Wetlands (2018) 38:401–409
https://doi.org/10.1007/s13157-017-0977-2

ORIGINAL RESEARCH

Relationships of Marsh Soil Strength to Belowground Vegetation Biomass in Louisiana Coastal Marshes

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Received: 5 May 2016 / Accepted: 21 November 2017 / Published online: 27 December 2017

Abstract
Wetland plants are subject to a range of physical stresses (e.g. inundation, salinity) that affect their productivity or health, which in turn may translate into wetland soils that vary in resistance to physical perturbations in the coastal setting. A primary goal of this study was to test a newly developed instrument designed to measure in-situ resistance to shear failure (soil strength) of marsh soils. The Wetland Soil Strength Tester (WSST) was used at 11 marsh types in coastal Louisiana, where soil bulk density ranged from organic to mineral (0.02–1.24 g cm^{-3}). Based on analyses of live and dead components of both above and belowground biomass, live belowground biomass explained the most variation in marsh soil strength among the vegetation types. The WSST was capable of detecting in-situ live root biomass differences for 8 of 11 marsh types, where only the young deltaic marsh types were not significant. For all the sample plots ($n = 227$), an increase of 10-Nm soil strength corresponded to an increase of 200 g m^{-2} of live belowground biomass ($R^2 = 0.35$, $p < 0.0001$). WSST measurements, combined with other monitoring data, may help in the assessment of wetland condition.

Keywords Coastal wetlands · Vegetation biomass · Marsh soil strength · Soil bulk density · Wetland monitoring

Introduction

Subsidence, inundation, sediment deprivation, and salinity changes have contributed to decreased plant productivity and ultimately high rates of coastal wetland loss in Louisiana (DeLaune et al. 1983; Blum and Roberts 2009; Nyman et al. 1993). Hurricanes have also caused direct and large scale losses of wetlands with extreme tidal surge (Barras 2007). Given the significant investments in coastal restoration (CPRA 2012), a growing need to improve monitoring tools to help assess wetland condition to support decision making is apparent.

Vegetation productivity and biomass measurements provide an indication of wetland condition and marsh stability, but these measurements are time-consuming and have been generally excluded from most ecosystem monitoring efforts (e.g., CRMS). Belowground biomass, in particular, is labor intensive to sample and process, but ecologically important because roots represent a significant portion of overall plant productivity, contribute to soil vertical accretion, and provide resistance to erosion. While root density is generally recognized as a factor that contributes to soil strength, neither a rapid method nor a quantitative relationship between the two has been examined for use in marsh systems. There has been interest in developing a simple and inexpensive instrument that is sensitive enough to detect differences in plant and soil parameters and their subsequent contribution on soil strength. Several soil strength testing devices are currently available, such as vanes and penetrometers that have been designed for measuring geotechnical properties of soils and follow documented methods (ASTM D 2573). Several of these commercial strength testers have been applied in Louisiana wetlands (Table 1); however one concern with use of small vane devices (1–3 cm) is whether an adequate volume, where both roots and rhizomes interact with the surrounding soil, is being characterized.

The goal of this study was to test the use of a newly developed soil strength device that was designed to measure the

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Table 1 Studies in Louisiana coastal wetlands that include soil strength measurements

Soil Strength Instrument	Units	Design	Studies
Torvane	kg cm^{-2}	vane; in situ or laboratory	McGinnis 1997
Dutch Cone Penetrometer	kg cm^{-2}	in situ penetrometer	Are et al. 2002
Torvane	kg cm^{-2}	vane; in situ or laboratory	Sasser et al. 2005
Torvane	kg cm^{-2}	vane; in situ or laboratory	Swarzenski et al. 2008
Wykeham Farrance Lab Vane	kPa	laboratory vane	Howes et al. 2010
Seiken Field Vane	Nm	in situ hand vane	Howes et al. 2010
Dunham E-290 Hand Vane Tester	kPa	in situ hand vane	Turner 2011
Dutch Cone Penetrometer	g cm^{-2}	in situ penetrometer	Day et al. 2011
Geotechnics Shear Vane	kPa	in situ hand vane	Graham and Mendelssohn 2014
Geotechnics Shear Vane	kPa	in situ hand vane	Lin et al. 2016
Wetland Soil Strength Tester (WSST)	Nm	in situ horizontal rotating disk with vertical pins	This study

resistance to soil failure (referred to as 'soil strength' hereafter). This goal included understanding how these measures of strength are associated with plant biomass and soil bulk density. The instrument was used to measure how surface soil strength varies across a range of coastal marsh types.

