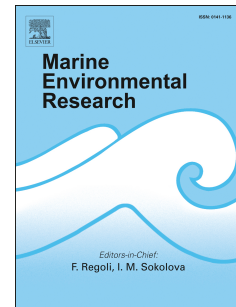


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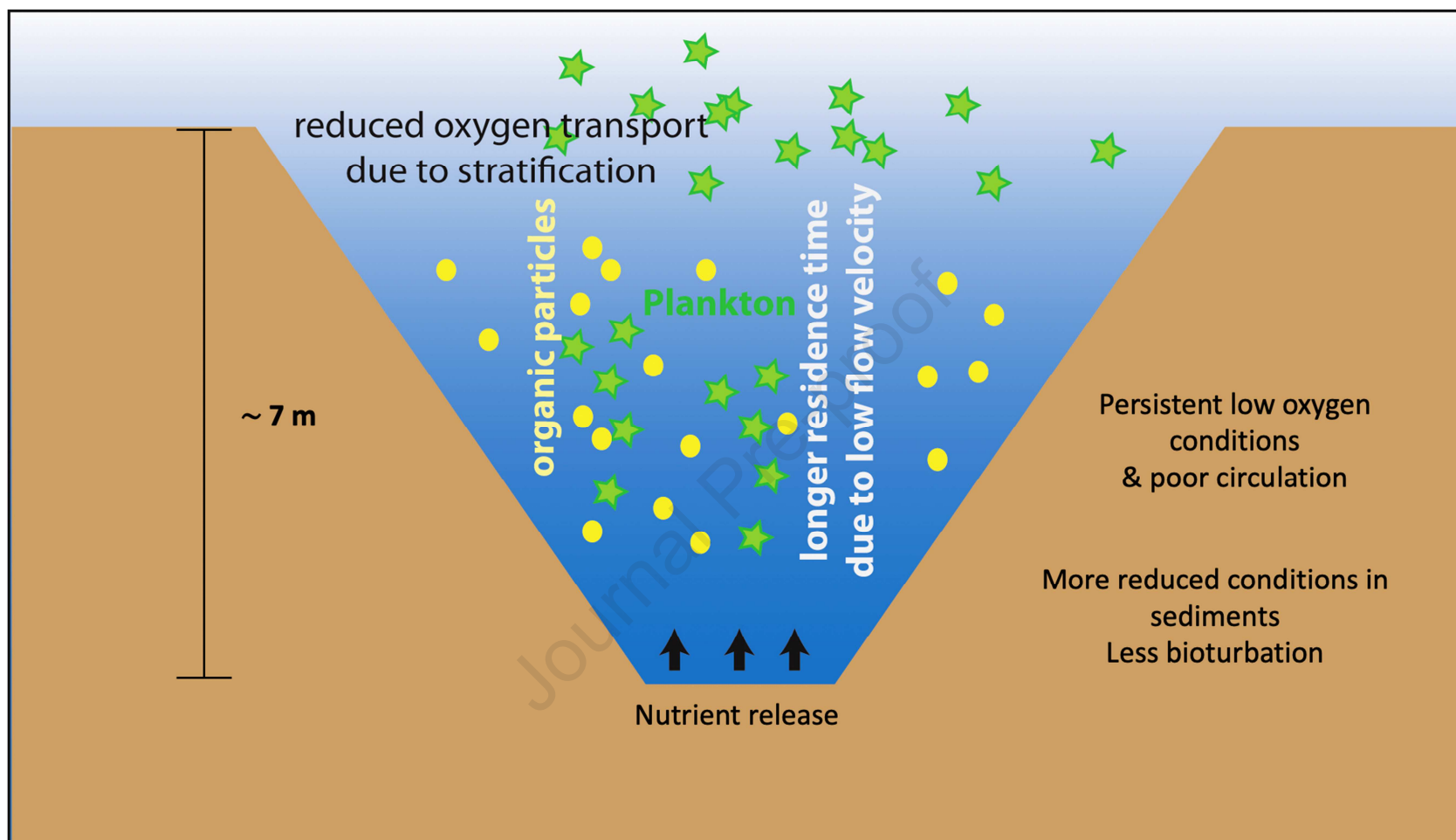
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Graphical Abstract Figure. A conceptual model of a dredge pit. Black arrows indicate release of nutrients as a result of low oxygen conditions.

Author Statement

Laura Thompson: Validation, Formal Analysis, Investigation, Data Curation, Writing – Original Draft **Kanchan Maiti:** Conceptualization, Methodology, Investigation, Writing – Review and Editing **John White:** Resources, Writing – Review and Editing **Christopher DuFore:** Writing – Review and Editing, Supervision, Project Administration, Funding Acquisition **Haoran Liu:** Software, Writing – Review and Editing

The impact of recently excavated dredge pits on coastal hypoxia in the northern Gulf of Mexico shelf

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Abstract

Large volumes of sand are needed in order to combat coastal land loss due to global sea-level rise for restoration of barrier island systems and beaches undergoing rapid erosion and submergence. The sediment required for such projects often originates from dredging of sand deposits on the adjacent shelf. Two dredge pits, with contrasting geology and located at varying distances from the Mississippi River Delta in the northern Gulf of Mexico shelf were sampled during spring and summer. Samples were also collected concurrently from surrounding continental shelf stations that are subject to seasonal hypoxia every summer. The bottom water dissolved O_2 inside the dredge pits were found to be consistently hypoxic or near hypoxic throughout both seasons, with high sediment O_2 consumption (SOC) rates of 51.8 to 23.7 $mmol\ m^{-2}\ d^{-1}$ in spring and 51.3 to 34.3 $mmol\ m^{-2}\ d^{-1}$ in summer. In contrast, control stations immediately outside the dredge pits showed lower SOC rates ranging between 6.3 to 35.9 $mmol\ m^{-2}\ d^{-1}$. The SOC rates of the surrounding continental shelf subjected to annual seasonal hypoxia ranged between 25.7 to 59.6 $mmol\ m^{-2}\ d^{-1}$ indicating that the dredge pits experienced similar high rates of SOC. Our results suggest that sluggish water circulation inside these topographic depressions coupled with higher SOC rates does result in persistent low bottom O_2 conditions inside these dredge pits well beyond the duration of the seasonal hypoxia period in this region. This is the first study to provide insight on the impacts of dredge pits to surrounding hypoxia in this region which is critical as future dredging operations are expected to increase worldwide with projected sea-level rise.

1. Introduction

The current global consumption of sand is 50 billion metric tons every year which poses a major sustainability challenge (UNEP, 2019). In coastal regions, sand is needed for beach nourishment which represents a widely used and rapidly expanding strategy to counter erosion and sea level rise (Finkl et al. 2006; Hanson 2002; Crowe et al., 2016). Sand is also utilized for land reclamation projects and construction of coastal protection for storm surges. Sea level rise, local land subsidence, and dam construction have contributed to extensive land loss around the world (Syvitski et al., 2009; Wang et al., 2018). The need for sand to replenish eroding beaches and land subsidence is a global issue which has led to increasing interest in sand mining on continental shelves. The sediment required for nourishment projects often originates from dredging of sand deposits on the shelf but the impact of such dredge pits and borrows on coastal water quality and ecology remains understudied. The rate of infilling of such dredge pits can be highly variable and can take from decades to hundreds of years to infill, depending on proximity to sediment source, transport, prevailing currents as well as pit geometry (Byrnes et al., 2004a,b; Crowe et al., 2016; Desprez, 2000; Jones et al., 2009). Even when completely infilled, these areas can continue dewatering and consolidation processes for a much longer time scale (Robichaux et al., 2020; Nairn et al., 2005). The biological recoveries may not occur for many years depending on the environmental conditions and the nature of the dredging impact (Crowe et al., 2016; Cooper et al., 2007; Williamson et al., 2006). Several countries in Europe, and parts of the United States have all undergone beach nourishment projects using dredged sediments in efforts to restore eroding coastlines (Wilber et al., 2003; Graca, 2009; Hanson et al., 2002; Xu et al., 2014). In United States, coastal Louisiana in northern Gulf of Mexico is currently experiencing one of the highest rates of land loss in the world due to both natural and human-induced processes (Syvitski et al., 2009; DeLaune and White, 2012; Couvillion 2017; Sapkota

and White, 2019). The estimated land loss in this region since the 1930s is approximately 1,829 square miles (Khalil et al., 2010; Barras et al., 2008). Louisiana's barrier islands play a critical role in shoreline protection by reducing effects of storm surges, coastal flooding, and maintaining coastal basin wetlands and estuaries. In order to combat coastal erosion, dredged sediment from offshore areas on the northern Gulf of Mexico (NGOM) continental shelf are often excavated and supplied to deteriorating coastal beaches and wetlands (Palmer et al., 2008; Lui et al., 2018; Wang et al., 2018; Lui et al., 2020a,b).

Offshore dredging results in deep depressions (up to ~10m) on the northern Gulf of Mexico (NGOM) shelf, a shallow sloping area that extends 100 to 200 km from the coast (Roberts, 1997; Kulp et al., 2005). These depressions, referred to as borrow areas or dredge pits, result in areas that are physically different from the surrounding environment (Palmer et al., 2008). For example, dredge pits have been recorded to impact wave and current dynamics (Niu and Yu, 2011), change or cause loss of benthic community species composition (Palmer et al., 2008), and induce hypoxic (low oxygen) or anoxic (no oxygen) conditions (Graca et al., 2009 and 2004, Sonders et al., 2014). Dredge pits are often associated with decreased current velocities (Chaichitehrani 2018) and can act as effective sediment traps with high organic matter accumulation (Graca et al., 2004; Obelcz et al., 2018; Robichaux et al., 2020), which has the potential to further intensify hypoxia formation. However, there are no studies in the U.S. that systematically investigate the sediment oxygen consumption or biogeochemical drivers of oxygen dynamics within dredge pits.

Understanding the impacts of dredge pits to bottom water biogeochemistry are especially crucial due to the need for hundreds of millions of cubic meters of sediments for coastal and wetland restoration (Khalil et al., 2010). Sand is needed for beach nourishment, finer sands and

muddy sediments for wetland restoration, and clay for levee construction. In order to restore diminishing coastlines, repeated nourishment projects are often needed in order to combat erosion (Wilber et al., 2003). Thus, the need is likely to increase significantly in future decades as sea-level rise and storm intensity increases (Bird and Lewis, 2014; Zhang et al., 2004), leading to future excavation of many dredge pits in this region and elsewhere. Thus, it is imperative to better understand the impact of such dredge pits on inducing or exacerbating coastal hypoxia, a chronic water quality problem reported from over 400 areas worldwide, which are expected to intensify under future climate change scenarios (Rabalais and Turner, 2019). This is especially relevant for our current study region, as the NGOM shelf is also subjected to seasonal hypoxia when dissolved O₂ concentrations drop below 2 mg L⁻¹. This hypoxic region, or “dead zone”, spans from Louisiana’s Bird Foot Delta to eastern regions of the Texas coastline. It has been reported as the second largest human-induced seasonal hypoxic zone in the world, spanning an area of 23,000 km² (Rabalais and Turner, 2019). The well-known occurrence of hypoxia in the NGOM compels a better understanding of water quality and sediment oxygen dynamics within excavated dredge pits and the adjacent seafloor outside of the pit. However, sediment oxygen consumption (SOC) in dredge pits has not yet been reported in the United States. Thus, this study specifically investigates SOC rates from the recently excavated dredge pits in comparison to seasonal hypoxia zone.

