floating	0.47	0.04	25.03	3.25	0.11	0.012
Saline	CRMS0175	BA	Saline	Non-Floating	0.64	0.18	8.42	1.65	0.04	0.004
Saline	CRMS0224	BA	Saline	Non-Floating	0.24	0.02	22.47	2.88	0.05	0.006
Saline	CRMS0237	BA	Saline	Non-Floating	0.58	0.07	7.10	1.43	0.04	0.004
Saline	CRMS0337	TE	Saline	Non-Floating	0.46	0.08	9.88	1.88	0.04	0.004
Saline	CRMS0377	TE	Saline	Non-Floating	0.52	0.05	6.52	0.64	0.03	0.003
Saline	CRMS4455	TE	Saline	Non-Floating	0.37	0.03	11.67	2.67	0.04	0.007

BA, Barataria; CRMS, Coastwide Reference Monitoring Systems; TE, Terrebonne.
[a]Sample depths >12 cm.

GLMMIX). Accretion and carbon accumulation data were evaluated to meet statistical assumptions for a pooled variance *t*-test (using PROC TTEST), such as normality of residuals and homogeneity of variance.

3. Results

3.1. Most Frequently Occurring Marsh Habitat

A total of 12 out of 24 sites transitioned to different marsh habitats at least once since 1949 (Figure 2, Table 1). In 2014, six sites were evenly categorized in each of the four marsh habitats, which differed from the past with each marsh habitat (based on most frequently occurring habitat from 1949 to 1988 maps) represented by the following number of sites: fresh = 8 sites, intermediate = 1 site, brackish = 9 sites, and saline = 6 sites (Figure 4). For example, BA-01-04 was classified as an intermediate marsh site in 2014; however, the most frequently occurring marsh habitat classification was fresh. In 2014, the sites CRMS0225, 0398, 4045, and 4245 were considered an intermediate marsh, although it occurred most frequently as brackish (Figure 2). CRMS2825 was observed as a brackish marsh site in 2014 but experienced frequently fresh marsh habitat conditions (Figure 2).

3.2. Soil Composition Analysis

The total carbon depth profile as indicated by the mean total carbon percentage of the fresh marsh habitat was generally higher (~30%) than the depth profiles from the other marsh habitats (~20%) (Figure 3). The depth profile of carbon content in the saline marsh habitat was less variable than the other marsh habitats and contained ~10% TC consistently throughout the depth profile (Figure 3). The depth averaged or mean total carbon content was significantly higher in the fresh marshes (32%, $F_{2,154} = 65.37$, $p = 0.0001$) than in the other marsh habitats (<20%) (Figure 4). The mean bulk density was significantly lower in fresh marshes (~0.23 g cm^{-3}, $F_{2,165} = 22.14$, $p = 0.0001$) compared to the other two marsh habitats (>0.35 g cm^{-3}) (Figure 4). Therefore, the mean total carbon density was lowest in the saline marshes (~0.04 g cm^{-3} represented by nine sites) and intermediate marsh (representing only one site) compared to the others (>0.06 g cm^{-3}, $F_{2,154} = 13.74$, $p = 0.001$) (Figure 4).

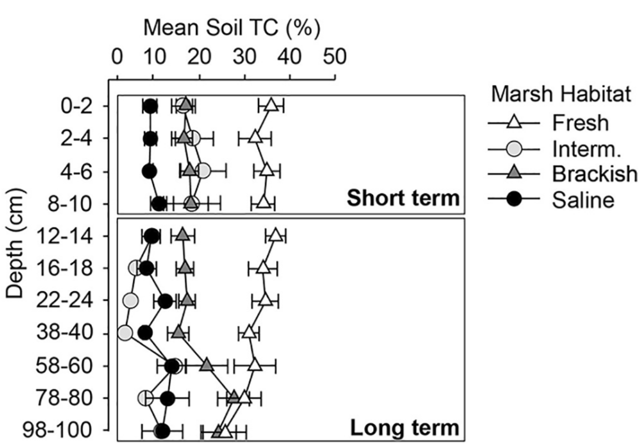

Figure 3. Mean (±std. error) total carbon content (TC%) of select soil layers in the top 10 cm (representing short-term carbon pools, from Baustian et al., 2017) and from select intervals from 12 to 100 cm (representing long-term carbon pools) of 24 marsh sites in Barataria and Terrebonne basins of coastal Louisiana that were classified as fresh, intermediate, brackish and saline. Sites with short-term soil mean TC (%) were classified based on 2014 observations (Baustian et al., 2017). Sites with long-term soil mean TC (%) were classified based on most frequently occurring marsh habitat between 1949 and 1988 (soil cores per habitat included: fresh = 8, intermediate = 1, brackish = 9, and saline = 6).