Methods

Instrument Description and Usage

Prior to this study, we designed prototype instruments for measuring wetland soil resistance, and preliminary lab and field tests were conducted on rooted sods and several natural wetlands. After these initial trials, we recognized that the device should integrate the following properties: 1) achieve an appropriate soil volume, where roots are prevalent; 2) disrupt the soil volume as little as possible during insertion; and, 3) withstand high torsional resistance. After initial testing, a refined design was settled upon that could withstand relatively high torsional resistance. Thus, the refined Wetland Soil Strength Tester (WSST) design consisted of four stainless steel 'pins' that are 15 cm long and positioned with a diameter of 9.6 cm (Fig. 1). The individual pin width and thickness was 1.91 cm and 0.64 cm, respectively. The WSST was coupled with a Northern Industrial Tools D4-135BN digital torque wrench that was capable of recording the peak torque required to produce soil failure.

During field measurements, the device was rotated in the soil with a steady force from the torque wrench until the rotational movement produced shear failure. The peak force exerted through the torque wrench required to produce the shear failure was recorded as 'soil strength' in Newton-meters (Nm), which is a measure of torque, equivalent to 1 Newton of force applied at a distance of 1 m from the pivot at a right angle to the radius (1 Nm = 0.74 ft pounds).

Study Sites

Soil strength measurements, biomass, and soil bulk density were collected at 51 locations representing 11 marsh types across coastal Louisiana (Visser and Sasser 1998 and Visser et al. 2000), which correspond to the vegetation types monitored by the Coastal Reference Monitoring System (CRMS) program (Table 2, Fig. 2; Steyer et al. 2003). Site selection was coordinated with the Louisiana Coastal Protection and Restoration Authority (CPRA) and United States Geological Survey (USGS) with existing CRMS sites used as primary locations for sampling. At several CRMS sites, more than one vegetation type was present and sampled (designated by triangles in Fig. 2). Additional locations not associated with CRMS monitoring were also sampled to provide additional data for the analysis. Since site selection was not based on a pre-determined productivity assessment, the wetland health condition at the study locations likely varied.

Field Data Collection

Fifty-one locations were sampled during peak plant growth during 2009–2011, from a range of freshwater to saline coastal herbaceous marsh types, which were grouped into 11 marsh types for analysis purposes (Table 2, Fig. 2). The number of samples per location was typically between 3 and 5 plots (see Table 3 for the number of samples per marsh type). Measurements and samples taken at each study plot included vegetation species composition, aboveground and belowground (live and dead) biomass, bulk density, and soil strength. At each plot, an aboveground sample (0.1 m^2) of live and dead vegetation biomass was first harvested, then a WSST measurement was taken from within the clipped plot, followed by a belowground soil core, which was taken directly from the area where strength was measured. A soil core was also

