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Determining the Spatial Variability of Wetland Soil Bulk Density, Organic Matter, and the Conversion Factor between Organic Matter and Organic Carbon across Coastal Louisiana, U.S.A.

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ABSTRACT

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Soil bulk density (BD), soil organic matter (SOM) content, and a conversion factor between SOM and soil organic carbon (SOC) are often used in estimating SOC sequestration and storage. Spatial variability in BD, SOM, and the SOM–SOC conversion factor affects the ability to accurately estimate SOC sequestration, storage, and the benefits (*e.g.,* land building area and vertical accretion) associated with wetland restoration efforts, such as marsh creation and sediment diversions. There are, however, only a few studies that have examined large-scale spatial variability in BD, SOM, and SOM–SOC conversion factors in coastal wetlands. In this study, soil cores, distributed across the entire coastal Louisiana (approximately 14,667 km^2) were used to examine the regional-scale spatial variability in BD, SOM, and the SOM–SOC conversion factor. Soil cores for BD and SOM analyses were collected during 2006–09 from 331 spatially well-distributed sites in the Coastwide Reference Monitoring System network. Soil cores for the SOM–SOC conversion factor analysis were collected from 15 sites across coastal Louisiana during 2006–07. Results of a split-plot analysis of variance with incomplete block design indicated that BD and SOM varied significantly at a landscape level, defined by both hydrologic basins and vegetation types. Vertically, BD and SOM varied significantly among different vegetation types. The SOM–SOC conversion factor also varied significantly at the landscape level. This study provides critical information for the assessment of the role of coastal wetlands in large regional carbon budgets and the estimation of carbon credits from coastal restoration.

ADDITIONAL INDEX WORDS: *Soil organic carbon sequestration, Coastwide Reference Monitoring System, hydrological basins, vegetation types, van Bemmelen factor.*

INTRODUCTION

Soil bulk density (BD) and soil organic matter (SOM) content are two important descriptors of soil physical and biological structures in terrestrial and wetland ecosystems (Gosselink, Hatton, and Hopkinson, 1984; Mitsch and Gosselink, 2000). BD is an indicator of pore space and solid particles within the soil profile, which determine soil water-holding capacity (McKee and Cherry, 2009; Mitsch and Gosselink, 2000). SOM is an indicator of soil development and an important source of nitrogen and micronutrients required for plant growth (Bruland and Richardson, 2006). These two soil parameters are often used in estimating soil organic carbon (SOC) stocks and sequestration capacity (Hansen and Nestlerode, 2013; Markewich *et al.,* 2007; Zhong and Xu, 2009), which, in turn, are used to assess contributions of ecosystems to global and regional carbon budgets and mitigation of greenhouse gas emissions (*e.g.,* Crooks *et al.,* 2011; DeLaune and White, 2012). To reduce chemical analysis costs, SOM is often used as a predictor of SOC, and the conversion factor of 1.724 from SOC to SOM (the van Bemmelen factor), which assumes organic matter is 58% organic carbon, has been widely used in not only terrestrial ecosystems but also wetland soils (DeLaune and White, 2012; Hatton, DeLaune, and Patrick, 1983; Zhong and Xu, 2009).

Ecosystem restoration efforts have increased worldwide to mitigate the loss of wetlands, which provide critical ecosystem services, including carbon sequestration (*e.g.,* Couvillion *et al.,* 2013; Crooks *et al.,* 2011). In coastal wetlands, BD and SOM are also used in estimating vertical accretion and surface elevation change (Couvillion *et al.,* 2013; Day *et al.,* 2011; DeLaune, Patrick, and van Breemen, 1990; Hatton, DeLaune, and Patrick, 1983; Nyman *et al.,* 1993, 2006; Wang *et al.,* 2014). Often, BD and SOM are required to assess restoration benefits, such as sustained or new land-building areas and carbon sequestration of sediments and nutrients at a scale equal or larger than project boundaries (Boustany, 2010; Couvillion *et al.,* 2013; Crooks *et al.,* 2011; DeLaune and White, 2012; Wamsley, 2013). The American Carbon Registry has recently approved a standard wetlands restoration methodology for the Mississippi Delta in which SOM and BD data in different stratums are required to estimate carbon sequestration capacity (http://americancarbonregistry.org/). Therefore,

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changes in BD and SOM could largely affect the estimation of coastal restoration benefits. For example, the potential land-building area created by a freshwater diversion could be reduced by 22–38% when a BD value from the high end of the spectrum (0.5 g cm^{-3}) is used to replace a BD value from the low end of the expected range (0.21 g cm^{-3}) for saline marsh (Wamsley, 2011).

It is well established that BD and SOM vary spatially at landscape scales for a number of ecosystems, including wetlands, because of changes in soil texture, age, depth, and plant community structure (*e.g.,* Bruland and Richardson, 2005). In the Gulf of Mexico coastal wetlands, soil BD is largely controlled by mineral matter content (*e.g.,* Hatton, DeLaune, and Patrick, 1983), which is often a function of tidal action, riverine sediment delivery, and hurricanes and winter storms, and is associated sediment deposition and erosion (Meselhe *et al.,* 2013; Nyman, DeLaune, and Patrick, 1990; Piazza *et al.,* 2011; Turner *et al.,* 2006; Wamsley, 2013). These physical processes vary across the landscape. For example, the highest bulk densities in coastal Louisiana after the passage of hurricanes Katrina and Rita were coincidental with the thickest, newly deposited sediments on the eastern side of the center of the storm track (Smith *et al.,* 2015; Turner *et al.,* 2006). SOM is mainly determined by primary production and decomposition (Neubauer, 2008; Nyman, DeLaune, and Patrick, 1990; Nyman *et al.,* 1993), which are biological processes controlled by environmental conditions, such as porewater salinity and soil nutrient concentrations, and ecological characteristics, such as plant and microbial community composition (Neubauer *et al.,* 2013) that vary spatially. For example, wetland above- and belowground productivity declines with decreasing elevation beyond an optimum elevation, which can vary at both local and landscape scales (*e.g.,* Kirwan and Guntenspergen, 2012). In Breton Sound Estuary, along coastal Louisiana, significant increases in organic matter accumulation and nutrient input were found at sites nearest the Caernarvon Freshwater Diversion Structure (DeLaune *et al.,* 2003). Thus, spatial variation of wetland soil attributes may also be influenced by inundation and salinity changes associated with restoration activities (*e.g.,* Snedden, Cretini, and Patton, 2015). Therefore, it is not surprising that the van Bemmelen factor, 1.724 converting SOC to SOM is too low for most soils, including wetland soils (Ahn and Jones, 2013; Nelson and Sommers, 1996; Pribyl, 2010).