3.3. Radionuclide Dating

Examples of ^{137}Cs and $^{210}Pb_{xs}$ profiles of soil cores representing the four marsh habitats (based on most frequently occurring habitat between 1949 and 1988) are presented in Figure 5. The distribution of the 15 field sites with adequate ^{137}Cs soil profiles was not uniform among the four marsh habitats (Figure 6a). Only one soil core from the fresh marsh was dated with ^{137}Cs, while there were none from intermediate marsh, nine cores from brackish marsh, and five cores from saline marsh. The sample size distribution of ^{210}Pb estimated accretion rates was similar to ^{137}Cs accretion rates with the addition of one soil core (CRMS0305) that represented the intermediate marsh habitat (Figure 6b). The estimated long-term accretion rates did not differ between brackish and saline marsh habitats ($p = 0.09$) based on ^{137}Cs radionuclide dating methods nor ^{210}Pb radionuclide dating methods ($p = 0.24$) (Figures 6a and 6c).

3.4. Long-Term Total Carbon Accumulation Rates

The long-term total carbon accumulation rates ranged from a minimum of 137 g TC m^{-2} yr^{-1} to a maximum of 998 g TC m^{-2} yr^{-1}, $n = 15$ using ^{137}Cs and included a minimum of 62 g TC m^{-2} yr^{-1} and a maximum of 638 g TC m^{-2} yr^{-1} using ^{210}Pb, $n = 16$. Long-term total carbon accumulation rates differed between brackish and saline marsh habitats as

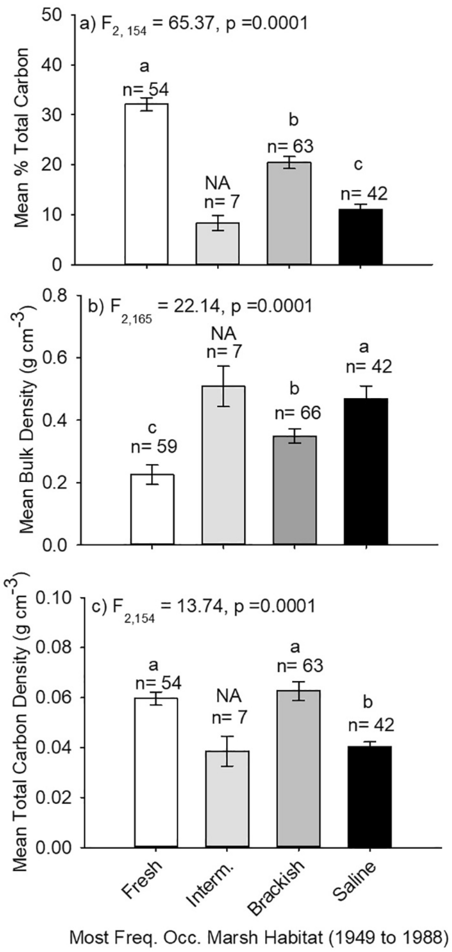

Figure 4. Mean long-term (from depths between 12 and 100 cm) soil properties of (a) total carbon (b) bulk density, and (c) total carbon density representing marsh sites in coastal Louisiana that were classified as fresh ($n = 8$ sites), intermediate ($n = 1$ site), brackish ($n = 9$ sites), and saline ($n = 6$ sites) based on the most frequently occurring habitat between 1949 and 1988. Different letters indicate significant difference among fresh, brackish, and saline marsh habitats based on ANOVA. ANOVA, analysis of variance.

estimated from both ^{137}Cs and ^{210}Pb accretion rates ($p \leq 0.05$ for both ^{137}Cs and ^{210}Pb, Figure 6b and 6d). The sample size for fresh and intermediate marsh habitats was too low for statistical analyses (Figure 6).

3.5. Long-Term Total Carbon Burial Rates

In coastal Louisiana, the total marsh area decreased from about 17×10^3 km^2 to 15×10^3 km^2 between 1949 and 2013 (Figure 7a), which diminishes the rate of long-term TC burial rates from 5.3 to 4.3 Tg TC yr^{-1} (Figure 7b). The same trend in marsh area is evident in the two basins (Barataria and Terrebonne) where the soil cores were collected and that in total represent approximately 40% of the 2013 marsh area of coastal Louisiana (supporting information). Between 1949 and 2013, the marsh area declined from ~ 7.5 to 5.9×10^3 km^2 in Barataria and Terrebonne basins (Figure 7). Therefore, the long-term TC burial rates reflect this areal trend in those two basins with values declining from about 2.3 ± 0.5 to 1.6 ± 0.5 Tg TC yr^{-1} (supporting information). The State of Louisiana's Coastal Master Plan modeling results from the medium scenario suggest that the total coastal Louisiana marsh area could be about 8.0×10^3 km^2 after 50 years with no coastal restoration activity, compared to a future marsh area of 9.7×10^3 km^2 if restoration plans are fully implemented (Alymov et al., 2017). Therefore, after 50 years, coastal Louisiana marshes are expected to bury ~2.1 ± 0.8 Tg TC yr^{-1} with no coastal restoration activity and to bury ~2.6 ± 1.0 Tg TC yr^{-1} with full implementation of coastal restoration (Figure 7).