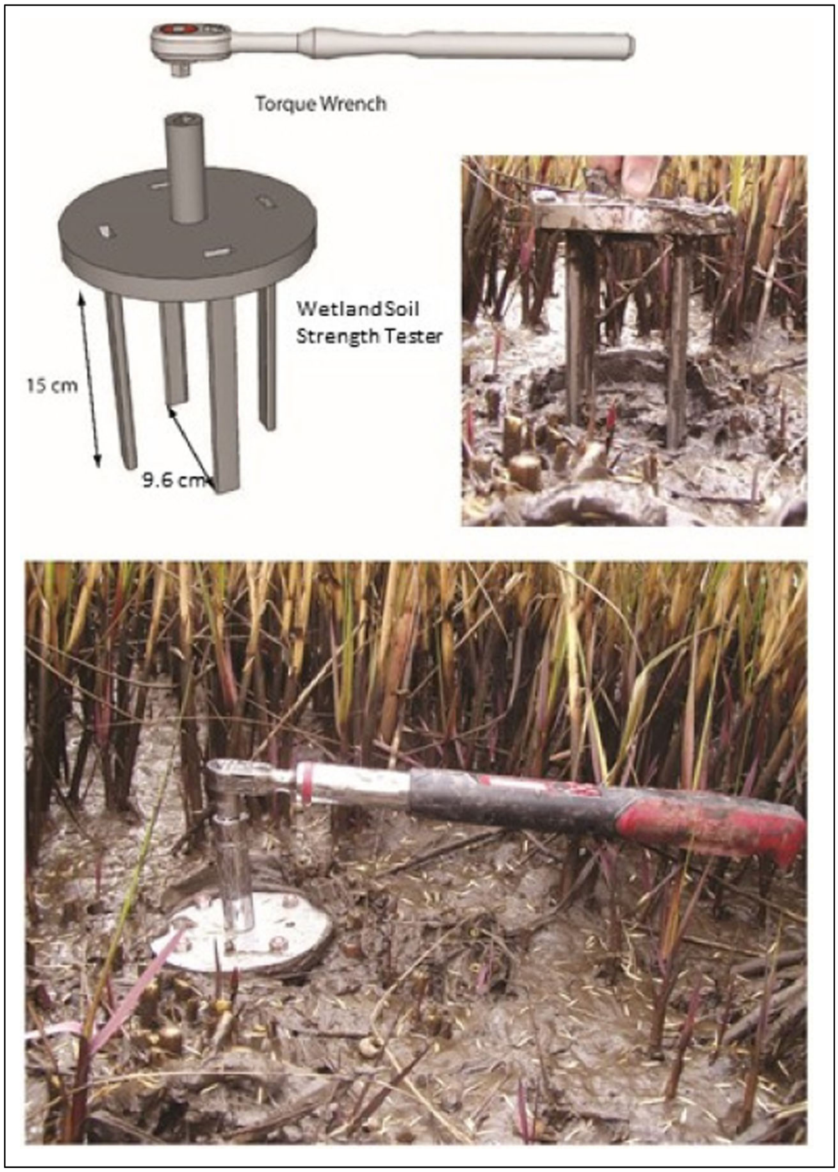

Fig. 1 Schematic of the Wetland Soil Strength Tester (WSST), which is coupled with a digital torque wrench that records peak torque (Newton meters (Nm)

Table 2 Wetland vegetation community types that were sampled

Marsh Type	Dominant and Co-dominant Species
Deltaic *Sagittaria*	*Sagittaria platyphylla*
Deltaic Mixture	*Colocasia esculenta*
Deltaic Roseau Cane	*Phragmites australis*
Fresh Bulltongue	*Sagittaria lancifolia*
Fresh Maidencane	*Panicum hemitomon*
Oligohaline Bulltongue	*Sagittaria lancifolia*, *Eleocharis* spp.
Oligohaline Spikerush	*Eleocharis* spp.
Oligohaline Wiregrass	*Spartina patens*, *Vigna luteola*, *Eleocharis* spp. *Cyperus* spp., *Typha* spp., *Phragmites australis, Schoenoplectus americanus*
Mesohaline Mixture	*Distichlis spicata, Spartina alterniflora, Spartina patens*
Mesohaline Wiregrass	*Spartina patens*
Polyhaline Oystergrass	*Spartina alterniflora*

collected from an area nearby the above- and belowground sample plot for determination of soil bulk density. Vegetation species composition was determined within the plots used for soil strength measurements. Aboveground vegetation was harvested and returned to the laboratory for processing.

