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Impact of Containment and Elevation on Created Marsh Plant Community and Ecosystem Dynamics

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**IMPACTS OF CONTAINMENT AND ELEVATION ON
CREATED MARSH PLANT COMMUNITY AND ECOSYSTEM
DYNAMICS**

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science

In

The Department of Oceanography and Coastal Sciences

by
Kevin Stoner
B.S, Clemson University, 2021
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Abstract

Coastal marsh restoration is increasing globally, as marshes are impacted by anthropogenic impacts. Billions of dollars are allocated to marsh restoration in the Mississippi River delta where wetland loss rates are extremely high. The recovery of structural and functional attributes of created marshes varies by attribute measured and project. Here, two marshes created in 2018 and one natural marsh were used to examine how variations in hydrologic connectivity and marsh elevation influence subsurface hydrology and salinity, vegetation community structure, soil properties, accretion, and denitrification. I established a comparative field study in a created marsh contained within a higher elevation containment dyke (Confined), an unconfined created marsh where the dredge sediment was allowed to settle naturally (Unconfined), and a nearby natural marsh on the northeast shore of Lake Pontchartrain in Big Branch National Wildlife Refuge, Louisiana. Most marsh creation projects in Louisiana have a surrounding higher-elevation containment dyke to limit the loss of dredge sediment. The long-term effects of containment dykes on tidal exchange, plant dispersal, sediment delivery, and accretion are unknown. Marshes were surveyed for elevation and vegetation by species ($n = 12$). Surface accretion rates were measured in the Natural marsh and created marshes using feldspar marker horizons ($n = 5$). Vegetation communities differed among marshes with *Spartina patens* dominating in the Natural marsh, *Typha domingensis* dominating low to moderate elevations and *Baccharis halimifolia* dominating high elevations in the Confined marsh, and *Schoenoplectus americanus*, which is a desirable species for wildlife, dominating in the Unconfined marsh. The Unconfined marsh accreted more mineral matter than the Natural marsh. Denitrification rates were lower in the Confined marsh than in the Unconfined and Natural marshes. Overall, this study illustrates large differences among marshes related largely to elevation, though containment dykes may also be fostering the colonization of wind-dispersed species, such as *Typha domingensis*. The Unconfined marsh has higher accretion rates, lower maximum salinities during low water events, and higher denitrification rates than the Confined marsh. Ultimately, these findings show the importance of marsh creation design in facilitating the development of desired ecosystem structure and functions.

Introduction

Coastal wetlands provide numerous ecosystem services, including carbon sequestration, erosion control, storm surge protection, water purification, and habitat for commercially important species (Barbier et al. 2011). However, coastal wetlands are threatened by sea level rise (SLR) and other anthropogenic impacts. From 1999 to 2019, approximately 13,700 km² of tidal wetlands were lost globally (Murray et al. 2022). However, over that same period, tidal wetland area gained was approximately 9,700 km² with wetland restoration accounting for 14% (1,350 km²) of new tidal wetland area (Murray et al. 2022). Thus, marsh restoration is increasing around the world in response to degradation by human activities including those that impact hydrology and sediment availability (Bilah et al. 2022). As the number of restoration projects has increased, so has the need to evaluate the effectiveness of restoration projects in restoring ecosystem structure and function.

Marsh restoration has had mixed success, with some restored marshes failing to create suitable habitat for target species (Lindig-Cisneros et al. 2003, Williamshen et al. 2021) or failing to fully recapture ecosystem structure (e.g., plant community development) or function, (e.g., biogeochemical cycling; Brooks et al. 2015; Moreno-Mateos et al. 2012), while others have similar vegetation and process rates to natural marshes (Craft and Zheng 2003; Abbot et al. 2019; Drexler et al. 2019). Of the many elements that go into the design of restoration projects, restoring natural hydrology and sediment delivery have emerged as key components that lead to the development of important structural and functional marsh components (Moreno-Mateos et al. 2012). Hydrologic connectivity through the removal of tidal gates and levees, and the facilitation of tidal channel development is important for allowing natural flooding dynamics and delivery of sediment. Restoration of natural hydrology promotes marsh plant growth and establishment while also facilitating marsh functions such as accretion and nutrient cycling (Moreno-Mateos et al. 2012, Wolf et al. 2013). A meta-analysis of restored coastal wetlands showed that restoring sediment delivery, which is related to the restoration of hydrology, was the most important factor contributing to restored wetlands resilience to SLR (Liu et al. 2021). The deposition of sediment and organic material contributes to wetland accretion, but this process relies on suitable elevation, functional hydrology, and productive marsh vegetation (Kirwan and Megonigal 2013; Cahoon et al. 2019).

Coastal wetlands exist within a narrow range of elevations relative to the tidal prism. A key factor in the survival of these ecosystems is their ability to raise their elevation through accretion to keep up with SLR and local subsidence (Kirwan et al. 2016). Inundation, sediment deposition, plant growth, and organic matter accretion have complex interactions that contribute to marsh accretion (Kirwan et al. 2010). A model proposed by Morris et al. (2002) suggests that there is a peak accretion rate at an elevation where primary productivity is at its maximum. Above this elevation, a marsh is considered stable because an increase in sea level rise will increase the accretion rate by increasing primary productivity and sediment deposition, thus allowing the marsh to equilibrate with sea level. Elevations below the maximum productivity are considered unstable because an increase in sea level rise will decrease primary productivity and therefore decrease accretion rates, which will eventually lead to the conversion of the marsh to open water. However, different marsh species have different flood and salinity tolerances, which causes above-ground and below-ground production to peak at different elevations for different species (Snedden 2015, Willis and Hester 2004). Sediment deposition increases with time flooded, but various other factors including sediment availability and stem density affect the rate

at which sediment is deposited (Gleason 1979). Understanding how restoration designs influence marsh accretion and resilience to sea-level rise is vital to maximizing the longevity and ecological value of restored marshes.

Coastal wetlands also play an important role in water quality, taking up and transforming nutrients into organic forms that make them less available. Nitrogen, for example, is transformed and removed by wetlands through plant uptake, denitrification, ammonia volatilization, and burial in sediment (Valiela & Teal 1979). Studies in marshes of coastal Louisiana have shown that denitrification accounts for about 65% of water column nitrogen removal (White et al. 2019). The ability of restoration sites to function similarly to natural marshes in nutrient cycling is not well known. A meta-analysis showed that nitrogen storage in restored marshes generally was still lower 30 years after restoration (Moreno-Mateos et al. 2012). However, nitrogen removal rates in restoration sites can be similar to natural marshes while the nitrogen pool is still much lower (Kleinhuizen & Mortazavi 2018). Further, some studies have found that created marshes can be as effective as or better than reference natural marshes at removing nitrogen (Cheng & White 2022; Kleinhuizen & Mortazavi 2018), while others have shown that created wetlands are less effective at removing nitrogen (Peralta et al. 2010; Yao et al. 2018). Restored wetlands typically have lower soil organic matter than natural wetlands, and multiple studies have found that soil amendments that increase soil organic matter increase denitrification in restored wetlands (Sutton-Grier et al. 2009; Ballantine et al. 2014; Yao SiQi et al. 2018). However, soil core incubations using created marsh soils with only 3-8% soil organic matter removed nitrate from the water column faster than a reference natural marsh (Cheng and White 2022). While Cheng and White 2022 measured changes in the concentration of nitrate in the water column and not denitrification directly, they argued that denitrification would not be carbon limited. Denitrification requires 5 mol of carbon to denitrify 4 mol of nitrate and carbon is typically found in quantities of at least an order of magnitude greater than nitrate, even when organic matter is low. While the stoichiometry of the denitrification process suggests carbon availability is unlikely to impact denitrification rates, reduced rates of denitrification in restored wetlands have been linked to different bacterial community assemblages and soil fertility (e.g., soil moisture, total organic matter, and available nitrate; Peralta et al. 2010). In addition to soil organic matter, denitrification also is related to the amount of surface area between aerobic and anaerobic soils because denitrification is generally reliant on the diffusion of nitrate and ammonia between aerobic and anaerobic soils (Reddy et al. 1989). Thus, denitrification generally is increased by live roots that transport oxygen to the anaerobic soil zone layer (Christensen and Sorensen 1986). The expansion and contraction of oxidized rhizospheres between day and night (Penton et al. 2013) also causes denitrification rates to depend on live root biomass. A better understanding of how restoration activities impact nitrogen cycling is needed to improve the design of restoration and to quantify benefits from restoration projects.

Marsh restoration in the Mississippi River Delta and along the Gulf Coast is becoming commonplace with billions of dollars being allocated to marsh creation and river diversions. Marsh creation through the pumping and placement of dredge sediment in areas that were once wetlands but now open water is one of the primary methods of restoration (CPRA 2023). Because of the relatively fine sediment and high background rates of subsidence and sea-level rise, many marshes are created within higher-elevation containment dykes and at relatively high elevations. Here, I used two created marshes, one where dredge sediment was pumped within a containment dyke (i.e., Confined) and another where the dredge material settled in an area of open water not surrounded by a containment dyke (i.e., Unconfined) to examine differences

among marshes with respect to vegetation, hydrology, accretion, and denitrification, and to examine relationships among these variables. I hypothesized that confinement, which may limit or concentrate hydrologic connectivity to areas where the dyke is gapped, and a high initial elevation will have several impacts on ecological structure and functions. First, I predict that plant communities in the confined marsh will be more dominated by wind-dispersed species and upland species, due to potential limitations on seed dispersal and higher elevation (Edwards and Proffitt 2003). Secondly, the containment dyke is predicted to change the hydrology of the marsh, affecting the depth and frequency of inundation, sediment delivery, and, potentially, salinity. Both high elevation and reduced flooding from the containment dyke is predicted to result in lower accretion rates in the confined created marsh as compared to the lower elevation, unconfined created and natural marshes. Thirdly, I expect that denitrification will be lower in the created marshes than in the natural marsh, and lower in the higher elevation confined marsh due to the potential for lower soil organic matter content and decreased flooding.

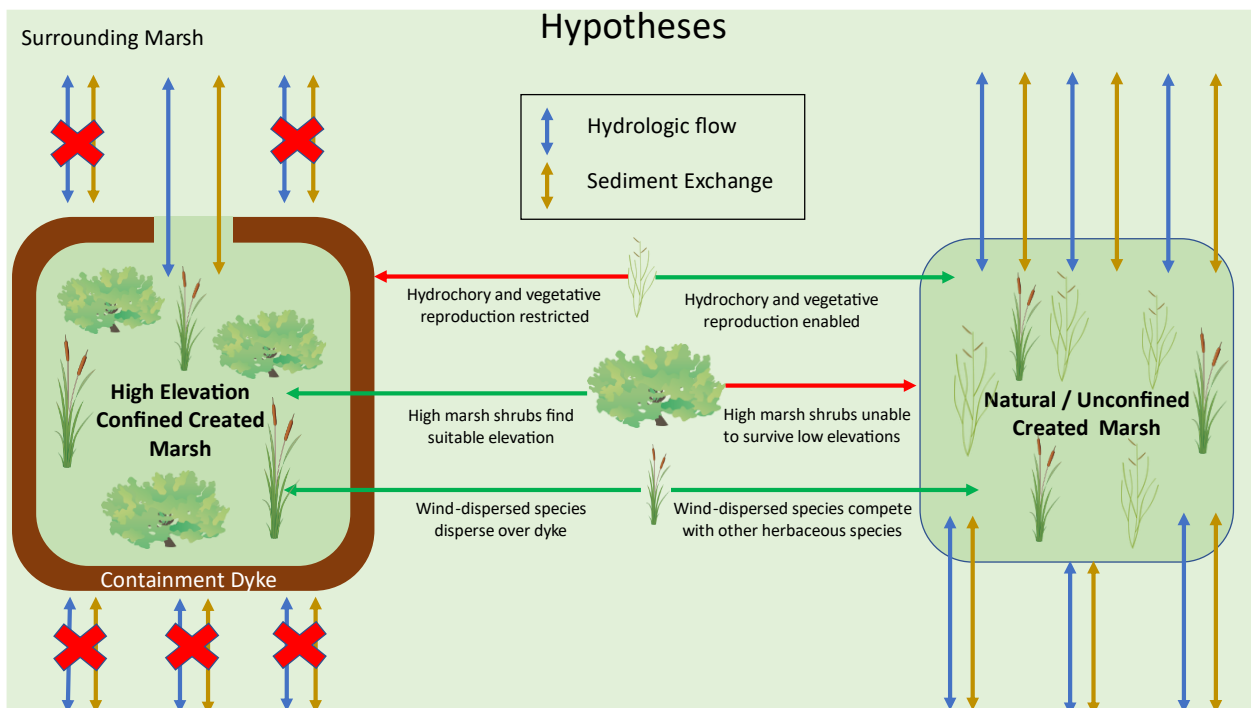


Figure 1. Conceptual model illustrating hypothesized effects of containment and elevation on marsh processes in created marshes.

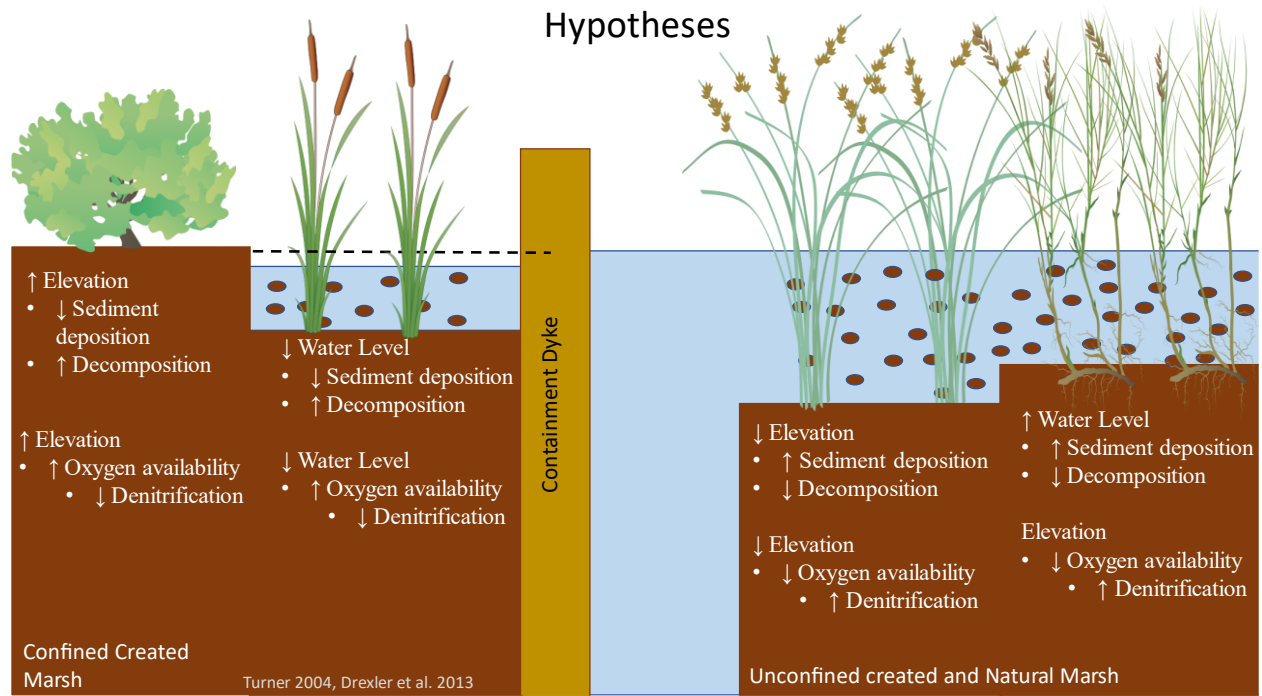


Figure 2. Conceptual model illustrating impacts of containment and elevation on accretion and denitrification in created marshes

Methods

Study Sites

Three marshes in Bayou Bonfouca in Big Branch National Wildlife Refuge, Lacombe, Louisiana, USA were the focus of this study (30°15'N 89°51'W). Big Branch National Wildlife Refuge is on the north shore of Lake Pontchartrain and contains brackish, intermediate, and freshwater marshes. Lake Pontchartrain was enclosed around ~3,000 years ago by sediment delivered by the eastward propagation of the St. Bernard Delta. Further deltaic development fostered the growth of marshes along the shores of Lake Pontchartrain (Kindinger et al. 1997). Since 1932, the Pontchartrain basin has experienced major wetland loss with approximately 22% of the marsh area converted to open water (Penland et al. 2000). However, marshes in this specific area were considered relatively stable until Hurricane Katrina in 2005 which created a strong storm surge and converted large areas of the marsh to open water (Reed and Hester 2009). To mitigate marsh loss, several marshes were created using dredge sediment sourced from Lake Pontchartrain. In 2017, two large areas totaling 245 hectares of former low-salinity marsh were targeted for restoration. Containment dykes were constructed and dredged sediment was pumped in from Lake Pontchartrain (CWPPRA Project Information Po-104, Figure 3).

