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Comparing carbon accumulation in restored and natural wetland soils of coastal Louisiana

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ABSTRACT

Louisiana's chronic wetland deterioration has resulted in massive soil organic matter loss and subsequent carbon release through oxidation. To combat these losses, and reestablish ecosystem function, goods, and services, many restoration projects have been constructed or planned throughout coastal Louisiana. There are significant data gaps and conflicting results regarding wetland contributions to global warming, especially related to carbon sequestration in restored wetlands. An exceptionally large data set was used to derive carbon accumulation rates from key soil characteristics and processes. Assessments and comparisons of bulk density, organic matter, total carbon, vertical accretion (short- and longer-term), and carbon accumulation rates were made across time (chronosequence) and space (i.e., coastwide, watershed basins, and vegetation zones). Carbon accumulation rates in the Louisiana coastal zone were generally correlated to hydrogeomorphology, with higher rates occurring in zones of high river connectivity or in swamp or higher salinity tolerant marsh. On average, naturally occurring wetlands had higher carbon accumulation rates than restoration sites. Although some restoration measures were higher, and most showed increasing carbon accumulation rates over time. Results demonstrate that although wetland restoration provides many ecosystem benefits, the associated carbon sequestration may also provide useful measures for climate change management.

1. Introduction

Recent and future-projected effects from climate change have stimulated the need to reduce greenhouse gas (GHG) sources and to increase GHG sinks to help mitigate those effects. Wetlands, provide numerous ecosystem goods and services ranging from protecting and improving water quality, providing critical fish and wildlife habitat, and storing floodwaters, to providing important biogeochemical processes where nutrients, organic compounds, metals, and components of organic matter are transformed and stored (Brady & Weil, 1999; Osland et al., 2012; Reddy & DeLaune, 2008). Though they only occupy approximately 5% of the Earth's surface, wetlands represent the largest component (40%) of the terrestrial biological carbon (C) pool (~2,500 Pg), and are important links in the sequestration of carbon and cycling of atmospheric gases (Armentano & Menges, 1986; Chmura et al., 2003; Hossler & Bouchard, 2010; Lal & Pimentel, 2008; Mitsch et al., 2013; Mitsch & Gosselink, 2000). Wetlands also are important because they sequester carbon for much longer periods than other systems due to their anaerobic, acidic, and thermal conditions (Burkett & Kusler, 2000).

Carbon sequestration in wetland systems consists of the rapid accumulation and storage of soil organic matter (SOM) in wetland sediments (Bridgham et al., 2006; Mcleod et al., 2011; Sifleet et al., 2011). North American wetlands account for 42% of the global carbon pool (Bridgham et al., 2006). This sheer abundance, in addition to the potential and critical nature of carbon sequestration (i.e., buffers the emissions of GHGs from soil to the atmosphere), make SOM one of the Nation's most important resources (Albrecht, 1938; Lal, 2004). The SOM content within wetland systems is primarily driven by processes such as biodegradation, photochemical oxidation, sedimentation, volatilization, and sorption (Kayranli

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et al., 2010). Since these processes are highly dependent on wetland health and productivity, the release of stored carbon to the atmosphere is significantly increased when wetland conditions degrade (Lane et al., 2016).

With extreme reductions in wetlands worldwide, 50% wetland loss since 1900, many wetland goods and services are at risk (Davidson, 2014). Wetlands, through natural function and losses, have significantly contributed to GHG emissions, accounting for 15%–40% of the annual global methane (CH_4) flux per year (Ehhalt et al., 2001; Poffenbarger et al., 2011). In the United States, wetland loss in the 19th and 20th centuries was dominated by the draining and conversion of wetlands to agricultural lands, which accelerated oxidation of stored carbon and its release to the atmosphere as carbon dioxide (CO_2) (Armentano & Menges, 1986; Dahl & Allord, 1982, p. 2425). In Louisiana, which accounts for 40% of the Nation's wetlands, but 80% of its loss (since 1800), marsh deterioration has resulted in massive organic matter loss through the exportation to estuaries and offshore areas, and subsequent carbon release through oxidation (DeLaune & White, 2011; Williams, 1995).

To remediate these losses, many ecosystem stakeholders have advanced protection and restoration strategies to reestablish critical wetland goods and services. One relatively new strategy is to utilize wetland creation and restoration measures to increase soil organic carbon (SOC) density, distribution, and stability in the soil (Lal, 2004). However, in many cases carbon sequestration and storage are secondary benefits or “added value” of wetland restoration. Uncertainties persist about the long-term linkages between global warming and wetland processes, especially in managed systems (Chmura et al., 2003; Edwards & Proffitt, 2003). Though some created wetlands have been shown to quickly achieve vegetative equivalency to naturally occurring target wetlands (specifically when sites are planted), most require decades or longer (especially for SOC accumulation), or, they never achieve equivalency (Edwards & Proffitt, 2003; Hogan et al., 2004; Hossler & Bouchard, 2010; Moreno-Mateos et al., 2012; Osland et al., 2012).