This study focuses on determining the potential differences in sediment oxygen consumption rates of two dredge pit sites and additional locations in the hypoxic region on Louisiana’s continental shelf. Two recently excavated dredge pits, Caminada and Sandy Point, their adjacent outside counterparts, as well as four surrounding sites located within the seasonal hypoxic zone are investigated in this study (*Fig. 1*). These two dredge pits have contrasting

qualities. They differ in (i) age since completion of dredging operations, (ii) proximity to the Mississippi River Delta, and (iii) substrate type (sandy vs. mud-capped). In the current study we compared these two dredge pits in addition to the seasonal hypoxic sites to test our driving hypotheses that (i) the dredge pits will have higher SOC rates, resulting in more intense hypoxic conditions, compared to adjacent regions outside of the pits and the surrounding hypoxic shelf stations, (ii) the mud-capped dredge pits will have higher SOC rates compared to sandy pits due to higher rates of organic matter supply and less physical mixing, thus resulting in higher SOC rates, and (iii) SOC of dredge pits sites will be higher in summer months compared to the earlier spring months due to organic matter accumulation from biological productivity and increased temperature.

Thus, the main objectives of this study are to (i) provide a comprehensive understanding of the oxygen dynamics and SOC rates within dredge pits off the coast of Louisiana on a seasonal scale and (ii) compare the oxygen dynamics and SOC rates of dredge pits to the seasonal hypoxic zone that occurs every summer. Quantifying the magnitude of SOC rates from the dredge pit stations are needed to better understand the effects of human-induced dredging and the water quality conditions that may negatively affect marine life compared to other stations along the continental shelf.

2. Materials & Methods

2.1 Study area descriptions

Two recently excavated dredge pits, Caminada and Sandy Point, and four seasonal hypoxia sites (C6, B5, D3, and D5) located along the commonly used hypoxia transects (*Fig. 1a*) are the chosen sites for this study. Rabalais et al., (1999) illustrates the past usage and nomenclature of hypoxia sites for this study, and the hypoxia shelf transects, dating back to 1985, are consistently used by various studies in the NGOM (Rabalais et al., 1999; McCarthy et

al., 2013; Ghaisas et al., 2019; and others). Using these sites will allow a comprehensive comparison of the potential post-dredging effects in Caminada and Sandy Point to the hypoxic shelf stations.

Caminada (CA) (*Fig. 1b*) was dredged in two increments from 2013-2016 as a part of the Caminada Beach and Dune Restoration Project. This site is a mixed-sediment dredge pit located on Ship Shoal, made up of previously existing sandy sediments combined with fine-grained bypassing mud sediments sourced from either from the Mississippi River or the Atchafalaya River. After a total volume of 9.07 million m³ of sediment was mined, the area of the Caminada dredge pit is approximately 6.3 km², with depth ranging between 6-7 meters below the ambient seafloor (Liu et al., 2019). CA is presently infilling at a rate of 150 cm yr⁻¹, or 27,480 m³ yr⁻¹ (Liu et al., 2018). This study focuses on two inside stations, CA2_IN (28°54.8324'N, 90°37.2931'W) and CA5_IN (28°54.7441'N, 90°36.6542'W), along with two outside stations, CA8 (28°54.9426'N, 90°37.7588'W) and CA11 (28°55.1721'N, 90°36.3052'W).

The Sandy Point (SP) (*Fig. 1c*) dredge pit, located on a paleo river channel, was excavated in 2012 to replenish Pelican Island, Louisiana. SP is ironically referred to as a mud-capped dredge pit after near 1 million m³ of muddy overburden was removed in order to excavate over 2.7 million m³ of underlying sand for restoration (Chaichiterani et al., 2019). After a total of 3.7 million m³ of sand was mined (Sonders et al., 2014; Obelcz et al., 2018), the area of the SP dredge pit is approximately 0.37 km² (Sonders et al., 2014). SP has been recorded to accumulate sediment at an average rate of 54 cm yr⁻¹ and is predicted to completely infill within ~15 years (Obelcz et al., 2018). The major sources of sediment for these dredge pits are: (i) reworked and resuspended sediment in shallow coastal waters due to wave-current interaction, (ii) sediment flux from the Mississippi River and (iii) sediment advected during the frontal

passage (Chaichiterani et al., 2019; Obelcz et al., 2018). In correspondence with CA, this study investigates two inside stations, SP3_IN (29°06.246' N, 89°30.577' W) and SP5_IN (29°05.9142' N, 89°30.607' W), along with two outside stations, SP4 (29°06.189' N, 89°30.919' W) and SP11 (29°07.788' N, 89°31.350' W).

2.2. Sample collection

Sediment cores were collected in spring (April-May) and summer months (July-September) from Caminada (CA) dredge pit in 2018 and Sandy Point (SP) dredge pit in 2019 using R/V Coastal Profiler and R/V Acadiana. Samples were collected from two locations inside each dredge pit designated as CA2_IN, CA5_IN and SP3_IN, SP5_IN for Caminada and Sandy Point. Two outside stations designated as CA8, CA11 and SP4, SP11 were also sampled at the same time, adjacent to Caminada and Sandy Point dredge pits respectively. Intact sediment cores were collected in triplicate from each station using an Ocean Instruments MC400 multi-corer. The only exception was Caminada dredge pit in which the multi-corer failed to collect samples, due to the coarse substrate; and a box corer was used in its place. The same 10cm diameter polycarbonate core tubes used in the multi-corer were used to subsample the box corer. For shelf wide stations, intact sediment cores were collected onboard the R/V Pelican in summer 2018 (August) and 2019 (July) from Louisiana continental shelf stations C6, B5, D3, and D5 using the multi-corer. At every station an additional core was collected and analyzed for total organic carbon (%TOC) content at 1-2 cm depth intervals. Filtered (1µm) bottom water samples were also collected at each station for use in sediment core incubation experiments. Bottom water parameters for depth, temperature, salinity, and dissolved O₂ at each station were measured using a Seabird HydroCAT-EP.

2.3. Sediment oxygen consumption measurements

Temperature-controlled recirculating water baths adjusted to the bottom water temperature were used for all incubation experiments. Filtered bottom water was used to gradually fill up the core tube with minimum disturbance to the sediment-water interface. The overlying water column height was adjusted between 20-25 cm from the sediment surface to ensure similar water column volume among all cores using custom PVC core caps. Care was taken to avoid any visible air bubbles or headspace. The custom designed lids are fitted with two O-rings for gas-tight incubations, and include one tube attachment for the corresponding water reservoir, one tube attachment for sample extraction, and two tube attachments that connect to each other in a peristaltic pump, allowing continuous flow and circulation in the core for the entire duration of the incubation (Upreti et al., 2019; Ghaisas et al., 2019). Sediment cores were fully submerged into the temperature-controlled water bath, and reservoir tanks along with the incubation water bath were covered with an opaque shroud to ensure no primary production. The incubation was terminated when dissolved O_2 in the cores fell below 1.0 mg L^{-1} .

To obtain oxygen concentrations, water samples were extracted from the cores every 4-6 hours in Labco septa vials, in which water was allowed to overflow the vial before capping (Upreti et al., 2019). Gravity-driven water replenishment from the reservoir allowed the simultaneous collection of water samples and water refill within the core without any introduction of O_2 (Hopkinson et al., 1999; Upreti et al., 2019). Approximately 10 mL of the “dead water” in the tubing was released at each time interval before collecting samples. Once water samples were taken for each core, they were immediately measured for O_2 concentration using a Presens Microx 4 O_2 sensor. The changes in concentration over time were plotted to calculate the flux of O_2 into the sediment, or the SOC rate after appropriate volume correction.

Only data points with dissolved O₂ concentration greater than 1.0 mg L⁻¹ was used for flux calculation to maintain consistency among cores with different rates of SOC.

2.4. Total organic carbon (TOC) analysis

Total organic carbon analysis (TOC) of the top 10 cm was conducted after sediment was subsampled, weighed, and dried at 50 °C. Dried sediment samples were ground using a traditional mortar and pestle and homogenized using a 125 µm sieve. Samples were weighed into open Costech silver capsules and placed in a vacuum glass desiccator alongside the fumigation of 12N hydrochloric acid (HCl) for 12 hours to remove inorganic carbon (Hedges et al., 1984; Hedges and Stern 1984). Samples were then repacked into tin capsules to ensure no loss of sample and analyzed in Costech 1040 CHNOS Elemental Combustion system following the standard EPA method 440.0 (Zimmerman et al., 1997).

2.5. Statistical analysis

Differences in SOC were analyzed using a two-way T-test of equal variance between inside pit, outside pit, and shelf stations. Similarly, differences in SOC were compared seasonally using a two-way paired T-test for individual sites. A Pearson correlation test was used to test the linear correlation of SOC rate with observed temperatures and bottom water dissolved O₂. Data reported in this study is presented in the mean ± standard deviation format with parenthesized p values if associated with any statistical references.

3. Results

3.1 General water chemistry

Caminada depth inside the pit was ~13 m from the surface water with an outside ambient depth of ~7-8 m, thus the dredge pit was roughly 6 m deep. Spring bottom water temperatures for Caminada were warmer outside the pit, ranging from 24.5 to 25.5 °C, compared to cooler temperatures inside the pit, ranging from 22.9 to 23.1 °C (*Table 1*). Bottom water temperatures increased in summer, however, similarly, the temperatures were warmer outside the pit ranging

from 28.5 to 29 °C, compared to cooler temperatures inside the pit and 24.5 to 25.5 °C. In spring, the bottom water salinity in Caminada was notably higher inside the pit compared to outside the pit, ranging 34.0 to 34.4 inside and only 22.9 to 27.9 outside. Salinities slightly increased in the summer season, reporting approximately 34.8 inside the pit and ranging 30.3 to 30.6 outside the pit, and still the salinity inside the pit was higher than outside. Based on CTD data, bottom water concentrations for Caminada remained hypoxic year-round at both inside stations CA5_IN and CA2_IN, at 1.43 and 1.93 mg O₂ L⁻¹ in spring, with a slight decrease in summer to 1.42 and 1.46 mg O₂ L⁻¹, respectively. In contrast, both outside pit stations CA11 and CA8 remained above 2 mg O₂ L⁻¹ year-round, at 6.71 and 6.88 mg O₂ L⁻¹ in spring, with a decrease in summer to 3.50 and 5.46 mg O₂ L⁻¹, respectively. The dissolved O₂ concentration outside the pit was 4x higher than the inside concentration in spring, and over 2x the dissolved O₂ concentration in summer (*Table 1*).