In 2020, the containment dyke of the northern created marsh (hereafter referred to as the Confined marsh) was gapped in three locations with a tidal channel connecting two of the gaps with two ponds created along the path of the tidal channel, which provide areas of concentrated hydrologic connectivity to the surrounding environment. The Confined marsh is 65 hectares, including two 1.5-hectare ponds that were created to increase fishing and hunting opportunities. The two ponds are connected to each other and surrounding channels by created tidal creeks. There is another tidal channel that follows the western side of the containment dyke to a gap created in the northwestern portion of the containment dyke. Other smaller open water areas are located along the southern boundary of the marsh near the containment dyke.

The containment dyke of a created marsh to the south was breached on its southeast boundary and dredged sediment flowed into an area of fragmented marsh and open water (hereafter referred to as the Unconfined marsh). Excess dredged sediment was also purposefully placed outside the containment dyke to raise the elevation for marsh establishment. A portion of the dredge material outside of the containment dyke dispersed and/or settled at subtidal elevations with the remaining forming emergent marsh. In total about 60 hectares of marsh was created by the settlement of sediment outside of the containment dyke. The creation of a potentially higher-elevation confined marsh in close proximity to a potentially lower-elevation unconfined marsh provides a unique opportunity to study the impacts of elevation and confinement on created marsh ecosystems. A natural marsh that was unimpacted by restoration activities located directly across a tidal channel from the Confined marsh is used as a reference marsh (Figure 3).

Elevation and Vegetation Surveys

Elevation and vegetation surveys were conducted in each of the study sites during the 2022 and 2023 growing seasons. Sampling points were selected within each marsh using a grid applied to a Google Earth map using GE PATH to select 12 equally-spaced sampling plots at cross sections of the grid (Fig. 4). Grid sampling was selected to ensure full spatial coverage of

each marsh. Results from a field study comparing grid sampling to stratified random sampling can find little difference in results, except grid sampling can define groups in non-metric multidimensional (NMDS) analysis more clearly and provide stronger environmental correlations than stratified random sampling (Bhatta et al., 2012).

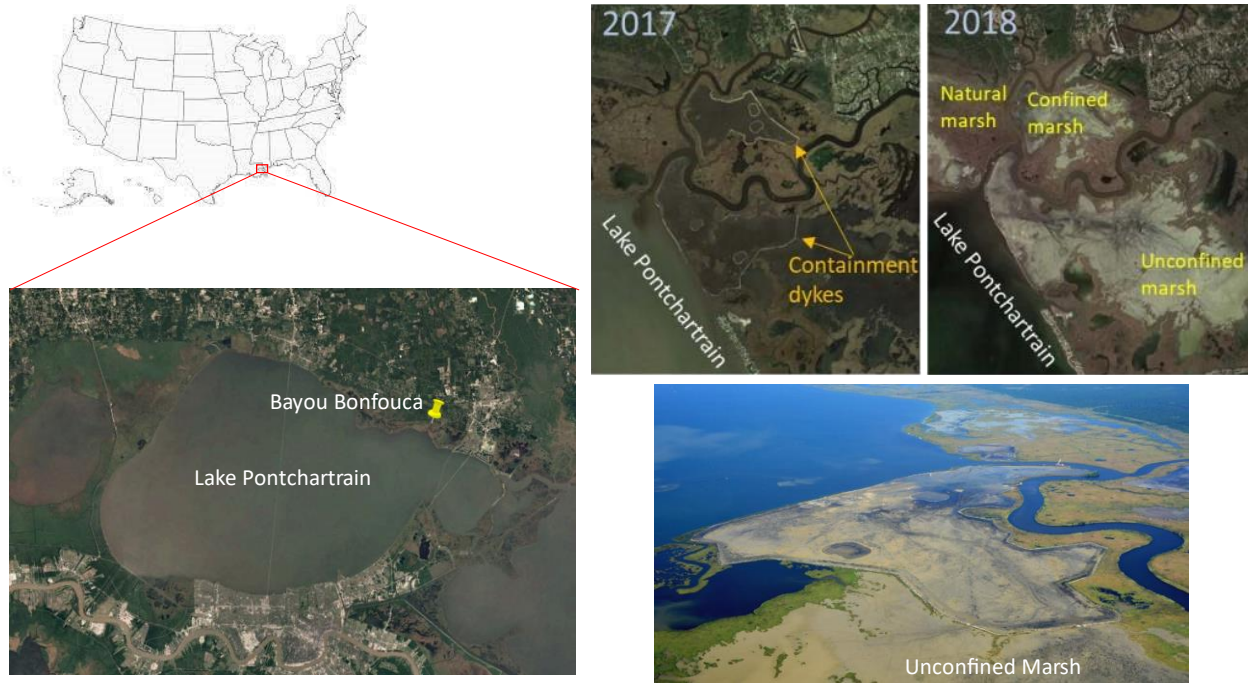


Figure 3. Google Earth Imagery of the study site showing the location and the area before and after sediment delivery. The three study units (confined, unconfined, and natural marsh) are all low-salinity marshes located on the eastern shore of Lake Pontchartrain in Big Branch National Wildlife Refuge.

Elevation was measured at each sampling point using an RTK GPS (Leica GS-14) with an accuracy of ± 1 vertical cm. Three elevation measurements were collected at each sampling location and averaged for analysis. A 0.5 m^2 plot was established at each sampling location and vegetation measurements including species and percent coverages were collected. Percent cover was recorded using the Daubenmire cover class method with ranges of 0-5, 5-25, 25-50, 50-75, and 75-100% (Daubenmire 1959). All sampling was conducted from September-October in 2022 and 2023.

Hydrology

Continuous water level and conductivity probes (Aqua TROLL 200) were placed in each marsh to measure water depth and salinity. The probes were installed in a well ~ 50 cm deep at least 15 m from the nearest tidal creek. Water level data was recorded every 15 minutes and conductivity every 30 minutes. To convert water levels to North American Vertical Datum 1988, RTK elevation measurements were taken on the marsh surface at each probe. NAVD88 water level for each marsh was calculated as the water depth plus the elevation of the marsh at the

location of the probe. Once the NAVD88 water level was calculated for each marsh, it was compared to the nearest Coastwide Reference Monitoring System (CRMS) station, which is CRMS3667 located about 1.5 mi from our study sites. The average difference between the water level measured by the CRMS station and the calculated NAVD88 water level in each marsh was used as an offset to hindcast water level in each marsh based on CRMS water level data from 2020 to the placement of our water probes.

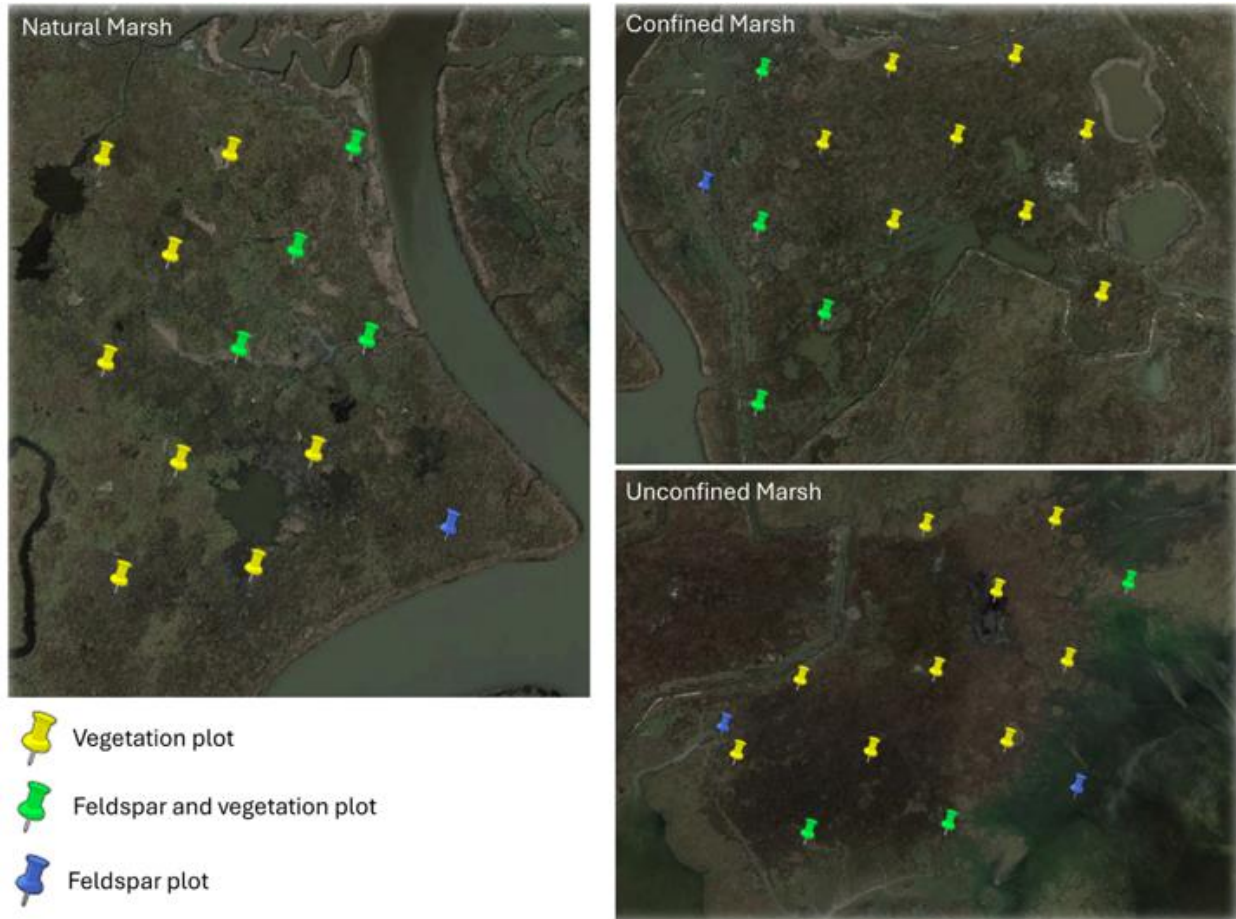


Figure 4. Google Earth imagery of Confined and Unconfined created and Natural marshes with the location of vegetation plots and feldspar marker horizon plots.

Accretion Rates

Surface accretion was measured using feldspar marker horizons (Cahoon and Turner 1989; DeLaune et al. 1983). Five of the 12 sampling points in each marsh were randomly selected for accretion measurement however access during low water conditions ultimately determined marker horizon plot locations (Fig. 4). Feldspar plots were established within a 0.5 m² plot area in late January through early February 2023 and accretion measurements were collected approximately one year later. Accretion was measured by cutting a small rectangular block of soil and measuring the distance between the top of the marker horizon and the soil surface. The depth of the feldspar layer was measured on three sides of each block. A sample of

accreted material was collected from each plot and soil organic matter was measured by percent loss after combustion at 550°C for 6 hours.

Longer-term accretion rates in two natural marshes were determined using ^{137}Cs -dating. Two 1-m deep soil cores with a diameter of 14.5 cm were collected in March 2022. Cores were sectioned into 2 cm slices and cut in half. One-half of each slice was dried and then ground using a Wiley grinder and analyzed for ^{137}Cs and organic matter. The peak of ^{137}Cs activity will be assumed to be in 1963, and the accretion rate between 1963 and the core collection date was calculated (Delaune et al. 1978).

Soil Properties

Soil cores (30 cm depth X 6.25 cm diameter) were collected at plots where feldspar marker horizons were established. Cores were sliced in 2 cm intervals and sediment was dried at 60°C to a constant weight. Bulk density was calculated using the dry weight divided by the volume. After drying, the slices were homogenized using a Wiley grinder and then a subsample was weighed and combusted in a furnace (550°C) for 6 hours and reweighed. The difference in weight was used to calculate soil organic matter content (i.e., percent loss on ignition).

Denitrification Rates

Cores collected from the Natural, Confined, and Unconfined marsh were incubated using a continuous flow incubation and measured denitrification using MIMS. A ^{15}N tracer was used to determine the source of denitrification. Nitrogen removal through denitrification can use nitrate from the water column (direct denitrification) or nitrate produced in the soil via nitrification (coupled nitrification-denitrification). With the water column spiked with ^{15}N , denitrification of nitrate (NO_3^-) from the water produces ^{15}N -nitrogen gas while denitrification of nitrate produced in the soil by coupled nitrification-denitrification produces ^{14}N -nitrogen gas because ^{14}N is vastly more abundant in the environment than ^{15}N (Steingruber et al. 2001).

Three plots in each marsh were randomly selected for soil core collection. Soil cores (20 cm depth X 10 cm diameter) were collected from each plot between clumps of vegetation to exclude live stems and overlaid with about 10 cm of site water. Cores were transported to the lab under *in situ* temperature. Site water was collected the previous day and filtered through 30, 5, 1, and 0.2-micron filters to reduce biological activity in the water during the incubation. After filtration, site water was spiked with 25-26.8 μM of $^{15}\text{N}\text{-NO}_3^-$, to differentiate direct denitrification and coupled nitrification-denitrification. In the lab, overlaying water was carefully decanted and replaced with the ^{15}N -nitrate spiked site water. Cores were then connected to a continuous water flow system with a flow rate of 3 ml/min, for a residence time of ~4 hours. Two cores filled with site water only were included for measurement of biological activity in the water column. Bubble-free conditions were maintained for 24 hours in a dark room before the experiment began. Dissolved nutrient and gas samples were collected every 4 hours for a total of 3 sampling events. Nutrient samples were filtered through 25 mm GF/F glass microfiber filters into duplicate vials (20 ml) and stored at 4 °C until NO_2^- , NO_3^- , and NH_4^+ concentrations were analyzed. Duplicate gas samples were collected in 12 ml gas exetainers. Exetainers were filled, and then 200 μl of 50% ZnCl_2 solution was added before the exetainers were capped and stored under DI water at 4 °C until MIMS analysis. At each sampling event, inflow samples were

collected from tubing connecting to each carboy to represent the inflow concentrations, and outflow samples were collected from the outflow tubing of each core.