Vegetation was sorted by live and dead portions, with the live portion separated into species. All plant material was then dried in an oven at 65 °C, and the dry weight of live and dead aboveground biomass was determined. After the aboveground vegetation material was harvested and the soil shear strength measured, belowground vegetation biomass was sampled from the same 0.1 m^2 aboveground biomass plot by extracting a 10 cm diameter core. The cores were taken to a depth of 15 cm, which corresponded with the WSST pin depth. Cores were returned to the laboratory

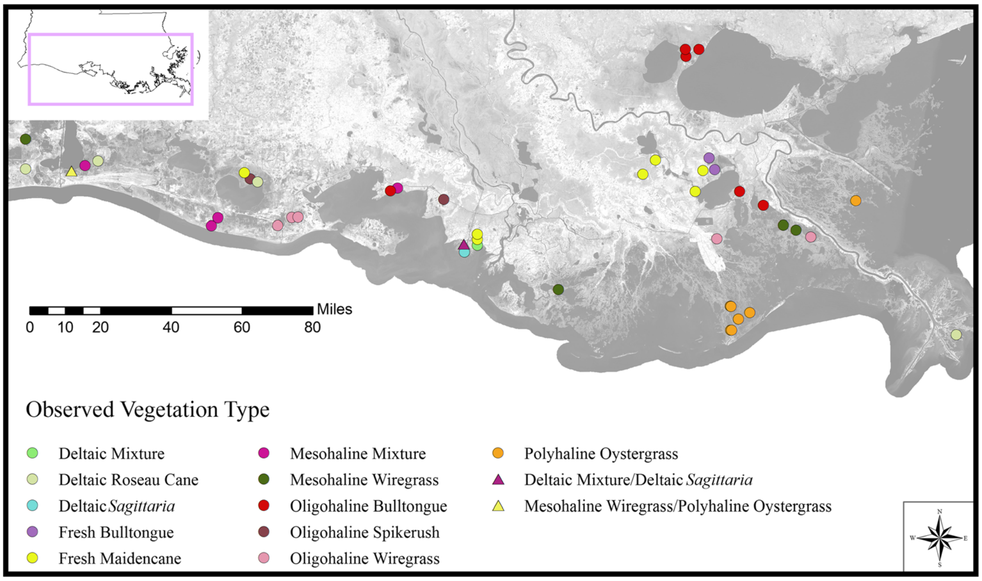

Fig. 2 Coastal wetland sampling locations for this study, designated by circles and triangles. At several locations, more than one vegetation type was sampled (designated by triangles)

and washed in a 0.5-mm mesh sieve to remove fine mineral soil particles from the macro-organic matter. Live roots and rhizomes were separated from the remaining dead macro-organic matter by assessing several characteristics, including turgidity, color, root hairs, and physical resistance to pressure/force. Belowground dead and live matter were dried to constant weight at 65 °C. Soil bulk density was sampled with a 5 cm diameter core to depth of 15 cm from an area nearby each plot after the soil strength had been measured. For bulk density determinations, the samples were returned to the laboratory where each core was dried to constant weight at 65 °C.

Data Analyses

The dataset comprised a total of 227 plots from 51 locations. Data analyses were generated using SAS software, Copyright © 2002–2010 SAS Institute Inc., Version 9.3 of the SAS System for Windows (SAS/STAT). To satisfy the model assumptions for normality and homogeneity of variance, 13 samples were deemed outliers and removed from the final analysis. An evaluation of the relationship of soil strength to above- and belowground live and dead biomass, and bulk density was accomplished using a general linear regression with a stepwise selection process to determine which, if any, of the effects were

Table 3 Soil strength (Nm) and live belowground biomass (g m^{-2}) summary statistics by wetland type