Despite the functional importance of BD and SOM, few investigations have examined the spatial variability in wetland soil properties, including BD, SOM, and the SOM–SOC conversion factor across a range of multiple vegetation types within different hydrologic basins and coastal plains at regional scales. This lack of information is partially due to the difficulty of collecting a large number of samples covering entire basins. The ability to accurately estimate ecosystem capacity to store carbon and nutrients and the ecosystem's role in mitigating greenhouse gas emissions is limited without an understanding of the spatial variability in BD, SOM, and the SOM–SOC conversion factor. In addition, large uncertainties exist in assessing carbon credits and restoration benefits without examining the spatial variability within the larger spatial scales (*e.g.,* land building or land-loss reduction) (*e.g.,* Mack *et al.,* 2015).

The Coastwide Reference Monitoring System (CRMS) network, which was established and authorized in 2003 under the Coastal Wetlands Planning, Protection and Restoration Act (CWPPRA), provides a large, unique data set for examining the spatial variability in soil properties, including SOM and BD and the relationship between SOM and SOC across the entire Louisiana coast (Couvillion *et al.,* 2013; Piazza *et al.,* 2011; Steyer *et al.,* 2003). CRMS is a regional-scale ecosystem monitoring system that provides data on wetland hydrology, ecology, soil, and geomorphology for large-scale coastal restoration and management applications (http://lacoast.gov/crms2/home.aspx). CRMS also provides a platform for scientific research on structure and functions of coastal wetlands (Piazza *et al.,* 2011). The objectives of this study were to use coastal Louisiana as an example to examine the spatial variability in (1) BD and SOM, and (2) the SOM–SOC conversion factor in coastal wetlands at a regional scale by relating BD, SOM, and the SOM–SOC conversion factor to hydrological basins and vegetation types. Hydrological basins across coastal Louisiana represent variation in hydrology (magnitude, duration, and frequency of flooding) because of the Mississippi River, Atchafalaya River, Mississippi River tributary channels, interdistributary lakes, bays, and tidal channels (Cahoon *et al.,* 1995). These basins also represent variations of mineral sediment transport and delivery from riverine and marine sources because of the changing location of the Mississippi River depocenter during the Holocene (review of Cahoon *et al.,* 1995). Vegetation types and associated community composition, density, and biomass are mainly determined by estuarine salinity (Visser *et al.,* 2002), which is affected by tidal forcing, river flow, winds, and sea-level rise (SLR) (*e.g.,* Day *et al.,* 2000; La Peyre *et al.,* 2016). A quantification of the spatial variability of these variables will contribute to a better understanding of the role of coastal wetlands in the national and global carbon budget and mitigation of climate change and, importantly, improve the assessment and prediction of restoration outcomes in the selection of the most cost-effective projects for coastal restoration.

METHODS

This study was carried out using wetland soil samples collected during 2006–2009 across the entire coastal Louisiana. Coastal Louisiana was classified into different hydrologic basins and vegetation types to examine the regional-scale spatial variability in BD, OM and the SOM–SOC conversion factor.

Study Area

Coastal Louisiana (Figure 1) is one of the most wetland-rich regions of the world, containing about 40% of the coastal marshes in the contiguous United States. Coastal Louisiana's wetlands are interspersed with 7284 km^2 of ponds and lakes, 8903 km^2 of bays and sounds, and 13,196 km of navigation, drainage, and petroleum access canals (USDOI, 1994). In 2011, land in coastal Louisiana comprised approximately 14,667 km^2 of the coastal zone (Couvillion *et al.,* 2011). Most soils in coastal Louisiana are histosols, which are characterized by high