4. Discussion

4.1. Most Frequently Occurring Marsh Habitats

Coastal Louisiana's Terrebonne and Barataria basins are located in an estuarine deltaic region and have experienced long-term changes in important environmental drivers, such as freshwater and riverine sediment input, sea level, and air and water temperatures (Boesch et al., 1994). As a result, vegetation in wetland communities change over time among fresh, intermediate, brackish, and saline marsh habitats (Wang et al., 2011). Fresh and saline marsh habitats tended to persist more often through time, while intermediate and brackish marsh habitats underwent transition more frequently. This study confirms that it is important to consider historical habitats when evaluating long-term carbon accumulation rates because recently observed marsh habitat patterns (year 2014) might not reflect historically dominant marsh habitats that ultimately influence the carbon content and accumulation rates (Van de Broek et al., 2018). Additional paleoecological proxies for historical dominant marsh habitats could also be useful and are suggested for future studies because rhizomes, pollen, diatoms, or algal pigments could help validate the historical vegetation surveys and maps (e.g., Kim & Rejmánková, 2001; Orson, 1999).

4.2. Soil Composition in Coastal Louisiana Marshes

This study presents new information from deep soil cores (>50 cm, see Table 3) that represent long-term soil properties and influence soil carbon sinks in four marsh habitats of coastal Louisiana. Fresh marshes had significant differences in long-term soil properties (i.e., %TC, bulk density, total carbon density) compared to the other marsh habitats, which confirms results from previous salinity gradient studies (Baustian et al., 2017, 2020; Craft, 2007). For example, the mean %TC of fresh marshes (~32%) was at most three times higher than the other marsh habitats (~8%–20%) and about half the bulk density. All carbon