Sandy Point depth inside the pit was ~17 m from the surface water and an outside ambient depth of ~10, thus the dredge pit was roughly ~6-7 m deep, similar to Caminada. However, Sandy Point did not experience the differences between inside and outside stations like Caminada experienced. Spring bottom water temperatures for both inside and outside Sandy Point were similar, with inside temperatures ranging 22.5 to 22.6 °C and outside temperatures ranging 22.9 to 23.1 °C in the spring. Bottom water temperatures increased in the summer, yet were still similar between inside and outside stations, ranging 27.4 to 27.5 °C inside the pit and somewhat warmer outside the pit ranging 28.9 to 29.0 °C. Bottom water salinities inside the pit were slightly higher than outside stations, ranging from 34.6 to 34.8 inside and approximately 31.7 outside during spring. In contrast to Caminada, the salinities decreased in summer months, at approximately 31.9 inside the pit, and outside the pit ranging 28.9 to 30.8. Based on spring

CTD data, bottom dissolved O₂ concentrations of inside pit stations SP3_IN and SP5_IN were 1.79 to 2.81 mg O₂ L⁻¹, respectively, with SP3_IN being the only station to fall below hypoxia. The outside stations SP11 and SP4 remained above hypoxia with concentrations of 2.36 and 4.92 mg O₂ L⁻¹, respectively. SP11's concentration overlapped with inside station concentrations, further indicating possible similarities of inside and outside pit conditions. In summer, all stations remained above hypoxia, with inside bottom water dissolved O₂ concentrations of 2.75 and 2.32 mg O₂ L⁻¹ for stations SP3_IN and SP5_IN, and outside stations SP11 and SP4 with concentrations of 3.03 and 4.56 mg O₂ L⁻¹, respectively. Stations SP3_IN and SP11 increased in dissolved O₂ from spring to summer. Summer dissolved O₂ concentrations for inside and out the pit did not overlap, although outside station SP11 was close to inside station SP3_IN in O₂ concentration.

Shelf station depths ranged from 16.0 to 19.1m, with an exception of D5, which is at ~33m water depth being the farthest offshore. In summer 2018, bottom water temperatures ranged from 22.8 to 27.3 °C, D5 having the coolest and B5 having the warmest temperature. In summer 2019, station C6 had the warmest temperature of all other hypoxic shelf stations, while D5 consistently had the coolest temperature at 16.8 °C, with all stations ranging from 16.8 to 27.8 °C. Salinities for shelf stations in summer 2018 ranged from 35.5 to 36.3, with B5 having the lowest and D5 having the highest salinity. In summer 2019 bottom water salinities were overall lower than the previous year, ranging from 29.5 to 35.9, with C6 having the lowest and D5 consistently having the highest salinity. Dissolved O₂ concentrations were hypoxic or near hypoxic at shelf stations. In summer 2018, bottom water dissolved O₂ concentrations ranged from 0.79 to 1.98 mg O₂ L⁻¹, with D3 having the lowest and D5 having the highest dissolved O₂.

Summer 2019 reported wider ranges, from 0.44 to 3.92 mg O₂ L⁻¹, with B5 having the lowest and C6 having the highest dissolved O₂.

Caminada inside pit stations showed similarities in bottom water temperature and dissolved O₂ compared to hypoxic shelf stations in summer 2018. Temperatures in Caminada ranged 26.6 to 26.7 °C while hypoxic shelf stations C6, B5, and D3 were similar but slightly warmer, ranging 27.0 to 27.2 °C. Caminada outside stations even were warmer than shelf stations, ranging 28.5 to 29.0 °C. Bottom water dissolved O₂ concentrations inside the pit (~1.4 mg O₂ L⁻¹) fell within range of hypoxic shelf sites (0.79 to 1.98 mg O₂ L⁻¹), however dissolved O₂ concentrations outside the pit (>3.5 mg O₂ L⁻¹) were more saturated than all of the hypoxic shelf sites. Sandy Point's inside pit stations showed similarities in bottom water temperature, salinity, and dissolved O₂ compared to hypoxic shelf stations in summer 2019, while the outside pit stations varied compared to hypoxic shelf ranges. Temperatures inside the pit (~27.5 °C) fell within range of the shelf stations C6, B5, and D3 (27.0-27.8 °C). Outside pit temperatures (~29 °C) were slightly warmer than the shelf stations. Salinity inside Sandy Point (31.9) fell within range of hypoxic sites (29.5-35.9), while outside pit station salinities (~28.9-30.8) were slightly lower, though did overlap with the hypoxic shelf range. Inside pit bottom dissolved O₂ (~2.32-2.75 mg O₂ L⁻¹) fell within range of the hypoxic shelf stations (0.44-3.92 O₂ L⁻¹), while outside pit stations were slightly more oxygenated (3.03-4.56 mg O₂ L⁻¹) and did overlap with the hypoxic shelf range.

3.2. Measured sediment O₂ consumption rates

The sediment oxygen consumption rates were calculated from triplicate sediment core incubation at each station. The rates are calculated for each individual core by assuming a linear drop in O₂ concentration over time and reported as average of the three cores with an uncertainty equal to its standard deviation. During spring, the sediment oxygen consumption at Caminada pit

station CA2_IN was much higher compared to outside, $\sim 5\times$ the rate of outside stations (*Fig. 2*). SOC rates for inside pit station CA2_IN averaged $51.80 \pm 27.70 \text{ mmol m}^{-2} \text{ d}^{-1}$ (higher variability is due to a low rate of $26.5 \text{ mmol m}^{-2} \text{ d}^{-1}$ in one of the triplicate cores), while outside stations CA8 and CA11 reported lower SOC rates of 10.84 ± 3.02 and $6.27 \pm 1.19 \text{ mmol m}^{-2} \text{ d}^{-1}$, respectively, averaging $8.55 \pm 3.23 \text{ mmol m}^{-2} \text{ d}^{-1}$ (*Table 2*). During summer incubations similar to spring, the SOC rates were higher inside the pit, $\sim 2\times$ higher compared to outside stations. In summer, SOC rate for inside station CA2_IN remained consistently high from spring with an average rate of $51.28 \pm 5.73 \text{ mmol m}^{-2} \text{ d}^{-1}$, and CA5_IN reported SOC at a rate of $43.14 \pm 1.53 \text{ mmol m}^{-2} \text{ d}^{-1}$, with an inside pit average of $47.21 \pm 5.83 \text{ mmol m}^{-2} \text{ d}^{-1}$. SOC rates of outside stations in summer increased from spring, with station CA8 and CA11 consuming oxygen at a rate of 23.91 ± 4.51 and $20.69 \pm 4.32 \text{ mmol m}^{-2} \text{ d}^{-1}$, respectively (*Table 2*).

The Sandy Point inside pit stations SP3_IN and SP5_IN consumed oxygen at rates of 23.71 ± 4.77 and $26.81 \pm 5.27 \text{ mmol m}^{-2} \text{ d}^{-1}$, respectively, while outside pit stations SP4 and SP11 had SOC rates of 24.98 ± 5.83 and $30.93 \pm 1.12 \text{ mmol m}^{-2} \text{ d}^{-1}$, respectively, during spring. During summer, inside stations SP3_IN and SP5_IN consumed oxygen at rates of 34.30 ± 3.73 and $34.31 \pm 1.59 \text{ mmol m}^{-2} \text{ d}^{-1}$, respectively, averaging $34.31 \pm 2.56 \text{ mmol m}^{-2} \text{ d}^{-1}$. Outside pit stations SP4 and SP11 had SOC rates of 35.95 ± 5.57 and $32.33 \pm 2.25 \text{ mmol m}^{-2} \text{ d}^{-1}$, respectively, averaging $34.14 \pm 4.28 \text{ mmol m}^{-2} \text{ d}^{-1}$. In general, the SOC rates increased from spring to summer, but SOC rates for inside and outside stations did not greatly differ from each other (*Table 2, Fig. 2*).

The shelf wide stations showed large spatial and temporal variability in SOC rates (*Table 3*). Each shelf station was found to have at least 1-2 sediment cores reach hypoxia by the end of the incubation period. Dissolved O_2 concentrations for the hypoxic shelf were as low as 0.23 mg

L⁻¹ in 2018 and as low as 0.22 mg L⁻¹ in 2019. Station C6 consistently had the lowest SOC rates compared to all other sampling stations, with SOC rates of 25.67 ± 1.05 mmol m⁻² d⁻¹ for spring, and 27.02 ± 3.14 and 31.08 ± 7.13 mmol m⁻² d⁻¹ for summer 2018 and summer 2019, respectively (*Fig. 3*). The SOC rate at station B5 was 58.95 ± 3.41 mmol m⁻² d⁻¹, which decreased the following year to 32.46 ± 10.36 mmol m⁻² d⁻¹. Station D3 consumed oxygen at a rate of 37.64 ± 4.96 mmol m⁻² d⁻¹, which increased the following year to 52.94 ± 21.71 mmol m⁻² d⁻¹. Station D5 had a SOC rate of 55.65 ± 24.55 mmol m⁻² d⁻¹, which slightly increased the following year to 59.59 ± 38.84 mmol m⁻² d⁻¹ (high variability between all cores). All SOC rates increased from the previous year with the exception of station B5, which decreased by $\sim \frac{1}{2}$ the SOC rate from the previous year (*Fig. 3*).

3.3 Sediment TOC content

Caminada dredge pit had overall low organic matter outside of the pit compared to inside stations. Inside station CA5_IN had the highest organic matter content, at least 1% higher, compared to any other station for both seasons. In spring 2018, the total average percentages for stations CA2_IN, CA5_IN, CA8, and CA11 were 0.26 ± 0.07 , 1.51 ± 0.51 , 0.06 ± 0.02 , and 0.08 ± 0.01 , respectively (*Fig. 4a*). In summer 2018, stations CA2_IN and CA8 experienced decreases in TOC, while stations CA5_IN and CA11 experienced increases, with CA5_IN having the most notable increase of almost 1% from spring to summer. Sandy Point TOC fell within range of CA stations, however, overall SP stations had higher TOC compared to CA. In the spring, stations SP3_IN, SP5_IN, SP4, and SP11 had 2.22 ± 0.04 , 2.25 ± 0.12 , 0.63 ± 0.28 , and 1.13 ± 0.28 %TOC, respectively. All stations experienced decreases in organic matter from spring to summer, with the exception of station SP11 which experienced an increase of ~ 0.4 %TOC. Inside stations SP3_IN and SP5_IN had similar %TOC, which was consistently higher compared

to outside stations. In contrast, outside stations were lower in TOC, with SP4 consistently having the lowest %TOC during both seasons.