Fluxes of nutrients and dissolved gasses were calculated using the equation below (Li and Twilley 2021).

$$Flux = \frac{[(C_o - C_i) - (C_{bo} - C_{bi})]}{(Surface\ area)} \times Flow\ rate \quad (1)$$

where C_o and C_i refer to the outflow and inflow concentrations of a sediment core while C_{bo} and C_{bi} are the average outflow and inflow concentrations of the two blank cores for a given sampling event. Direct denitrification rates were determined by equation 2 from Steingruber et al. (2001) based on Nielsen (1992).

$$Dw^{tot} = {}^{14}N^{15}N + (2\ {}^{15}N^{15}N) \quad (2)$$

Where Dw^{tot} represents the total direct denitrification. I did not adjust total direct denitrification rates to account for the ratio of ${}^{14}NO_3^- / {}^{15}NO_3^-$ because the nitrate concentration before adding ${}^{15}NO_3^-$ was negligible. Coupled nitrification-denitrification rates were calculated by multiplying direct denitrification rates with the frequencies of ${}^{14}N$ and ${}^{15}N$ in N_2 production, which is shown in equation 3.

$$Dn = Dw^{tot} \times \frac{{}^{14}N^{15}N}{(2 \times {}^{15}N^{15}N)} \quad (3)$$

Soil organic matter content is predicted to affect denitrification rates and the source of nitrate used for denitrification. Therefore, cores were sliced every 2 cm for soil organic matter content. To estimate how flooding affects denitrification in each marsh, I used the percent time flooded at each vegetation site as the amount of time when denitrification will occur and multiplied it by the average rate calculated for each marsh to estimate the total denitrification of each plot per year. I averaged the value from the 12 vegetation plots to estimate average denitrification per m^2 in each marsh.

Data Analysis

Analysis of variance (ANOVA) was used to test differences among marshes in hydrology metrics, accretion rates, denitrification rates, plant species cover, and soil organic matter content. The homoscedasticity of the data was tested using Levene's test and when the data was not homoscedastic, Welch's test was used. Water level data relative to NAVD88 from January 2020 and January 2024 for each marsh and elevation survey data for each plot were used to calculate flooding metrics for all sampling plots. Percent time flooded was the percentage of time water level was above the marsh surface.

Differences among marshes in total and species percent cover and frequency of occurrence for the most prevalent species were tested using ANOVAs. To test differences in the vegetation community among marshes, a non-metric multidimensional scaling approach (NMDS) was used. The NMDS analysis used the percent cover of every species at each plot to determine the similarity in species composition across plots and then the similarity of plots within the same marsh was compared to the similarity of plots in different marshes. A Bray Curtis dissimilarity matrix was used to calculate the ranks of similarity between plots. Species identified only once were removed from analysis. Pairwise ANOSIM tests with a Bonferroni

correction were run to test for significant differences in vegetation communities among marshes. The ordination of percent time flooded was added to the analysis and tested for a significant correlation.

Soil organic matter values from the core collection were logit transformed to increase normality. Logit-transformed results were tested with a mixed model with depth, marsh, and their interaction as fixed effects and depth as a repeated measure.

To determine the effects of flooding and marsh on accretion, percent time flooded, marsh, and their interaction was tested using analysis of covariance (ANCOVA). The intercept for percent time flooded was set at zero because zero accretion was expected in areas that did not flood over the study period. The effect of percent time flooded, marsh, and their interaction was also tested on the organic and inorganic density of accreted material. The accreted organic and inorganic matter densities were estimated using soil bulk density of surface soil (0 – 2 cm depth) from soil cores, multiplied by the proportion of organic or inorganic matter of the accreted material (via LOI).

Denitrification rates were tested for differences among marshes as related to soil organic matter content in the top 2 cm using ANCOVA. Regression analyses were used to test relationships between total denitrification rate and nitrate-N, oxygen, ammonium-N fluxes, and direct-coupled denitrification rates.

Results

Hydrology, Elevation, and Salinity

Water levels were measured from October 1st, 2022 to February 8th, 2024, and spanned a severe drought during the summer of 2023 when water levels fell below the pressure sensor at 50 cm depth in the created marshes (Figure 5). To examine water level dynamics over a longer time period, water level data were extrapolated to hindcast approximately two years after marsh creation in 2020. Daily water levels from 2020 to 2024 illustrate that marshes differ slightly in maximum and minimum water levels (Figure 4). The Unconfined marsh tended to have higher water depths than the Natural marsh and the Confined marsh by an average of 3.2 and 7.7 cm, respectively. During high-water events, the difference remains the same. However, during low water events when water levels dropped below that marsh surface, the created marshes tended to drain more. During these events, the Natural marsh had the highest water level. The extreme summer drought exemplifies this phenomenon, because during the drought the created marshes' water level dropped to below the level of the water probe which was placed about ~55 cm below the marsh surface, while the water level in the Natural marsh lowered much slower and never reached below the probe.

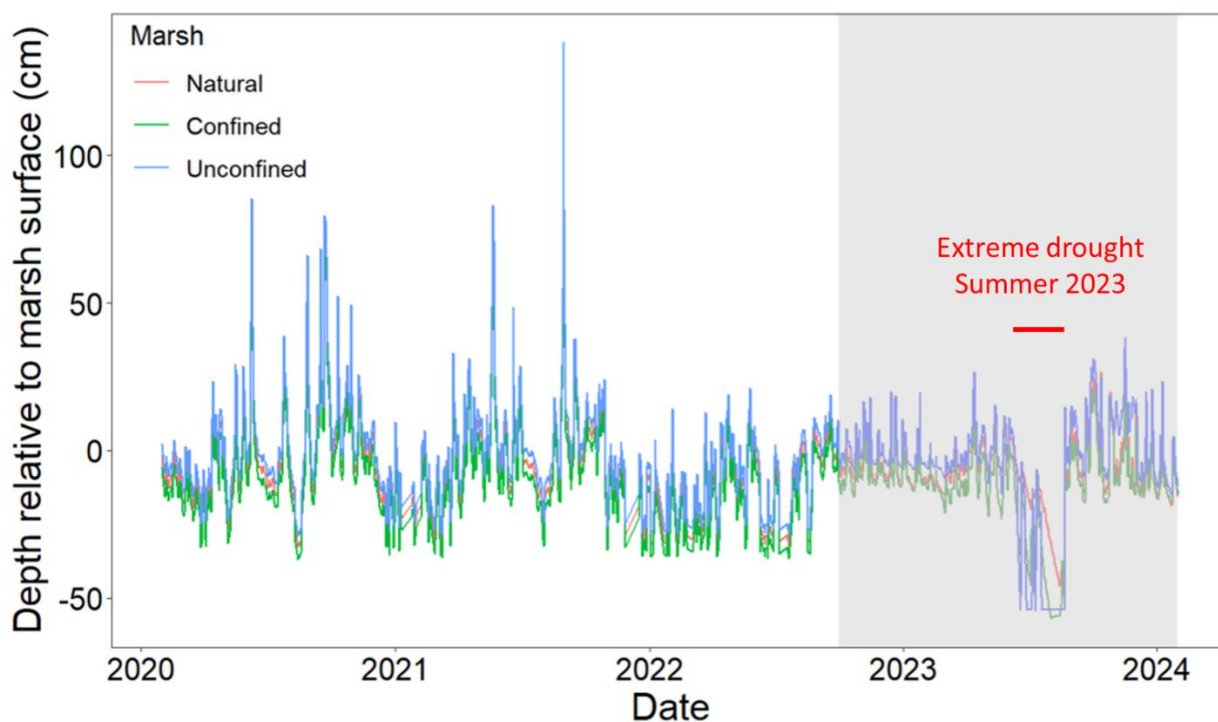


Figure 5. Daily water levels in a Natural and Confined and Unconfined created marsh in Pontchartrain Basin, LA. The shaded area is water probe data from each marsh and the unshaded area is hindcasted data based on CRMS station water data.

The mean marsh elevation across the twelve survey locations was similar among marshes however, the variability in elevations was much greater in the created marshes. The Natural marsh elevations occurred within a narrow range between 15 and 30 cm, NAVD88 with the majority plots between 25 and 30 cm (Fig. 6 and 7). The Confined created marsh had the most

extreme high and low elevations with the greatest number of plots between 15 and 25 cm (Fig. 6 and 7). The Unconfined marsh had more variable elevations than the Natural marsh, but not the Confined marsh with elevations varying between 10 and 45 cm, NAVD88 with half of the plots between 15 and 20 cm, NAVD88 (Fig. 6 and 7).

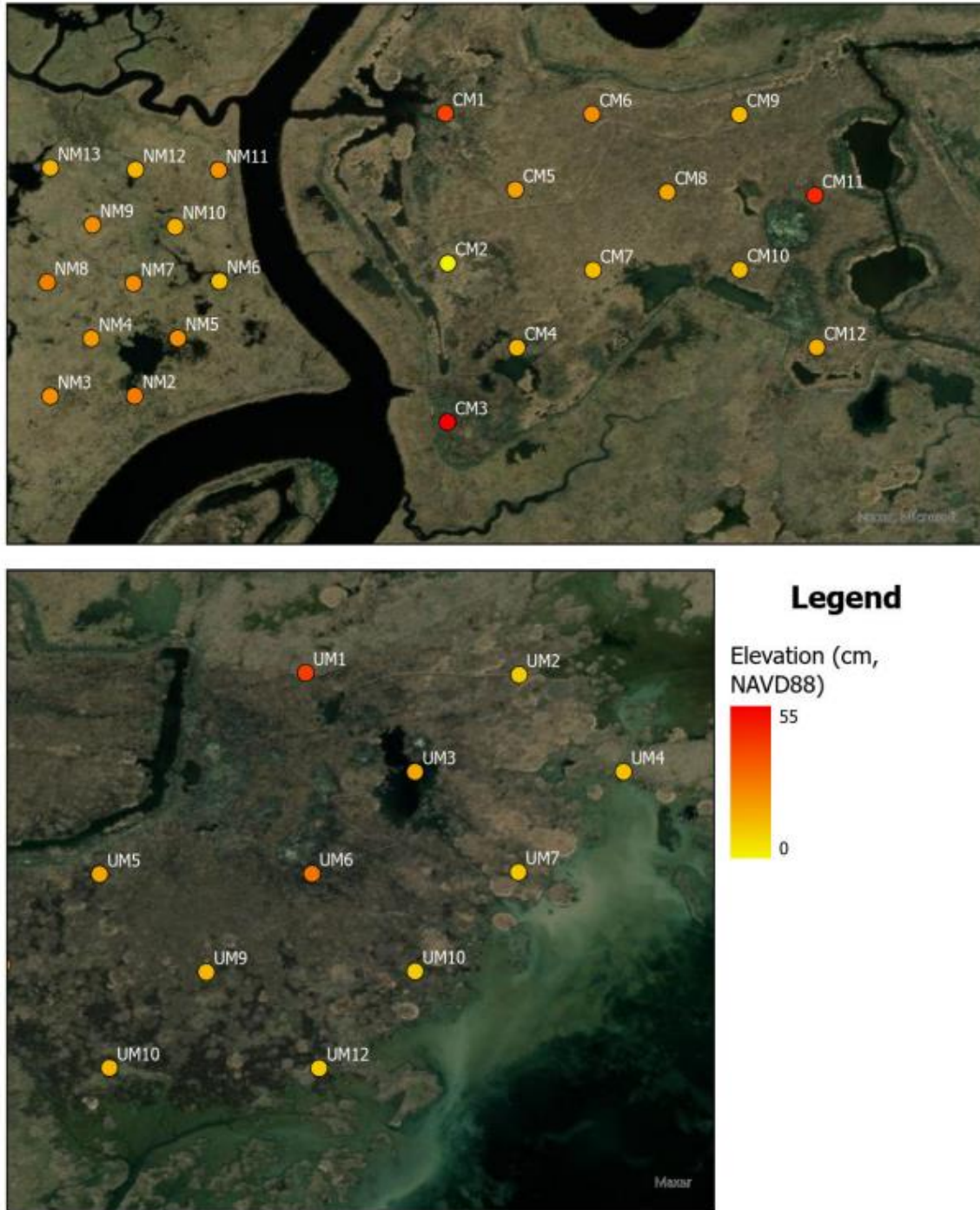


Figure 6. Elevations at vegetation plots (n=12) in Natural and Confined and Unconfined created marshes in the Pontchartrain Basin, LA

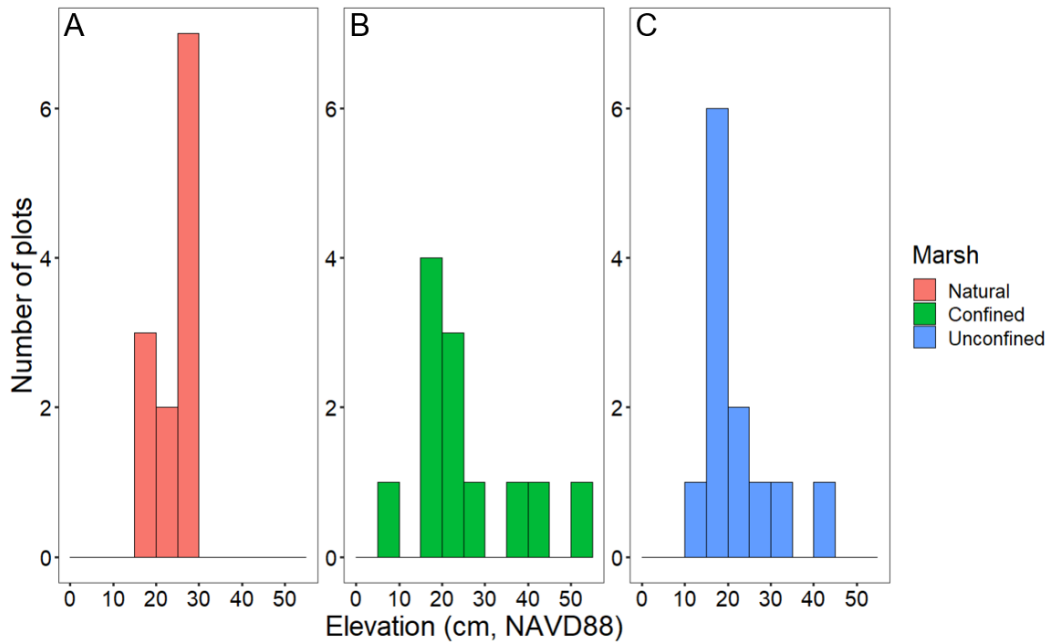


Figure 7. Frequency distribution of elevations (i.e., number of plots) in a Natural (A) and Confined (B) and Unconfined (C) created marshes in Bayou Bonfouca, Pontchartrain Basin, LA (n = 12).

Hydrology metrics reflected elevation differences between marshes with the created marshes showing higher variability. The mean percent time flooded was 27 ± 3 and ranged from 15 to 47% in the Natural marsh. In the Confined marsh, the mean was similar (26 ± 5), but percent time flooded ranged from 2 to 74%. The mean percent time flooded in the Unconfined marsh was $43\% \pm 5$ and ranged from 6 to 63%. At plots with an elevation above 35cm, plots were rarely flooded with a percent time flooded less than 7% and the mean flooding depth was > 20 cm below the surface of the marsh. None of the Natural marsh plots and only one of the Unconfined marsh plots were above 35 cm, NAVD88, while twenty-five percent of Confined marsh plots were above 35 cm, NAVD88 resulting in decreased flooding.

Table 1. Hydrologic metrics in the Natural and Confined and Unconfined created marshes in Pontchartrain Basin, LA (n = 12, \pm standard error).