For more informed resource management decisions, considerable research is needed to evaluate and compare the rates of carbon sequestration in managed ecosystems to naturally occurring reference wetlands (Loomis & Craft, 2010). Therefore, the purpose of this study was to evaluate the influence that wetland ecosystem management and restoration have on carbon sequestration potential and chronosequence. This was accomplished by comparing organic material, bulk density, carbon content, and rates of accumulation between various ages and types of restored and reference wetlands. The specific objectives of this study were to (1) compile a comprehensive set of all relevant restoration project and soils data, (2) map the spatial distribution of relevant wetland soils characteristics, (3) compute carbon sequestration rates for restored and natural wetland sites, (4) compare soil function across type and age of restoration measures, and (5) evaluate implications for future restoration and climate change.

2. Methods

2.1. Study area and assessment units

The Louisiana coastal zone is dominated by histosol wetlands that occupy an ecological niche across unique ranges of condition and function, ranging from riverine-influenced fresh and brackish areas to “Blue Carbon” marshes nearest the coast where salinities above 17 ppt reduce the production of methane and other GHGs to negligible amounts (Chambers et al., 2013; DeLaune et al., 2013). To evaluate key wetland functions, this study utilized soil samples, data from the scientific literature, and data collected as part of multiple restoration and monitoring programs and projects (Fig. 1). Qualifying samples and sites were selected from wetland restoration areas (i.e., wetland creation, terracing, hydrologic alteration, freshwater diversion, and sediment diversion) and target reference areas where soil nutrient analyses have been done or where soil cores were available for analyses.

The Program sites consisted primarily of Coastal Reference Monitoring Stations (CRMS) and Coastwide Wetlands Planning, Protection, and Restoration Act (CWPPRA) monitoring stations. These stations are part of a large-scale data collection and monitoring system that was developed to characterize and compare wetland hydrology, ecology, soil, and geomorphology conditions across project and non-project areas throughout coastal Louisiana (Steyer et al., 2003; Wang et al., 2017). The size and density of these data sets offer unprecedented opportunities for studying coastal wetland dynamics and subtle soil processes and interactions (Jankowski et al., 2017). The Program sites were supplemented with Project sites, where samples were collected (by the authors and others) at the (1) Sabine Refuge Marsh Creation project cycles (Suir & Sasser, unpublished), (2) Wax Lake Delta (DeLaune et al., 2016), (3) Atchafalaya Big Island Mining creation project (Suir and Sasser, unpublished), (4) Davis Pond Freshwater Diversion (DeLaune et al., 2013), (5) Bayou Labranche Wetland Creation project (Richardi, 2014), and (6) Little Lake Marsh Creation project (Suir and Sasser, unpublished) (Fig. 1).

The coastal zone was divided into multi-scale assessment units to evaluate potential correlations between soil function and restoration type, whilst considering geomorphic and hydrologic settings. These assessment units include 1) coastal zone (CZ), 2) watershed basins (WB), 3) vegetation zones (VZ), and 4) vegetation by basin units (VB) (Fig. 1). This approach allowed for spatial and chronosequence approaches (i.e., space-for-time substitution) to evaluate impacts and age of restoration on soil function. Mean relative short-term (feldspar) and longer-term (decadal from cesium data) vertical accretion, bulk density, organic matter, carbon content, and short-term carbon accumulation rates were calculated and evaluated for each scale and combination of assessment units.

2.2. Soil acquisition, sampling, and analysis

Soils data utilized in this study consisted of those from the scientific literature, from previously collected Program soils (Coastal Protection and Restoration Authority [CPRA] of Louisiana, 2017), or were sampled from select Project sites. Project soil cores were collected from restoration and reference stations at the Sabine (October 2015), Wax Lake (June 2013), Atchafalaya (September 2015), Davis Pond (2011), Bayou Labranche (multi-year), and Little Lake (November 2014 and October 2015) study sites. Subsurface soils at the Project sites were sampled with a 5-cm diameter thin walled aluminum corer (with a sharpened edge) to a depth of 15-cm. This depth typically contains the highest soil carbon content and is a reasonable proxy for use in standard carbon estimation (Jenkins et al., 2010). The Program sites are typically sampled with 10.2-cm diameter corers to a depth of 30-cm, and sliced into 4-cm increments. The standard for both Project and Program samples were to place soils into labelled sealable storage bags and transport them to Louisiana State University (LSU) or contracting laboratories for processing.

Key soil characteristics and processes in the marsh soils were determined using techniques previously reported by DeLaune et al. (2013). Short- and longer-term vertical accretion rates also were extracted from Program repositories and the scientific literature, respectively. The short- and longer-term (decadal) vertical accretion data were calculated using the Feldspar marker and Cesium 137 (^{137}Cs) methods described in DeLaune et al. (1978) and Folse et al. (2014), respectively. For bulk density determinations,