Marsh Type	Samples	Soil Strength (Nm)				Live Belowground Biomass (g m^{-2})			
		Min	Max	Mean	S.D.	Min	Max	Mean	S.D.
Deltaic *Sagittaria*	8	32	58.9	42.2	10.2	0	302	43	106
Deltaic Mixture	7	25.7	92.7	52.5	22.1	30	1,209	586	514
Deltaic Roseau Cane	13	32.7	88.1	49.9	15.6	349	2,933	1,274	932
Fresh Maidencane	40	21.9	176.6	81.3	42.7	184	3,663	1,335	887
Fresh Bulltongue	30	14.5	68.6	34.1	14.9	0	3,242	669	896
Oligohaline Bulltongue	30	20.4	103.2	49.6	22.9	6	4,328	1,469	1,186
Oligohaline Spikerush	8	23	51.8	38.4	8.9	52	1,754	830	622
Oligohaline Wiregrass	20	17.9	104.8	43.7	24.6	52	3,196	903	810
Mesohaline Mixture	15	25.4	63	42.5	11.1	417	2,857	1,678	788
Mesohaline Wiregrass	13	22.9	110	60.7	27.4	376	3,958	1,879	1,106
Polyhaline Oystergrass	43	24.3	79.6	47.1	12.5	181	3,546	1,185	756

Table 4 Total aboveground and belowground biomass among the marsh types

Marsh Type	Total Belowground Biomass (g m^{-2})				Total Aboveground Biomass (g m^{-2})			
	Min	Max	Mean	S.D.	Min	Max	Mean	S.D.
Deltaic *Sagittaria*	152	1,002	364	281	40	856	337	396
Deltaic Mixture	565	3,373	2,137	1,301	559	4,812	1,691	1,538
Deltaic Roseau Cane	993	10,502	3,881	2,534	2,397	18,571	7,436	5,228
Fresh Maidencane	2,336	4,961	3,549	623	347	3,185	1,311	557
Fresh Bulltongue	112	4,506	1,419	1,417	53	651	301	187
Oligohaline Bulltongue	2,286	8,277	4,470	1,590	48	3,301	760	864
Oligohaline Spikerush	2,399	5,057	3,532	917	68	513	282	171
Oligohaline Wiregrass	2,023	8,267	3,947	1,325	1,069	6,814	3,371	1,677
Mesohaline Mixture	1,514	5,667	3,836	1,012	1,379	4,406	2,514	893
Mesohaline Wiregrass	2,432	6,594	4,469	1,320	2,232	7,071	4,209	1,550
Polyhaline Oystergrass	1,578	4,836	3,142	866	531	4,146	1,793	759

significant. From the results of the evaluation of all components, relationships of soil strength with the selected vegetation productivity component (live belowground biomass) were determined using an analysis of covariance, with marsh type as the covariate.

Results

Summary statistics for soil strength by vegetation type are included in Table 3. The mean soil strength for all samples was 49.8 Nm, and the median was 41.9 Nm. The range in soil strength varied from a minimum of 14.5 Nm from a Fresh Bulltongue site, dominated by *Sagittaria lancifolia,* to a maximum of 177 Nm from a Fresh Maidencane marsh, dominated by *Panicum hemitomon* (Table 3). The mean soil strength values for marsh types ranged from 34 to 81 Nm.

The marsh types had mean total aboveground biomass that ranged from 282 to 7,436 g m^{-2}, and mean total belowground biomass that ranged from 364 to 4,470 g m^{-2} (Table 4). In contrast to the other biomass variables, a highly significant effect of live belowground biomass on soil strength was detected ($p < 0.01$). Overall, the linear relationship of live belowground biomass to soil strength was: *live belowground biomass* (g m^{-2}) = 20.012 x *soil strength* (Nm) + 126.43 ($R^2 = 0.35$). Including vegetation types into the analysis of covariance increased the coefficient of determination from 0.35 (Fig. 3) to 0.56 (Fig. 4). All of the vegetation types had significant, positive slopes at a threshold of $p < 0.06$ except for the deltaic wetland types (Deltaic Mix, Deltaic Roseau Cane, and Deltaic *Sagittaria)* which were not significant (Table 5). Live mean belowground biomass ranged from 43 to 1879 g m^{-2}. (Table 3). Live aboveground biomass and dead aboveground biomass were not