In 2018, shelf station TOC content was within the range of Caminada's inside and outside stations, with stations C6, D3, and D5, averaging at 1.18 ± 0.17 , 0.65 ± 0.07 , and 0.71 ± 0.05 , respectively (*Fig. 4*). Hypoxic shelf stations overall had higher %TOC compared to CA stations, except CA5_IN, which had the highest TOC content of all stations. In 2019, TOC at C6, B5, D3, and D5 averaged 1.26 ± 0.42 , 1.43 ± 0.29 , 0.41 ± 0.17 , and 0.68 ± 0.03 , respectively. This data shows overall lower TOC in sediments in comparison to SP, with the exception of SP4 which had the lowest %TOC of all SP stations.

4. Discussion

4.1. Seasonal variability of dredge pit conditions

This study shows there was no significant difference in dredge pit SOC across different seasons. Sampling at both dredge pits was designed around the high river discharge period which fuels seasonal primary productivity and associated particulate organic carbon that fuels peak hypoxic period in late summer (July/August), at which time the river is usually at a low discharge period. Thus, our sampling seasons reflected SOC before the onset of peak hypoxia in May and during the hypoxia period in August (Rabalais et al., 2001).” Sediment oxygen consumption rates did vary among seasons and in most cases SOC increased from spring to summer as expected, however no station from either dredge pit experienced significant seasonal differences in SOC, with the exception of Caminada outside station CA11 ($p = 0.039$). The SOC at station CA11 increased by factor of three ($19 \text{ mmol O}_2 \text{ m}^{-2} \text{ d}^{-1}$) from spring to summer. The adjacent outside station CA8 also demonstrated an increasing trend from spring to summer, but the increase was not significant ($p = 0.067$). There was not enough data to determine seasonal differences in Caminada inside station CA5_IN, but SOC rates at the other inside station

CA2_IN were similar between the two seasons (51 to 52 mmol O₂ m⁻² d⁻¹) with bottom water being consistently hypoxic from spring to summer. Overall, only outside station CA11 showed a significant difference, whereas inside the pit there were no seasonal differences in SOC rates. This is surprising given that no station experienced significant differences in sediment TOC content between spring and summer, with the exception of inside station CA5_IN ($p = 0.009$). This points to the fact that SOC in sediment is a complex interplay between temperature, quantity and quality of organic matter present in sediments, and bottom O₂ conditions, among other factors. The observed increase in SOC (*Fig. 2*) outside the pit from spring to summer can be partly attributed to the observed higher temperatures in summer at these sites compared to spring, which promotes higher microbial activity (Lomas et al., 2002). The Mississippi River discharge peaked in March 2018 and declined thereafter (*S.I.*), which is likely reflected by concurrent increase in bottom water salinity changes between spring and summer (*Table 1*). Thus, the spring bloom associated with biological productivity from the river plume that supplies fresh organic matter to the sediment may have a smaller impact on sediment organic matter content in spring than in the summer, when the bloom is declining and hence supplying more organic matter to the seafloor. The same factors should also impact the inside pit stations but that is contrary to our data which shows no significant change in SOC inside the pit pointing to possible influence of other lateral sources of sediment and organic matter to the pits. However, the bottom water inside the pit was consistently low in dissolved O₂ from spring to summer, suggesting that the inside of the pit is persistently stratified, leading to a hypoxic environment for extended periods of time. This is not surprising as numerical studies carried out for Sandy Point suggests 19% drop in current velocity over the dredge pit and lower bottom current inside the pit ranging between 1-5 cm sec⁻¹, with lowest velocities in the deeper middle section of the pit

(Chaichitehrani et al., 2018, 2019). This coupled with lower wave orbital velocity near the dredge pit floors due to increased water depth can result in longer residence time of bottom water inside the pit, leading to persistent hypoxic conditions even when SOC rates are not significantly different from adjacent shelf. This persistently low O₂ condition inside pit bottom will lead to very shallow O₂ penetration depth inside the sediments (Cai et al., 1996; Rowe et al., 2008; Glud, 2008) resulting in more pronounced anaerobic respiration (Sorensen 1982; Lehrter et al., 2012).

The SOC rates for Sandy Point also showed increasing trends from spring to summer, but these increases were not significant. This scenario is different from Caminada, where there was a seasonal difference outside the pit but not inside. The same factors mentioned above for lack of significant seasonal variability inside the pit at CA is equally applicable for this site. However, one important factor that can exert additional influence is the proximity of SP to Mississippi River discharge. During our sampling season of 2019, the river discharge was high in February, peaked in March, and finally began to decline in August after an unusually long period of flood stage discharge (*Fig. S1*), thus Sandy Point could have been continuously influenced by energetic currents and fresh organic matter over the course of both seasons. Salinities at all stations were higher in spring compared to summer, supporting that the high freshwater influence during spring continued until summer months. Temperatures at all stations warmed from spring to summer, however temperatures between inside and outside stations were similar, differing only 1.5 °C or less each season. Bottom water dissolved O₂ concentrations at inside station SP5_IN and outside station SP4 decreased by ~0.5 mg L⁻¹, while inside station SP3_IN and outside station SP11 experienced increases from spring to summer by almost 1.0 mg L⁻¹. All stations experienced decreases in TOC content from spring to summer, with the exception of

SP11 which increased, however, this increase was not significant due to variability. This increase in TOC was unexpected due to SP11 having the smallest increase in SOC of $\sim 1.5 \text{ mmol O}_2 \text{ m}^{-2} \text{ d}^{-1}$ between seasons, while all other stations increased at least $7 \text{ mmol O}_2 \text{ m}^{-2} \text{ d}^{-1}$ or more between seasons. Although inside stations SP3_IN and SP5_IN significantly decreased from spring to summer ($p = 0.0006$ and $p = 0.003$, respectively), TOC inside the pit remained substantial throughout both seasons. Similar to CA, increases in SOC along with decreases in TOC between seasons rely on the factors of bottom water dissolved O_2 availability, temperature, and substrate quality. In addition, the continuous freshwater river influence in 2019 provided energetic currents and promoted a well-mixed water column at SP, contributing to the increased TOC at station SP11 and allowing the inside stations to have high organic matter between seasons.

The lack of seasonal differences reported in the dredge pits could be attributed to lateral sources of sediment and organic matter through pit infilling, an important component to dredge pit evolution and morphology (Obelcz et al., 2018; Robichaux et al., 2020). Constant infilling from lateral sediment transport could lead to similarities reported between seasons, which can occur just 1-2 months after dredging and continues until the pit is almost completely filled to capacity (Obelcz, et al., 2018). In fact, during a three-year survey in Sandy Point, sediment volume was found to be comprised of 90% far-filled sediment (Obelcz et al., 2018), highlighting that lateral sediment sources play an important role in not only pit infilling and substrate type, but also the biogeochemical processes. As a result, one of our main hypotheses, that SOC of dredge pits would increase from spring to summer due to increased water column primary production, organic matter accumulation and temperature is not observed, at least for the period of this study.

4.2. SOC variability between inside and outside pit environments

Seasonality did not widely affect dredge pit conditions, though we can further compare the differences of SOC between inside and outside stations of Caminada and Sandy Point. Caminada sediment oxygen consumption data demonstrated significant differences between inside and outside stations. In spring, SOC rate of inside station CA2_IN was not significantly higher than outside stations CA8 and CA11 ($p = 0.113$), probably due to an outlier replicate core that was 2-fold lower than other two replicate cores, which when removed, shows that inside is significantly different than outside ($p = 0.0001$). On average SOC rates in spring were 5-fold higher inside the pit compared to outside, and similarly in summer, SOC rates were significantly higher inside the pit than outside stations ($p = 0.00001$), by a factor of two. Sediment TOC content was higher inside the pit compared to outside, but only station CA5_IN had significantly higher TOC than outside stations in spring and summer ($p = 0.003$ and 0.00001 , respectively). The CA5_IN station also had higher TOC content than CA2_IN although both are located inside the pit, suggesting variability in sediment TOC distribution inside the pit associated with the topographical variability of the dredge pit seafloor. However, despite higher TOC content at CA5_IN, station CA2_IN had higher SOC rates. This points to the fact that SOC in sediment is not just a function of sediment TOC content but other variables like bottom O_2 concentration and efficiency of reoxidation of reduced species (Lehrter et al., 2012). Further, this complex relationship suggests that other anaerobic processes could be driving organic matter remineralization and O_2 consumption, such as nitrification, particularly ammonia oxidation (Campbell et al., 2019; Pakulski et al., 2000; Nunnally et al., 2014), and oxidation of other reduced species such as hydrogen sulfide oxidation (Brooks and Mahnken, 2003; Lee et al., 2019). Hydrogen sulfide oxidation has been observed in previously studied dredge pits (Graca, 2009), as well as reduced iron and manganese oxidation (Lehrter et al., 2012; Jorgensen, 1982;

Sampou and Oviatt, 1991; Aller et al., 1996; Jones et al., 2015). Overall, the larger differences in SOC rates inside versus outside the pit does impact the overlying bottom water O₂ conditions. The stations inside Caminada had consistently low O₂ compared to outside stations, about 2x lower, suggesting that sluggish bottom water current coupled with high SOC inside the pit is responsible for the persistent hypoxic conditions inside the pit (Johnston 1981; Nairn et al., 2004; Flocks and Franze, 2002; Graca, 2009).

The sediment oxygen consumption rates at Sandy Point did not show statistically significant differences between inside and outside stations. In spring, SOC inside and outside the pit stations fell within the same range, with outside station SP11 having the highest SOC. Similarly, summer SOC rates of inside and outside stations fell within the same range, with outside station SP4 having the highest SOC. %TOC was significantly higher inside SP compared to outside ($p = 0.02$), however, all SP stations were relatively higher in TOC than CA stations, except CA5_IN. This is contrary to our expectations of higher SOC inside the pit driven by higher organic matter accumulations, which differs from what was observed in CA. However, closer comparisons of bottom O₂ variabilities inside versus outside the two different pits shows interesting patterns. CA shows dramatic bottom O₂ differences inside versus outside, whereas SP does not (*Table 1*). This suggests that SP, which has a much more energetic setting than CA, replenishes bottom water at a faster rate. In fact, acoustic doppler velocity (ADV) based bottom current velocities were found to be consistently higher inside Sandy point pit with respect to Caminada pit (Bales et al., 2019).

Overall, inside CA stations had significantly higher (~2x higher) SOC rates than inside SP stations for both spring and summer ($p=0.04$ and $p=0.001$, respectively). This does not support one of our main hypotheses, that the mud-capped dredge pit Sandy Point will have

higher SOC rates compared to the sandy dredge pit Caminada due to higher rates of organic matter supply and less physical mixing, thus resulting in higher SOC rates. For the duration of this study, it is likely that Caminada was less energetic and more stratified than Sandy Point as a result of proximity to the Mississippi River delta, suggesting that prevailing physical processes may play a more dominant role in determining dredge pit O₂ dynamics than sediment biogeochemistry. Sandy Point dredge pit is located ~25km from the mouth of the Southwest Pass, which is the main Mississippi river outflow and is influenced by clockwise gyre of the Louisiana Bight which advects the river plume over this region (Walker et al., 1996; Obelcz et al., 2018). In contrast the Caminada pit is located over 100 km from the river mouth and has a weaker river plume influence, supporting a less energetic environment.