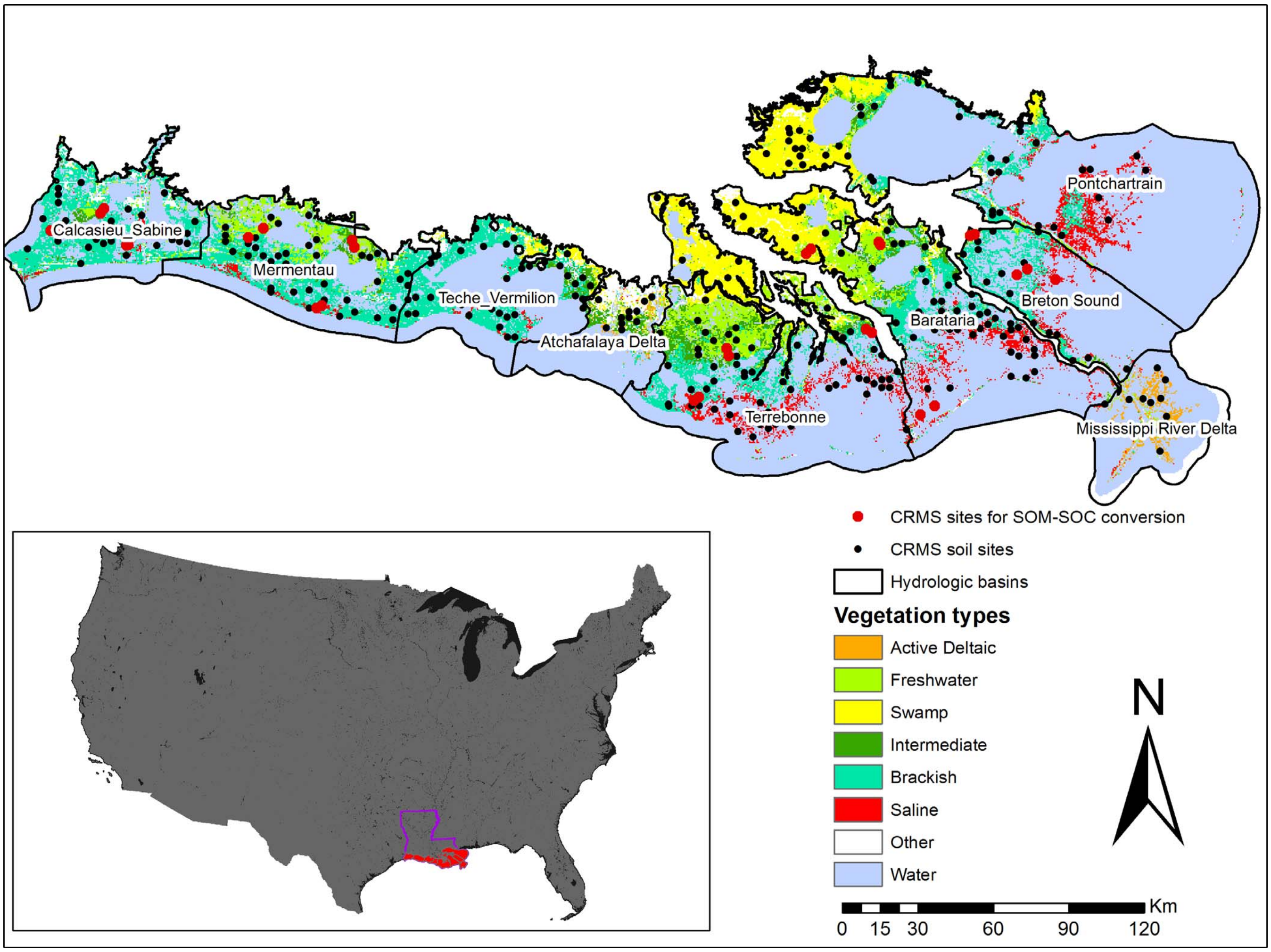

Figure 1. Location of CRMS soil sample sites within different hydrologic basins and vegetation types across coastal Louisiana. Data for BD and SOM analysis were from 331 CRMS soil sites sampled during March 23, 2006, to July 23, 2009. Data for SOM–SOC conversion were from 15 CRMS sites sampled during spring 2006 to fall 2007.

vegetation productivity and high organic matter accumulation (Markewich *et al.,* 2007).

Classifications of Soil Samples

CRMS sites were classified into nine hydrologic basins (Figure 1) that are separated largely by current or abandoned Mississippi River distributary channels and their adjacent levee deposits (Cahoon *et al.,* 1995; Day *et al.,* 2000). These hydrologic basins are, from west to east, (1) Calcasieu/Sabine (CS) and (2) Mermentau (ME) in the Chenier Plain, (3) Teche/Vermilion (TV) and (4) Atchafalaya (AT) in the marginal deltaic plain, (5) Terrebonne (TE), (6) Barataria (BA), (7) Breton Sound (BS), (8) Mississippi River Delta (MR), and (9) Pontchartrain (PO) in the deltaic plain (Barras, 2007). This hydrologic basin classification has been widely used by different programs conducting research, monitoring, and management in coastal Louisiana (Barras, 2007; Day *et al.,* 2000; Steyer *et al.,* 2003).

CRMS sites were classified into six vegetation types (Figure 1): (1) active deltaic (D), (2) freshwater (F), (3) intermediate (I), (4) brackish (B), (5) saline marshes (S), and (6) swamp (Sw). Dominant species are *Panicum hemitomon* and *Sagittaria lancifolia* for freshwater marsh, *Sagittaria lancifolia* and *Schoenoplectus americanus* for intermediate marsh, *Spartina patens* for brackish marsh, *Spartina alterniflora* and *Juncus roemerianus* for saline marsh, and *Phragmites australis* for active deltaic marsh (Sasser *et al.,* 2008; Visser *et al.,* 2003). Active deltaic marshes occur at the termini of the Mississippi and Atchafalaya rivers, including the Wax Lake Delta, and have a distinct vegetation community composition and productivity (Day *et al.,* 2000). Active deltaic marshes are distinguished from freshwater marshes and other vegetation types, which also belong to deltaic wetlands, based on a different stage of delta development and/or abandonment (Day *et al.,* 2000; Nyman, 2014). Swamps are dominated by *Taxodium distichum* and *Nyssa aquatica* (Sasser *et al.,* 2008; Visser *et al.,* 2003).

Vegetation zones across coastal Louisiana run roughly parallel to the coast and are determined primarily by estuarine salinity (Day *et al.,* 2000; Gosselink, Hatton, and Hopkinson, 1984). In general, vegetation types distribute seaward from freshwater marsh to saline marsh for nonactive delta areas, with swamp forest interspersed with freshwater and intermediate marshes. CRMS site-specific species, collected during the soil sample collection period (2006–09), were used to classify vegetation types. A land-cover data set was created using 2007–09 Landsat TM imagery (a spatial resolution of 30 m) and a 2007 coastwide vegetation helicopter survey (Sasser *et al.,* 2008), which was used as training data. This land-cover data set was used to create a 2007–09 vegetation map with the six vegetation types (Figure 1). The 200 m × 200 m grid of each CRMS site was assigned its vegetation type using the "majority" rule for all 30-m pixels within the 200 m × 200 m grid with a 150-m buffer along the site center point using ESRI ArcGIS 9.3.

Soil Sampling Distribution, Core Collection, and Laboratory Analysis

Soil samples to evaluate BD and SOM spatial variability were collected at CRMS sites from March 23, 2006, to July 23, 2009. CRMS sites were well distributed among different hydrologic basins and vegetation types (Figure 1) *via* a stratified sampling technique (Steyer *et al.,* 2003). A soil depth of 24 cm was used in CRMS because this depth includes most of the living root zone in coastal Louisiana wetland soils (Day *et al.,* 2011; Nyman, DeLaune, and Patrick, 1990; Nyman *et al.,* 1993, 2006). Three cores were taken at each soil sampling site using a 4-inch (10.2 cm) inside-diameter core tube sharpened on the end and made of aluminum or polyvinyl chloride (PVC) and a PVC coring handle for insertion to a depth of $\sim$30 cm and sectioned into 4-cm intervals in the field (Folse *et al.,* 2012), resulting in six depth increments: 0–4, 4–8, 8–12, 12–16, 16–20, and 20–24 cm. Core compaction was controlled to 10% or less in most soils and less than 20% for highly organic soils (*e.g.,* floating marsh and flooded swamp sites) during core collection. Soil samples at some sites were too fluid or unconsolidated to collect all three cores at all six depths; therefore, these sites were excluded, resulting in a total of 331 sites (sample size was 1986) in this study. Soil cores for spatial variability in BD and SOM cover all nine hydrologic basins and six vegetation types.