Hydrologic metric	Natural	Confined	Unconfined
Percent time flooded (%)	27.5 ± 3.0	26.7 ± 5.7	43.2 ± 5.5
Mean water level (cm, relative to marsh surface)	-7.1 ± 1.2	-11.6 ± 3.8	-3.9 ± 2.3
Mean high water (cm, relative to marsh surface)	134.4 ± 1.2	130.2 ± 3.8	138.3 ± 2.3
Mean low water (cm, relative to marsh surface)	-47.8 ± 1.2	-57.2 ± 3.8	-54.4 ± 2.3
Mean salinity (PSU)	$4.1 \pm .01$	$5.4 \pm .01$	$4.8 \pm .01$
Maximum salinity (PSU)	9.3	12.5	9.2

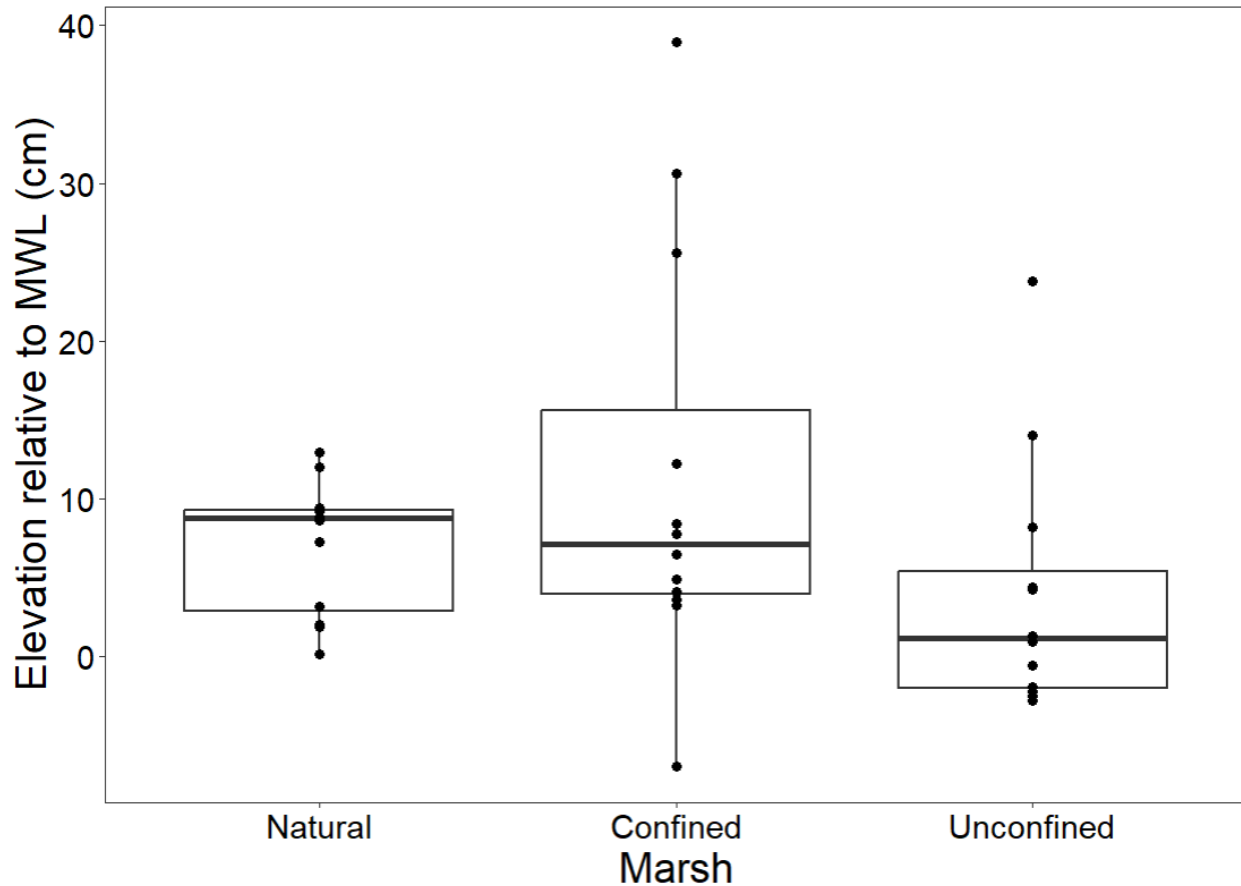


Figure 8. Elevation relative to mean water level (MWL) for Natural and Unconfined and Confined created marshes in the Pontchartrain Basin, LA.

Drought conditions impacted the study sites over the summer of 2022 and 2023. Percent time flooded during the summer months decreased in every marsh in 2022 and 2023 compared to the non-drought years of 2020 and 2021 (Fig. 9). Summertime percent time flooded decreased on average $20.6 \pm 2.8\%$ in the Natural marsh, $21.8 \pm 4.4\%$ in the Confined marsh, and $28.5 \pm 6.4\%$ in the Unconfined marsh during the drought years.

Salinity generally increased over the deployment period with a marked increase in all marshes during the drought in the late 2023 summer. The Natural marsh had a mean salinity of 2.8 ± 0.4 PSU before the drought and increased to 7.87 ± 0.3 after the drought. The Confined marsh had higher mean salinity values both before and after the drought with means of 4.47 ± 0.3 PSU before the drought and $8.5 \pm .4$ PSU after. The Unconfined marsh was the least impacted by the drought in salinity with mean salinity changing from 4.2 ± 0.3 PSU to 6.7 ± 0.3 PSU. Over the entire study period, the Natural marsh had the lowest mean salinity followed by the Unconfined Marsh and the Confined Marsh had the greatest mean salinity. The Natural marsh had smaller maximum salinity peaks than the created marshes. The difference between mean and maximum salinity in the Natural marsh was only greater than 2 PSU in one month when the difference was 4 PSU. However, the Unconfined marsh had peaks 4 and 6 PSU greater than the mean salinity and the Confined marsh had two peaks with a difference of 3 PSU and one

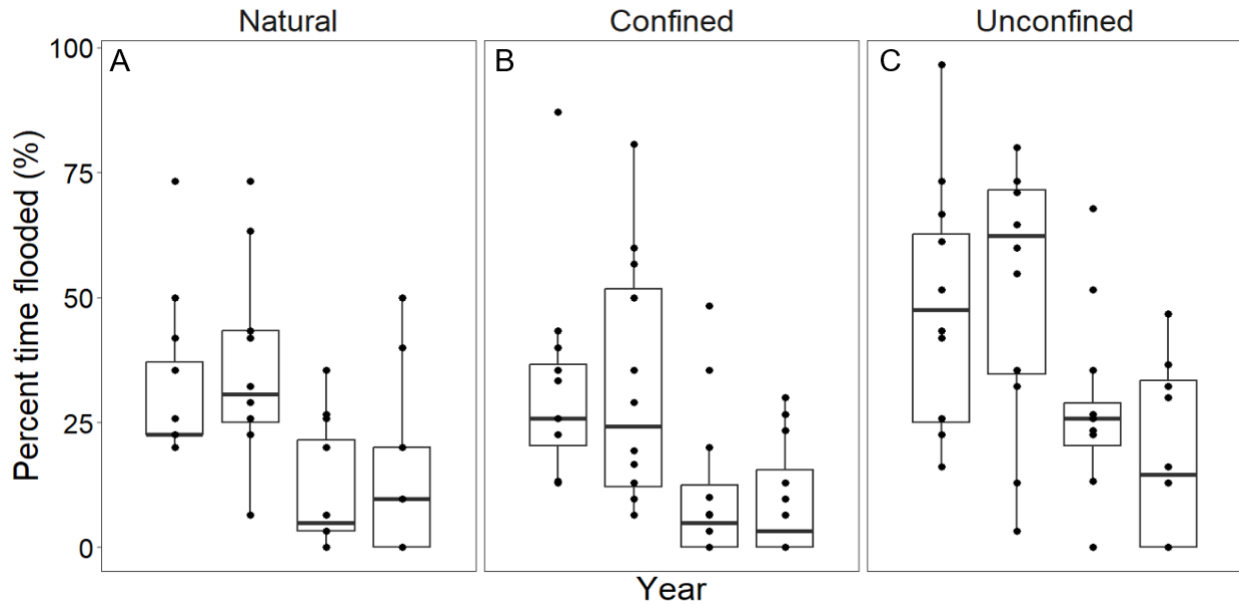


Figure 9. Percent time flooded for summer months of each year from 2020-2023 at 12 locations in a Natural (A) and Confined (B) and Unconfined (C) created marshes in the Pontchartrain Basin, LA.

with a difference of 6 PSU (Fig. 10). The maximum salinity peaks did not always occur in all marshes at the same time. In early 2023, the Confined and Unconfined marsh both had high salinity peaks but they were in different months. When the Confined marsh had a peak of 3 PSU above the mean in March, the difference between maximum and mean salinity in the Unconfined marsh was less than 0.25 PSU. Similarly, the Unconfined marsh had a spike of 4 PSU greater than the mean during April, while the biggest difference in the Confined marsh that month was less than 0.25 PSU. During late 2023, the Confined marsh had a large peak, reaching the highest salinities recorded in this study, whereas the Unconfined and Natural marsh differences were less than 0.6 PSU in that month.

Vegetation

Marshes differed in the frequency of occurrence of individual plant species. A total of 16 species were identified in the vegetation surveys with 7 species found in only one plot. *S. patens*, *S. americanus*, and *V. luteola* occurred in multiple plots in all marshes (Table 2). In the Natural marsh, *S. patens* and *S. americanus* occurred in 100 and 83% of plots, respectively. Both created marshes had a high occurrence of *S. americanus*, however, *S. patens* occurrence was lower, particularly in the Confined marsh (Table 2). The Confined marsh had a high occurrence of both *T. domingensis* and *S. americanus*, while the Unconfined created marsh had the greatest frequency of *S. americanus* with a mix of other species. *B. halimifolia*, a high marsh shrub occurred in 25% of plots in the Confined marsh.

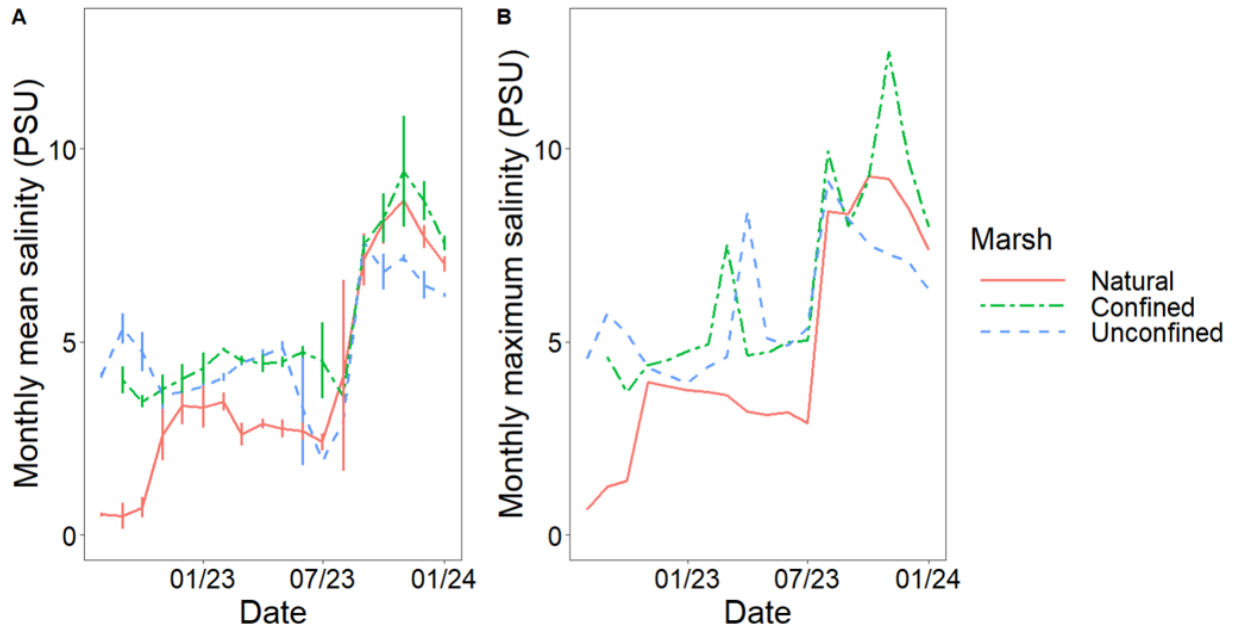


Figure 10. Monthly mean and maximum salinity in a Natural and Confined and Unconfined created marsh in Pontchartrain Basin, LA. Error bars represent the standard deviation.

Table 2. Percent occurrence of plant species in each marsh.

Species	Natural	Confined	Unconfined
<i>Baccharis halimifolia</i>	0	25	0
<i>Bolboschoenus robustus</i>	0	17	8
<i>Cuscuta indecora</i>	0	0	8
<i>Echinochloa crus-galli</i>	8	0	0
<i>Eleocharis palustris</i>	0	8	0
<i>Ipomoea sagittata</i>	0	0	8
<i>Juncus roemerianus</i>	0	17	0
<i>Lythrum lineare</i>	33	0	8
<i>Polygonum punctatum</i>	8	0	0
<i>Sacciolepis striata</i>	0	0	8
<i>Salix nigra</i>	0	8	0
<i>Schoenoplectus americanus</i>	83	75	92
<i>Spartina patens</i>	100	17	33
<i>Symphotrichum subulatum</i>	17	8	50
<i>Typha domingensis</i>	0	75	17
<i>Vigna luteola</i>	33	33	17

Total percent cover of vegetation was similar among marshes, but the coverage of individual species differed significantly. The Natural marsh was dominated by *S. patens*, which occurred in every plot with an average cover of $58 \pm 5\%$. The percent cover of *S. patens* was significantly higher in the Natural marsh than in the Confined and Unconfined marshes ($F_{2, 33} = 17.39$, $p = 0.00007$; Figure 11). *S. americanus*, which occurred at a high frequency in the Natural marsh had a relatively low coverage of $14 \pm 3\%$. The Confined marsh was dominated by *T.*

domingensis with an average cover of $30 \pm 6\%$ in plots where it was found. *T. domingensis* had significantly higher percent cover in the Confined marsh than in the Natural and Unconfined marshes ($F_{2, 33} = 15.71$, $p = 0.00001$; Figure 11). The abundance of *T. domingensis* in the Confined marsh was highest at low elevations with its percent cover increasing as percent time flooded increased. *Baccharis halimifolia* was the most prevalent species at sites with a percent time flooded between 0-20% in the Confined marsh with an average percent cover of $25 \pm 17\%$. *S. americanus* appeared at similar frequencies in the Confined marsh but at lower abundances with an average percent cover of $17 \pm 6\%$ in plots where it was found. The Unconfined marsh was dominated by *S. americanus* with an average percent cover of $42 \pm 8\%$. *S. americanus* had significantly higher percent cover in the Unconfined marsh than in the Natural and Confined marshes ($F_{2, 33} = 6.34$, $p = 0.0047$).

