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Controls on Surface and Downcore Sedimentary Organic Matter in a Constructed Oyster Reef

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Abstract: Oysters provide a suite of important ecosystem services, and recent research shows that oyster restoration rapidly enhances sedimentary organic carbon deposition. In 2012, an oyster reef enhancement project began in the GTM National Estuarine Research Reserve in Northeast FL, USA. We analyzed the spatial and downcore variability in sedimentary organic matter (OM) and particle sizes in the intertidal zone between the reefs and the marsh, along with oyster reef characteristics, to better understand physical and/or biological influences on sediment. Our data indicate that OM in the top 20 cm of sediment cores was negatively correlated with reef age. Similar decreases in particles <63 μm suggest remobilization of sediment, likely driven by the degradation of the reef structure over its approximately 9-year lifetime. Likewise, a survey of surface sediments showed that adjacent reef structural metrics were the best predictor of sediment OM and particle size. These results highlight the importance of reef structure as a control on sedimentary organic carbon deposition and stability in areas where physical energy is relatively high. This result is discussed in the context of implications for carbon budgets and biogeochemical ecosystem services of oysters as a part of living shorelines.

Keywords: oyster restoration; sediment; organic carbon; living shoreline; *Crassostrea virginica*; sediment deposition

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1. Introduction

Living sustainably in a coastal environment entails multiple intersecting challenges from climate change, overharvesting, eutrophication, and land development [1–3]. Anthropogenic stressors such as these have taken a heavy toll on coastal ecosystems and also pose numerous risks to human health and well-being [4]. Nature-based solutions, such as living shorelines, have gained incredible momentum over the past two decades as an alternative to coastal armoring that can preserve or even increase coastal habitat [5–7]. Oyster restoration is often a critical component of these projects in the form of a marsh sill or breakwater [8]. These efforts can help mitigate the severe global declines in the oyster population [9,10] while providing additional ecosystem services: oysters improve water quality via filtration and sediment stabilization and provide refuge for a variety of fish and invertebrates [11–13]. Because of their potential to ameliorate several problems at once, living shorelines with an oyster component have gained tremendous momentum in the rate of implementation and the number of research projects [7].

Despite the accelerating research in living shorelines and oyster restoration, critical knowledge gaps remain, partly due to the newness of the practice and the wide variety of techniques and configurations employed. In a review by Smith et al. [7], the authors found that the living shoreline literature is dominated by studies of projects < 5 years old, with uneven geographic coverage. However, the somewhat longer history of oyster reef restoration suggests that the protective function of oysters is complex and context-dependent; therefore, the best configurations for shoreline stabilization are still emerging [14–17]. Furthermore, changes in the surrounding ecosystem due to factors such as climate change, land development, and storm disturbance complicate efforts to understand the drivers of project success or failure. Additional research and monitoring are therefore needed to understand project outcomes in terms of oyster populations and coastal defense over the long term [16].