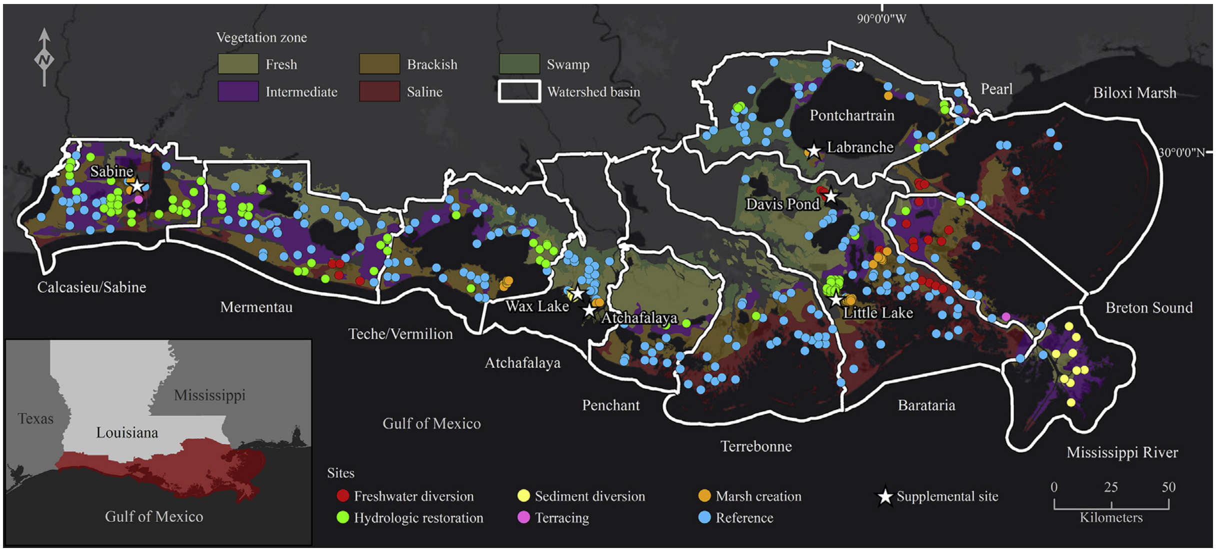

Fig. 1. Location map of the Assessment Units (coastal zone, watershed basins, and vegetation zones), and Program (circles) and supplemental Project (stars) sites in coastal Louisiana.

subsamples were oven-dried to a constant weight at 60 °C. For SOM percentage, the Walkley-Black acid-dichromate oxidation method was used for the Project soils (Nelson & Sommers, 1996), and the loss on ignition (LOI) method was used for the Program soils (Andrejko et al., 1983). The LOI method (described in Folse et al., 2014), is a quicker and less expensive alternative to other methods, and is a reliable and suitable method for soil C analysis (Wright et al., 2008).

For each Program site, data from the top segments (0–16 cm) were averaged for congruity with Project samples. The SOM measurements were transformed to total carbon content (percentage) by dividing by a factor of 1.724, based on the van Bemmelen factor, and multiplying by 100 (Allen, 1974; Craft et al., 1991; Pribyl, 2010). The van Bemmelen factor has been shown to be a suitable value for organic marsh soils, returning a coefficient of determination (r-squared) relation of 0.97 between LOI and total carbon in organic soils of the everglades (Wright et al., 2008). Some recent studies have speculated that the conventional conversion factor of 1.724 is relatively low for some soils, especially mineral soils (Leong & Tanner, 1999), with newly proposed factors ranging from 1.9 to 2.2 (Pribyl, 2010; Wang et al., 2017). However, any factor used to convert organic matter to organic carbon is not a universal physical constant, and given the complex factors influencing carbon content (i.e., vegetation cover, organic matter composition, depth in profile, amount of clay) this study used the traditional van Bemmelen factor since the purpose was to evaluate trends in carbon accumulation in organic soils across various restoration measures and large-scale assessment units (Pribyl, 2010).

The carbon sequestration rates (gC/m^2 y) for each site were calculated by multiplying the short-term sediment accretion rate (cm^3/y) by the soil bulk density (g/cm^3) and by the carbon content (percentage) (Bernal & Mitsch, 2013). With recent efforts to standardize carbon sequestration and GHG emission units, the gC/m^2 y rates were converted to CO_2 equivalents (CO_2e). Every 12 g of carbon (atomic mass is 12 g/mol) is equal to 44 g of CO_2 (atomic mass is 44 g/mol), therefore, the sequestration rates were converted to CO_2e by multiplying the gC/m^2 y rate by 44 gCO_2e and dividing by 12 gC (Sifleet et al., 2011). ESRI ArcGIS was used to manage, analyze, and map the spatial distribution of these wetland soil attributes, and their differences, over space and time. These data were used as general measures of restoration impacts on carbon fluxes, primarily through sequestration. Though wetlands also emit GHG, which can be a major component of the carbon cycle and influence or counteract sequestration rates, GHG flux assessments were beyond the scope of this study.

2.3. Statistical analyses

In order to attain comparability among soil attributes and rates for each assessment scale, statistical analyses were done using Statistical Analysis System software version 9.2. The PROC General Linear Models (GLM) procedure was used to do a one-way analysis of variance (ANOVA) and a means separation test (Tukey's, $\alpha = 0.05$) to evaluate the significance of differences between soil attributes for each assessment unit (Assaad et al., 2014, p. 474). Additionally, a second order polynomial regression with a coefficient of determination (R^2) was used to evaluate correlations between soil attributes and age of restoration.