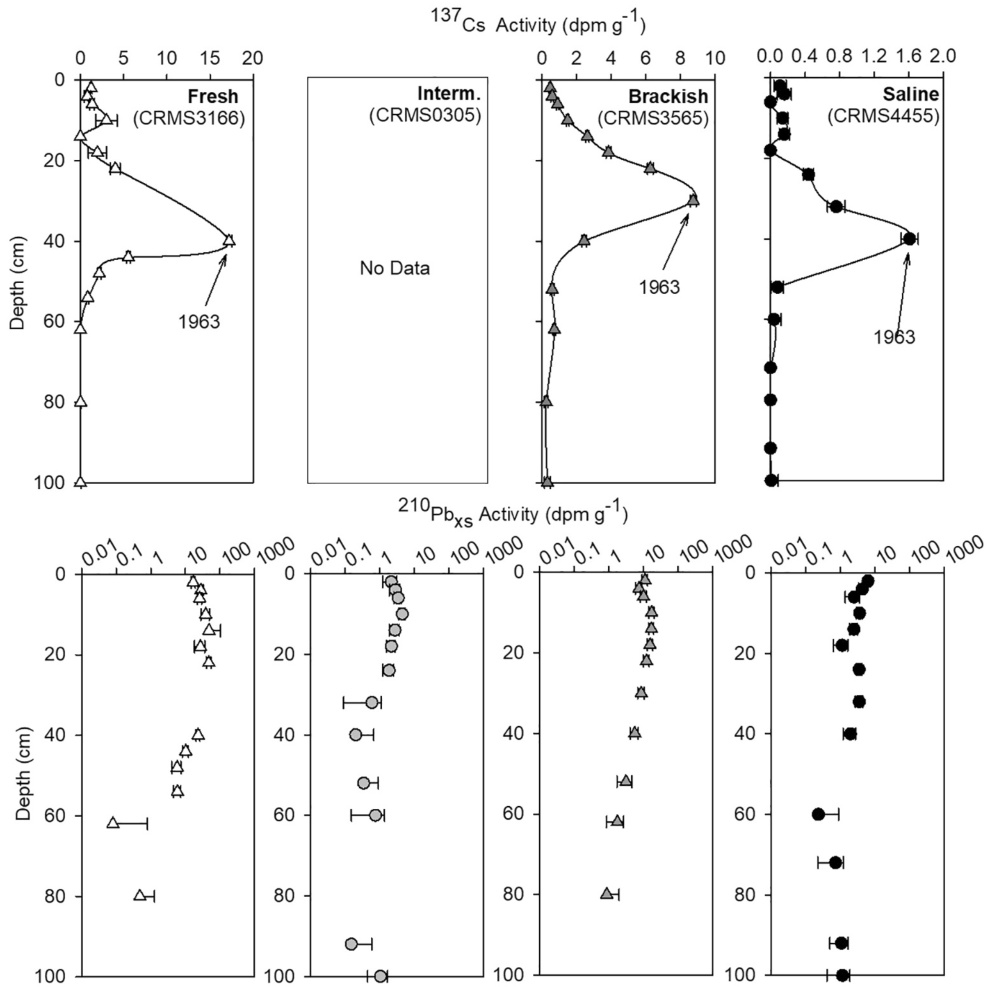

Figure 5. Examples of downcore trends in ^{137}Cs and ^{210}Pb$_{xs}$ activity of soil cores collected from four marsh habitats (based on most frequently occurring marsh habitat between 1949 and 1988) in coastal Louisiana to estimate sediment accretion rates (see Table 2).

densities measured for these marshes (0.04–0.06 g C cm^{-3}) were higher than the mean carbon density value of ∼0.03 g C cm^{-3} synthesized for tidal wetland soils in the conterminous United States of America (Holmquist et al., 2018). However, the bulk density values and calculated %TC values were within the range of other tidal marshes as suggested by an ideal mixing model (Morris et al., 2016).

The ^{137}Cs and ^{210}Pb radionuclide activity of 100-cm deep cores produced long-term accretion rates that ranged from 0.2 to 0.9 cm yr^{-1} with a mean of ∼0.5 cm yr^{-1} ($n = 16$). Other estimates from coastal Louisiana indicate marsh accretion at 0.4–0.9 cm yr^{-1} based on soil cores with depths near 50 cm that were dated with ^{137}Cs and 100 cm soil cores that were dated with ^{210}Pb (DeLaune et al., 1989). Wetland soil accretion estimates are not only important for estimating carbon accumulation rates but are a key factor in understanding marsh vulnerability to sea-level rise (Crosby et al., 2016).

The mean long-term TC accumulation rates per marsh habitat ranged between 211 and 381 g TC m^{-2} yr^{-1} (with ^{210}Pb dating methods, see Section 2.7) based on deep soil cores (Table 2). There was only sufficient data from two marsh habitats, the brackish and saline, to statistically compare accumulation rates and the saline marshes accumulated about 170 g TC m^2 yr^{-1} less than the brackish marshes. Within fresh and intermediate habitats, many of the sediment radionuclide activities were below detection and could not be used for dating. These habitats warrant further investigation to determine accretion rates (to depths of 100 cm). The long-term carbon accumulation rates reported by others (Cai, 2011; Callaway et al., 2012; Hill