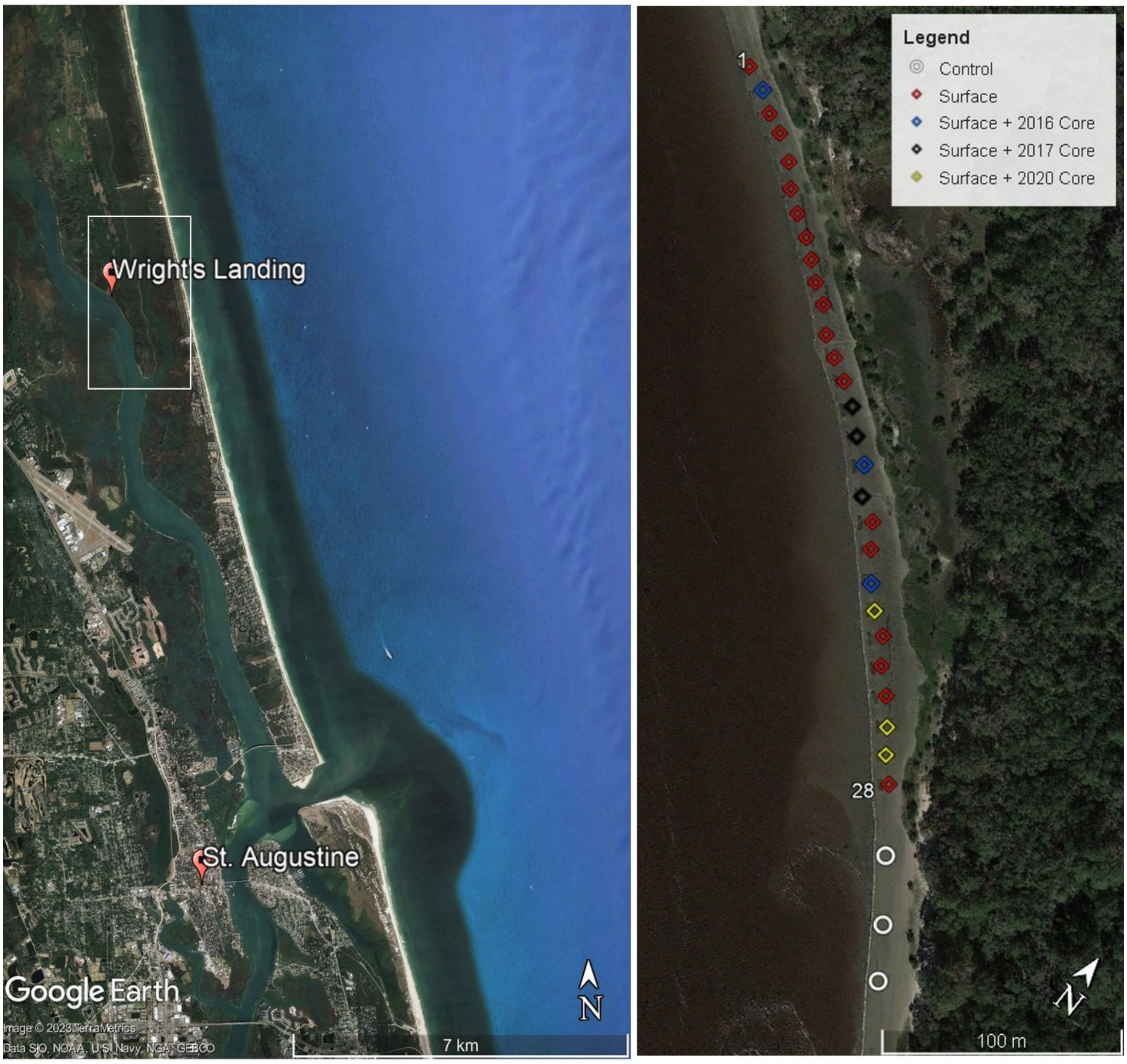
The coastal protection function of reefs has often been assessed based on changes in shoreline position or bottom bathymetry, with less analysis of the sediment itself [8,14,15,18]. However, there are three important reasons to focus on sediments. First, sedimentation has been identified by several authors as an important variable in larval settlement, health, and long-term persistence of oyster reefs [19–24]. Second, the particle size distribution of the sediment itself may be a useful time-integrated indicator of the physical energy of the system [15,25–27]. That is, the size-dependent erosion and deposition of surface sediments allow researchers to broadly relate changes in sediment particle size distribution to shoreline protection. Finally, several studies show that oyster reef-associated sediments are extremely active zones of biogeochemical ecosystem services such as denitrification, nutrient cycling, and carbon burial [28–32]. This is because oyster reefs alter sediment chemistry by facilitating the deposition of finer sediment with more labile OM, which in turn alters respiration rates and redox conditions [33,34]. The feces and pseudofeces (collectively called biodeposits) of oysters are composed of fine mineral particles, phytoplankton remnants, and the organic matrix used to package this material into a larger aggregate [35]. The reef structure can also attenuate the energy of waves and currents, facilitating the deposition of particles [14,22]. However, little is known about the ultimate fate of the organic matter (OM) buried in constructed oyster reef sediments with regard to remobilization, remineralization, or sequestration. This fate is especially uncertain in the context of the many potential stressors known to impact the oysters [9,23,36].