Soil cores for the SOM–SOC relationship were taken from 15 sites across coastal Louisiana from spring 2006 to fall 2007 (Piazza *et al.,* 2011). This data set was part of a study on the geomorphic and ecological effects of hurricanes Katrina and Rita on coastal Louisiana marsh community dynamics, including species composition, vegetation productivity, biomass, and mineral and organic matter accumulation (Piazza *et al.,* 2011). At each site, two cores were taken using a 10-cm-diameter, thin-walled aluminum or PVC cylinder to $\sim$50 cm. Compaction was minimized by using large, thin-walled cores. Soil cores were sectioned into 2-cm increments in the field. These soil cores represent four vegetation types (freshwater, intermediate, and brackish and saline marshes) in five of the hydrologic basins (CS, ME, TE, BA, and BS). The final total sample size was 315 to a depth of 44 cm for SOM–SOC analysis in this study.

Soil bulk density is defined as the total weight of both organic and inorganic materials in a known volume of sample in units of grams per cubic centimeter. Bulk density was measured from dry weight (oven dry at 60°C for 48 h). Organic matter content was determined with the loss-on-ignition method (550°C for 2 h) (Folse *et al.,* 2012). Organic carbon content was measured using a Costech Elemental combustion system (Costech Analytical Technologies Inc., Valencia, CA, U.S.A.). Samples were treated with acid fumigation to remove carbonates before organic carbon (OC) analysis. For details on procedures of soil core collection and laboratory analysis, refer to Folse *et al.* (2012); Heiri, Lotter, and Lemcke (2001); and Piazza *et al.* (2011).

Statistical Analysis

This study used split-plot analysis of variance (ANOVA) with incomplete block design to examine the effects of hydrological basin, vegetation type, and soil depth on BD, SOM, and the SOM:SOC ratio. In the split-plot design, the hydrological basin was treated as a blocking factor, vegetation types as the whole plots nested within the block (Basin), and soil depth was treated as split-plots nested within the whole plots (Veg). Vegetation factor can be called a *between-subjects factor*, whereas the split-plot factor (Depth) can be called a *within-subjects factor*, and within-subjects factors can be correlated. The CRMS design and soil data meet the requirements of the assumptions of the split-plot design including the dependent samples of depth slices. The hypothesis was that BD, SOM, and SOM/SOC ratio vary significantly across coastal Louisiana in a spatial gradient defined by both hydrological basins and vegetation types. Data on the three cores for BD and SOM analysis and the two cores for the SOM:SOC ratio were averaged for each depth at each site for statistical analysis. BD, SOM, and SOM:SOC ratio were power transformed to obtain normality (Shapiro-Wilk Test) and homogeneity of variance (Bartlett's test) values for the model residuals. The SOM–SOC relationships were determined using linear regression. Statistical analyses were conducted using the SAS 9.2 software package (SAS Institute, Cary, NC, U.S.A.). All the tests were two-tailed based on type III sums of squares and were considered significant at $p < 0.05$.

RESULTS

This section presents the results of the ANOVAs on the effects of hydrological basin, vegetation type, soil depth, and their interaction on BD, SOM, and the SOM–SOC relationship. The spatial variability in BD, SOM, and SOM–SOC conversion factors across the entire Louisiana coast was investigated based on these results.

Spatial Variability in BD and SOM

The split-plot ANOVA results showed that there was a significant basin × vegetation type interaction for both BD ($p < 0.0001$) and SOM ($p < 0.0001$) (Table 1). Horizontal variability in BD and SOM across coastal Louisiana can be described by hydrological basin and vegetation type combined groups (basin–vegetation groups). Mean BD and SOM for the 0–24-cm depth varied significantly across coastal Louisiana, as demonstrated by the variations of BD and SOM among the 34 basin–vegetation groups (Figures 2 and 3). Values of mean BD

Table 1. *Statistical summary of split-plot ANOVA testing for the effects of hydrologic basin (Basin), vegetation type (Veg), and soil depth (Depth), and their interactions on soil bulk density, soil organic matter content, and SOM:SOC ratio (significant* P *values (<0.05) are highlighted in bold).*

	Bulk Density			Organic Matter			SOM/SOC		
Source	df	*F*	*P*	df	*F*	*P*	df	*F*	*P*
Basin	8	25.56	**<0.0001**	8	37.79	**<0.0001**	4	7.74	**<0.0001**
Veg	5	76.09	**<0.0001**	5	70.77	**<0.0001**	3	35.13	**<0.0001**
Basin × veg	20	6.44	**<0.0001**	20	5.58	**<0.0001**	4	10.70	**<0.0001**
Depth	5	4.68	**0.0003**	5	1.49	0.1882	21	1.49	0.0809
Veg × depth	25	3.12	**<0.0001**	25	2.69	**<0.0001**	61	0.98	0.5280
Model	63	25.59	**<0.0001**	63	25.24	**<0.0001**	93	3.00	**<0.0001**
Error	1922			1922			221		
Corrected total	1985			1985			314		

larger than 0.6 g cm^{-3} were found in marsh types within the two active deltas (Mississippi River deltaic and saline marshes, and Atchafalaya deltaic marsh). Basin–vegetation groups with BDs ranging from 0.4 to 0.6 g cm^{-3} were found mostly in saline marshes. Freshwater marshes at Calcasieu/Sabine and Barataria basins had bulk density values less than 0.1 g cm^{-3} because of a larger amount of organic matter than mineral sediment in the soil development. SOM generally showed opposite trends to soil BD. The highest SOM values (>60%) were found in Calcasieu/Sabine freshwater marsh and the Barataria freshwater and intermediate marshes, whereas the lowest SOM values (<10%) were found in the Mississippi River deltaic and saline marshes and the Atchafalaya deltaic marsh.

The split-plot ANOVA results also showed that there was significant 'vegetation type × soil depth' interaction for both BD ($p < 0.0001$) and SOM ($p < 0.0001$) (Table 1). Vertical variability in BD and SOM (0–24 cm) across coastal Louisiana can be described by vegetation types. Along the 0–24 cm depth profile, active deltaic marsh and swamp had a mean BD increasing with depth but with different magnitudes (from 0.65 to 1.04 g cm^{-3} for deltaic marsh and from 0.2 to 0.4 g cm^{-3} for swamp; Figure 4). Freshwater, intermediate, and brackish marshes had relatively stable BD with depth, whereas mean BD decreased with depth in saline marsh (Figure 4). For SOM distribution with depth, active deltaic marsh had a relatively stable SOM (<10%); swamp had a decreasing SOM (from 51 to 30%), whereas SOM in freshwater (~55%), intermediate (~48%), brackish (~39%), and saline (~21%) marshes varied slightly with depth (Figure 4).