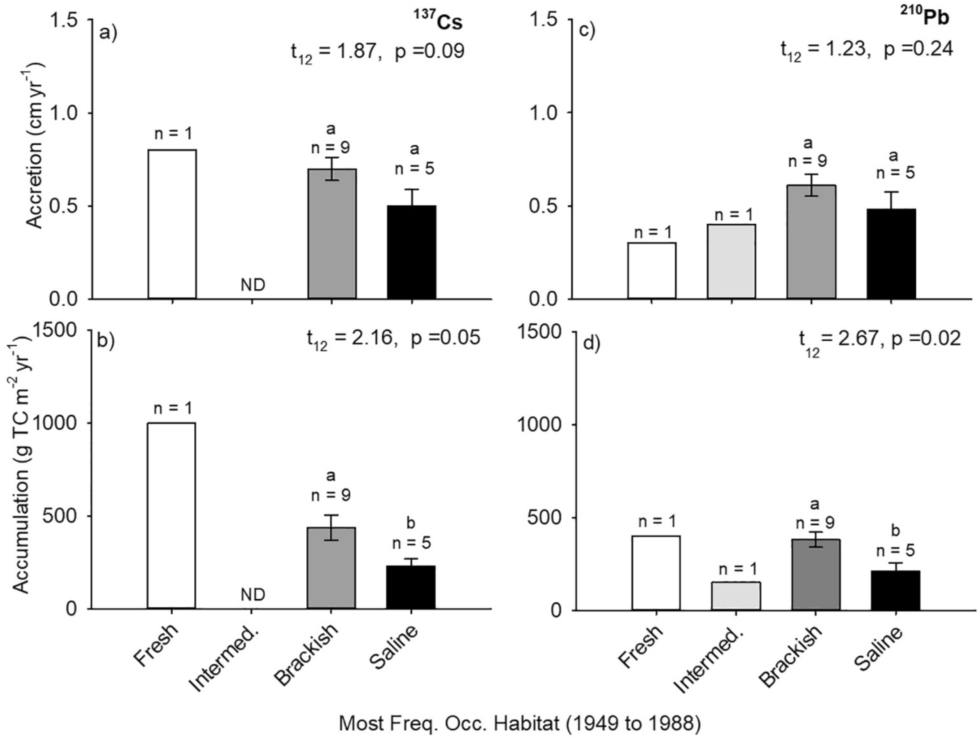

Figure 6. Mean (±std. err.) long-term values of ^{137}Cs and ^{210}Pb-based accretion (panels a and c) and the corresponding total carbon accumulation rates (panels b and d) based on mean site soil characteristics from depths of 12–100 cm that represent marsh sites in coastal Louisiana that were classified as fresh, intermediate, brackish and saline based on their most frequently occurring marsh habitat between 1949 and 1988. *T*-tests were conducted only on the brackish and saline marsh habitats because of the low sample size for the fresh and intermediate marsh habitats.

& Anisfeld, 2015; Hopkinson et al., 2012; McLeod et al., 2011) tend to fall in the lower portion of the range of values from this study (Table 3). Long-term TC accumulation rates tend to be highly variable (Table 3), and this was found to be true among marsh habitats within and between basins in this study (Table 2). For example, Hatton et al. (1983) examined all four marsh habitats in Barataria Basin, Louisiana and found a similar range in accumulation rates (~126–200 g TC m^{-2} yr^{-1}) among the habitats by analyzing 50 cm deep soil cores (Table 3). Another study examined fresh and non-fresh marsh sites near Barataria Bay, Terrebonne Bay, and Vermillion Bay, Louisiana by collecting 50 cm deep soils cores and found no significant difference overall in accumulation rates (~250 g TC m^{-2} yr^{-1}) (Nyman et al., 2006, Table 3). The high variability of long-term TC accumulation rates between and within a marsh habitat is likely due to variation in the historical environmental conditions (e.g., flooding, salinity, mineral sediment), which caused marsh habitat transitions and were mediated through various changes. These changes include vegetation productivity (Osland et al., 2018; Stagg, Schoolmaster et al., 2017) and organic matter decomposition (Stagg, Baustian et al., 2017) that influenced the soil processes (Baustian et al, 2017, 2020; Neubauer, 2008). However, the high variability among long-term TC accumulation rates measured from various studies may also be due to the soil core depth (Breithaupt et al., 2014; DeLaune et al., 2018; Sadler, 1981) and the accretion rate radiotracer utilized (e.g., ^{137}Cs vs. ^{210}Pb) (Van de Broek et al., 2016, 2018).

4.3. Coastal Louisiana's Current Contribution to Regional and Global Carbon Burial Rates

Based on data collected in this study, the current estimated long-term TC burial rate within coastal Louisiana marsh soils (area of ~15 × 10^3 km^2) was ~4.3 Tg C yr^{-1}. This is about 15 times the amount of carbon buried by coastal marshes in the South Atlantic Bight, USA, which buries about 0.29 Tg C yr^{-1} (Cai, 2011; Loomis & Craft, 2010). However, the coastal Louisiana marsh area is only about three times larger than the South Atlantic Bight (~5 × 10^9 m^2). Regionally, these coastal Louisiana marsh soils contribute about 47% of

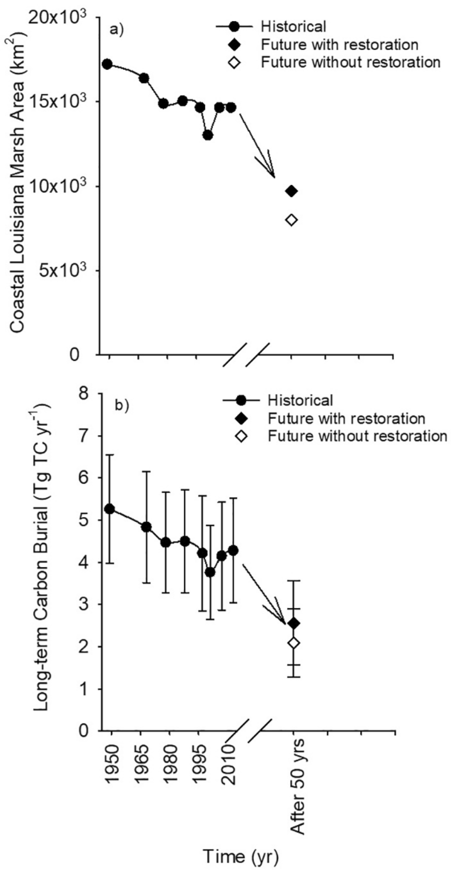

Figure 7. Total coastal marsh area in Louisiana (panel a) and mean (±std. error) long-term total carbon burial (Tg TC yr^{-1}, panel b) of those marshes for historical years (from 1949 to 2013). Future modeled estimates (after 50 years) were based on future with restoration action (filled circles) based on the State of Louisiana's 2017 Coastal Master Plan, and future without restoration (open circles) by using moderate estimates of sea level rise rate (0.63 m over 50 years) and subsidence rate (lowest quantile of the range) (Alymov et al., 2017).