Several authors have called for more research on the long-term trajectories of constructed reefs, especially in areas outside of the Chesapeake Bay and the Gulf of Mexico, where much of the early oyster research occurred [7,17,37]. In addition, there is still a considerable amount to learn about the effects on the sedimentary environment, both as an indicator of physical energy and as a potential carbon sequestration site. Here, we present sediment and reef characteristics nine years postconstruction of an oyster reef enhancement project in Northeast Florida. Although this enhancement project was not originally set up as an experiment, the outcome of this project is informative for better understanding the complexity of constructed reefs' physical and biological characteristics and their influence on adjacent sediments. We discuss the results in the context of living shoreline design and the implications for sediment and organic carbon deposition.

2. Materials and Methods

2.1. Study Site

The study site is located on the shoreline of the Tolomato River at 30°00′07.12 N 81°20′04.17 W, within the boundaries of the Guana Tolomato Matanzas National Estuarine Research Reserve (hereafter GTM Research Reserve) in Northeast Florida. Biologically, the GTM Research Reserve is located in an ecotone, where both mangrove and salt marsh habitats overlap. Consistent with this, both saltmarsh (*Spartina alterniflora*) and black mangroves (*Avicennia germinans*) were present at our site, as well as maritime forest in the upland zone. Our study site is locally known as "Wright's Landing" and is oriented approximately NW to SE along the Intracoastal Waterway (ICW) on the Tolomato River, approximately 11 km north of St. Augustine Inlet (Figure 1). There is a water quality monitoring station at the convergence with the Guana River, 1 km south of our site. For the years 2016–2020, the station mean salinity was 31.2 psu (SD = 4.7), the mean Total Suspended Solids was 18 mg/L (SD = 10), and the mean water temperature was 23 °C (SD = 5) [38]. The Tolomato River is approximately 0.5 km wide at this point, not including fringing marshes. Boat wake energy has been reported to be the primary driver of erosion in this area, which was estimated at 0.35 m/yr [39,40]. At a site approximately 1 km south of our study area, Safak et al. [39] recorded an average of 60 boat wake events per day, with significant effects on sediment transport.



(a) (b)

Figure 1. Map of Northeast Florida coastline (**a**) with detail of study area (**b**) in the GTM Research Reserve. Sample sites are shown in panel (**b**), and reef numbers are 1–28 from top to bottom of the panel. Surface sediment samples were collected from all reefs in 2021. Images obtained from Google Earth Pro; panel (**a**) is from 2023, and panel (**b**) is from 2017 (to show low tide conditions).

The Wright's Landing Oyster Reef Enhancement Project was initiated and conducted by the GTM Research Reserve staff, along with volunteers. The impetus for the project and for this particular design was to combat the erosion of the marsh along the shoreline. There were no oysters present in this section of the shoreline; therefore, this project was considered to be enhancement rather than restoration. Before the project began, the sediments at the study site were characterized as 9% silt + clay and 1.1% OM [25]. The project utilized plastic mesh bags of recycled oyster shells stacked into 28 reef segments oriented as breakwaters parallel to the shoreline near the low tide line (Figure 2). Throughout this paper, we refer to these breakwaters as reefs or reef segments. They are numbered 1–28, with 1 being the northernmost reef (Figure 1b). Construction began in June 2012, and reef segments were added every few months over the next 15 months (Table S1). The segments were initially approximately 5 m long, 2 m wide, and 0.5 m tall; the total length of all the reef segments and intervening gaps is approximately 315 m. No oyster seed or spat was added; the bags were colonized with *Crassostrea virginica* from the ambient water (Figure 2b). Mean live cover increased to over 50% within 15 months [27]. Over the next few years, minor maintenance tasks were occasionally performed, such as replacing dislodged bags.