Conversion Factor between SOM and SOC

The split-plot ANOVA result showed that there was significant basin × vegetation type interaction for the SOM:SOC ratio ($p < 0.0001$) (Table 1). The highest mean SOM:SOC ratio (mean ± standard error [SE]: 3.87 ± 0.12) was found for brackish marsh in Mermentau, whereas the lowest mean SOM:SOC ratio (2.03 ± 0.03) was found for intermediate marsh in Terrebonne (Figure 5). Mean values of the SOM:SOC ratio ranges were 2.04 ± 0.01 to 2.32 ± 0.04, 2.03 ± 0.03 to 3.35 ± 0.24, 3.16 ± 0.25 to 3.87 ± 0.12, and 2.7 ± 0.18 to 2.86 ± 0.10 for freshwater, intermediate, brackish. and saline marshes, respectively (Figure 5). Overall, SOM:SOC ratios ranged from 1.19 (saline marsh in Terrebonne) to 8.17 (intermediate marsh in Calcasieu/Sabine) with a mean value of 2.67.

Linear regression equations can describe the relationships between SOM and SOC across the landscape defined by hydrological basins and vegetation types (Table 2). Regression equations were given to determine the average value of the SOM–SOC conversion factors for different basin and vegetation-type combinations. The SOM–SOC conversion factors

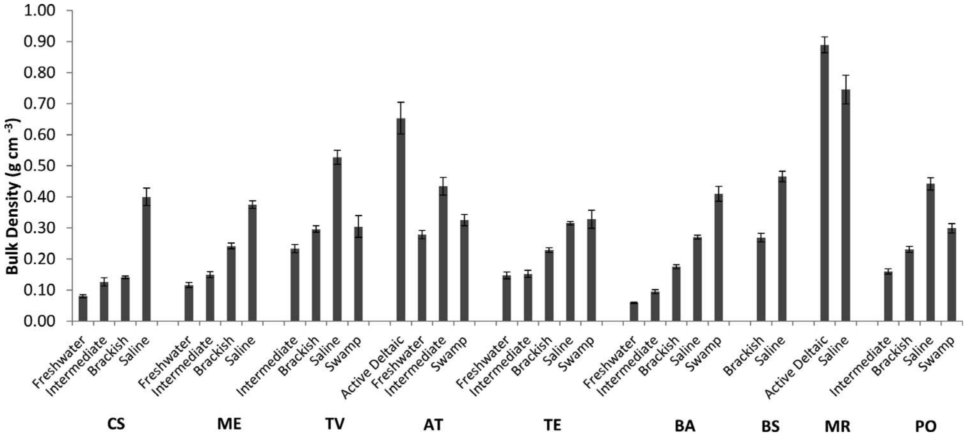

Figure 2. Spatial variation in soil bulk density defined by nine hydrologic basins and six vegetation types combined groups across coastal Louisiana. The nine hydrologic basins are listed from west to east: Calcasieu/Sabine (CS), Mermentau (ME), Teche/Vermilion (TV), Atchafalaya (AT), Terrebonne (TE), Barataria (BA), Breton Sound (BS), Mississippi River Delta (MR), and Pontchartrain (PO). Bars represent mean − 1 SE to mean + 1 SE.

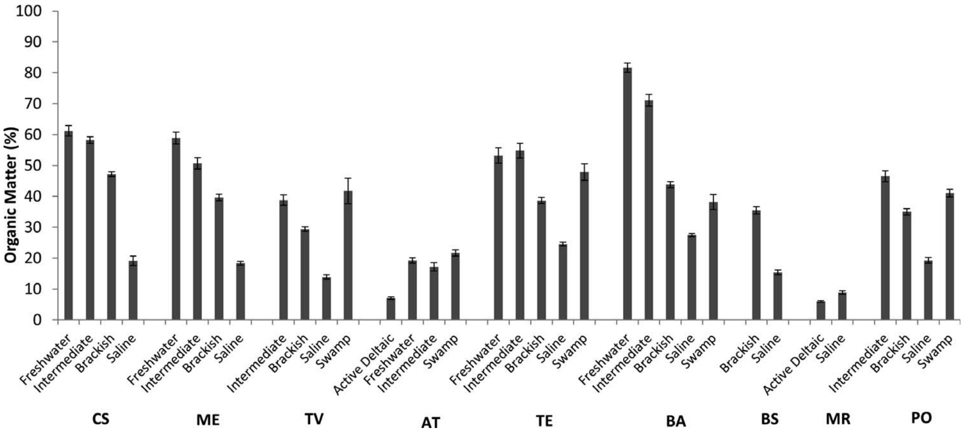

Figure 3. Spatial variation in soil organic matter defined by nine hydrologic basins and six vegetation types combined groups across coastal Louisiana. The nine hydrologic basins are listed from west to east: Calcasieu/Sabine (CS), Mermentau (ME), Teche/Vermilion (TV), Atchafalaya (AT), Terrebonne (TE), Barataria (BA), Breton Sound (BS), Mississippi River Delta (MR), and Pontchartrain (PO). Bars represent mean − 1 SE to mean + 1 SE.

derived from these linear regression equations were in the range of 0.28 to 0.49 (or 2.04 to 3.58 for SOC-to-SOM conversion). Specifically, the SOM:SOC ratios were 0.44–0.49, 0.33–0.49, 0.28–0.41, and 0.37–0.40 for freshwater, intermediate, brackish, and saline marshes, respectively (Table 2). Overall, the average value of the SOM–SOC conversion factor based on a linear regression model was 0.45 (SOC-to-SOM equal to 2.2) for soils of coastal Louisiana.

DISCUSSION

This section presents the explanations of the regional-scale spatial variability in BD, SOM, and the SOM–SOC conversion factor. The impact of such spatial variation on coastal restoration benefits (*e.g.,* land building and SOC sequestration) is also demonstrated in this section.