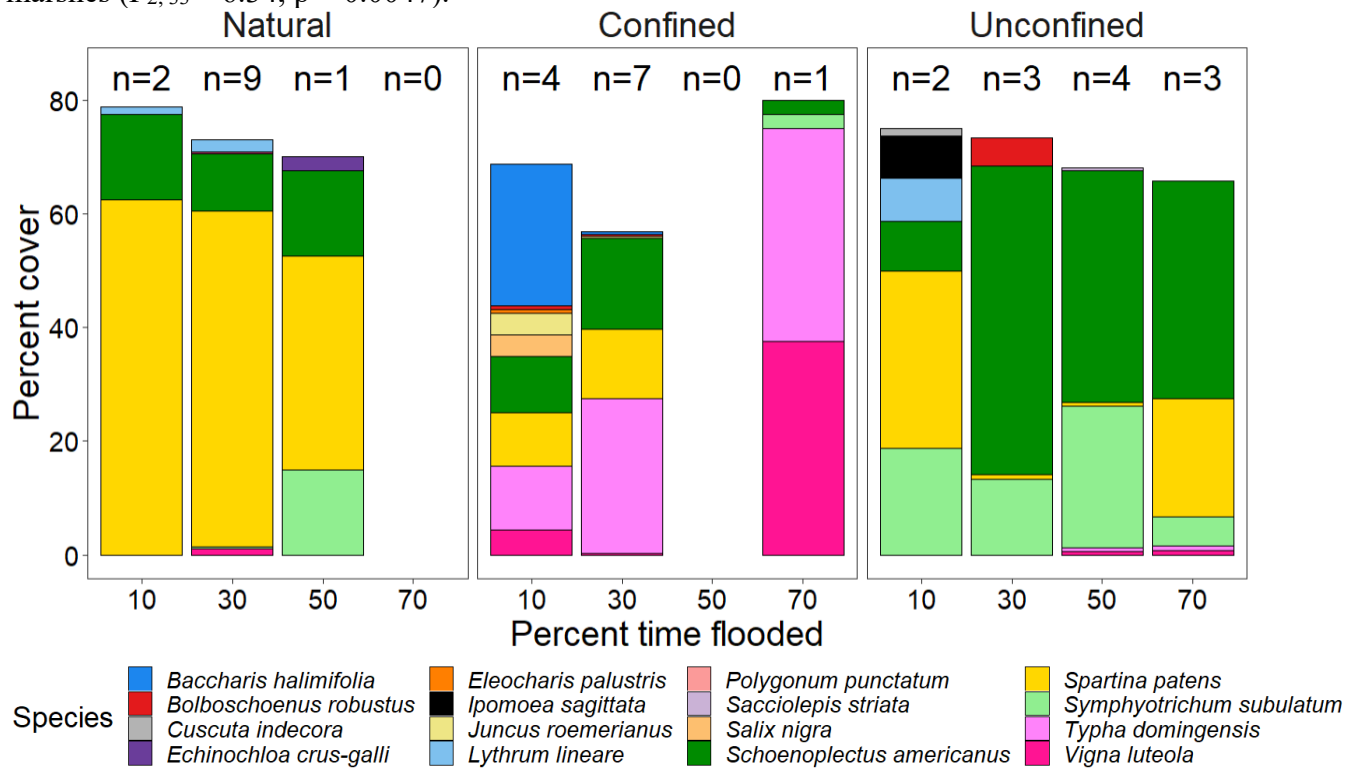


Figure 11. Mean percent cover by species and percent time flooded in a Natural, and Confined and Unconfined created marsh in the Pontchartrain Basin, LA.

Differences in vegetation community were apparent both between marshes and within marshes when the percent time flooded was different between sites. The created marshes had several sites that were flooded a high percentage of the time (60-80%). However, the vegetation community differed between the created marshes at these low-elevation areas. *S. americanus* dominated low elevations of the Unconfined marsh, while *T. domingensis* and *V. luteola* dominated low elevations in the Confined marsh. *S. americanus* and *T. domingensis* were present in both marshes but *T. domingensis* had low abundance in the Unconfined marsh and the abundance of *S. americanus* was low in the Confined marsh. Similarly, at sites with a percent time flooded between 20-40% and 40-60%, the Natural marsh and Unconfined marsh had similar species composition, with 3 species common in both marshes. However, the dominance was different with *S. patens* dominating in the Natural marsh and *S. americanus* dominating in the Unconfined marsh. Both species appear in the Confined marsh at sites with a percent time

flooded between 20-40% at medium abundances, but *T. domingensis* is still the most abundant species at those sites in the Confined marsh. At sites with a percent flooded of 0-20% *S. patens* dominated in both the Natural marsh and the Unconfined marsh, while *B. halimifolia* dominated in the Confined marsh.

Pairwise ANOSIM tests showed that vegetation community differed significantly among marshes ($R = 0.49$, $p = 0.0001$; Fig. 12, Table 3). The dominance of *S. patens* in the Natural marsh led to a tight clustering of the Natural marsh in the NMDS analysis compared to the Confined and Unconfined points that were more spread. Pairwise comparisons including the Natural marsh had the highest R-statistic, indicating the greatest dissimilarity was between the Natural marsh and the created marshes, which is likely due to the tight clustering of the Natural marsh points around *S. patens*. Vegetation community structure was significantly correlated to flooding frequency across sites ($R^2 = 0.18$, $p = 0.046$; Fig. 10).

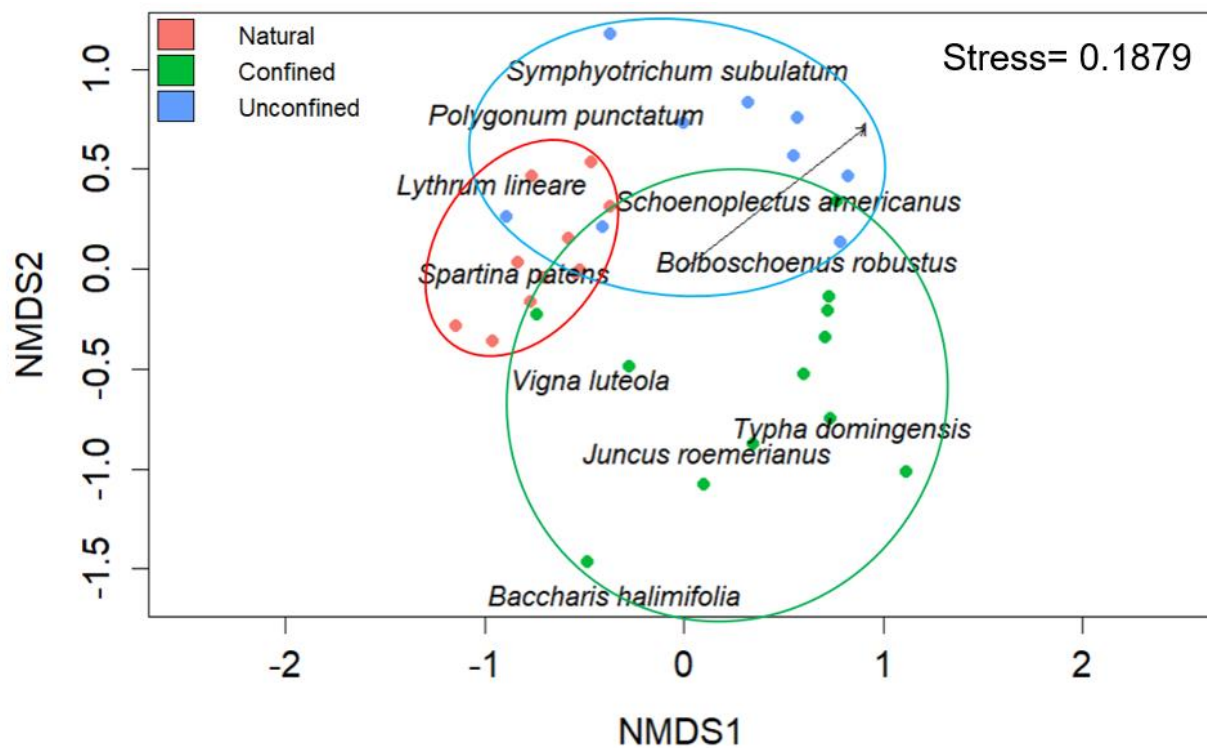


Figure 12. NMDS (Non-metric multi-dimensional scaling) plot of vegetation communities with vegetation points in a Natural and Confined and Unconfined created marsh in Pontchartrain Basin, LA. The arrow shows the ordination of flooding frequency with the flooding frequency increasing in the direction of the arrow.

Table 3. R statistic and ANOSIM results from NMDS analysis. * $p < 0.017$ significant due to Bonferroni correction accounting for multiple comparisons

Marshes	R statistic	p-value
Confined-Natural	0.59	0.0001*
Confined-Unconfined	0.34	0.0005*
Natural-Unconfined	0.53	0.0002*

Soil Properties

Soil organic matter was significantly lower in the two created marshes than in the Natural marsh and was lowest in the Unconfined created marsh overall ($F_{2, 123} = 124.45$, $p < 0.0001$, Fig. 13). Soil organic matter in the Natural marsh averaged 44% and increased with depth, in the confined marsh soil organic matter averaged 25% and slightly decreased with depth, and in the Unconfined marsh soil organic matter averaged 11% and decreased with depth. The Confined marsh had the highest variability in soil organic matter with a standard deviation of 11.7%, compared to 8.9% in the natural marsh and 4.7% in the Unconfined marsh. The high variability of the Confined marsh soils is due to the presence of pre-existing soil that mixed with the dredged sediment as it was pumped into the marsh. The mixing of soil and dredged sediment appears to have been random with different cores having different amounts of preexisting soil at different depths.

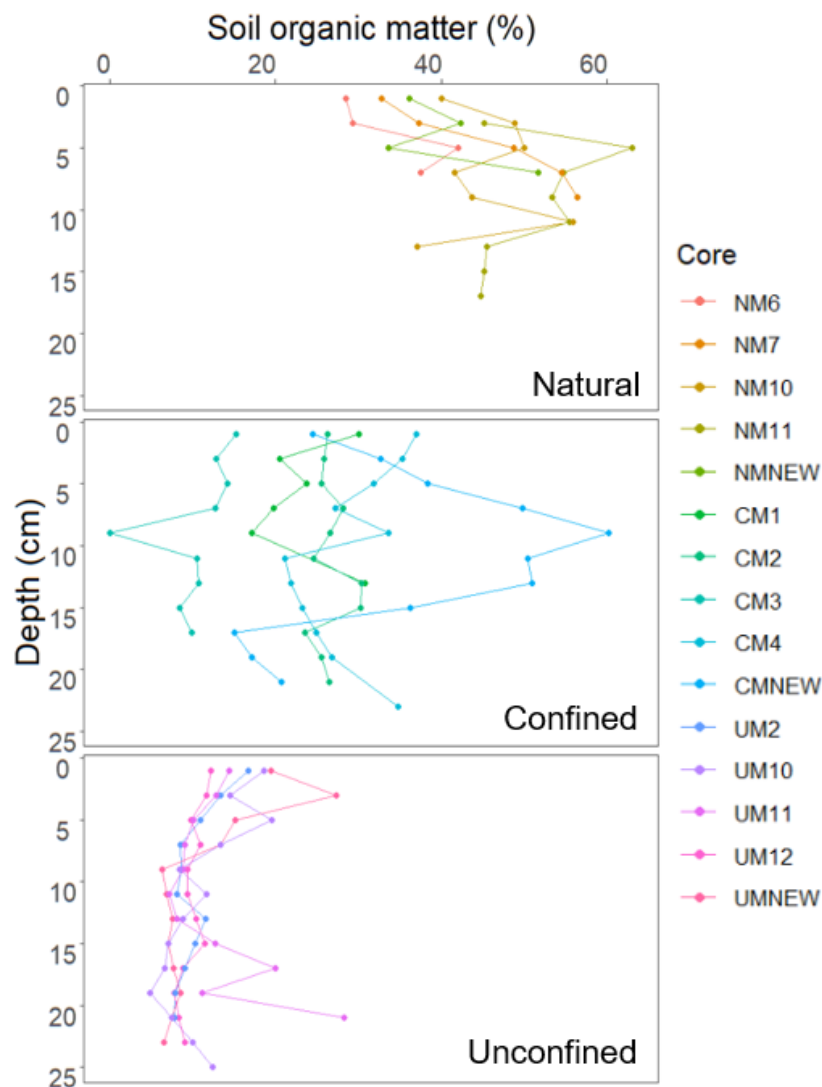


Figure 13. Soil organic matter profiles in a Natural and Confined and Unconfined created marsh in Pontchartrain Basin, LA (n = 5).

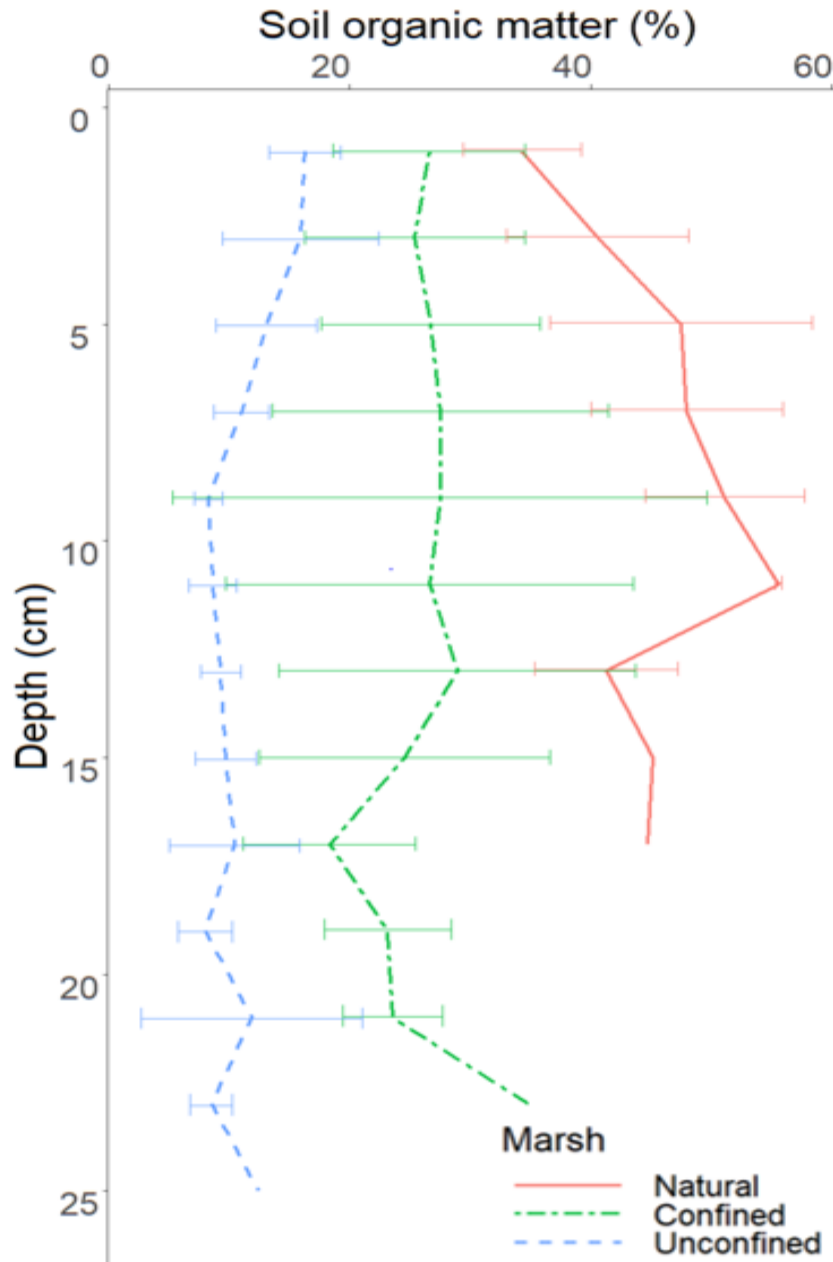


Figure 14. Soil organic matter at 2 cm depth intervals in a Natural and Confined and Unconfined created marsh in Pontchartrain Basin, LA. Data are means \pm the standard deviation ($n = 5$).

Soil bulk density ranged from 0.08 to 1.27 g/cm^3 and soil organic matter ranged from 6% to 63%. Soil bulk density averaged $0.15 \pm .01 \text{ g}/\text{cm}^3$ in the Natural marsh, $0.47 \pm 0.05 \text{ g}/\text{cm}^3$ in the Confined marsh, and $0.59 \pm 0.03 \text{ g}/\text{cm}^3$ in the Unconfined marsh. Soil organic matter and bulk density follow an expected relationship where soil bulk density decreases exponentially as soil organic matter increases (Fig. 15).