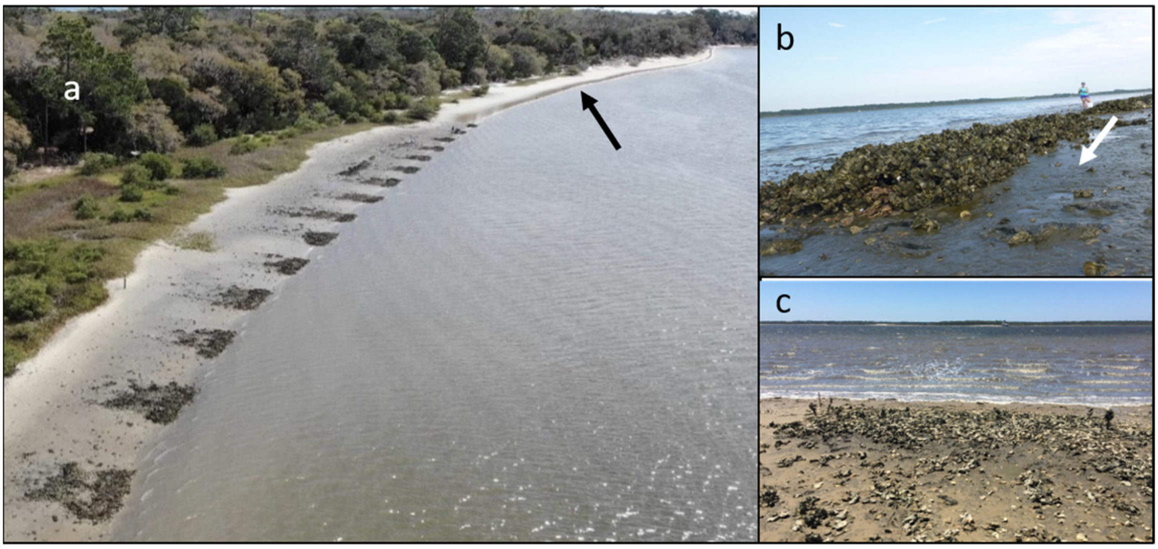


Figure 2. Photos of constructed oyster reefs at Wright's Landing: (**a**) drone image overview from 2021 showing reefs 14–28 in the foreground (note the displaced oyster clumps pushed up the beach slope) and control area indicated by the black arrow; (**b**) photo of reef in 2015 with approximate sediment sampling location shown by the white arrow; (**c**) close-up view of a reef in 2021.

2.2. Sample Collection

At each sampling event in June 2016, December 2017, and January 2020, we haphazardly chose three reefs from which to obtain sediment cores. We avoided coring behind the same reef segment more than once because we observed that digging out the cores disturbs the sediment layers in the surrounding areas, confounding future core sampling. Each reef core was located 2 m landward of the midpoint of an oyster reef segment (Figure 2b). For comparison, control cores were taken in 2016 and 2020 (n = 3 for each year.) They were located 25 m, 50 m, and 75 m south of the restoration project at an equivalent elevation in the intertidal zone (Figure 1b). There were no oysters present in the control area. All cores were 7 cm diameter push cores of 20 cm or greater depth, obtained using a clear polycarbonate cylinder. We sectioned the cores into 2 cm layers while on site and stored them in Ziplock bags. We noted observations of the sediment color, texture, and appearance, then transported the samples to the lab in a cooler and placed them in a freezer (−20 °C) within 4 h.