Spatial Variability in BD and SOM

Within a specific hydrologic basin, there is a trend that average soil BD over a depth of 24 cm increases, whereas SOM decreases from freshwater marsh to saline marsh. This is mainly because rates of mineral sediment accumulation generally increased seaward from freshwater marshes toward the salt marshes and with higher rates adjacent to natural water bodies (*e.g.,* lakes, rivers, and bayous) than in the interior marshes (Hatton, DeLaune, and Patrick, 1983). Mineral sedimentation is the principal determinant of variation in soil BD in marshes of coastal Louisiana (Gosselink, Hatton, and Hopkinson, 1984; Hatton, DeLaune, and Patrick, 1983). Grain size also increases from freshwater to saline marshes (Allison *et al.,* 2012; Hatton, DeLaune, and Patrick, 1983). Deltaic marshes of the Mississippi River and Atchafalaya deltas were found to have the highest mean BD (>0.65 g cm^{-3}) mainly because of the regular delivery of relatively large quantities of mineral sediments with large particle sizes (sands) from the Mississippi and Atchafalaya rivers (Allison *et al.,* 2012; Hupp *et al.,* 2008), which can be incorporated into the soil (Nyman, DeLaune, and Patrick, 1990). Mineral sediment is not the only determinant of soil BD. For freshwater, intermediate and brackish marshes where SOM composes >50% of the dry weight, total soil BD is also driven by organic matter accumulation from vegetation growth (Hatton, DeLaune, and Patrick, 1983; Nyman *et al.,* 2006).

Previous studies found that active deltaic marsh and swamp soils would consolidate and gain strength through surface (0–15 cm) desiccation and, at greater depths, respond to compaction (Cahoon *et al.,* 2011; Day *et al.,* 2011). In addition, in these soils, sediment settling out of the water column tended to be transformed into a soil layer that bonds with the preexisting surface, thus decreasing pore space, resulting in increased BD (*e.g.,* Nyman *et al.,* 1993). In contrast, mean BD decreased with depth in the saline marsh. Besides a larger quantity of mineral sediment being deposited and incorporated into the soil surface layer than into the subsurface layers, it is also possible that the deeper portions of the salt marsh soil profiles could represent earlier freshwater or brackish marshes with lower BD because of conversion to salt marsh from SLR and salt water intrusion (DeLaune, Patrick, and van Breemen, 1990).

Higher SOM in freshwater, intermediate and brackish marshes, and swamp than in active deltaic and saline marshes could be attributed to several factors, including larger organic inputs due to higher plant productivity, lower organic matter loss from decomposition, gains in organic matter from upper basin deposition, and dilution of organic matter by a greater abundance of mineral matter (Day *et al.,* 2000; DeLaune, Nyman, and Patrick, 1994; Nyman *et al.,* 2006). SOM generally decreased with depth from the soil surface to the bottom of the soil profile, especially in swamps, reflecting the variations in growth and distribution of root and rhizome, and the decomposition with depth. The high SOM in the subsurface layers (8–12 cm) in freshwater and intermediate, brackish, and saline marshes might be partially explained by the large-scale influence of hurricanes and storms, such as 2005 hurricanes Katrina and Rita, which caused surface organic matter to be buried because of mineral sediment deposition on the wetland surface (Piazza *et al.,* 2011; Turner *et al.,* 2006). For example,

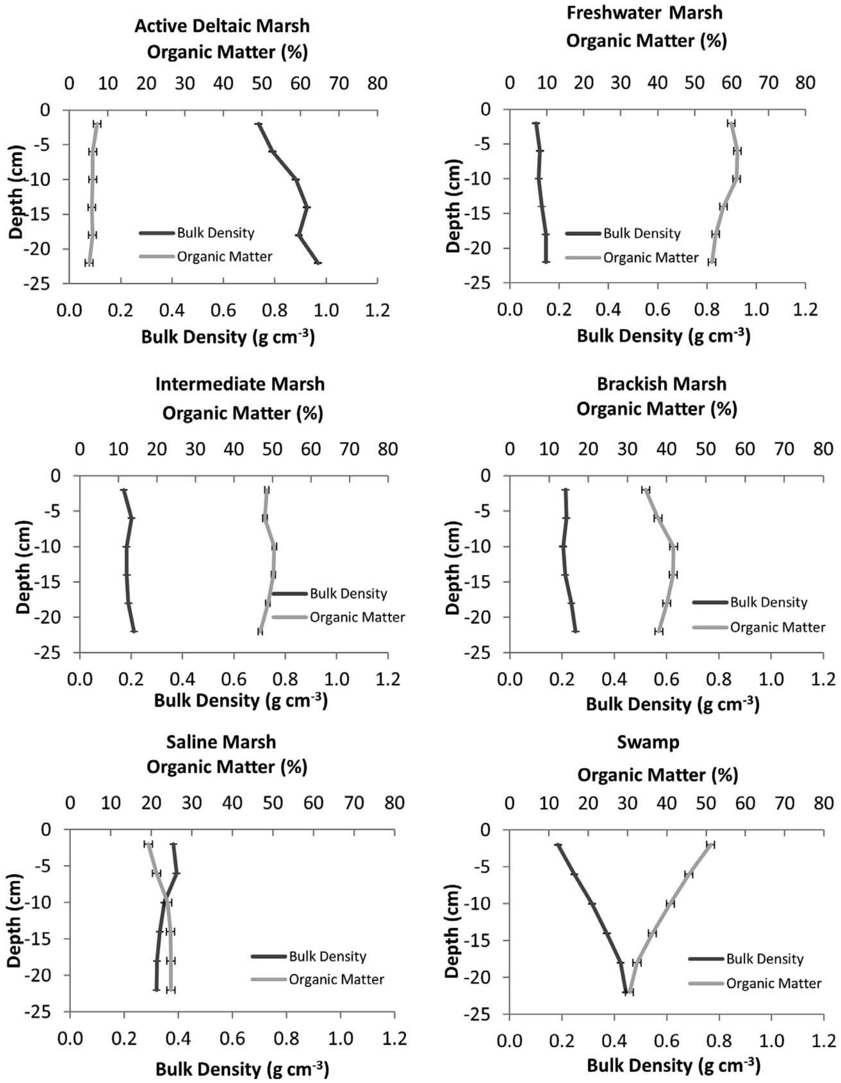

Figure 4. Vertical variation in soil bulk density and organic matter by vegetation type across coastal Louisiana. Bars represent mean – 1 SE to mean + 1 SE.

Turner *et al*. (2006) found that the thickness of the deposited mud layer because of hurricanes Katrina and Rita across coastal Louisiana was 5.18 ± 7.7 cm, and these newly deposited sediment layers tended to have higher mineral, but lower organic, contents (bulk density: 0.37 ± 0.35 g cm^{-3}).