the Gulf of Mexico's long-term carbon burial rate (6.6 ± 4.7 Tg C yr^{-1}) and 65% of the North American long-term carbon burial rate (9.1 ± 4.8 Tg C yr^{-1}) (Windham-Myers et al., 2018). It has been estimated that tidal wetlands bury about 20–80 Tg C yr^{-1} on a global scale but these estimates greatly depend on the carbon accumulation rates (including depths of soil cores) and the estimated area of those habitats (Bouillon et al., 2008; Cai, 2011; Duarte et al., 2005; Hopkinson et al., 2012). Therefore, coastal Louisiana marsh soils may currently contribute between 5% and 21% of the global tidal wetland annual carbon burial rate. It is important to note the lack of numerous sample sites representing the fresh and intermediate marshes across the Louisiana coast introduces uncertainty in these large-scale burial estimations. Therefore, these estimates and assumptions should be considered when assessing and comparing to other regional and global soil carbon burial estimates.

4.4. Coastal Restoration Impacts on Future Long-Term Soil Carbon Burial Rates

With historical and projected land loss rates (Couvillion et al., 2011, 2017), the area of coastal marshes in Louisiana is predicted to continue to decline because of subsidence and sea level rise and will influence the fate of current and future buried soil carbon (Wang et al., 2017). About 1.86 Tg C yr^{-1} has the potential to be removed due to current marsh loss rates (DeLaune & White, 2012), which is similar to the long-term TC burial loss rate in this study of 2.2 Tg C yr^{-1}, based on numerically modeled land loss after 50 years with no coastal restoration and based on deep cores from various marsh habitats in coastal Louisiana. Assuming future long-term carbon accumulation rates stay the same across marsh habitats, coastal Louisiana marshes can be expected to decrease their total long-term carbon burial after 50 years from the current 4.3 Tg C yr^{-1} to 2.1 Tg C yr^{-1} with no coastal restoration (future without action scenario, Alymov et al., 2017) and to 2.6 Tg C yr^{-1} with full implementation of all proposed coastal restoration activities (full project implementation, Alymov et al., 2017). Subtracting the current estimates by the future (with full implementation of coastal restoration and with no coastal restoration activity) from the 2013 estimates equals ∼1.7 and 2.2 Tg C yr^{-1} in reduced burial rates after 50 years due to coastal wetland loss in Louisiana, potentially equating to a loss of 3%–11% of annual carbon burial from wetlands globally.

There are some known uncertainties when estimating future potential carbon burial rates in coastal Louisiana. Burial rates may be underestimated due to increased accommodation space with sea-level rise (Rogers et al., 2019; Schuerch et al., 2018), black mangrove expansion into saline wetlands (Osland et al., 2013), and responses to nutrient enrichment (Lu et al., 2019; Pastore et al., 2017). Conversely, burial rates may be overestimated if future sea-level rise and inundation related stressors negatively impact wetland vegetation (Snedden et al., 2015). It was also assumed that the long-term rate of total carbon accumulation in each marsh habitat was constant in the past (from 1949 to 2013) and into the future (after 50 years), and that the entire stock of buried carbon (to a depth of 100 cm) would be removed from the system when wetland areas are lost. Therefore, these assumptions about future carbon burial conditions need to be considered when evaluating coastal restoration activities.

Calculation of greenhouse gas emissions (i.e., carbon dioxide, methane, and nitrous oxide) in addition to soil carbon burial will be needed to determine if these coastal marshes are net sources or sinks, to ultimately address their climatic influence (Holm et al., 2016; Krauss et al., 2016). For example, carbon dioxide is released from these marshes through aerobic mineralization of organic matter, but the fresh marshes may produce more methane gas during anaerobic metabolism than saline marsh habitats where

Table 2
^{137}Cs and ^{210}Pb Radionuclide-based Accretion and Accumulation Rate Estimates