4.3. Shelf wide comparison

In order to have a broader understanding of the bottom water O₂ dynamics at CA and SP on a regional scale, shelf wide sampling was carried out in summer to provide a baseline comparison for our dredge pit data. The timing for shelf wide sampling coincided with the peak hypoxia period reported to occur in June-August (Rabalais et al., 1999) and thus the SOC rates can be considered an upper limit for the region. The spatial variability in SOC rates between the four shelf stations ranged by a factor of two, likely due to differences in oceanographic settings. However, the temporal variability in SOC rates between the two years at most stations is not significantly different. Nevertheless, the 2018 average shelf wide SOC rates of $25.67 \pm 1.05 - 55.65 \pm 24.55 \text{ mmol m}^{-2} \text{ d}^{-1}$ in 2018 can be compared with CA, which was sampled in 2018, while the 2019 average shelf wide SOC rates of $31.08 \pm 7.13 - 55.65 \pm 24.55 \text{ mmol m}^{-2} \text{ d}^{-1}$ can be compared with SP, which was sampled in 2019. Our shelf wide SOC rates are similar to those previously reported from this region which ranged from $1.9 - 21.9 \text{ mmol m}^{-2} \text{ d}^{-1}$ in months June-August from 2003-2007 (Murrell & Lehrter, 2011), $2.5 - 24.5 \text{ mmol m}^{-2} \text{ d}^{-1}$ in months June-

August from 2006-2007 (Lehrter et al., 2012), $16.44 - 43.20 \text{ mmol m}^{-2} \text{ d}^{-1}$ in months May-August in 2010-2011 (McCarthy et al., 2013), and $28.53 \text{ mmol m}^{-2} \text{ d}^{-1}$ in August 2015 (Ghaisas et al., 2019). At CA, the SOC inside the pit was not significantly different from the hypoxic shelf. This data suggests that inside CA is not significantly different from the shelf wide SOC rates. SP stations did not show any significant differences compared to the shelf wide stations in summer 2019. The SOC inside SP averaged $34.31 \pm 2.56 \text{ mmol m}^{-2} \text{ d}^{-1}$, while the average for all shelf stations in summer 2019 was $42.60 \pm 20.83 \text{ mmol m}^{-2} \text{ d}^{-1}$. Some hypoxia shelf stations actually showed even higher rates than SP, for example the highest rate in summer 2019 was station D5 at $59.59 \pm 38.44 \text{ mmol m}^{-2} \text{ d}^{-1}$, which is ~ 2 times higher than any of the rates from Sandy Point in summer 2019. This difference in SOC between SP and shelf wide stations is probably due to proximity of Sandy point to Mississippi river outflow. The comparisons between the shelf stations and inside pit stations are further complicated by the fact that the dredge pits acts a sediment traps for the region, receiving a larger fraction of the sediment and associated organic matter not only from the primary productivity in the overlying water column but from adjacent shelf due to wave-current induced transport as well as the Mississippi river and far field sources during passage of fronts (Chaichiterani et al., 2019; Obelcz et al., 2018). Thus, the nature of organic matter in the dredge pit sediments may not be similar to adjacent shelf, where the SOC is driven by the sinking of fresh organic matter from the spring bloom (Fry et al., 2015; Wang et al., 2018). The spring and summer sampling cruises in our study are also punctuated by passage of tropical storms which also makes it difficult to access the processes influencing SOC. We believe this to have a significant impact on the summer SOC rates at Sandy Point, where sampling was carried out three weeks after passage of Hurricane Barry (category 1) and anecdotal data points to greater than 1m thick layer of storm deposit inside the pit.

Overall, our results suggest that SOC rates inside dredge pits are statistically similar to observed shelf wide SOC rates despite persistently low bottom O₂ concentration recorded inside the pits. This result is surprising as previous studies using static core incubations and benthic chambers (Lehrter et al., 2012; Rowe et al., 2008), observed lower sediment oxygen consumption coinciding with lower bottom-water oxygen concentration. In fact, in this study we find a weak opposite trend ($R^2 = 0.42$; $p = 0.0006$) (*Fig. S2*) with high sediment oxygen consumption coinciding with lower bottom-water oxygen concentration (*Fig. 5*). Bottom-water temperature and sediment oxygen consumption also were not significantly related ($p = 0.831$), suggesting that seasonal variability does not explain this relationship nor does this relation change when comparing spring and summer values separately. Similar relationship between bottom O₂ and SOC has been previously reported by McCarthy et al. (2013) from this region using flow through core incubations, and they concluded that oxygen concentration may be regarded as the dependent variable instead of assuming it be an independent variable affecting sediment oxygen consumption (Murrell & Lehrter, 2011). Thus, SOC rates may be driven by quantity and quality of sediment organic matter associated with various sources instead of bottom O₂ concentration, which would explain the lack of variability seen in our current data.

Sediment oxygen consumption rates measured in this study were higher than or fell within range of previous hypoxic NGOM shelf studies. From years 2003 to 2007, SOC rates measured by Lehrter et al. (2012) and Murrell & Lehrter (2011) ranged from 1.3-23.3 mmol m⁻² d⁻¹ during spring months (March-April), and 1.9-24.5 mmol m⁻² d⁻¹ during summer months (June-September). In the following years of 2008-2011, SOC rates measured by McCarthy et al. (2013) increased, ranging from 14.95-43.20 mmol m⁻² d⁻¹ during spring (May) and 9.94-26.09 mmol m⁻² d⁻¹ during summer months (August-September). A more recent study by Ghaisas et al.

(2019), measured SOC at station C6 to range from 27.03-28.53 mmol m⁻² d⁻¹ during summer (August) 2015, slightly higher than previous years. In this study, SOC rates on the hypoxic shelf from 2018 to 2019 ranged higher than previous studies, from 25.67 to 59.59 mmol m⁻² d⁻¹ in summer. Seasonal hypoxia in this area has increased due to agricultural practices and increased population growth (Bianchi et al., 2010; Scavia and Bricker, 2006; Rabalais and Turner, 2019), which is evident from the trends in previous data.

5. Conclusion

This study provides the first efforts to report SOC data within NGOM dredge pits, and also provide insight for future dredging operations which are expected to escalate in the next few decades due to persistent coastal erosion and sea level rise. The contributions of this study are especially crucial to the Louisiana shelf due to the regular occurrence of hypoxia every summer. Thus, understanding the effects of post dredging on water quality on a regional scale is critical. The two main drivers of hypoxia were seen to affect the Caminada dredge pit, where the depressional pit was severely stratified and accumulated high organic matter, resulting in SOC rates significantly higher than the adjacent outside region. However, from a regional perspective these rates are similar to those observed in the shallow Louisiana shelf prone to seasonal hypoxia. Conversely, Sandy Point dredge pit did not show any significant differences in SOC compared to adjacent outside areas due to a more energetic environment, indicating that sluggish water circulation inside pits along with enhanced trapping of organic matter plays an important role in the observed low bottom water conditions inside dredge pits. Low oxygen conditions are known to cause changes to benthic community composition, such as loss of fauna and recolonization of faunal species that can withstand hypoxic conditions (Diaz and Rosenberg, 1995). Hypoxic conditions coupled with sediment disturbance from dredging could potentially impact benthic communities in terms of infaunal abundance and diversity, recolonization of new

species, or even loss of benthic species that may take several years to recover. (Byrnes et al., 2004; Crowe et al., 2016). Benthic community shifts in relation to sediment disturbance have been reported in recent years due from species associated to coarser grains to recolonization of species new species associated with finer grains as a result in finer sediment trapping within dredge pits (Crowe et al., 2016). Thus, biogeochemical changes associated with dredging activities are likely to impact benthic ecology on decadal timescales.

In summary, our study suggests that SOC rates inside recently excavated dredge pits can be similar to the surrounding shelf but can sustain for a longer period of time, which when coupled with sluggish water circulation results in persistent low bottom O₂ conditions, well beyond the duration of the seasonal hypoxia in this region. These conditions may have negative impacts on the benthic communities inside these pits. This study provides valuable insight on the impacts of dredge pits to surrounding hypoxia in this region which is critical as future dredging operations are expected to increase worldwide with projected sea-level rise.

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References

1. Aller, R. C., Blair, N. E., Xia, Q., & Rude, P. D. (1996). Remineralization rates, recycling, and storage of carbon in Amazon shelf sediments. *Continental Shelf Research*, 16(5-6), 753-786.
2. Bales, R., Xu K., Li, G., Bargu, S., Bentley, S., Maiti, K., White, J., Wilson, C., Xue, Z.G. (2019) An assessment of sediment transport and water quality between contrasting dredge pits of Louisiana shelf. *25th Biennial Conference of the Coastal and Estuarine Research Federation*. November 2019; Mobile, AL, USA
3. Barras, J. A., Bernier, J. C., & Morton, R. A. (2008). *Land area change in coastal Louisiana, a multidecadal perspective (from 1956 to 2006)* (p. 14). Reston: US Department of the Interior, US Geological Survey.
4. Bird, E., & Lewis, N. (2014). *Beach renourishment*. Springer.
5. Bianchi, T. S., DiMarco, S. F., Cowan Jr, J. H., Hetland, R. D., Chapman, P., Day, J. W., & Allison, M. A. (2010). The science of hypoxia in the Northern Gulf of Mexico: a review. *Science of the Total Environment*, 408(7), 1471-1484.
6. Brooks, K. M., & Mahnken, C. V. (2003). Interactions of Atlantic salmon in the Pacific Northwest environment: III. Accumulation of zinc and copper. *Fisheries Research*, 62(3), 295-305.
7. Byrnes, M. R., Hammer, R. M., Thibaut, T. D., & Snyder, D. B. (2004a). Effects of sand mining on physical processes and biological communities offshore New Jersey, USA. *Journal of Coastal Research*, 20(1 (201)), 25-43.
8. Byrnes, M. R., Hammer, R. M., Thibaut, T. D., & Snyder, D. B. (2004b). Physical and biological effects of sand mining offshore Alabama, USA. *Journal of Coastal Research*, 20(1 (201)), 6-24.
9. Cai, W. J., & Sayles, F. L. (1996). Oxygen penetration depths and fluxes in marine sediments. *Marine Chemistry*, 52(2), 123-131.
10. Campbell, L. G., Thrash, J. C., Rabalais, N. N., & Mason, O. U. (2019). Extent of the annual Gulf of Mexico hypoxic zone influences microbial community structure. *PloS one*, 14(4).
11. Chaichitehrani, Nazanin, "Numerical Experiment of Sediment Dynamics over a Dredged Pit on the Louisiana Shelf" (2018). LSU Doctoral Dissertations. 4510. https://digitalcommons.lsu.edu/gradschool_dissertations/4510