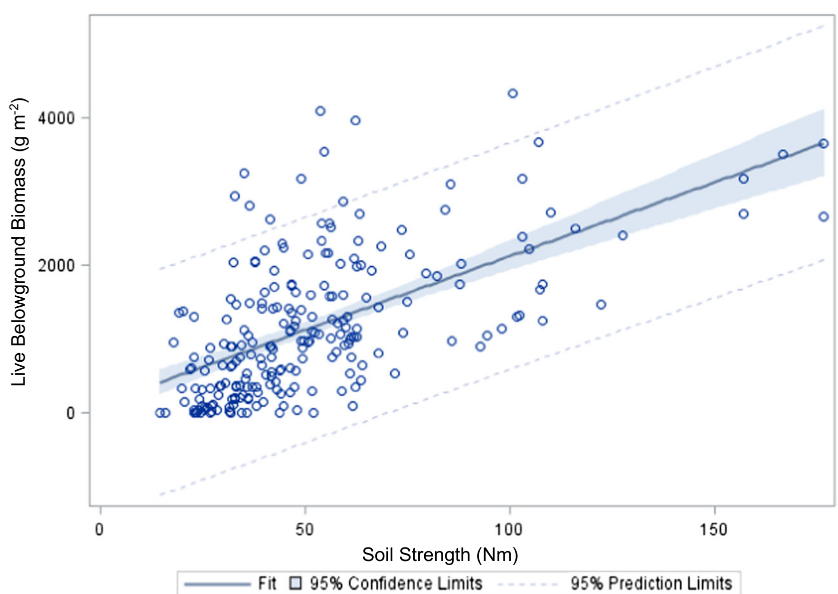

Fig. 3 Linear regression of soil strength versus live belowground biomass for all sample plots. *Live belowground biomass* = 20.012**soil strength* + 126.43 ($R^2 = 0.35$, $p < 0.0001$)

Fig. 4 Live belowground biomass and soil strength from the eleven vegetation types, along with the significant slopes (lines) as determined by the ANCOVA ($R^2 = 0.56$, see also Table 5 for corresponding equations, R^2 and p-values)

significantly correlated to soil strength as measured with the WSST. Linear regression results showed that soil strength as measured with the WSST explained less than 1% of the variation in live aboveground ($y = 4.1\times + 1139.2$, $R^2 = 0.003$, $p = 0.41$) and dead aboveground biomass ($y = -1.02\times + 585.0$, $R^2 = 0.002$, $p = 0.50$). A marginally significant effect of dead belowground biomass on soil strength ($p = 0.06$) was noted; however, only 2% of the variation in dead belowground biomass could be explained by soil strength. In summary, live belowground biomass explained the most variation in marsh soil strength among the vegetation types.

Mean soil bulk density of the various marsh types ranged from 0.07 to 1.08 g cm^{-3} (Table 6). While an overall significant effect of bulk density on soil strength was detected with all sample plots combined ($p < 0.01$), bulk density explained only 5% of the variability in soil strength, and the general trend was that high soil strength was associated with low soil bulk density. When the analysis of bulk density was partitioned by vegetation type, slopes of eight of the 11 vegetation types were not significantly different from zero. Vegetation types with significant negative slopes were Deltaic Mixture and Fresh Bulltongue, and a significant positive slope was observed for Deltaic Roseau Cane.

Table 5 Regression relationships (ANCOVA) for live belowground biomass (y) and soil strength (x) for the marsh types. All mature marsh types exhibited significant relationships (or marginally significant for Oligohaline Spikerush, $p < 0.064$); whereas, the young delta marsh types did not show a significant effect between live belowground biomass and soil strength

Marsh Type	Live Belowground Biomass (y) Soil strength (x) $y = mx + b$	Coefficient of Determination R^2	Slope significance Pr > |t|
Deltaic *Sagittaria*	7.3 x - 265.6	0.50	0.766
Deltaic Mixture	16.3 x - 266.5	0.48	0.184
Deltaic Roseau Cane	17.1 x + 419.2	0.08	0.162
Fresh Maidencane	18.7 x - 183.8	0.81	<0.0001
Fresh Bulltongue	43.5 x - 815.3	0.52	<0.001
Oligohaline Bulltongue	39.9 x - 314.5	0.40	<.0001
Oligohaline Spikerush	52.5 x - 1182.7	0.56	0.064
Oligohaline Wiregrass	30.2 x - 445.3	0.63	<0.0001
Mesohaline Mixture	49.8 x - 441.7	0.49	0.002
Mesohaline Wiregrass	27.7 x + 199.1	0.47	<0.001
Polyhaline Oystergrass	18.8 x + 298.8	0.10	0.042