3. Results and discussion

3.1. Coastal zone

Soil measurements were calculated using 1,224 data points from across the coastal zone of Louisiana. The collective means and standard deviations (independent of project type, geomorphology, hydrology, and age) for select soil characteristics (i.e., bulk density, organic matter, total carbon, short-term accretion [feldspar], longer-term accretion [^{137}Cs], and short-term carbon accumulation) are listed in Table 1.

Sites within the coastal zone had significantly higher short-term accretion rates (mean 1.03 ± 0.8 cm/y) compared to longer-term rates (decadal), which averaged (0.79 ± 0.36 cm/y). Though accretion rates determined from feldspar marker horizons are typically greater than those determined from ^{137}Cs dating, the surface material deposited over the feldspar marker horizons would with time undergo a certain degree of compaction and oxidation reducing the average vertical accumulation from short-term feldspar measurements (DeLaune et al., 2003). Since soil data with adequate core depths were not available for the computation of longer-term accretion rates at each site, and, since shorter-term (feldspar) accretion rates were largely similar to longer-term accretion rates

Table 1
Average bulk density, organic matter, total carbon, accretion, and carbon accumulation from all sites within the Louisiana coastal zone.

Coastal zone	Count	Bulk density	Organic matter	Total carbon	Short term accretion (feldspar)	Longer term accretion (^{137}Cs)[a]	Short term carbon accumulation	
		g/cm^3	Percent	Percent	cm/y	cm/y	gC/m^2 y	gCO$_2$e
Mean	1,224	0.299	33.919	19.67	1.03	0.79	371.88	1,363.56
Std	1,224	0.245	21.11	12.24	0.80	0.36	294.7	1,080.57

[a] Longer term accretion data from DeLaune et al. (1989), DeLaune et al., (1992), Nyman et al., (1993), Swenson and Turner (1994), Foret (1997), Bryant and Chabreck (1998), Foret (2001), Rybczyk and Cahoon (2002), Sasser et al. (2002), and Day et al. (2012).

(Tables 2–4), the feldspar-based rates were used as surrogates for estimating longer-term carbon accumulation.

Average short-term carbon accumulation rates for each sample site are provided in Fig. 2. This figure illustrates the range and distribution of carbon accumulation rates across the coastal zone, where lower rates were observed in the west (Chenier Plain), higher rates occurred in the "Middle Coast", and a wider range of rates occurred in the eastern portion of the Deltaic Plain. Overall, the average carbon accumulation rate for the coastal zone was 371.88 ± 294.7 gC/m^2 y (1,363.56 ± 1,080.57 gCO$_2$e). This is above the average rate (118 gC/m^2 y; 432.67 gCO$_2$e) of carbon sequestration for wetlands throughout the world (Mitsch et al., 2013), and is indicative of the coastal processes and productivity in Louisiana's wetlands.

3.2. *Watershed basin*

Previous small-scale studies have reported increased carbon sequestration with increasing river connectivity due to decreasing mineralization of soil organic matter (Wang & Dodla, 2013). Watershed basins, delineated primarily on hydrologic connectivity, were used as large-scale assessment units for evaluating general hydrologic influence on carbon accumulation. The mean values for key soil characteristics are listed in Table 2. Mean bulk density ranged from 0.19 to 0.79 g/cm^3 for the Mermentau River and Mississippi River basins, respectively. For total carbon, the means ranged from 4.1 to 26.2% for the Mississippi River and Mermentau River basins, respectively. Comparisons of short- and longer-term accretion rates agree with previous studies which show that over time accretion slows (Sadler, 1981; Smith, 2009). The sediment in the basins that receive larger river inputs (i.e., Atchafalaya, Mississippi River, Penchant, Vermilion-Teche) had significantly ($p < 0.05$) higher carbon accumulation rates than those with lower inputs (i.e., Biloxi Marsh, Calcasieu/Sabine, Mermentau). The Mississippi River basin had the highest mean carbon accumulation rate (585 ± 476 gC/m^2 y; 2,145 ± 1,745.3 gCO$_2$e), and the Calcasieu/Sabine basin had the lowest (132 ± 111 gC/m^2 y; 484 ± 407 gCO$_2$e). The general tendency in these data show a correlation between carbon accumulation and river hydrogeomorphology.

3.3. *Vegetation zone*

Short-term carbon accumulation rates in the surface layer (~15 cm) of wetlands are largely driven by net primary productivity (above- and below-ground biomass) and microbial decomposition (Baustian et al., 2017; Bernal & Mitsch, 2008; Kayranli et al., 2010; Powlson et al., 2011). Since primary productivity is significantly correlated to salinity (i.e., vegetation zone) (Steyer, 2008), carbon accumulation rates were evaluated across the vegetation zones in coastal Louisiana. The means and standard deviations of key soils characteristics by vegetation zone are listed in Table 3. Similar to findings by Craft (2007), the fresh, intermediate, and brackish zones had lower bulk density and greater percent carbon than the saline zone. The carbon accumulation rates ranged from a low of 300 ± 254 gC/m^2 y (1,100 ± 931.3 gCO$_2$e) for the Intermediate zone, to a high of 468 ± 247 gC/m^2 y (1,716 ± 905.67 gCO$_2$e) for the Swamp zone. The means of carbon accumulation rates in the Saline zone were significantly different ($p < 0.05$) from those in the Brackish and Intermediate zones, while those in the Swamp zone were significantly different from the Brackish, Fresh, and Intermediate zones. Though the Saline and Swamp zones were significantly different from other zones, no definitive relation was observed between salinity (vegetation zone) and carbon accumulation rate. These findings corroborate

Table 2
Average bulk density, organic matter, total carbon, accretion, and carbon accumulation from sites within each watershed basin assessment unit.