12. Chaichitehrani, N., Li, C., Xu, K., Allahdadi, M. N., Hestir, E. L., & Keim, B. D. (2019). A numerical study of sediment dynamics over Sandy Point dredge pit, west flank of the Mississippi River, during a cold front event. *Continental Shelf Research*.
13. Cooper, K., Boyd, S., Eggleton, J., Limpenny, D., Rees, H., & Vanstaen, K. (2007). Recovery of the seabed following marine aggregate dredging on the Hastings Shingle Bank off the southeast coast of England. *Estuarine, Coastal and Shelf Science*, 75(4), 547-558.
14. Couvillion, B. R., Beck, H., Schoolmaster, D., & Fischer, M. (2017). Land Area Change in Coastal Louisiana (1932 to 2016) Scientific Investigations Map 3381. *U.S. Geological Survey Scientific Investigations Map 3381*, 16.
15. Crowe, S. E., Bergquist, D. C., Sanger, D. M., & Van Dolah, R. F. (2016). Physical and biological alterations following dredging in two beach nourishment borrow areas in South Carolina's coastal zone. *Journal of Coastal Research*, 32(4), 875-889.
16. DeLaune, R. D., & White, J. R. (2012). Will coastal wetlands continue to sequester carbon in response to an increase in global sea level?: A case study of the rapidly subsiding Mississippi river deltaic plain. *Climatic Change*, 110(1-2), 297-314.
17. Desprez, M. (2000). Physical and biological impact of marine aggregate extraction along the French coast of the Eastern English Channel: short-and long-term post-dredging restoration. *ICES Journal of Marine Science*, 57(5), 1428-1438.
18. Fenchel, T., Blackburn, H., King, G. M., & Blackburn, T. H. (1998). *Bacterial biogeochemistry: the ecophysiology of mineral cycling*. San Diego, CA: Academic press, 1-27.
19. Finkl, C. W., Benedet, L., & Campbell, T. J. (2006). Beach nourishment experience in the United States: Status and trends in the 20 th century. *Shore & Beach*, 74(2), 8-16.
20. Flocks, F., & Franze, C. (2002). Environmental Issues-Dredge Pit Characterization. *Environmental Atlas of the Lake Pontchartrain Basin: Lake Pontchartrain Basin Foundation, New Orleans, LA US Geological Survey Open File Report*.
21. Fry, B., Justic, D., Riekenberg, P., Swenson, E. M., Turner, R. E., Wang, L. X., Boyd, B. (2015). Carbon Dynamics on the Louisiana Continental Shelf and Cross-Shelf Feeding of Hypoxia. *Estuaries and Coasts*, 38(3), 703-721.
22. Ghaisas, N. A., Maiti, K., & White, J. R. (2019). Coupled iron and phosphorus release from seasonally hypoxic Louisiana shelf sediment. *Estuarine, Coastal and Shelf Science*, 219, 81-89.

23. Glud, R. N. (2008). Oxygen dynamics of marine sediments. *Marine Biology Research*, 4(4), 243-289.
24. Graca, B., Burska, D., & Matuszewska, K. (2004). The impact of dredging deep pits on organic matter decomposition in sediments. *Water, air, and soil pollution*, 158(1), 237-259.
25. Graca, B. (2009). The Puck Bay as an example of deep dredging unfavorably affecting the aquatic environment. *Oceanological and Hydrobiological Studies*, 38(2), 109-127.
26. Hanson, H., Brampton, A., Capobianco, M., Dette, H. H., Hamm, L., Laustrup, C., ... & Spanhoff, R. (2002). Beach nourishment projects, practices, and objectives—a European overview. *Coastal engineering*, 47(2), 81-111.
27. Hedges, J. I., Turin, H. J., & Ertel, J. R. (1984). Sources and distributions of sedimentary organic matter in the Columbia River drainage basin, Washington and Oregon 1. *Limnology and Oceanography*, 29(1), 35-46.
28. Hedges, J. I., & Stern, J. H. (1984). Carbon and nitrogen determinations of carbonate-containing solids 1. *Limnology and oceanography*, 29(3), 657-663.
29. Hopkinson, C. S., Giblin, A. E., Tucker, J., & Garritt, R. H. (1999). Benthic metabolism and nutrient cycling along an estuarine salinity gradient. *Estuaries*, 22(4), 863-881.
30. Johnson, R. O., & Nelson, W. G. (1985). Biological effects of dredging in an offshore borrow area. *Florida Scientist*, 166-188.
31. Johnston, S. A. (1981). Estuarine dredge and fill activities: a review of impacts. *Environmental management*, 5(5), 427-440.
32. Jones, P., Maiti, K., & McManus, J. (2015). Lead-210 and Polonium-210 disequilibria in the northern Gulf of Mexico hypoxic zone. *Marine Chemistry*, 169, 1-15.
33. Jørgensen, B. B. (1982). Mineralization of organic matter in the sea bed—the role of sulphate reduction. *Nature*, 296(5858), 643.
34. Jørgensen, B. B., & Revsbech, N. P. (1985). Diffusive boundary layers and the oxygen uptake of sediments and detritus 1. *Limnology and oceanography*, 30(1), 111-122.
35. Khalil, S. M., Finkl, C. W., Roberts, H. H., & Raynie, R. C. (2010). New approaches to sediment management on the inner continental shelf offshore coastal Louisiana. *Journal of Coastal Research*, 591-604.
36. Kulp, M., Penland, S., Williams, S. J., Jenkins, C., Flocks, J., & Kindinger, J. (2005). Geologic framework, evolution, and sediment resources for restoration of the Louisiana coastal zone. *Journal of coastal research*, 56-71.

37. Lee, T., Kim, H. C., & Son, Y. B. (2019). Sediment oxygen consumption and hydrogen sulfide release in hypoxic areas of Gamak Bay, Korea. *Applied Ecology and Environmental Research*, 17(2), 3199-3214.
38. Lehrter, J. C., Beddick, D. L., Devereux, R., Yates, D. F., & Murrell, M. C. (2012). Sediment-water fluxes of dissolved inorganic carbon, O₂, nutrients, and N₂ from the hypoxic region of the Louisiana continental shelf. *Biogeochemistry*, 109(1-3), 233-252.
39. Liu, H., Xu, K., Bentley, S. J., Wilson, C., Xue, Z., & Miner, M. D. (2018, December). Sediment transport and geomorphologic response in multiple dredge pits near Ship Shoal of coastal Louisiana. In *AGU Fall Meeting Abstracts*.
40. Liu, H., Xu, K., Li, B., Han, Y., & Li, G. (2019). Sediment Identification Using Machine Learning Classifiers in a Mixed-Texture Dredge Pit of Louisiana Shelf for Coastal Restoration. *Water*, 11(6), 1257.
41. Liu, H., Xu, K., & Wilson, C. (2020a). Sediment infilling and geomorphological change of a mud-capped Raccoon Island dredge pit near Ship Shoal of Louisiana shelf. *Estuarine, Coastal and Shelf Science*, 106979.
42. Liu, H., Xu, K., Ou, Y., Bales, R., Zang, Z., & Xue, Z. G. (2020b). Sediment Transport near Ship Shoal for Coastal Restoration in the Louisiana Shelf: A Model Estimate of the Year 2017–2018. *Water*, 12(8), 2212.
43. Lomas, M. W., Glibert, P. M., Shiah, F. K., & Smith, E. M. (2002). Microbial processes and temperature in Chesapeake Bay: current relationships and potential impacts of regional warming. *Global Change Biology*, 8(1), 51-70.
44. McCarthy, M. J., Carini, S. A., Liu, Z., Ostrom, N. E., & Gardner, W. S. (2013). Oxygen consumption in the water column and sediments of the northern Gulf of Mexico hypoxic zone. *Estuarine, Coastal and Shelf Science*, 123, 46-53.
45. Murrell, M. C., & Lehrter, J. C. (2011). Sediment and lower water column oxygen consumption in the seasonally hypoxic region of the Louisiana continental shelf. *Estuaries and coasts*, 34(5), 912-924.
46. Nairn R., Johnson J.A., Hardin D., Michel J. (2004). A biological and physical monitoring program to evaluate long-term impacts from sand dredging operations in the United States outer continental shelf. *Journal of Coastal Research*, 20(1), 126–137
47. Nairn, R. B., Lu, Q., & Langendyk, S. K. (2005). A study to address the issue of seafloor stability and the Impact on Oil and Gas infrastructure in the Gulf of Mexico. US Dept. of the Interior, MMS, Gulf of Mexico OCS Region, New Orleans, LA OCS Study MMS, 43, 179.

48. Nunnally, C. C., Quigg, A., DiMarco, S., Chapman, P., & Rowe, G. T. (2014). Benthic–pelagic coupling in the Gulf of Mexico hypoxic area: Sedimentary enhancement of hypoxic conditions and near bottom primary production. *Continental Shelf Research*, 85, 143-152.
49. Niu, X., & Yu, X. (2011). Analytical study on long wave refraction over a dredge excavation pit. *Wave Motion*, 48(3), 259-267.
50. Obelcz, J., Xu, K., Bentley, S. J., O'Connor, M., & Miner, M. D. (2018). Mud-capped dredge pits: An experiment of opportunity for characterizing cohesive sediment transport and slope stability in the northern Gulf of Mexico. *Estuarine, Coastal and Shelf Science*, 208, 161-169.
51. Palmer, T. A., Montagna, P. A., & Nairn, R. B. (2008). The effects of a dredge excavation pit on benthic macrofauna in offshore Louisiana. *Environmental management*, 41(4), 573-583.
52. Pakulski, J. D., Benner, R., Whitledge, T., Amon, R., Eadie, B., Cifuentes, L., & Stockwell, D. (2000). Microbial metabolism and nutrient cycling in the Mississippi and Atchafalaya River plumes. *Estuarine, Coastal and Shelf Science*, 50(2), 173-184.
53. Penland, S., & Ramsey, K. E. (1990). Relative sea-level rise in Louisiana and the Gulf of Mexico: 1908-1988. *Journal of Coastal Research*, 323-342.
54. Rabalais, N. N., Turner, R. E., Justic, D., Dortch, Q., & Wiseman Jr, W. J. (1999). Characterization of hypoxia: topic I report for the integrated assessment on hypoxia in the Gulf of Mexico.
55. Rabalais, N. N., Turner, R. E., & Wiseman Jr, W. J. (2001). Hypoxia in the Gulf of Mexico. *Journal of environmental quality*, 30(2), 320-329
56. Rabalais, N. N., & Turner, R. E. (2019). Gulf of Mexico Hypoxia: Past, Present, and Future. *Limnology and Oceanography Bulletin*, 28(4), 117-124.
57. Roberts, H.H. (1997). Dynamic changes of the Holocene Mississippi River Delta Plain: The delta cycle. *Journal of Coastal Research*, 13, 605–627.
58. Robichaux, P., Xu, K., Bentley, S. J., Miner, M. D., & Xue, Z. G. (2020). Morphological evolution of a mud-capped dredge pit on the Louisiana shelf: Nonlinear infilling and continuing consolidation. *Geomorphology*, 354, 107030.
59. Rowe, G.T. (2002) Chapman Continental shelf hypoxia: some nagging questions. *Gulf of Mexico Sci.* (2) pp. 153-160