Table 6 Soil bulk density summary statistics among the marsh types

Marsh Type	Bulk Density (g cm^{-3})			
	Minimum	Maximum	Mean	S.D.
Deltaic *Sagittaria*	0.86	1.23	1.08	0.13
Deltaic Mixture	0.24	0.73	0.49	0.20
Deltaic Roseau Cane	0.17	1.24	0.60	0.46
Fresh Maidencane	0.02	0.24	0.11	0.05
Fresh Bulltongue	0.04	1.14	0.57	0.42
Oligohaline Bulltongue	0.07	0.28	0.14	0.06
Oligohaline Spikerush	0.06	0.08	0.07	0.00
Oligohaline Wiregrass	0.08	0.38	0.16	0.07
Mesohaline Mixture	0.16	0.50	0.31	0.11
Mesohaline Wiregrass	0.15	0.23	0.19	0.02
Polyhaline Oystergrass	0.17	0.40	0.28	0.06

Discussion

This study was designed to understand how surface soil strength varies among different coastal marsh types, and how these measures of strength with the WSST are associated with plant biomass and soil bulk density variables. Bulk density was not an important factor in describing soil strength as measured by the WSST, which is not entirely surprising, since this instrument was primarily designed to measure the resistance of complex root networks to failure. Mineral soils have cohesive properties that interact with plant roots to impart strength, but mineral soil strength is probably better measured with penetrometer or vane devices, rather than the WSST. When examined among wetland types, the highest bulk density marsh types (Deltaic) were also the only marsh types in the study that did not exhibit a significant effect between soil strength and live belowground biomass.

A potential downside to some vane devices is the small sample area, which may not capture the complex dimensions of the root network of coastal wetland soils. From this study, we found that the WSST may be well suited for estimating the contribution of live belowground biomass to soil strength, in at least the upper 15 cm of the soil profile. Thus, the WSST measurements may complement other soil strength devices that have the capability of sampling soil strength properties below the zone of most active root turnover.

Fresh Maidencane marsh had the highest mean soil strength of all the marsh types. A higher soil strength for this marsh type seemed reasonable, given the tough, tightly woven marsh mat typical of this species and its co-dominant grasses and sedges. In contrast, some of the lowest soil strength values were observed in the marshes dominated by *Sagittaria* spp., which possesses soft, aerenchymatous roots that are likely weaker than other more fibrous root types.

Given the breadth of wetland sites that were sampled for this study, which were not selectively chosen based on prior knowledge of condition or health, some observations are worth noting about the capacity of certain wetland and plant types to resist failure. We had expected that the *Panicum hemitomon*-dominated sites would possess a high upper limit of soil strength given the dense root and rhizome characteristics of the dominant species that are typically combined with a high diversity of co-occurring species. These mature delta wetlands occur in the upper reaches of the estuary, and while they possess high internal resistance to failure, these communities are also vulnerable to massive physical upheaval with catastrophic storm surge (Howes et al. 2010) given their natural buoyancy and detachment from underlying mineral soils (Sasser and Gosselink 1984; Sasser et al. 1995).

The areas dominated by *Spartina patens*, which is a common grass of oligohaline and mesohaline reaches of the estuaries, had maximum soil strengths over 100 Nm, and their live belowground biomass was relatively high (> 3,500 g m^{-2}; Fig. 5). While *S. patens* is capable of high resistance through dense, adventitious rooting in surface soils (Nyman et al. 2006), it is also a species that is vulnerable to belowground productivity declines with inundation stress (Snedden et al. 2015).