Basin	Count	Bulk density[b]	Organic matter[b]	Total carbon	Short term accretion (feldspar)[b]	Longer term accretion (^{137}Cs)[a]	Short term carbon accumulation[b]	
		Mean ± std	Mean ± std	Mean ± std	Mean ± std	Mean ± std	Mean ± std	Mean ± std
		g/cm^3	Percent	Percent	cm/y	cm/y	gC/m^2 y	gCO$_2$e
Atchafalaya	90	0.38 ± 0.3b	19.5 ± 13.1ef	11.34 ± 7.6	1.57 ± 1.04c	1.43 ± 0.29	436 ± 293	1,599 ± 1,074bc
Barataria	233	0.3 ± 0.31bde	37.8 ± 25ab	21.9 ± 14.5	1.31 ± 0.89bc	0.76 ± 0.19	451 ± 389	1,654 ± 1,426bc
Biloxi	36	0.43 ± 0.27c	21.5 ± 12.9df	12.48 ± 7.5	0.72 ± 0.85efg	0.65 ± 0.09	256 ± 343	939 ± 1,258def
Breton Sound	54	0.33 ± 0.17cdef	26.4 ± 12.9de	15.34 ± 7.5	1.02 ± 0.83bdf	0.81 ± 0.35	414 ± 390	1,518 ± 1,430bce
Calcasieu-Sabine	148	0.22 ± 0.2fg	41.5 ± 19.7bc	24.04 ± 11.4	0.4 ± 0.3g	0.41 ± 0.13	132 ± 111	484 ± 407f
Mermentau	156	0.19 ± 0.13g	45.2 ± 21.6c	26.22 ± 12.6	0.72 ± 0.39f	0.69 ± 0.18	272 ± 180	997 ± 660d
Mississippi River	30	0.79 ± 0.2a	7 ± 3f	4.06 ± 1.7	2.18 ± 1.94a	1.9 ± 0.11	585 ± 476	2,145 ± 1,745b
Pearl	9	0.29 ± 0.07cdg	24.6 ± 5bcdf	14.29 ± 2.9	0.95 ± 0.18cdfg	0.78 ± 0	374 ± 77	1,371 ± 282bcdf
Penchant	39	0.33 ± 0.13cdef	23.2 ± 9.7de	13.46 ± 5.6	0.85 ± 0.33ef	0.85 ± 0.36	321 ± 112	1,177 ± 411cd
Pontchartrain	179	0.27 ± 0.2eg	39.3 ± 19.7bc	22.78 ± 11.5	0.92 ± 0.36ef	0.73 ± 0.28	406 ± 234	1,489 ± 858ace
Terrebonne	99	0.27 ± 0.12dg	30.9 ± 15.9ad	17.92 ± 9.2	1.34 ± 0.9cd	0.83 ± 0.2	501 ± 302	1,837 ± 1,107ab
Vermilion-Teche	150	0.36 ± 0.22cd	27.4 ± 17.1de	15.9 ± 9.9	1.05 ± 0.29de	0.8 ± 0.18	408 ± 136	1,496 ± 499bce

[a] Longer term accretion data from DeLaune et al. (1989), DeLaune et al. (1992), Nyman et al. (1993), Swenson and Turner (1994), Foret (1997), Bryant and Chabreck (1998), Foret (2001), Rybczyk and Cahoon (2002), Sasser et al. (2002), and Day et al. (2012).

[b] Mean values within each column followed by the same letter(s) are not significantly different ($p > 0.05$) as analyzed by one-way ANOVA and the TUKEY test.

Table 3
Average bulk density, organic matter, total carbon, accretion, and carbon accumulation from sites within each vegetation zone assessment unit.

Vegetation zone	Count	Bulk density[b]	Organic matter[b]	Total carbon	Short term accretion (feldspar)[b]	Longer term accretion (^{137}Cs)[a]	Short term carbon accumulation[b]	
		Mean ± std	Mean ± std	Mean ± std	Mean ± std	Mean ± std	Mean ± std	Mean ± std
		g/cm^3	Percent	Percent	cm/y	cm/y	gC/m^2 y	gCO$_2$e
Fresh	171	0.28 ± 0.29ac	38.1 ± 26.2a	22.1 ± 15.2	1.27 ± 1.11a	1.02 ± 0.46	376 ± 268	1,379 ± 983bc
Intermediate	293	0.24 ± 0.21c	39.6 ± 21.3a	23.0 ± 12.3	0.86 ± 0.65b	0.76 ± 0.43	300 ± 254	1,100 ± 931c
Brackish	353	0.32 ± 0.28ab	32.1 ± 20.1b	18.7 ± 11.7	0.96 ± 0.54b	0.7 ± 0.22	345 ± 261	1,265 ± 957c
Saline	215	0.35 ± 0.19b	23.2 ± 11.2c	13.4 ± 6.5	1.16 ± 1.13a	0.72 ± 0.2	435 ± 413	1,595 ± 1,514ab
Swamp	153	0.28 ± 0.21bc	39.5 ± 20.4a	22.9 ± 11.8	1.03 ± 0.43ab	0.9 ± 0.37	468 ± 247	1,716 ± 906a
Other	38	0.39 ± 0.24ab	26.0 ± 22.0bc	15.1 ± 12.8	1.23 ± 0.76ab	0.88 ± 0.35	408 ± 195	1,496 ± 715ac