60. Rowe, G. T., Morse, J., Nunnally, C., & Boland, G. S. (2008). Sediment community oxygen consumption in the deep Gulf of Mexico. *Deep Sea Research Part II: Topical Studies in Oceanography*, 55(24-26), 2686-2691.
61. Sampou, P., & Oviatt, C. A. (1991). A carbon budget for a eutrophic marine ecosystem and the role of sulfur metabolism in sedimentary carbon, oxygen and energy dynamics. *Journal of marine research*, 49(4), 825-844.
62. Sapkota, Y. and J.R. White. (2019). Marsh edge erosion and associated carbon dynamics in coastal Louisiana: A proxy for future wetland-dominated coastlines world-wide. *Estuarine, Coastal and Shelf Science*, 226, 106289.
63. Scavia, D., & Bricker, S. B. (2006). Coastal eutrophication assessment in the United States. In *Nitrogen Cycling in the Americas: Natural and Anthropogenic Influences and Controls*(pp. 187-208). Springer, Dordrecht.
64. Sonders, C., Forrest-Vandera, B. and Andrews, J. (2014) Louisiana Borrow Area Management and Monitoring (BAMM) Program-Final Report. Boca Raton, Florida: Coastal Planning & Engineering, Inc., A CB&I Company, 20p. (Prepared for Coastal Protection and Restoration Authority).
65. Sørensen, J. (1982). Reduction of ferric iron in anaerobic, marine sediment and interaction with reduction of nitrate and sulfate. *Appl. Environ. Microbiol.*, 43(2), 319-324.
66. Syvitski, J. P., Kettner, A. J., Overeem, I., Hutton, E. W., Hannon, M. T., Brakenridge, G. R., ... & Nicholls, R. J. (2009). Sinking deltas due to human activities. *Nature Geoscience*, 2(10), 681.
67. UNEP (2019). Sand and sustainability: Finding new solutions for environmental governance of global sand resources. GRID-Geneva, United Nations Environment Programme, Geneva, Switzerland. <https://doi.org/10.2112/JCOASTRES-D-15-00075.1>
68. Upreti, K., Maiti, K., & Rivera-Monroy, V. H. (2019). Microbial mediated sedimentary phosphorus mobilization in emerging and eroding wetlands of coastal Louisiana. *Science of The Total Environment*, 651, 122-133.
69. Walker, N. D. (1996). Satellite assessment of Mississippi River plume variability: causes and predictability. *Remote sensing of environment*, 58(1), 21-35.
70. Wang, H., Hu, X., Rabalais, N. N., & Brandes, J. (2018). Drivers of oxygen consumption in the northern Gulf of Mexico hypoxic waters—A stable carbon isotope perspective. *Geophysical Research Letters*, 45, 10,528–10,538. <https://doi.org/10.1029/2018GL078571>

71. Wilber, D. H., Clarke, D. G., Ray, G. L., & Burlas, M. (2003). Response of surf zone fish to beach nourishment operations on the northern coast of New Jersey, USA. *Marine Ecology Progress Series*, 250, 231-246.
72. Xu, K., Sanger, D., Riekerk, G., Crowe, S., Van Dolah, R. F., Wren, P. A., & Ma, Y. (2014). Seabed texture and composition changes offshore of Port Royal Sound, South Carolina before and after the dredging for beach nourishment. *Estuarine, Coastal and Shelf Science*, 149, 57-67.
73. Zimmerman, C. F., Keefe, C.W., & Bashe, J. (1997). Method 440.0 Determination of Carbon and Nitrogen in Sediments and Particulates of Estuarine/Coastal Waters Using Elemental Analysis. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-15/009.
74. Zhang, K., Douglas, B. C., & Leatherman, S. P. (2004). Global warming and coastal erosion. *Climatic change*, 64(1-2), 41.

Table 1. Summary of conditions at study sites. Months April-May are further referred to as 'spring' and July-September are referred as 'summer'. Caminada is represented as "CA" and Sandy Point is represented as "SP"

Station	Site Description	Year	Month	Depth (m)	Temp (°C)	Bottom Salinity	Bottom O ₂ (mg L ⁻¹)
CA2_IN	Inside Pit	2018	May	13.1	22.9	34.4	1.93
			July	12.9	26.6	34.8	1.46
CA5_IN	Inside Pit	2018	May	13.1	23.1	34.0	1.43
			July	13.2	26.7	34.8	1.42
CA8	Outside Pit	2018	May	7.0	25.5	22.9	6.88
			July	8.1	29.0	30.3	5.46
CA11	Outside Pit	2018	May	7.0	24.5	27.9	6.71
			July	9.3	28.5	30.6	3.50
SP3_IN	Inside Pit	2019	May	17.3	22.5	34.8	1.79
			September	16.7	27.5	31.9	2.75
SP5_IN	Inside Pit	2019	May	16.7	22.6	34.6	2.81
			September	16.5	27.4	31.9	2.32
SP4	Outside Pit	2019	May	10.6	23.1	31.7	4.92
			September	10.8	28.9	28.9	4.56
SP11	Outside Pit	2019	May	10.4	22.9	31.7	2.36
			September	10.3	29.0	30.8	3.03
C6	Shelf	2018	August	19.1	25.3	36.0	1.29
		2019	April	19.2	24.7	35.2	6.02
			July	19.0	27.8	29.5	3.92
B5	Shelf	2018	August	17.1	27.3	35.5	1.40
		2019	July	18.0	27.0	32.9	0.44
D3	Shelf	2018	August	17.1	26.4	35.7	0.79
		2019	July	16.0	27.0	31.6	2.60
D5	Shelf	2018	August	32.2	22.8	36.3	1.98
		2019	July	33.8	22.5	35.9	2.10

Table 2. Summary of sediment oxygen consumption (SOC) calculated from sediment core incubations for Caminada and Sandy Point dredge pit stations. A “-” sign indicates no data was collected.

Dredge Pit	Station	Average O ₂ Consumption (mmol m ⁻² d ⁻¹)					
		Spring			Summer		
Caminada	CA2_IN	51.80	±	27.7	51.28	±	5.73
	CA5_IN	-	±	-	43.14	±	1.53
	CA8	10.84	±	3.02	23.91	±	4.51
	CA11	6.27	±	1.19	20.69	±	4.32
Sandy Point	SP3_IN	23.71	±	4.77	34.30	±	3.73
	SP5_IN	26.81	±	5.27	34.31	±	1.59
	SP4	24.98	±	5.83	35.95	±	5.57
	SP11	30.93	±	1.12	32.33	±	2.25

Table 3. Summary of SOC rates calculated from sediment core incubations for shelf stations.
Data are summarized by station and season.

Summer 2018				Summer 2019			
Station	SOC Rate ($\text{mmol m}^{-2}\text{d}^{-1}$)			Station	SOC Rate ($\text{mmol m}^{-2}\text{d}^{-1}$)		
C6	25.67	$\pm$	1.05	C6	31.08	$\pm$	7.13
B5	58.95	$\pm$	3.41	B5	32.46	$\pm$	10.36
D3	37.64	$\pm$	4.96	D3	52.94	$\pm$	21.71
D5	55.65	$\pm$	24.55	D5	59.59	$\pm$	38.44

Figure 1. Study area displaying Caminada (CA) and Sandy Point (SP) with triangles, and shelf stations in circles (a), Caminada dredge pit including stations CA2_IN, CA5_IN, CA8, and CA11 (b), and Sandy Point dredge pit including stations SP3_IN, SP5_IN, SP4, and SP11 (c).

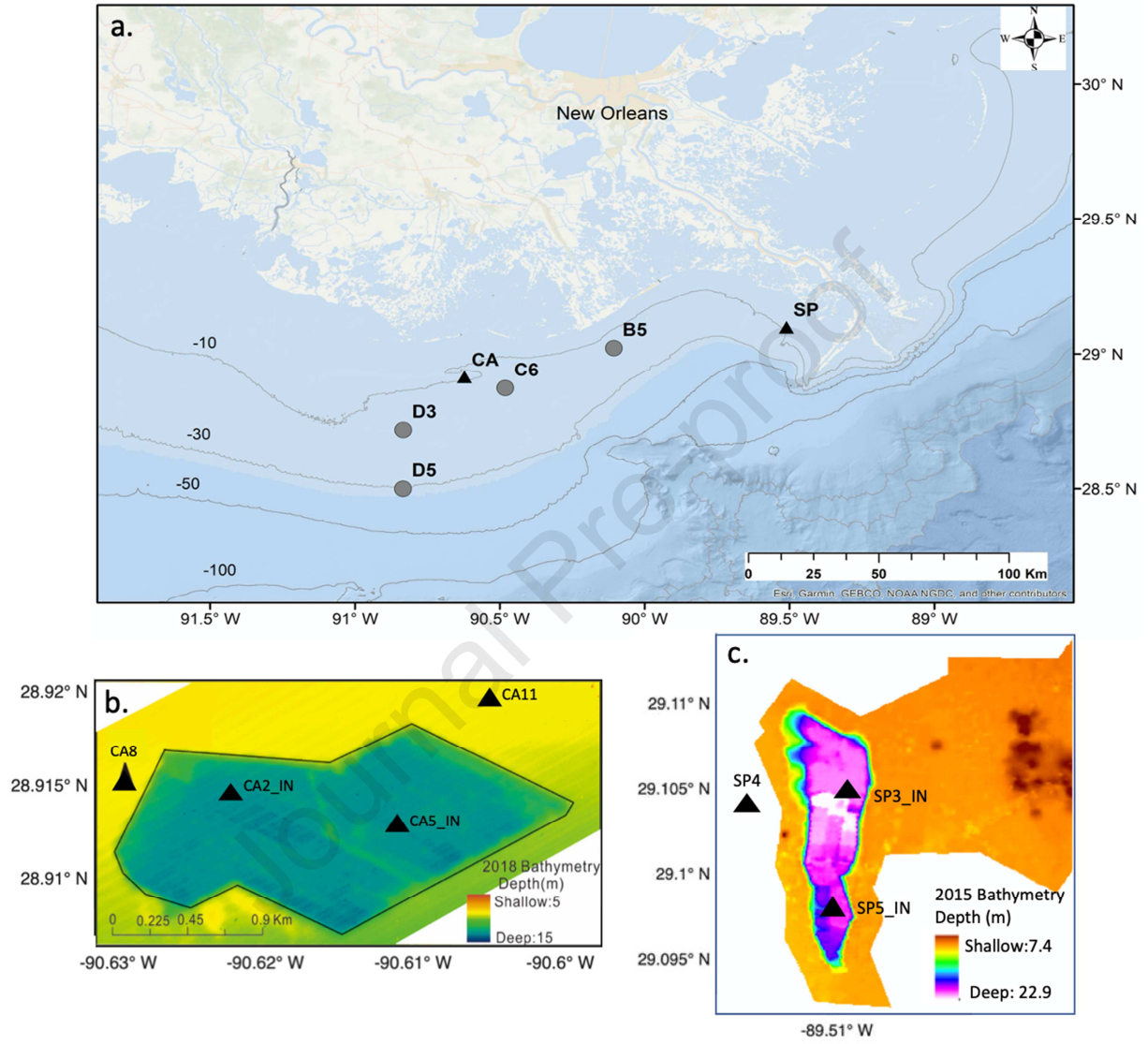


Figure 2. Comparison of SOC rates from Caminada and Sandy Point sediment core incubations. Inside stations are displayed with a dotted pattern fill, and outside stations are displayed without a pattern fill. 'ND' indicates no data was collected.