In order to assess the relationship between sediment characteristics and physical/biological reef condition, we collected samples of surface sediments and reef condition data from all 28 reefs in 2021. Surface sediments (0–2 cm) were obtained from 2 m landward of each of the reef midpoints. We pressed a Petri dish into the sediment and then slid a thin stainless steel plate underneath in order to collect a consistent depth interval [41]. Samples were stored, processed, and analyzed for particle size and OM content in the same manner as the core samples. We also recorded the following data for all 28 reef segments: percent cover, reef thickness, and tallest cluster. Briefly, a 0.25 m^2 gridded quadrat was placed in three locations along each reef segment: the north end, the middle, and the south end. We used the point-intercept method to quantify the percentage cover of live oysters, dead shells, bare sediment, and others. The "bare sediment" classification was used to describe points where the cultch was completely gone; "other" was most often used to describe detritus from the plastic mesh bags. The height of the tallest cluster in each quadrat was recorded, and "thickness" was defined as the average height of 5 haphazardly chosen shells/clusters within the quadrat. The tallest cluster and reef thickness were measured from the base of the substrate to the top of the cluster using a thin metal rod. We also measured the relative elevation of each reef crest and 1 m southwest of each reef midpoint using a stadia rod and optical level. The 1 m southwest point approximates the boundary (base) of the reef closest to the ICW. We used the difference in these elevations to calculate "reef height". We report reef crest elevations relative to Reef 1, which is also the lowest of the reef crests (i.e., Reef Crest 1 is arbitrarily called 0 cm elevation.)

2.3. Sample Analysis

We dried sediment samples at 80 °C until mass was constant, ground the sediments using a mortar and pestle, and then sieved the samples with a 2 mm sieve. Particles > 2 mm, which were mostly comprised of oyster shells, were weighed and discarded. The masses of these > 2 mm particles are not included in the calculated OM or percentage of silt + clay. The dried, sieved samples were then stored at room temperature until analyzed. We measured OM by the loss-on-ignition method, following the recommendations of Wang et al. [42] for estuarine sediments (550 °C for 12 h.) We calculated OM as a percentage of the dried sediment mass. One set of triplicate splits and one sample of a reference material was included in each batch for QA/QC. The standard deviation of triplicates was 0.05%, and the reference material was within 0.3% of values previously established by our lab.

Because of the greater time required for particle size analysis, not all sediment samples were analyzed: for 2020 cores, every other section layer was analyzed, and for surface samples, every other reef sample was analyzed. We used a pretreatment of 30–60 mL of 30% hydrogen peroxide for 24–96 h to remove organic matter from 30 g of sediment before we performed the rapid method for particle size determination, following Kettler et al. [43]. We added 100 mL of 5% sodium hexametaphosphate to each sediment sample to separate the sediment particles before placing them in an orbital shaker for two hours. Each sediment sample was separated by sieving into the following size fractions: coarse (2 mm–500 µm), medium (500 µm–250 µm), fine (250 µm–125 µm), and very fine (125 µm–63 µm) sands, and silt + clay (<63 µm). The proportion of each size fraction is calculated as a percent of the total OM-free dry sediment mass. We only report silt + clay content here in order to highlight changes in the fine particle fraction; a more comprehensive analysis of all particle sizes in 2016 and 2017 cores appears in a separate article [44]. The standard deviation of sample splits averaged 2%.

All results were compiled in Excel and analyzed in R, version 3.6.2. To evaluate OM change over time in the sediment cores, we used a linear regression model with the average OM over the top 20 cm as the dependent variable and both reef age and year as potential independent variables (reef age and year are not equivalent because the reefs were constructed up to 15 months apart). We averaged the sediment layers together because they cannot be considered independent of each other with respect to reef age or year. For the surface sediment dataset, we used a stepwise linear model with forward selection to analyze the influence of 8 potential reef characteristics on adjacent surface sediment OM and silt + clay (Table 1). For both linear models, the overall model fit was determined using the adjusted R^2 value, and the normality of residuals was assessed by visual inspection of predicted versus actual values in a Q-Q plot. The correlation between silt + clay and OM was evaluated using simple linear regression, including all samples (both core sections and surface samples) for which both parameters were analyzed. For all statistical tests, significance is defined at $\alpha = 0.05$.