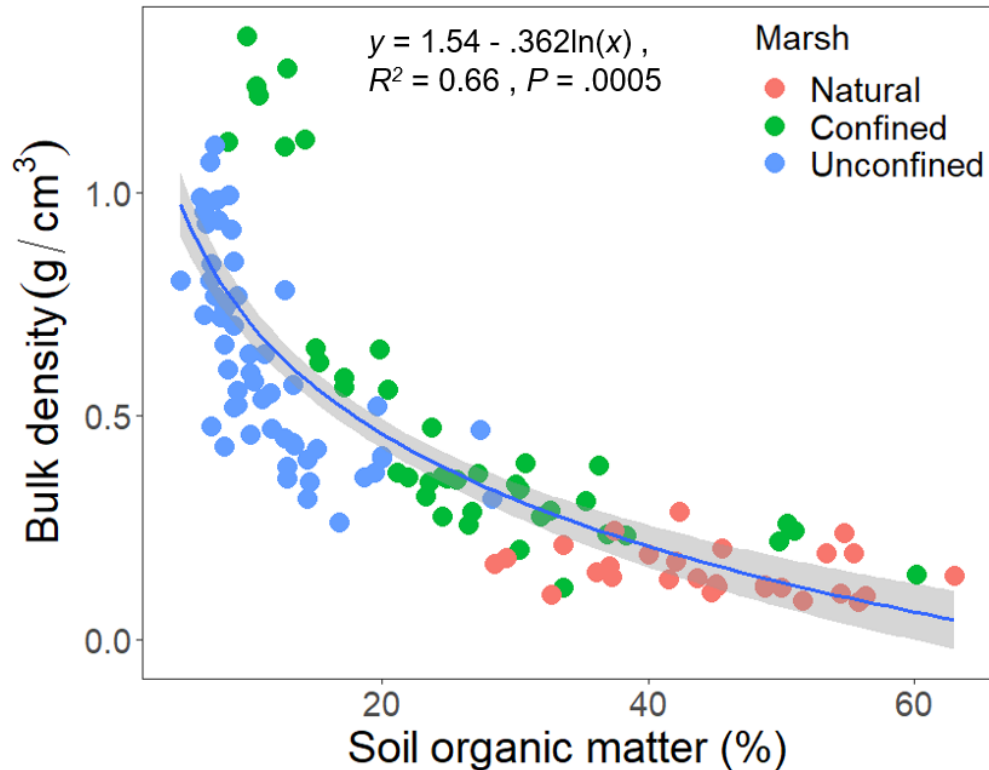


Figure 15. The relationship between soil bulk density and organic matter content in Confined and Unconfined created and Natural marshes in the Pontchartrain Basin, Louisiana (n = 5).

Accretion Rates

Cesium-137 activity in soil cores collected from the Natural marsh peaked at 24 and 30 cm depth. Core 3 had two peaks, which makes it unusable for accretion analysis. Using the clear peaks from soil cores 1 and 2, calculated long-term accretion rates were 4.2 and 5.3 mm/yr, averaging 4.7 mm/yr (Fig.16).

Accretion rates based on feldspar plots showed a large variation from 0.16mm/yr to 13.5 mm/yr. Accretion rates averaged 4.3 ± 1.1 mm/yr in the Natural marsh, 3.7 ± 1.4 mm/yr in the Confined marsh, and 9.7 ± 2.0 mm /yr in the Unconfined marsh (Fig. 17). Higher elevation areas that experienced little to no flooding had very low rates of accretion (e.g., 0.17 mm/yr). Accretion correlated to the percent time flooded but did vary across marshes ($R^2 = 0.64$, $p = 0.0009$; Fig. 18).

The contributions of organic and mineral sediment to accretion varied by marsh. Organic matter percentages of accreted material averaged $30 \pm 3\%$ in the Natural Marsh, $23 \pm 2\%$ in the Confined marsh, and $12 \pm 1\%$ in the Unconfined marsh. The Natural marsh had a significantly higher percent organic matter of accumulated material than the Unconfined marsh ($F_{5,8} = 4.9750$, $p = 0.0154$). However, the accumulation rate of organic matter wasn't significantly different between marshes ($F_{5,9} = 0.56$, $p = 0.589$, Fig. 19A) and the Unconfined marsh had the highest mineral sediment accumulation rate ($F_{5,9} = 4.51$, $p = 0.044$, Fig. 19B), with percent time flooded as a significant covariable in both the organic and mineral sediment accumulation models ($F_{5,9} = 5.21$, $p = 0.0313$; $F_{5,9} = 20.72$, $p = 0.0014$).

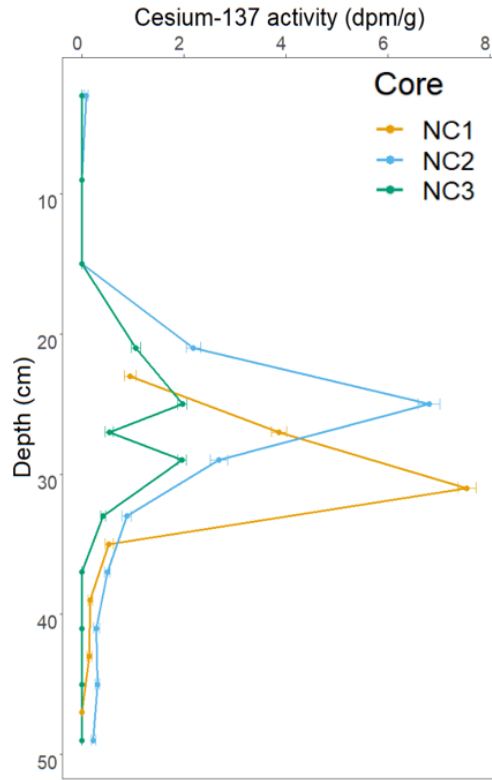


Figure 16. Depth profile of Cesium-137 activity from three cores collected from a natural marsh in the Pontchartrain Basin, LA

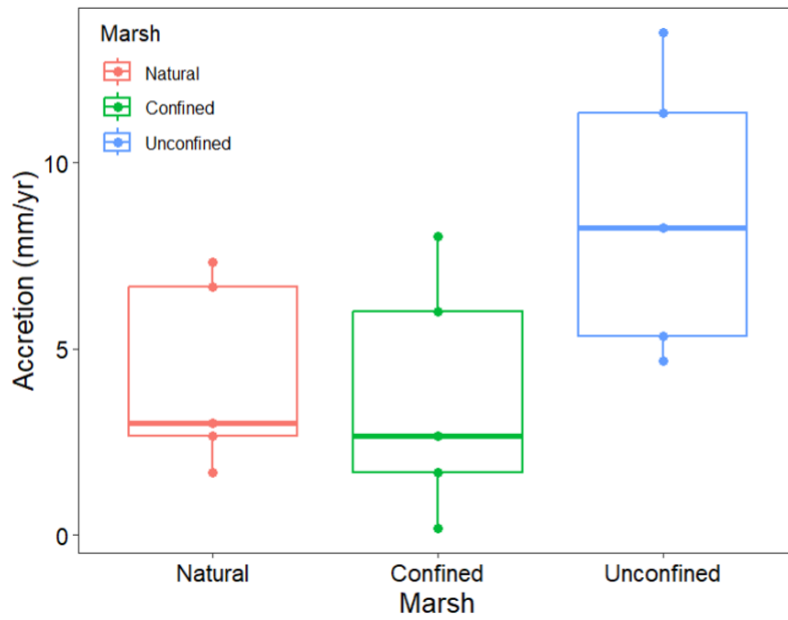


Figure 17. Accretion measurements from Unconfined and Confined created marshes and a Natural marsh in the Pontchartrain Basin, LA

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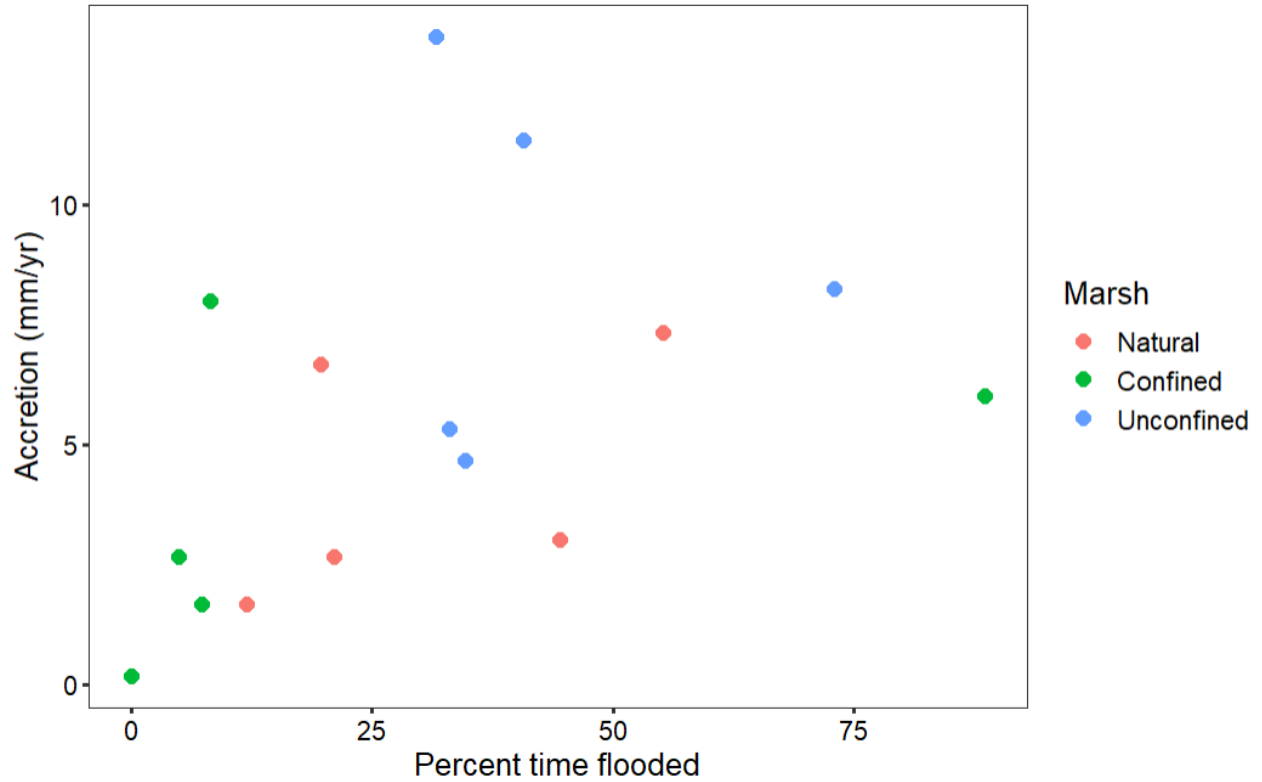


Figure 18. Relationship between accretion rate and percent time flooded for a Natural and Confined and Unconfined created marshes in Pontchartrain Basin, LA. The line represents the linear regression with intercept set to zero and the shaded area is the 95% confidence interval.

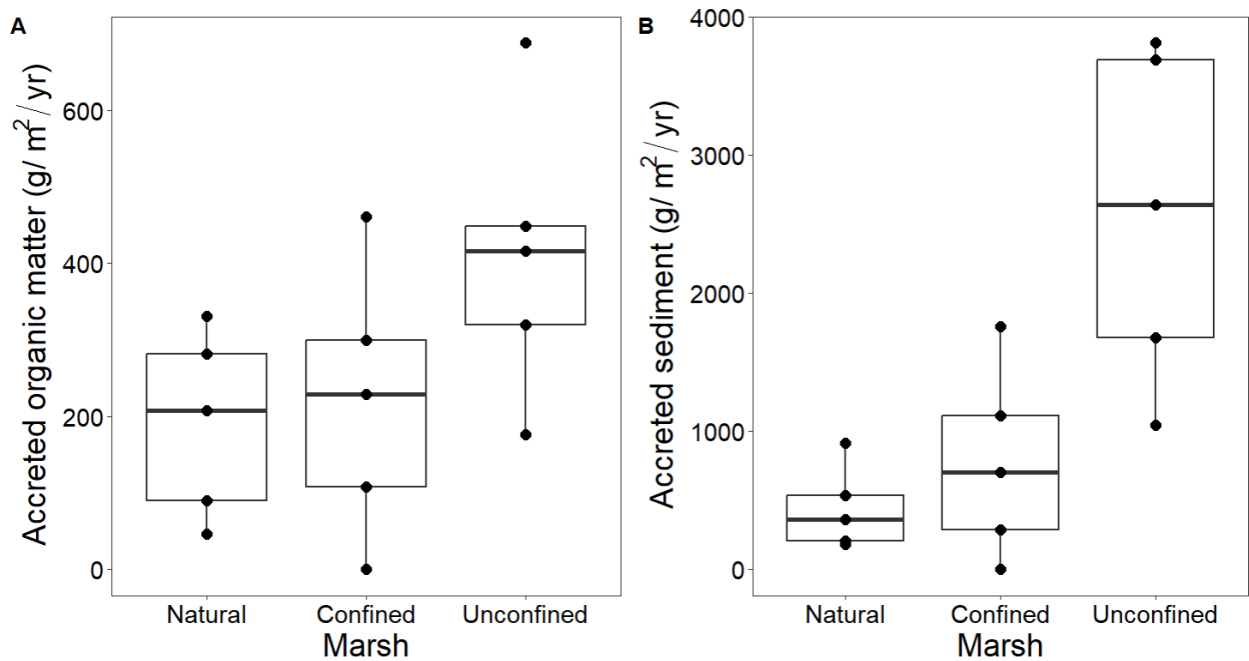


Figure 19. Organic matter (A) and sediment accumulation (B) rates above feldspar marker horizons in a Natural and Confined and Unconfined created marshes in the Pontchartrain Basin, LA.

Denitrification Rates

Nitrate-N concentrations were very low in the tidal channel water (i.e., below the detection limit of 1 μM). Site water was spiked with K^{15}NO_3 to 25- 26.8 μM (0.35-0.38 mg $\text{NO}_3\text{-N/L}$). Denitrification was dominated by direct denitrification in all marshes. Total rates of denitrification ranged from 6.4 to 39.9 mg $\text{NO}_3\text{-N/m}^2/\text{d}$ and averaged 26.0 ± 8.5 mg $\text{NO}_3\text{-N/m}^2/\text{d}$ in the Natural marsh, 8.1 ± 1.0 mg $\text{NO}_3\text{-N/m}^2/\text{d}$ in the Confined marsh, and 22.5 ± 7.14 mg $\text{NO}_3\text{-N/m}^2/\text{d}$ in the Unconfined marsh.