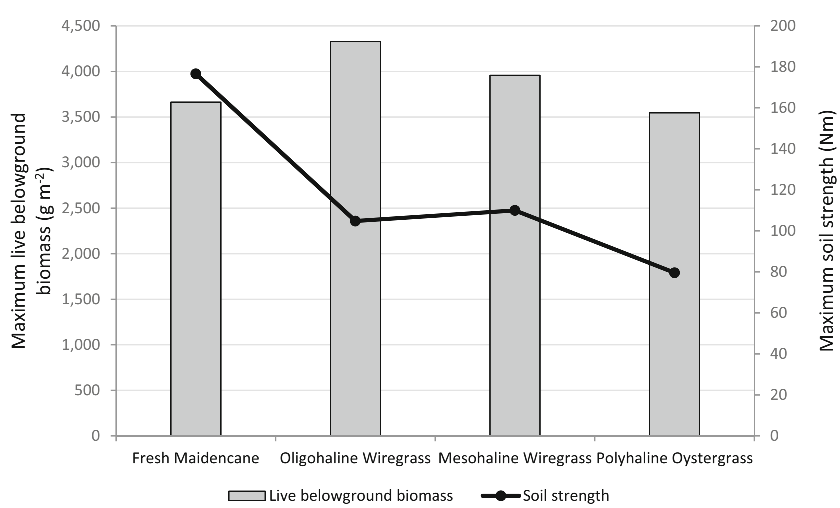

Fig. 5 The maximum soil strength and maximum live belowground biomass measured in the grass-dominated marsh types across the salinity gradient. While the study captured sites of similarly high maximum live biomass (> 3500 g m^{-2}), maximum soil strength did not follow a similar trend

An interesting finding from the study was the relatively low soil strength of Polyhaline Oystergrass marshes dominated by *Spartina alterniflora*, which was broadly sampled and well represented ($n = 43$). The maximum strength detected was <80 Nm despite a wide range in live belowground biomass (181 to 3,545 g m^{-2}) and bulk density (0.17 g m^{-2} to 0.40 g m^{-2}). As with the other grasses discussed earlier, we expected similarly high soil strength responses for *S. alterniflora* (Fig. 5). *Spartina alterniflora* marshes and their root network appear to reach a relatively lower threshold of strength as compared to other lower salinity, grass-dominated systems and deserve closer study. A poor correlation of surface soil strength with live belowground biomass for *S. alterniflora* in this study should not be misinterpreted to mean that these systems are subject to failure or erosion, but rather, *S. alterniflora* wetlands that occupy mineral-rich sediments at an optimal vertical position in the tidal frame certainly possess relatively high resistance to energy (storm surge, Howes et al. 2010), which may be primarily driven by the level of consolidation and type of mineral soil sediments, and secondarily by root biomass.

Summary

This study tested the WSST, a prototype instrument developed to measure in-situ soil strength across Louisiana marsh types to evaluate its performance in detecting plant biomass and soil properties. The WSST was most sensitive in detecting live belowground biomass differences for most coastal marsh soils, but less so for developing mineral soils in the active deltas. Adaptive management requires monitoring a spectrum of wetland variables to assess the performance of wetland restoration. While biomass monitoring is one of the long-standing techniques for evaluating wetland condition, the time and cost for belowground biomass processing is not always routinely practical for most large-scale monitoring. Soil strength measurements using the WSST are a useful, rapid technique for estimating changes in live belowground biomass and providing visibility to a complementary variable for assessing trajectories of wetland condition over time.

Acknowledgements Funding for this project was provided through State of Louisiana Interagency Agreement No. 2503-11-45 by the Louisiana Coastal Protection and Restoration Authority. We appreciate the input and assistance provided by Sarai Piazza (USGS) along with the helpful reviews by Louisiana Coastal Protection and Restoration Authority (CPRA) scientists. We thank Dr. James Geaghan, LSU Department of Experimental Statistics, for his assistance and guidance with the statistical analysis of the data, and two anonymous reviewers for their comments and suggestions that helped improve the manuscript. We also appreciate the assistance of Daniel Sasser with data collection in the field, and the help provided by the field teams who sample the Coastwide Reference Monitoring System (CRMS) sites used in this project and who accommodated this study.

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