Conversion Factor between SOM and SOC

The van Bemmelen factor (1.724) has been widely used to convert measurable SOC to SOM, based on the assumption that SOM contains 58% of SOC, including wetland soils (DeLaune and White, 2012; Gosselink, Hatton, and Hopkinson, 1984; Hatton, DeLaune, and Patrick, 1983; Zhong and Xu, 2009). This study found that the SOM–SOC conversion factor for soils of coastal wetlands tended to vary across a landscape defined by both hydrological basins and vegetation types. This study found that the values of the SOM–SOC conversion factor ranged between 1.19 and 8.17, with a mean value of 2.67 for coastal Louisiana wetland soils. The results are consistent with studies on wetland soils in other areas (Ahn and Jones, 2013; Craft, Seneca, and Broome, 1991). Craft, Seneca, and Broome (1991) reported that SOM:SOC ratios ranged from 1.67 to 4.44 for marsh soils in eastern North Carolina. Ahn and Jones (2013) found that, for created wetlands, SOM:SOC ratios ranged from 2.0 to 3.5. The SOM:SOC ratios for different basin–vegetation groups in this study were comparable to that of Craft, Seneca, and Broome (1991). The data showed that most (>85%) of SOM:SOC ratios also ranged from 2.0 to 3.5.

If a single conversion factor is needed, it should be 2.2, converting SOC to SOM (or 0.45 converting SOM to SOC) for wetland soils. Based on the consideration of the possible variation in organic matter composition, a range of conversion factors between 1.4 and 2.5 from SOC to SOM (0.40 to 0.71 from SOM to SOC) was predicted (Pribyl, 2010). The median and mean values of the conversion factor in Pribyl's synthesis of many published studies were 2.0 and 2.2, respectively, very

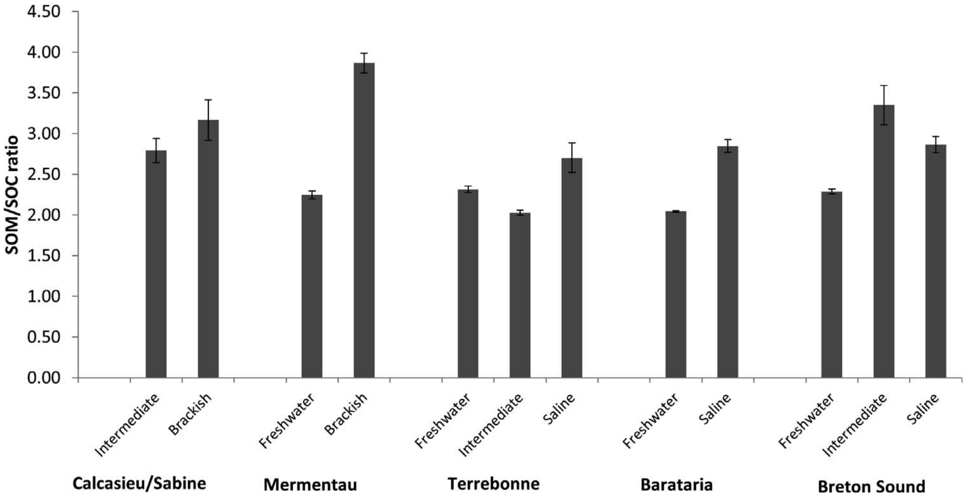

Figure 5. Spatial variation in SOM:SOC ratio defined by five hydrologic basins and four vegetation types combined groups across coastal Louisiana. Bars represent mean − 1 SE to mean + 1 SE.

close to the general regression–determined conversion factor value.

The variation in the relationship between SOM and SOC (or the ratio of SOM:SOC) across the landscape defined by hydrological basins and vegetation types in wetland soils of coastal Louisiana can be explained by the composition and quantity of SOM as well as the accumulation (*Production – Decomposition*) of various organic compounds (Craft, Seneca, and Broome, 1991; Wang *et al.,* 2011; Wright, Wang, and Reddy, 2008). For wetland soils in Louisiana, it was found that polysaccharide carbon tended to contribute more to the total carbon content in the freshwater marsh soils than it did in saline marsh soils, and the soils appeared to be highly stable and undergo little to no decomposition (Wang *et al.,* 2011), resulting in a low SOM:SOC ratio. In contrast, saline soils tended to have less polysaccharide carbon and more aliphatic carbon, with extensive decomposition of polysaccharide content and lignin content (Wang *et al.,* 2011), causing a higher SOM:SOC ratio compared with their freshwater marsh counterparts. It was found that the SOM:SOC ratio decreased with increasing SOM content in wetland soils (Craft, Seneca, and Broome, 1991; Wright, Wang, and Reddy, 2008). The data also showed this trend of decreasing SOM:SOC ratio with SOM content from saline and brackish marshes to intermediate marsh and freshwater marsh (Figure 5 and Table 3). The decreasing trend in SOM:SOC ratio might be a reflection of the accumulation of reduced organic compounds, such as refractory organic matter, fatty acids, and methane *via* anaerobic decomposition process (Craft, Seneca, and Broome, 1991).

Table 2. *Regression results between SOC and SOM for different basin- and vegetation-type groups.*

Basin-Veg Group	No. of Samples	Regression Equation	R^2	P
Calcasieu/Sabine				
Intermediate	58	SOC = 0.4176 × SOM	0.99	<0.0001
Brackish	18	SOC = 0.4054 × SOM	0.99	<0.0001
Mermentau				
Freshwater	40	SOC = 0.4855 × SOM	0.99	<0.0001
Brackish	20	SOC = 0.2785 × SOM	0.96	<0.0001
Terrebonne				
Freshwater	22	SOC = 0.4444 × SOM	0.99	<0.0001
Intermediate	19	SOC = 0.4949 × SOM	0.99	<0.0001
Saline	22	SOC = 0.4014 × SOM	0.92	<0.0001
Barataria				
Freshwater	29	SOC = 0.4908 × SOM	0.99	<0.0001
Saline	22	SOC = 0.3660 × SOM	0.99	<0.0001
Breton Sound				
Freshwater	21	SOC = 0.4380 × SOM	0.99	<0.0001
Intermediate	22	SOC = 0.3256 × SOM	0.96	<0.0001
Saline	22	SOC = 0.3751 × SOM	0.98	<0.0001

Assessment of Coastal Restoration Benefits

Regional-scale spatial variability in BD, SOM, and SOM–SOC conversion factor is a critical uncertainty issue for assessing wetland's role in global carbon budget and evaluating the benefits of wetlands restoration and protection activities (Couvillion *et al.,* 2013; Steyer *et al.,* 2012; Wamsley, 2013). This study found that SOM and BD varied significantly across landscape units defined by hydrological basin and vegetation types; therefore, values of BD, SOM, and the SOM–SOC conversion factor based on basin-vegetation–combined groups, rather than that based solely on vegetation type, should be used in assessing coastwide SOC sequestration and coastal