Most Freq. Occ. Habitat from 1949 to 1988	Site ID	Basin	# Cores comb.	Accretion rate (cm yr^{-1})						TC accumulation rate (g TC m^{-2} year^{-1})	
				^{137}Cs accr.	^{137}Cs accr. Err. (+)	^{137}Cs accr. Err. (−)	^{210}Pb accr.	^{210}Pb accr. Err. (±)	^{210}Pb R2	^{137}Cs	^{210}Pb
Fresh	BA-01-04	BA	3	ND	ND	ND	ND	ND	ND	ND	ND
Fresh	CRMS0211	BA	3	ND	ND	ND	ND	ND	ND	ND	ND
Fresh	CRMS0273	BA	3	ND	ND	ND	ND	ND	ND	ND	ND
Fresh	CRMS0327	TE	3	ND	ND	ND	ND	ND	ND	ND	ND
Fresh	CRMS0331	TE	3	ND	ND	ND	ND	ND	ND	ND	ND
Fresh	CRMS0367	TE	3	ND	ND	ND	ND	ND	ND	ND	ND
Fresh	CRMS2825	TE	3	ND	ND	ND	ND	ND	ND	ND	ND
Fresh	CRMS3166	BA	3	0.80	0.08	0.30	0.32	0.06	0.84	997.6	399.0
Intermediate	CRMS0305	TE	NA	ND	ND	ND	0.4	0.1	0.91	ND	153.1
Brackish	CRMS0225	BA	3	0.76	0.20	0.16	0.28	0.11	0.67	503.0	185.3
Brackish	CRMS0253	BA	3	0.76	0.40	0.30	0.64	0.16	0.93	417.7	349.6
Brackish	CRMS0309	TE	NA	0.40	0.31	0.08	0.81	0.11	0.89	176.2	356.8
Brackish	CRMS0398	TE	3	0.90	0.20	0.20	0.80	0.47	0.38	485.0	431.1
Brackish	CRMS0399	TE	3	0.76	0.20	0.31	0.79	0.11	0.91	383.7	396.4
Brackish	CRMS3565	BA	3	0.57	0.16	0.20	0.69	0.02	0.99	332.1	402.0
Brackish	CRMS3617	BA	3	0.41	0.40	0.08	0.52	0.21	0.57	295.2	374.4
Brackish	CRMS4045	TE	3	0.76	0.20	0.16	0.50	0.20	0.72	453.1	298.1
Brackish	CRMS4245	BA	3	0.76	0.39	0.27	0.54	0.46	0.44	903.6	638.1
Saline	CRMS0175	BA	NA	0.33	0.08	0.08	0.46	0.16	0.63	180.4	248.9
Saline	CRMS0224	BA	3	0.41	0.08	0.08	0.36	0.13	0.61	217.2	190.7
Saline	CRMS0237	BA	NA	ND	ND	ND	ND	ND	ND	ND	ND
Saline	CRMS0337	TE	NA	0.61	0.20	0.20	0.46	0.18	0.58	276.5	208.5
Saline	CRMS0377	TE	NA	0.40	0.04	0.04	0.18	0.05	0.73	136.7	61.5
Saline	CRMS4455	TE	NA	0.80	0.20	0.20	0.79	0.31	0.61	348.1	343.7

Note. Low activity at some sites prevented reliable accretion rate estimates (linear sedimentation rates) and thus ND = no data. BA, Barataria; TE, Terrebonne. Some of the field sites had three replicate cores combined from batch 2 (June/July 2015). NA = not applicable.

methanogenesis is limited (Poffenbarger et al., 2011). Soil core data, such as those collected in this study, contribute essential information to the long-term carbon burial rates used to assess the net cooling or warming effect these marshes may have now and into the future (Krauss et al., 2016; Neubauer, 2014; Neubauer & Megonigal, 2015).

5. Conclusions

Coastal marshes in Louisiana accumulate in the long-term, 211–381 g TC m^{-2} yr^{-1} (mean values per marsh habitat based on ^{210}Pb accretion rates) as estimated from one-meter deep soil cores sampled from fresh to saline marsh habitats. By using the estimated 2013 marsh area, approximately 4.3 Tg TC yr^{-1} is buried in marsh soils and this accounts for 5%–21% of the estimated global marsh/mangrove burial rate. With future wetland loss predicted, there is a risk of releasing pools of soil carbon accumulated over the long term as

Table 3
Long-Term TC Accumulation Rates From Marsh Habitats From Various Studies That Utilized Soil Cores > 30 cm and Radionuclide Methodologies of ^{137}Cs and ^{210}Pb to Estimate Accretion Rates