[a] Longer term accretion data from DeLaune et al. (1989), DeLaune et al. (1992), Nyman et al. (1993), Swenson and Turner (1994), Foret (1997), Bryant and Chabreck (1998), Foret (2001), Rybczyk and Cahoon (2002), Sasser et al. (2002), and Day et al. (2012).

[b] Mean values within each column followed by the same letter(s) are not significantly different ($p > 0.05$) as analyzed by one-way ANOVA and the TUKEY test.

Table 4
Average bulk density, organic matter, total carbon, accretion, and carbon accumulation for reference and restoration sites.

Project	Count	Bulk density	Organic matter	Total carbon	Short term accretion (feldspar)	Longer term accretion (^{137}Cs)[a]	Short term carbon accumulation[b]	
		Mean ± std	Mean ± std	Mean ± std	Mean ± std	Mean ± std	Mean ± std	Mean ± std
		g/cm^3	Percent	Percent	cm/y	cm/y	gC/m^2 y	gCO$_2$e
Reference	754	0.28 ± 0.18Ad	33.4 ± 18.7Ab	19.37 ± 10.9	1.07 ± 0.8Ab	0.81 ± 0.33	415 ± 300	1,522 ± 1,100Ab
Restoration	469	0.33 ± 0.32B	34.8 ± 24.5A	20.17 ± 14.2	0.97 ± 0.8B	0.78 ± 0.4	302 ± 272	1,107 ± 997B
Fresh Diversion	73	0.37 ± 0.4c	32.7 ± 20b	18.99 ± 11.6	1.05 ± 0.6b	0.64 ± 0.14	377 ± 295	1,382 ± 1,082ab
Hydro Restoration	243	0.14 ± 0.09e	50.5 ± 19.4a	29.31 ± 11.2	0.69 ± 0.38c	0.68 ± 0.22	240 ± 151	880 ± 554c
Marsh Creation	114	0.52 ± 0.31b	11.8 ± 9.5c	6.83 ± 5.5	1.19 ± 0.62b	0.75 ± 0.42	324 ± 324	1,188 ± 1,188ac
Sed. Diversion	33	0.84 ± 0.31a	6.3 ± 3.4c	3.67 ± 2	2.04 ± 1.99a	1.82 ± 0.22	520 ± 490	1,907 ± 1,797b
Terracing	6	0.46 ± 0.07bcd	14.5 ± 3.7bc	8.41 ± 2.2	0.92 ± 0.77bc	0.86 ± 0.59	318 ± 252	1,166 ± 924bc

[a] Longer term accretion data from DeLaune et al. (1989), DeLaune et al. (1992), Nyman et al. (1993), Swenson and Turner (1994), Foret (1997), Bryant and Chabreck (1998), Foret (2001), Rybczyk and Cahoon (2002), Sasser et al. (2002), and Day et al. (2012).

[b] Mean values within each column followed by the same letter(s) are not significantly different ($p > 0.05$) as analyzed by one-way ANOVA and the TUKEY test.

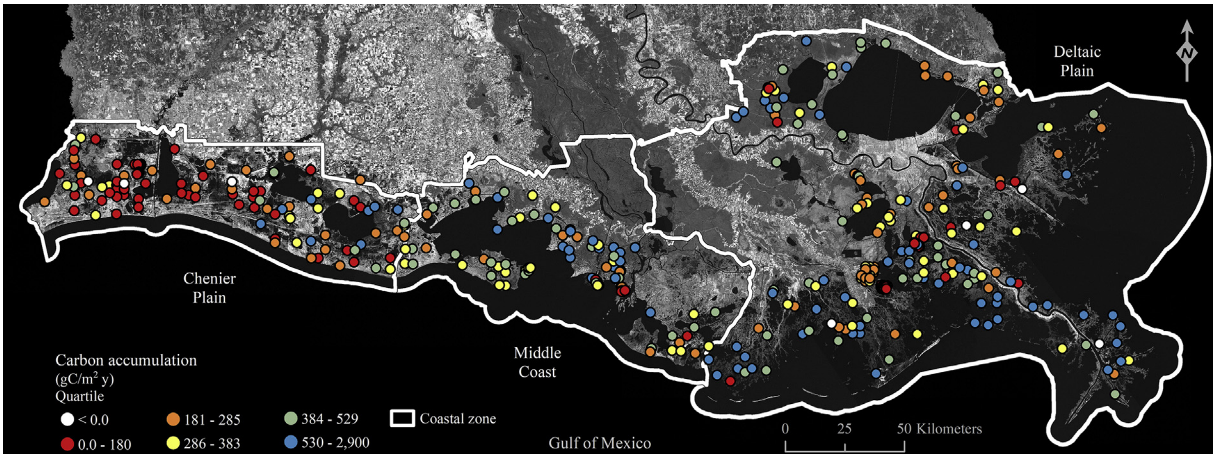

Fig. 2. Average short-term (feldspar) carbon accumulation rate for all sites within the Louisiana coastal zone assessment unit.

those from previous small-scale studies, which demonstrated carbon accumulation rates were similar in various marsh types in coastal Louisiana (DeLaune & White, 2011; Hatton et al., 1982; Nyman et al., 2006).