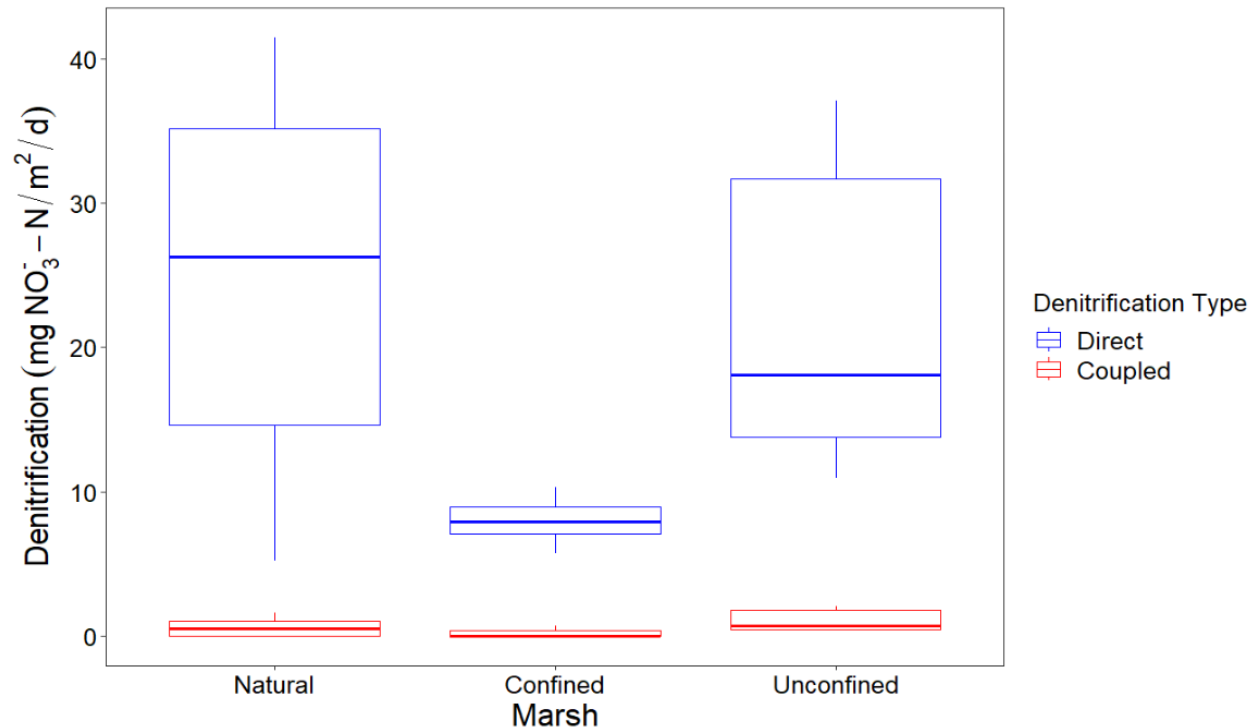


Figure 20. Direct and coupled denitrification rates measured through Isotope Pairing Technique on 9 cores collected from 2 created marshes and a natural marsh in the Pontchartrain Basin, LA.

Total denitrification differed among marshes related to the percent of organic matter at the surface ($F_{5,3} = 19.56$, $p = 0.0190$). Soil organic matter had a positive influence on total denitrification across marshes, but the effect size differed among marshes (Fig. 21). Differences in soil organic matter produced the largest change in total denitrification in the Natural marsh followed by the Unconfined marsh and then the Confined marsh.

Direct and coupled denitrification were positively correlated ($R^2 = 0.75$, $p = 0.0024$) indicating cores with high rates of direct denitrification also had relatively high rates of coupled denitrification and both were correlated with total denitrification ($R^2 = 1.00$, $p < 0.0001$; $R^2 = 0.78$, $p = 0.002$; Fig. 22A and 22B, respectively). Total denitrification was also related to the flux of nitrate ($R^2 = 0.89$, $p = 0.0006$; Fig. 23A) and oxygen ($R^2 = 0.83$, $p = 0.0002$; Fig. 23B), so as nitrate and oxygen uptake by the soil increased so did denitrification. The flux of nitrate from the water to the soil was approximately two times greater than the total denitrification rate suggesting soil uptake of nitrate unrelated to denitrification (Fig. 23A).

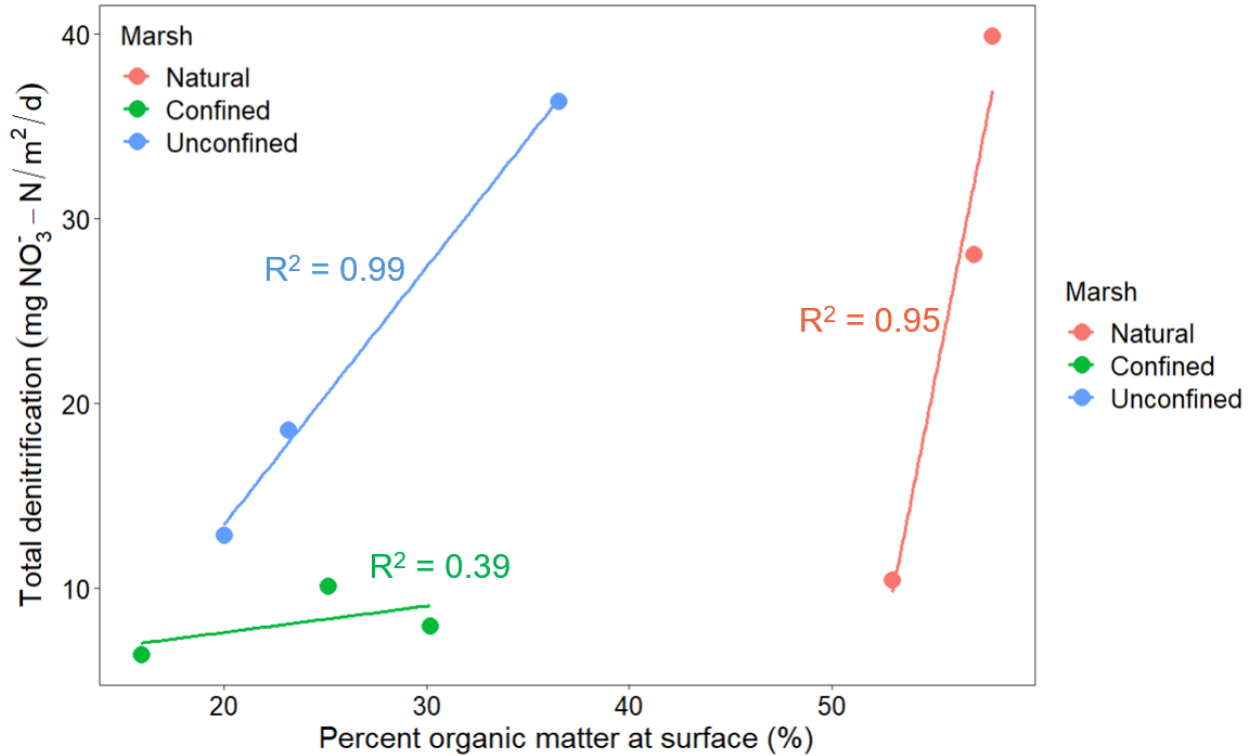


Figure 21 Relationship between total denitrification rate and soil organic matter content of surface soil (0 – 2 cm depth) in three marsh types, a Natural, Confined Created and Unconfined Created in Pontchartrain Basin, LA.

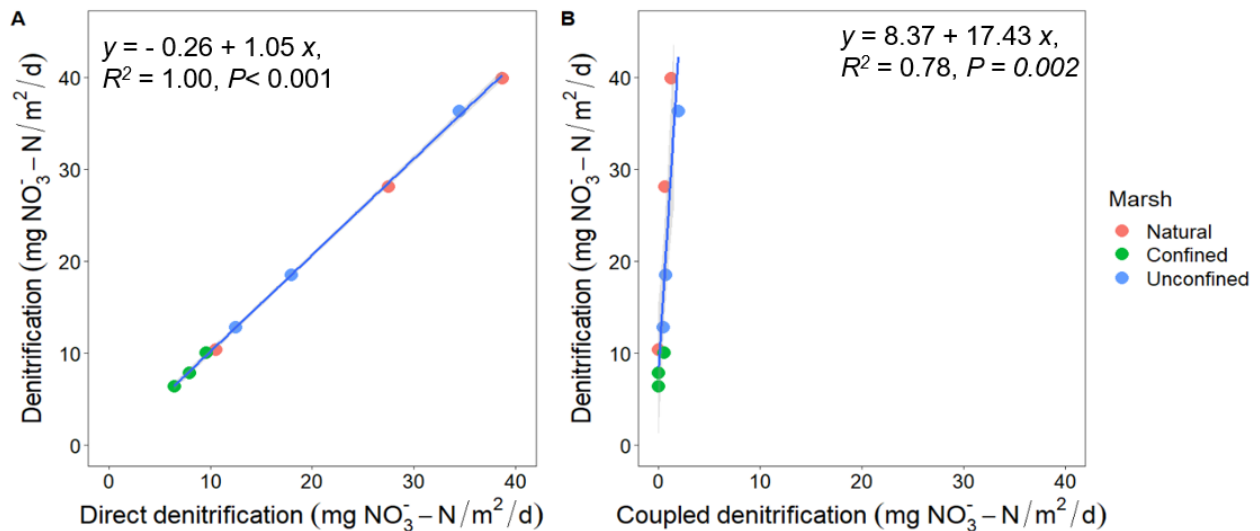


Figure 22. Relationship of direct (A) and coupled (B) denitrification to total denitrification in a core incubation experiment from cores (n=9) collected from two created marshes and a reference natural marsh in the Pontchartrain Basin, LA

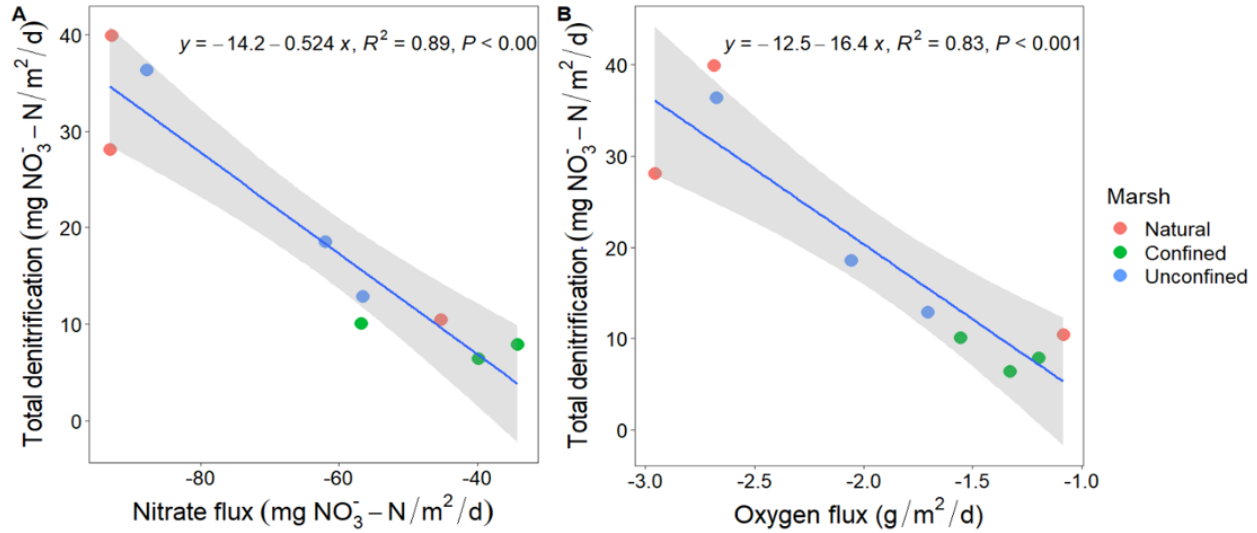


Figure 23. Relationship between total denitrification and nitrate (A) and oxygen (B) flux in soil cores collected from marshes in Pontchartrain Basin, LA. The line represents the linear regression and the shaded area is the 95% confidence interval.

To scale up from the core to the plot level, denitrification was assumed to occur only when plots were flooded. The average denitrification rate was calculated for each marsh and multiplied by the amount of time each plot was flooded. Denitrification rates at each plot based on the percent time flooded and the average denitrification rate of each marsh ranged from 0.1 to 4.9 g NO₃-N /m²/yr. Denitrification rate averaged $3.0 \pm .3$, 0.8 ± 0.2 , and 3.3 ± 0.4 g NO₃-N /m²/yr in the Natural, Confined, and Unconfined marshes, respectively. Estimated denitrification rates in the Confined marsh were significantly lower than in the Natural and Unconfined marshes ($F_{2,33} = 17.96$, $p = 0.000005$), which had similar rates of denitrification.

Discussion

Restoration of marshes has shown promise for creating habitat characteristics similar to that of natural marshes and of value for wildlife and fishes (Rezek et al. 2017; Llewellyn and Peyre 2011). However, some ecosystem attributes and functions lag behind and may never reach equivalence to natural marshes (Craft et al. 1991; Moreno-Mateos et al. 2012). Here, I illustrate important differences in the structure and function of two created marshes of similar age and in a similar location. Specifically, created marshes had distinct plant communities, differed in soil properties, accretion rates, and microbial denitrification rates. Both created marshes also differed from the Natural marsh in vegetation community and soil properties. Overall, this research shows the importance of fostering conditions to promote desired marsh vegetation and ecological functions.

Vegetation cover in restored marshes is typically one of the first ecosystem attributes to reach equivalency to natural marshes, generally within 5 years when suitable conditions are created (Edwards and Proffitt 2003; Edward and Mills 2005; Staszak and Armitage 2013). While vegetation cover was similar among natural and created marshes, species composition differed. Created marshes in the present study were 4 – 5 years old and vegetation cover averaged 63 to 74% across marshes, but the Natural marsh was dominated by *S. patens* while the Confined marsh had a more mixed species composition with *T. domingensis* as the most dominant species and the Unconfined marsh was dominated by *Scheonoplectus americanus*. Even at similar elevations, the plant communities were different in each marsh which shows that other factors likely drove the distribution of plants. Sites with a percent time flooded between 20 and 40% were most common, and each marsh had different communities. *S. patens* was dominant in the Natural marsh, *T. domingensis* was dominant in the Confined marsh, and *S. americanus* was dominant in the Unconfined marsh. This pattern was the same for sites with a percent time flooded of 40-60% and 60-80%. However, at sites with a percent time flooded of 0-20%, the dominant species in the Confined marsh was *B. halimifolia* and in the Unconfined marsh, the dominant species was *S. patens*. The major difference in plant communities is likely due to factors impacting plant dispersal or establishment in the created marshes.

Dispersal limitations can impact plant community composition in marshes (Rand 2000) and some species may be more effective colonizers of newly created marshes. The dominance of *T. domingensis* and *B. halimifolia* at high elevations in the Confined marsh, both wind-dispersed species, may be due to their greater ability to disperse over the containment dyke. *Typha domingensis* produces seeds that can be dispersed by wind several kilometers and can also spread via vegetative propagation (Soon 2006), and species of the *Typha* genus are known as effective invaders of disturbed areas (Visser et al. 1998; Bansal et al. 2019). Once established, *T. domingensis* can have an inhibitory priority effect by producing tall dense stands and outcompeting other species (Bansal et al. 2019; Hood 2013). *Typha angustifolia*, a related species, remained dominant after hydrologic restoration to a wetland in Washington, USA until repeated mowing allowed native vegetation to take hold, demonstrating the ability of *Typha* to exclude other species following establishment (Hood 2013). *Baccharis halimifolia* has light seeds with feathery pappus that facilitate wind dispersal over long distances (Westman et al. 1975). Dispersal of seed via water may also be inhibited by the containment dyke. High

elevations and plant aboveground biomass have also been shown to restrict seed dispersal in water (Smith 2007). The Confined marsh has limited tidal channels to facilitate hydrochory and the high elevations spread throughout the Confined marsh may have limited initial plant dispersal. *S. patens* and *S. americanus* were common and abundant in the Natural marsh but were rare in the Confined marsh. Both *S. patens* and *S. americanus* spread primarily through vegetative reproduction or the dispersal of seeds through water (Palmisano 1967; Lonard et al. 2010). Vegetative spread into the Confined marsh would be limited to openings in the containment dyke or potentially storm deposits. In contrast, the Unconfined marsh is directly connected to natural marshes to the north and south and its border with an area of open water to the east provides hydrologic connectivity.