Location	Marsh type	Dominant veg.	Core depth (cm)	Total no. of cores	Accretion method (Cs, Pb)	Long-term TC accumulation rates (g TC m^{-2} $year^{-1}$)	Reference
Louisiana	Fresh	*Panicum hemitomon*	NA	1	Cs	224	1
Louisiana	Fresh	Panicum hemitomon, Elocharis sp., Saggittaria falcata	50	1	Cs	143[a]	2
Louisiana	Fresh	*Panicum hemitomon, Sagittaria lancifolia*	50	14	Cs	253[a]	6
Louisiana	Fresh	NA	53	4	Cs	154–273	3
Georgia	Fresh	Zizaniopsis miliacea, Scirpus spp., Sagittaria lancifolia	60	12	Cs	124	4
Louisiana	Fresh	*Panicum hemitomon*	50	12	Cs	35–207	7
Louisiana	Fresh	NA	63	3	Cs	207	11
Louisiana	Fresh[b]	*Panicum hemitomon, Typha latifolia*	100	1	Cs, Pb	399–998	This study
Louisiana	Intermediate	*Spartina patens*	50	1	Cs	126[a]	2
Louisiana	Intermediate[b]	*Sagittaria lancifolia, Scheonoplectus americanus*	100	1	Pb	153	This study
Louisiana	Intermediate/Brackish	*Spartina patens*	50	11	Cs	80–204	7
Louisiana	Brackish	*Spartina patens*	NA	1	Cs	296	1
Louisiana	Brackish	*Spartina patens, Distichlis spicata*	50	1	Cs	163[a]	2
Louisiana	Brackish	*Spartina patens and Spartina alterniflora*	50	12	Cs	283	6
Louisiana	Brackish	NA	53	7	Cs	181–261	3
Georgia	Brackish	*Spartina cynosuroides, Juncus roemerianus*	60	12	Cs	93	4
California	Brackish	*Schoenoplectus acutus, Schoenoplectus californicus*	50	6	Cs, Pb	89–117	5
Louisiana	Brackish[b]	*Spartina patens and Scheonoplectus americanus*	100	9	Cs, Pb	176–904	This study
Louisiana	Saline	*S. alterniflora*	NA	1	Cs	183	1
Louisiana	Saline	Juncus romerianus, Distichlis spicata, Spartina alterniflora	50	1	Cs	200[a]	2
Mississippi	Saline	*Juncus romerianus, Spartina alterniflora, Spartina patens*	30–50	2	Cs	96–164	8
Georgia	Saline	*Spartina alterniflora*	60	12	Cs	40	4
New York	Saline	*Spartina patens, Distichlis spicata, Spartina alterniflora*	50	16	Cs, Pb	84	9
California	Saline	*Spartina foliosa*	50	12	Cs, Pb	46–81	5
North Carolina	Saline	*Spartina alterniflora*	30	10	Cs	24-64[a]	10
Louisiana	Saline	*Spartina alterniflora*	50	6	Cs	104–203	7
Louisiana	Saline	*Spartina alterniflora and Spartina patens*	50	12	Cs	199	6
Louisiana	Saline[b]	*S. alterniflora and Juncus romerianus*	100	5	Cs, Pb	62–348	This study

Note. Reference numbers refer to: 1 = Smith et al. (1983), 2 = Hatton et al. (1983), 3 = Delaune et al. (2013), 4 = Loomis and Craft (2010), 5 = Callaway et al. (2012), 6 = Nyman et al. (2006), 7 = Piazza et al. (2011), 8 = Callaway et al. (1997), 9 = Hill and Anisfeld (2015), 10 = Craft et al. (1993), 11 = DeLaune et al. (2018)
[a]Converted organic matter to TC based on Baustian et al. (2017). [b]This study, based on most frequently occuring habitat.

well as losing a significant active sink for atmospheric carbon dioxide. Protection and restoration of these marshes is vital to help protect the pool of buried carbon in the soils, and to prevent release of carbon to the atmosphere from soil oxidation. Proposed future restoration projects with costs of over 20 billion USD that are intended to influence the total area of marsh habitats in coastal Louisiana after 50 years (Coastal

Protection & Restoration Authority of Louisiana, 2017) could potentially bury, in the long term, about 2.6 Tg C yr^{-1}, which is about 60% of the estimated long-term burial rate in 2013 (4.3 Tg C yr^{-1}). Continual wetland loss in coastal Louisiana is likely to alter local, regional, and global carbon budgets as well as the climate mitigating effect of these diverse marshes.

Data Availability Statement

Data presented in this study are available through various resources. The most frequently occurring marsh habitat information in Table 1 and Figure 2 can be downloaded via the vegetation polygons from CRMS (2015) and available from Baustian et al. (2021) at Sciencebase.gov. The soil core information (Table 1 and Figures 3–5) is available from Baustian et al. (2021) at Sciencebase.gov. Data presented in Figure 6 are available in Table 2. Lastly, the marsh area estimates from the State of Louisiana's 2017 Coastal Master Plan (Figure 7) can be found from Alymov et al. (2017).

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