3.4. *Vegetation zone by watershed basin*

To assess the potential combined influence of salinity and hydrogeomorphology on carbon accumulation, evaluations were done using vegetation zone by watershed basin (VB) units. Fig. 3 provides a schematic of the mean carbon accumulation rates for reference sites by VB, represented as polygons (white represents lowest rates, black represent the highest rates, and hatched areas contained no reference sites), and the rates for restoration projects are represented by dots (graduated dots correlate to range of rate). The average carbon accumulation by VB for reference sites ranged from 141 ± 95 gC/m^2 y (517 ± 348.3 gCO$_2$e) for the Calcasieu-Sabine brackish zone to 804 ± 612 gC/m^2 y (2,948 ± 2,244 gCO$_2$e) for the Breton brackish zone. The reference sites with the highest mean carbon accumulation (darkest polygons) were those that are either in zones of high river connectivity or consist of swamp or higher salinity tolerant marsh. The average carbon accumulation by VB for

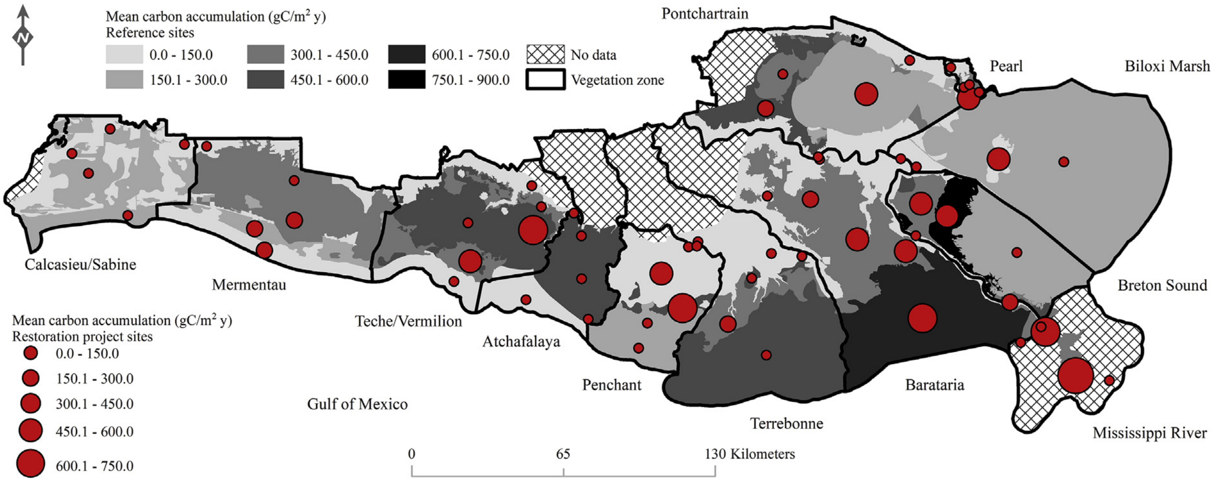

Fig. 3. Average short-term (feldspar) carbon accumulation within vegetation zone by basin (VB) assessment units for reference sites (polygons, lighter gray represents lower rates and darker gray represents higher rates) and restoration sites (red dots, smaller dots represent lower rates and larger dotes represent higher rates).

project sites ranged from 31 ± 3 gC/m^2 y (113.67 ± 11 gCO_2e) for the Calcasieu-Sabine fresh zone to 646 ± 424 gC/m^2 y (2,368.67 ± 1,554.67 gCO_2e) for the Mississippi River intermediate zone. The VZB zones with the highest project rates of carbon accumulation (large points in Fig. 3) were generally correlated to VB zones with highest reference site rates. This demonstrates the influence of local geomorphic, hydrologic, and coastal processes on wetland function. The variability in carbon accumulation rates across VB zones are largely driven by salinity, riverine inputs (i.e., nutrients and sediment), and potentially in areas receiving benefits from multiple restoration measures (e.g., marsh creation sites receiving added benefits from sediment or freshwater diversions).

3.5. Restoration project

Soils of newly constructed or restored wetlands initially retain properties more typical of the terrestrial (or source) soils from which they were created, and they generally take decades to achieve functional equivalency to naturally occurring wetlands (Edwards & Proffitt, 2003; Hogan et al., 2004). Comparisons of carbon accumulation rates between restoration and reference sites, and between restoration measures, were done. The mean values of bulk density, organic matter, total carbon, accretion, and carbon accumulation are listed in Table 4. When compared collectively, restoration sites had higher bulk densities and accretion rates, and lower SOM and TC, than reference sites, though none were significantly different (Table 4). The reference sites did have significantly higher short-term carbon accumulation rates averaging 415.17 ± 300.1 gC/m^2 y (1,522.29 ± 1,100.37 gCO_2e) compared to the restoration sites, which averaged 302.29 ± 271.75 gC/m^2 y (1,108.4 ± 996.42 gCO_2e).