Spartina patens dominated the Natural marsh but was lower in occurrence and abundance in both created marshes. At similar elevations, *S. americanus* was more dominant in the Unconfined marsh than in the Natural or Confined marshes. Similarly, *S. patens* was more abundant in natural marshes than in created marshes, which were dominated by *Spartina alterniflora* in the Chenier Plain region of Texas and Louisiana (Armitage 2021). In brackish-created marshes in the Chenier Plain, Louisiana, *S. patens* seemingly had limited dispersal or initial establishment into newly created marshes (Muench et al. 2019). Limited dispersal may reflect a tradeoff between putting energy towards vegetative reproduction or sexual reproduction through seeds and the *Spartina* genus has been reported to reproduce primarily through vegetative reproduction (Barkworth 2003). *Spartina patens* was shown to have limited dispersal by seeds compared to vegetative spread in areas of dredged soil placement in New Jersey (Burger and Shisler 1983). *Schoenoplectus americanus* also reproduces via vegetative reproduction, but it was found to recolonize areas where herbicide killed all vegetation, while *S. patens* remained almost completely absent in marshes co-dominated by both species, providing evidence that *S. americanus* is more likely to colonize bare areas by seed (Meert and Hester 2009). Greater colonization, due to increased dispersal, by *S. americanus* compared to *S. patens* could explain the relatively higher abundance in the Unconfined and Confined marsh. If differences in species dispersal and establishment are the drivers for the different plant communities in each created marsh, then it is possible that over time competitive interactions and succession will reshape the vegetation communities in the created marshes.

Spartina patens and *S. americanus* are often found in mixed stands (Visser et al. 1998) with *S. americanus* often favored for being more palatable for a wide range of wildlife, including muskrats and waterfowl (O'Neil 1949; Hoffpauir 1967; Flores and Bounds 2001). A greenhouse experiment that tested how salinity and flooding impacted competition between the two species found that salinity above 10 ppt reduced the growth of both species but favored *S. patens* and that increased flooding favored *S. americanus* (Broome et al. 1995). The results here generally align with these findings as *S. patens* decreased in cover in the Natural marsh as flooding increased, and *S. patens* only became dominant in the Unconfined marsh at flooding depths between 0-20%, although it did dominate one plot in the Unconfined with a percent time flooded of 61%. Competition between *Spartina patens* and *Schoenoplectus americanus* is also impacted by fire regimes and managers can use prescribed fire to increase the prevalence of *Schoenoplectus americanus* (Chabreck 1981).

Elevation influenced species composition differently in each marsh. At sites with greater than 20% flooded different species dominated in each marsh, but the effects of elevation are still present in each marsh. In the Natural marsh, *S. patens*, which is one of the most prevalent species across Louisiana's coast (Snedden 2019), cover decreased with increased flooding in all marshes, except for one plot in the Unconfined that had high cover of *S. patens* at a percent time flooded of 61%. *T. domingensis* has numerous adaptations to flooding stress that can give it an advantage in flooded conditions over other wetland plants (McKee et al. 1989). *T. domingensis* cover increased in the Confined marsh as flooding increased and it was only detected in the Unconfined marsh at plots with a percent time flooded greater than 40%, reflecting its ability to withstand flooding stress. The highest elevations in the Confined marsh, which were the highest elevation across marshes, were dominated by the high marsh shrub *B. halimifolia* with some *Salix nigra*. These species are more representative of upland areas and are not targets for typical marsh restoration projects.

Created marshes typically have low soil organic matter as compared to natural marshes though it accumulates over time under appropriate conditions (Edward and Proffitt 2003; Craft et al. 2003). Soil organic matter, as an electron donor for decomposition, is important for many biogeochemical reactions in wetlands (Reddy and DeLaune 2008). Here, the Confined marsh had variably high soil organic matter content due to the presence of natural soil from before restoration whereas the Unconfined marsh had mostly dredge material with relatively low (~10%) soil organic matter content. Thus, there is the potential for this higher SOM in the Confined marsh to provide a greater substrate for microbial reactions such as denitrification as well as a source of nutrients following mineralization. However, cores from the Confined marsh used in the denitrification experiment in this study showed almost no sign of remnant soil organic matter, with only one core showing high organic matter at around 15 cm of depth, which likely would be too deep to significantly affect denitrification rates and nutrient data was not collected at vegetation sites so I cannot determine the effects of remnant soil on nutrient availability.

As compared to the Natural marsh, soil organic matter content was lower in the Created marshes, which is expected as soil organic matter in Holocene coastal marshes has formed over hundreds to thousands of years. Dredged material typically has low organic matter content and in this study dredged sediment had an organic matter content of about 10% (Craft et al 1999; Edward and Proffitt 2003). The Natural marsh had an average of 30 to 60% organic matter. The Unconfined marsh had approximately 20% organic matter at the surface quickly dropped to about 10% in the dredged sediment layer at around 8 cm depth. The Confined marsh had variable soil organic matter content that can be attributed to relict marsh organic matter that was resuspended and mixed with the dredge sediment during marsh creation. Schrifft et al. (2008) refer to sites with relict soil organic matter near the surface as pop-up sites and found that the high organic matter pop-up sites, which were high in elevation, had higher vegetation cover than sites at similar elevations without relict soil present. The hypothesized mechanism was organic soil retaining moisture longer than dredged material, which was often cracked and dry at high elevations. Pre-existing soil may impact plant composition in created marshes because seeds and rhizomes may survive the placement of dredged sediment and it can alter moisture content and nutrient availability. However, because this study took place after vegetation had become well

established I am unable to determine if roots and rhizomes surviving the placement of dredged sediment affected the vegetation community.

Accretion rates averaged over the last 60 years in the Natural marshes averaged 4.7 ± 0.5 mm/yr. The short-term accretion rates in the Natural marsh were similar and averaged 4.3 ± 1.1 mm/yr. Short-term accretion rates are expected to be faster than that over the long term due to decomposition of organic matter and compaction that reduces soil volume over time. However, long-term accretion averaged 0.4 mm/yr faster than the short-term in the Natural marsh. Short-term accretion measurements from the nearest CRMS station ranged from 2.6- 11 mm/yr and averaged 7.6 mm/yr from 2008 to 2020, excluding one measurement of 91 mm/yr. The reason for slower short-term accretion rates in the Natural marsh is not clear but drought conditions may be responsible for slower short-term accretion rates over this one-year sampling period. For example, the percent time flooded was on average 21% lower in summer 2023 than in the 2020 and 2021 summers in the Natural marsh. Both 2022 and 2023 were drought years in Louisiana (National Integrated Drought Information System). Less flooding can slow accretion rates due to a combination of increased decomposition and slower sediment deposition (Drexler et al. 2013; Pethick 1981). During the drought, there were fewer storm events with the water level never reaching above 50 cm in any marsh during 2022 or 2023, but during 2020-2021 water level reached over 50 cm seven times in all marshes. Storms are known to increase accretion by depositing inorganic sediment on marshes (Turner et al. 2006; Pannoizzo et al. 2023). The combined effect of low water levels and low storm activity likely explains the slower than expected short-term accretion rates in the Natural marsh.

Accretion dynamics across the marshes align with other studies showing that accretion is positively related to inundation (Morris et al. 2002). In this study, organic matter accretion slowed with less flooding at high elevations, Less organic matter accretion slows carbon sequestration and delays wetland soil development. The percent time flooded was the only significant factor influencing accretion. The Unconfined marsh had the highest average percent time flooded, which resulted in the fastest accretion. Even though the Unconfined marsh had a significantly lower percentage of organic matter of accreted material, the analysis of total accreted organic matter and mineral sediment shows that the Unconfined marsh did not accrete less organic material than the natural marsh, instead, it accreted significantly more mineral sediment which decreased the percent of organic matter. Higher average percent time flooded increased the sediment deposition in the Unconfined marsh, but its proximity to a sediment source may have also played a role.

Sediment availability may have been increased by the method used to create the Unconfined marsh. Decreasing distance to a sediment source and increasing suspended sediment concentration have been shown to increase sediment deposition in coastal marshes (Butzeck et al. 2015). The placement of sediment that created the Unconfined marsh also led to the settlement of dredged material in an area of open water adjacent to the marsh. It is possible that winds or strong currents could resuspend the sediment that settled in the open water and increase sediment concentration in the water and increase deposition, which could explain some of the very high values of accretion at medium levels of percent time flooded in the Unconfined marsh and why the Unconfined marsh had significantly higher sediment accretion than the natural marsh even when percent time flooded was included in the model. Possible impacts of

containment were missed in this study because of the position of accretion plots. When plots were placed, low water levels made many locations inaccessible in all marshes, so plots were placed very close to tidal channels or edges of the marsh. In the Confined marsh, all plots were close to a gap in the containment dyke or to a tidal channel connected to the surrounding area

Denitrification rates were variable between and within marshes. The Natural and Unconfined marshes had similar ranges of total denitrification with the Natural marsh having a slightly higher average rate, while the Confined marsh had a much more limited range of values and a much lower average rate. Estimates of denitrification per year based on the percent time flooded at each plot highlights the importance of proper elevations to facilitate water quality improvements of created marshes. The Unconfined marsh was estimated to contribute the most to nitrogen removal through denitrification, even though the average rate of denitrification was lower than the natural marsh because of differences in percent time flooded. While direct denitrification dominated in our study, coupled nitrification-denitrification was found to be the dominant denitrification pathway accounting for between 41-97% of denitrification in a similar created marsh study (Kleinhuizen & Mortazavi 2018). That created marsh was significantly older (21 years), however the natural marsh in our study was still dominated by direct denitrification. Coupled nitrification-denitrification rates measured in this experiment may be an underestimation because live plants whose roots can stimulate denitrification by increasing aerobic-anaerobic interfaces in the soil by transporting oxygen to anaerobic zones were excluded from soil cores (Reddy et al. 1989). Both direct denitrification and coupled denitrification were found to increase with increased nitrate in the water column, but direct denitrification increased significantly more in a similar experimental set-up studying marshes in the Wax-Lake Delta (Li and Twilley 2021). Nitrate concentrations were spiked in our experiment, likely increasing the importance of direct denitrification. However, the nitrate concentration used is within the range of expected values for this site. Nitrate concentrations at Liberty Bayou, which directly borders the Natural and Confined marsh, were found to be 1.45 μM in the Spring and 42.2 μM in the Summer (Zhang et al. 2016). The nitrate concentration when I sampled the water was below 1 μM , which could be due to season and drought which would reduce the amount of nitrate by reducing runoff. The Unconfined marsh had similar levels of denitrification as the Natural marsh, which provides evidence that young-created marshes can provide some water quality improvements similar to that of a natural marsh. However, the Confined marsh showed limited denitrification potential, which highlights the need to determine the factors that affect nitrogen cycling in created marshes.

Vegetation differed between each marsh and at our denitrification plots. Plant communities at the locations where cores were taken were largely representative of the marsh where they were located, with *S. patens* dominating every location in the Natural marsh, *T. domingensis* dominating at every plot in the Confined marsh, and *S. americanus* dominating every plot in the Unconfined marsh, except one where it co-dominated with *Symphoricarum subulatum*. The difference in vegetation community may explain some differences between the denitrification rates I observed. The plant community significantly affected the microbial community and denitrification rates even when other factors such as elevation were controlled (Mason et al. 2021). Degradation of *Typha* spp. and *Schoenoplectus acutus* were compared in a restored wetland and *Typha* spp. was found to have significantly less mass loss than

Schoenoplectus acutus implying a higher resistance of *Typha spp.* to degradation (Hernes 2020). *T. domingensis* may have litter that is more resistant to degradation than *S. americanus* and that could explain the lower rates of denitrification and the differing effect size of soil organic matter on denitrification. Additions of more easily degraded organic matter increased denitrification more than recalcitrant material containing higher proportions of cellulose and lignin, but both additions increased the denitrification rates, in a study of marine sediments (Dahllof 2005).

Higher elevation areas may delay the development of ecosystem services provided by the created marshes. In this study, high elevations were dominated by upland shrubs, accretion decreased with increasing elevation, and denitrification was predicted to be very limited. High-elevation areas of created marshes have been shown to limit nekton, macroinfauna, and macroinvertebrate abundance in created marshes (Keppler et al. 2023; Tong et al. 2013; Minello and Webb 1997). The density of benthic invertebrates was found to be positively correlated with the development of soil organic matter in created marshes (Craft 2000), and the development of soil organic matter has been shown to increase with inundation in created marshes (Craft et al. 2002). Other ecosystem services may be provided in high-elevation marshes such as providing habitat for typical woodland species (Arizaga et al. 2013). However, with sea level rise predicted to continue to accelerate into the future, these areas will continue to receive more inundation, which will shift conditions to favor the development of wetland soil wetland soil. Rates of relative sea-level rise based on CRMS data from nearby sites are ~7 mm/yr (Jankowski et al. 2017)

Conclusions

Marsh creation is an important restoration technique for replacing the ecosystem functions and services lost when coastal marshes convert to open water. However, the ecological development of marsh creation sites can be highly variable depending on construction techniques, which control subsequent environmental conditions. Ecological structure, defined as elevation, soil organic content, and vegetation community differed among all three marshes: Natural, Confined, and Unconfined. Higher marsh elevations were much more common in the Confined marsh, which impacted the vegetation community, organic and mineral accretion, and is likely to limit nitrogen removal rates by decreasing denitrification. Upland vegetation will not provide habitat for wetland species. Decreasing organic matter accumulation associated with high elevations decreases carbon sequestration and slows the development of wetland soil. High elevations limit inundation and hydrologic connection, which limits the ability of those areas to impact water quality. Even at similar elevations created marsh vegetation communities differed from each other and the reference natural marsh. Vegetation communities may impact habitat provisioning and other ecosystem services provided by created marshes. Denitrification rates were similar in the Unconfined and Natural marshes but were reduced in the Confined for uncertain reasons. This highlights the need for further work on factors impacting nutrient cycling in created marshes. This study is a snapshot of structure and function 4-5 years after construction of these marshes. Vegetation succession may not be fully complete and with sea level rise expected to continue in the future, high-elevation areas will receive more inundation and the ecosystem functioning of high-elevation areas will likely increase as inundation increases.

Management Implications

Goals of created marsh projects vary by project. The specifics of restoration projects need to be tailored to meet the objectives of the project. If habitat for fish or wildlife is the goal, elevations that are sufficiently flooded to provide the vegetation types and habitat for target species should be created. Vegetation communities may differ from surrounding areas even if the created marsh is at similar elevations, and therefore planting may be necessary if specific vegetation is targeted for restoration. *Schoenoplectus americanus*, which is a common target species for wildlife managers, was dominant in the Unconfined marsh at lower elevations, but at higher elevations, it was outcompeted by *S. patens*. However, *S. americanus* was not abundant at the same elevations in the Confined marsh potentially due to the dispersal limitations created by the containment dyke.

Eutrophication due to nutrient pollution is increasingly impacting coastal ecosystems and if created marshes are created to remove nitrogen then proper elevations are needed to promote anoxic conditions. The Unconfined marsh was predicted to remove the most nitrogen through denitrification even though the Natural marsh had higher estimated rates because flooding that promotes anoxic conditions was more common in the Unconfined marsh. The factors impacting nitrogen cycling in created marshes are still being determined, but under the right conditions created marshes can provide nitrogen removal similar to natural marshes. Results from this study indicate that the vegetation community of created marshes may affect rates of nitrogen removal.

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Vita

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