Table 3. *Mean and range of soil bulk density and soil organic matter content (0–24 cm) of different vegetation types based on CRMS soil data analyses (the values in the parentheses represent the minimum and maximum of the observed data).*

Vegetation Type	Bulk Density (g cm^{-3})	Organic Matter (%)
Active deltaic	0.86 (0.65–1.04)	6 (3.7–7.1)
Freshwater	0.11 (0.06–0.28)	55 (19.3–81.7)
Intermediate	0.19 (0.11–0.43)	48 (17.2–66.6)
Brackish	0.22 (0.16–0.31)	39 (29.4–48.6)
Saline	0.38 (0.29–0.53)	21 (23.9–25.8)
Swamp	0.33 (0.20–0.41)	39 (21.7–47.9)

restoration benefits (*e.g.,* potentials of land building or land-loss reduction).

SOC storage in a region can be estimated by the product of BD, SOM, depth, and the area of each landscape unit divided by the SOM–SOC conversion factor (or the van Bemmelen factor). The van Bemmelen factor (1.724) appears to be low and should be adjusted to 2.2 (or SOM contains 45% of SOC rather than 58%) for coastal wetlands. Using soil BD and SOM for all the basin-vegetation–combined groups and the 2.2 SOC to SOM factor (0.46 for SOM to SOC conversion), it is estimated that coastwide SOC storage in the top meter of soil would be approximately 877 million metric tons (MMT) (Couvillion *et al.,* 2013). This is very close to the SOC storage of 800–900 MMT estimated by Markewich *et al*. (2007) using SOC measurements from field samples. However, if soil BD and OM values based on the vegetation type only were used, SOC storage would be approximately 592 MMT. This represents an approximate 32% underestimation of the coastwide total SOC storage. Using the 0.58 rather than 0.45 to convert SOM to SOC would result in approximately 29% overestimation of SOC storage.

Across the Louisiana coast, the greatest percentage of wetlands are brackish marshes dominated by *Spartina patens* (>35%, 2010 data), with an average BD of 0.22 g cm^{-3} and an SOM of 39% (Table 3). The results showed that within brackish marsh, the depth-averaged BD ranged from 0.16 to 0.31 g cm^{-3} and SOM ranged from 29.4 to 48.6% depending on location in hydrological basins. Thus, ignoring the spatial variability in soil BD and SOM could result in large differences in assessing the contributions of coastal wetlands to global carbon budget. Spatial variability also applies to within–basin-vegetation type–combined groups. However, such fine-scale variability is beyond the scope of this large-scale analysis.

The benefit of coastal restoration may be overestimated or underestimated when averaged BD and SOM values based on vegetation type only are used for a coastal area in which spatial heterogeneity in soil properties (*e.g.,* BD and SOM) is evident. Spatial information on soil BD and SOM varying with geomorphologic settings and vegetation distribution from this study has been applied to the prediction of wetland morphologic dynamics and associated SOC sequestration capacity under different future environmental scenarios in support of coastal Louisiana's Master Plan assessment of restoration alternatives (Couvillion *et al.,* 2013; Steyer *et al.,* 2012; Wang *et al.,* 2014). These future environmental scenarios include global SLR, subsidence, changes in storm intensity and frequency, Mississippi River discharge, rainfall and evapotranspiration (Peyronnin *et al.,* 2013). Variable soil BD and SOM are directly used to predict vertical accretion and SOC sequestration in the wetland morphology modeling (Couvillion *et al.,* 2013; Wang *et al.,* 2014) and the feedback mechanisms, such as when a vegetation type switches because of hydrodynamic and surface elevation change (Meselhe *et al.,* 2013; Visser *et al.,* 2013). The investigators found that, without restoration efforts, SOC storage (to a depth of 1 m) could decrease by between 108 and 250 MMT, a loss of 12 to 30% of the total coastwide SOC (877 MMT), but, with the Master Plan implemented, between 35 and 74% of the SOC loss could be offset (Couvillion *et al.,* 2013). This study's approach of spatial variability analyses of soil BD and SOM content and the relationship between SOM and SOC could be applied to other coastal regions for the assessment and prediction of the benefits of large-scale coastal restoration and protection under future environmental change, such as climate change, SLR, and changes in river discharge and reduction of sediment.

CONCLUSIONS

The regional-scale (multiple hydrologic basins and vegetation types) spatial variability in wetland soil BD, SOM, and the SOM–SOC conversion factor affects the ability to accurately estimate SOC inventory, stock, and sequestration capacity and the land building/land change benefits associated with coastal restoration efforts. Data from many well-distributed samples collected at regional scales were required to detect such spatial variability in wetlands across a large geographical region. Wetland soil cores distributed across the entire coastal Louisiana collected from CRMS were used to examine the regional-scale spatial variability in BD, SOM, and the SOM–SOC conversion factor. CRMS is a single comprehensive wetland monitoring program, providing data on wetland hydrology, ecology, soil, and landscape change for large-scale coastal studies.

Regional-scale spatial variability in soil BD and SOM across coastal Louisiana can be described by diverse geomorphological units with distinct hydroecological zones or basin–vegetation groups, and vertical variability can be described by vegetation types using soil data collected from CRMS sites. Classifying the spatial variation in BD and OM values within 34 basin–vegetation groups rather than within six vegetation types resulted in an approximately 32% difference in estimations of coastwide total SOC storage in the top meter of soils. Across coastal Louisiana, the SOM–SOC conversion factor also varied across the landscape defined by the combinations of hydrological basins and vegetation types. Therefore, variable SOM–SOC conversion factors should be used in assessing SOC sequestration and stock in coastal wetlands. At minimum, the van Bemmelen factor of 1.724 (converting SOC to SOM) should be adjusted to 2.2 for the soil of the coastal wetlands of Louisiana, if a single conversion factor is used. Sufficient sampling investments to detect spatial variation greatly improve the estimates of SOC storage and the assessments of land-building benefits associated with coastal restoration and protection. Improved understanding of spatial variability in soil properties and their relationships will allow coastal resource scientists and managers to generate more reliable assessments and predictions of changes in wetland morphology and SOC sequestration capacity under climate change, SLR, freshwater discharge changes, and reduction of mineral sediment supply.

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