The average carbon accumulation rates by restoration type ranged from a low of 240 ± 151 gC/m^2 y (880 ± 553.37 gCO_2e) for hydrologic restoration to a high of 520 ± 490 gC/m^2 y (1,906.67 ± 1,796.67 gCO_2e) for sediment diversions. The hydrologic restoration measure had significantly lower carbon accumulation rates than the reference, sediment diversion, and freshwater diversion sites, and the sediment diversion sites had significantly higher rates than the marsh creation sites ($p < 0.05$). Though the average total carbon (g/kg) at the sediment diversion sites was significantly lower than all other restoration types, the higher bulk density and accretion rates for the sediment diversion measure resulted in higher carbon accumulation rates.

3.6. Carbon accumulation by age

Previous studies have reported that wetlands can be both a source and sink of carbon depending on ecosystem condition and age (DeLaune et al., 2016; Kayranli et al., 2010). The relation between carbon accumulation and project maturity were evaluated for all restoration sites and for each restoration type. The general trends observed were slight increases in carbon accumulation (y) with age (x) for the freshwater diversion ($y = 18.9x + 69$) and hydrologic restoration ($y = 7.5x + 147.2$) measures, slight decrease for marsh creation ($y = -2.3x + 344.1$) sites, and considerable decreases for the terracing ($y = -50.9x + 903.6$) and sediment diversion ($y = -99x + 1{,}792.4$) measures. Except for the terracing sites, which consisted of only two temporal data points ($R^2=0.99$), carbon sequestration rates were not significantly correlated ($R^2 < 0.08$) with age. Overall, the trend in carbon accumulation for all restoration sites showed a slight increase ($y = 3.8x + 262.6$) with age. These findings corroborate previous studies that have reported gradual increasing carbon accumulation in restored or created wetlands over time (Craft et al., 2003, 2002; Moreno-Mateos et al., 2012). Though the chronosequences examined may be too short (<25 y) to investigate the maturity required for wetland restoration sites to reach equilibrium with reference wetland functions, they do provide a general trajectory of carbon accumulation rates by wetland restoration type over time.

4. Conclusions

The net balance of carbon in wetland systems is largely driven by hydrology (flooding regime), plant species, climate, soil organic matter decomposition (mineralization), and salinity (Bernal & Mitsch, 2008; Kayranli et al., 2010; Mitsch et al., 2013). However, there are data gaps and conflicting results regarding wetland contributions to global warming. This study set forth to compile and map the spatial distribution of relevant wetland soil characteristics, evaluate key pressures, functions, and chronosequence of restored and naturally occurring wetland soils, and assess implications for future ecosystem restoration and climate change. This was accomplished by utilizing an exceptionally large data set to do the first coast-wide assessment of carbon accumulation in Louisiana wetlands. Carbon accumulation rates in the Louisiana coastal zone were generally correlated to hydrogeomorphology and distinctive trends were observed within the Chenier Plain, Middle Coast, and

Deltaic Plains. Comparisons of carbon accumulation within smaller-scale assessment units revealed higher rates generally occurred in zones of high river connectivity or in swamp or higher salinity tolerant marsh. Naturally occurring wetlands had significantly higher carbon accumulation rates than all restoration sites, though the sediment diversion sites had significantly higher accumulation rates than all other sites.

Putting these results in the context of other studies, the high rates of accumulation in the high-salinity marsh was likely influenced by reduced methanogenesis in this traditional Blue Carbon ecosystem, whereas the lower salinity zones of high river connectivity and swamps probably emitted GHGs, but the rates were outstripped by the high levels of biological productivity in these systems (Gough & Grace, 1998; Janousek & Mayo, 2013; Steyer, 2008).

Future research considering a broader suite of GHG fluxes could further elucidate these patterns. A more thorough understanding of carbon fluxes in existing and restorable coastal wetlands is important because of the symbiotic relation that wetland processes have with climate change. The fate of carbon in natural and restored wetlands will be increasingly constrained by sea-level rise, salinity, and temperature, which in turn will be increasingly regulated by carbon cycling in wetlands. For instance, increasing temperatures will result in increased GHG emissions (wetlands become a major source of GHG), which in turn contribute to global warming (Kayranli et al., 2010). Many aspects of these processes are unknown, especially in the long-term functioning of restored wetlands. Few existing wetland restoration projects have the required age for adequate evaluation of function equivalency, therefore, future research should consider the use of analogs along longer periods of analyses for chronosequence assessments. Also, since the amount of carbon sequestration and release via numerous GHGs can be shifted by moderate changes to wetland systems, future studies should incorporate emissions measurements of at least CO_2 and CH_4 to provide a more complete assessment of carbon processes and balance within wetland restoration landscapes. Wetland restoration provides many opportunities to incorporate ecosystem structural and functional services. Though carbon sequestration is a relatively new focus of wetland restoration missions, it may prove to be one of the most critical for management of climate change.

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