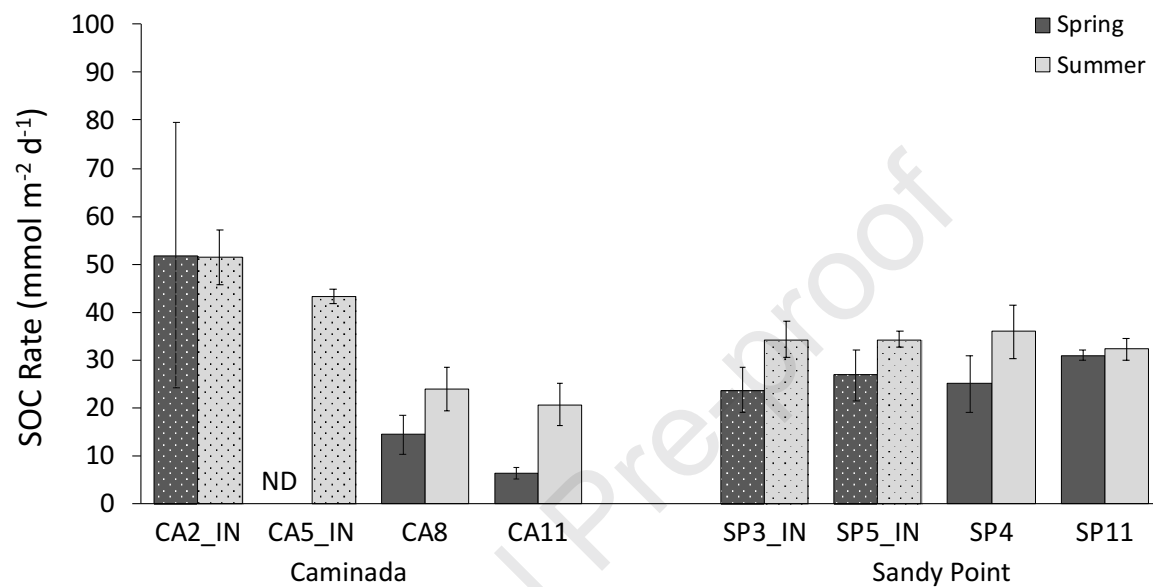


Figure 3. SOC rates from sediment core incubations of shelf stations.

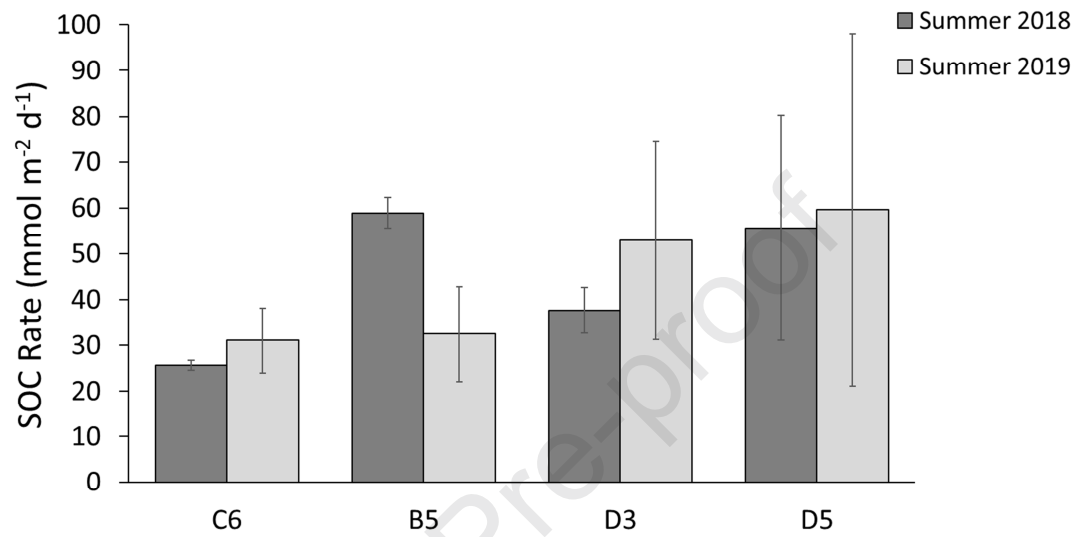


Figure 4. Total organic carbon (TOC) from (a) Caminada and Sandy Point and (b) shelf sediment cores. Inside pit stations are displayed with a dotted pattern fill. 'ND' indicates no data was collected.

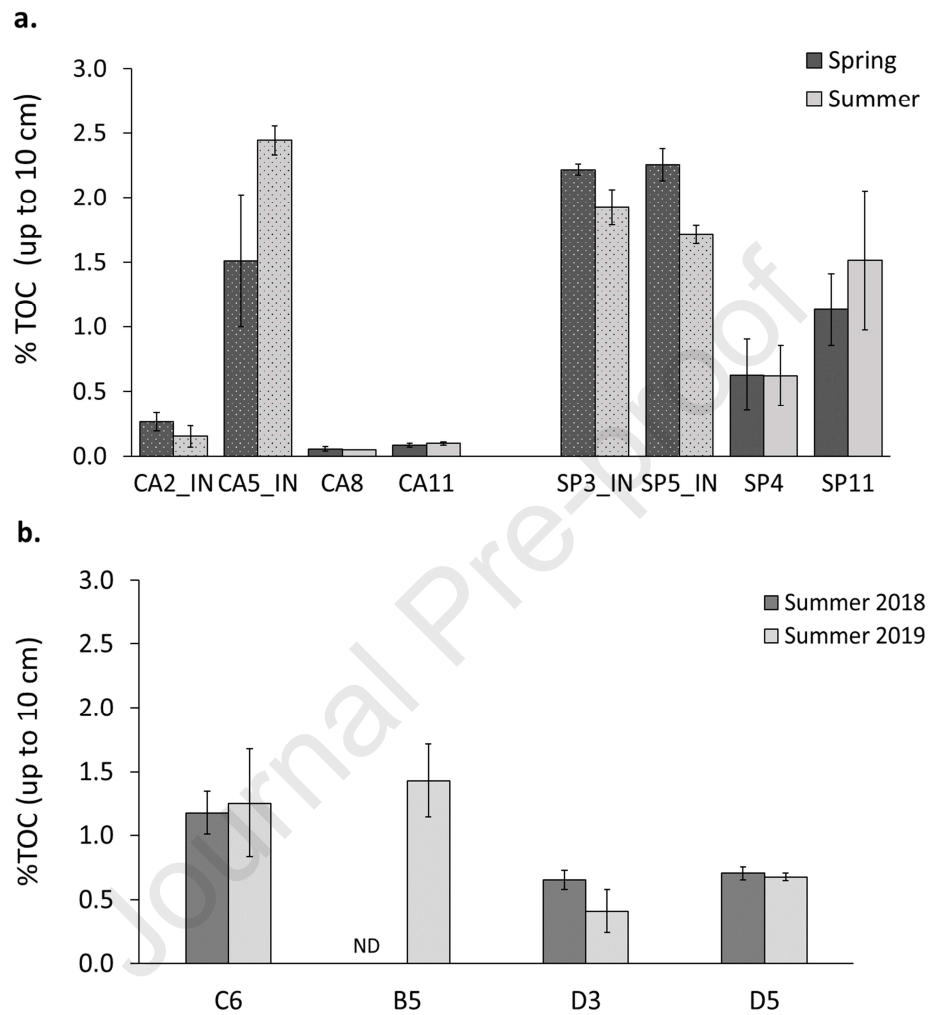
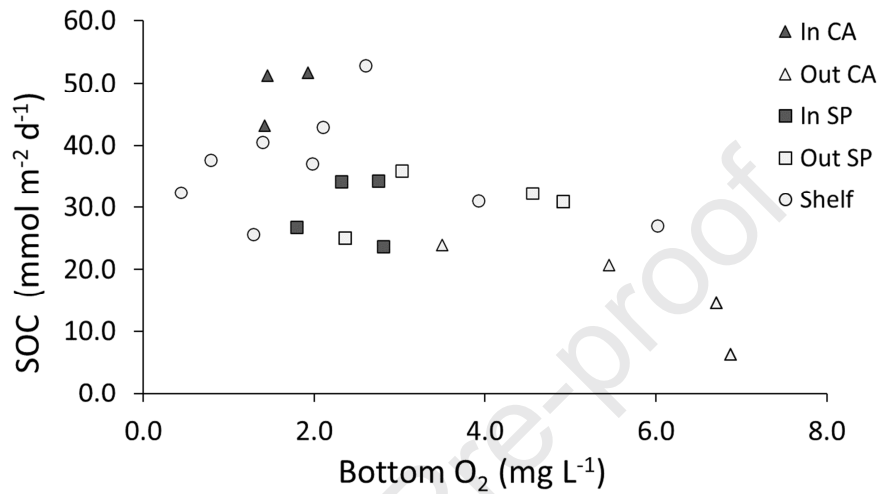


Figure 5. Relationship of bottom water dissolved oxygen concentrations and sediment oxygen consumption. Triangles indicate Caminada stations, squares indicate Sandy Point stations, and circles indicate shelf baseline stations. Filled symbols represent inside pit data. Each symbol represents the station average.



Highlights

- Offshore sand and mud dredging is being increasingly utilized to combat coastal erosion and land loss worldwide.
- Dredge pits in the northern Gulf of Mexico (NGOM) are found to have consistent low oxygen or hypoxic conditions in comparison to the surrounding seafloor.
- Sediment oxygen consumption inside NGOM dredge pits are found to be not significantly different from surrounding hypoxia region during both summer and spring.
- This is the first study from this region to investigate sediment biogeochemistry inside dredge pits.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

A handwritten signature in black ink, appearing to read 'Laura Thompson', is written inside a rectangular box. The signature is fluid and cursive.

Laura Thompson