Table 1. Summary of surface sediment and reef characteristics used in the linear model. Parameters with asterisks (*) were significant in the model, with the highest adjusted R^2 for both silt + clay and OM content. SD = standard deviation.

	Mean	SD	Min.	Max.
Silt + clay	27	14	9	55
OM	4.15	2.18	1.68	10.12
% Live cover	18	11	3	49
% Bare sediment *	8	8	0	40
% Dead	64	16	25	87
% Other	10	9	0	37
Thickness (cm)	6.0	1.7	3.1	9.9
Tallest cluster (cm)	14.2	2.3	8.2	18.3
Reef height (cm)	12.5	6.8	−3.0	24.0
Reef crest relative elevation * (cm)	56.1	25.3	0.0	95.5

3. Results

3.1. Sediment Cores

Organic matter content in sediment layers ranged from 1.0 to 10.5% for reef cores and 0.5 to 1.9% for control cores. Control cores exhibited low OM throughout the vertical profile (Figure S1) and very little change over time. OM content in control samples was similar in 2016 ($\overline{x}$ = 0.8%, SD = 0.5) and 2020 ($\overline{x}$ = 0.9%, SD = 0.4). Likewise, the average silt + clay fraction comprised 5% (SD = 3) in 2016 and 7% (SD = 3) in 2020. These control samples are similar to pre-restoration baseline values for the area where the reefs were constructed [25]. In contrast to the control site, reef cores exhibited a wider range of OM and silt + clay content, with higher values of both parameters often observed in the top 10 cm of the cores (Figure 3). Average OM in the top 20 cm of the cores declined by approximately half over the study period, with reef age a slightly better predictor than year (Figure 4; p = 0.01 vs. 0.03, respectively).

Some cores with lower OM were from reefs in poor condition. For example, field notes from 2016 indicate that Reef 2 already exhibited decreases in height and live oyster coverage, and its OM content is relatively low throughout the vertical profile (Figure 3). The GTM Research Reserve staff noticed that the plastic mesh bags containing the original oyster shell began to deteriorate after approximately four years. When this occurred, the reef structure began to deteriorate, with oyster clumps gradually becoming scattered across the intertidal zone (Figure 2).

3.2. Surface Sediment and Reef Characteristics

A summary of reef and sediment characteristics data is shown in Table 1. When these samples were collected in 2021, reef ages ranged from 7.7 to 8.9 years old. Reef height had diminished by 75% on average compared to the initial 50 cm postconstruction estimate. Live oyster cover averaged 18% (SD = 11), lower than that reported for natural oyster reefs on the Tolomato River [45] and previous measurements at this site [27]. Notably, the percent live cover of oysters was not significantly correlated with OM, even when it was used as the only independent variable in the model (adjusted R^2 = 0.03; p = 0.58). The regression analysis of surface sediments and reef characteristics showed that the best predictors of both OM and silt + clay were physical/structural. The model of OM with the highest adjusted R^2 value contained reef crest elevation, and the percent bare sediment as the independent variables, and these same factors were also in the best model of silt + clay content (Table 2). This agreement between OM and fine particle content is unsurprising given the strong correlation we observed (Figure 5, R^2 = 0.94, p < 0.001), which is also well documented in the literature [46,47]. This relationship was consistent for all years, for surface and core samples, as well as control samples.

Table 2. Results of linear models of OM and silt + clay content with the highest adjusted R^2.

Dependent Variable: OM	**Adjusted R^2**	***n***	***p***
	0.46	28	0.00016
Model Terms	**Coefficient**	***p* value**	
Reef Crest Elevation	0.045	0.001	
% Bare Sediment	−0.131	0.001	
Dependent variable: Silt + clay	**Adjusted R^2**	***n***	***p***
	0.356	14	0.0355
Model Terms	**Coefficient**	***p* value**	
Reef Crest Elevation	0.253	0.078	
% Bare Sediment	−0.738	0.034	

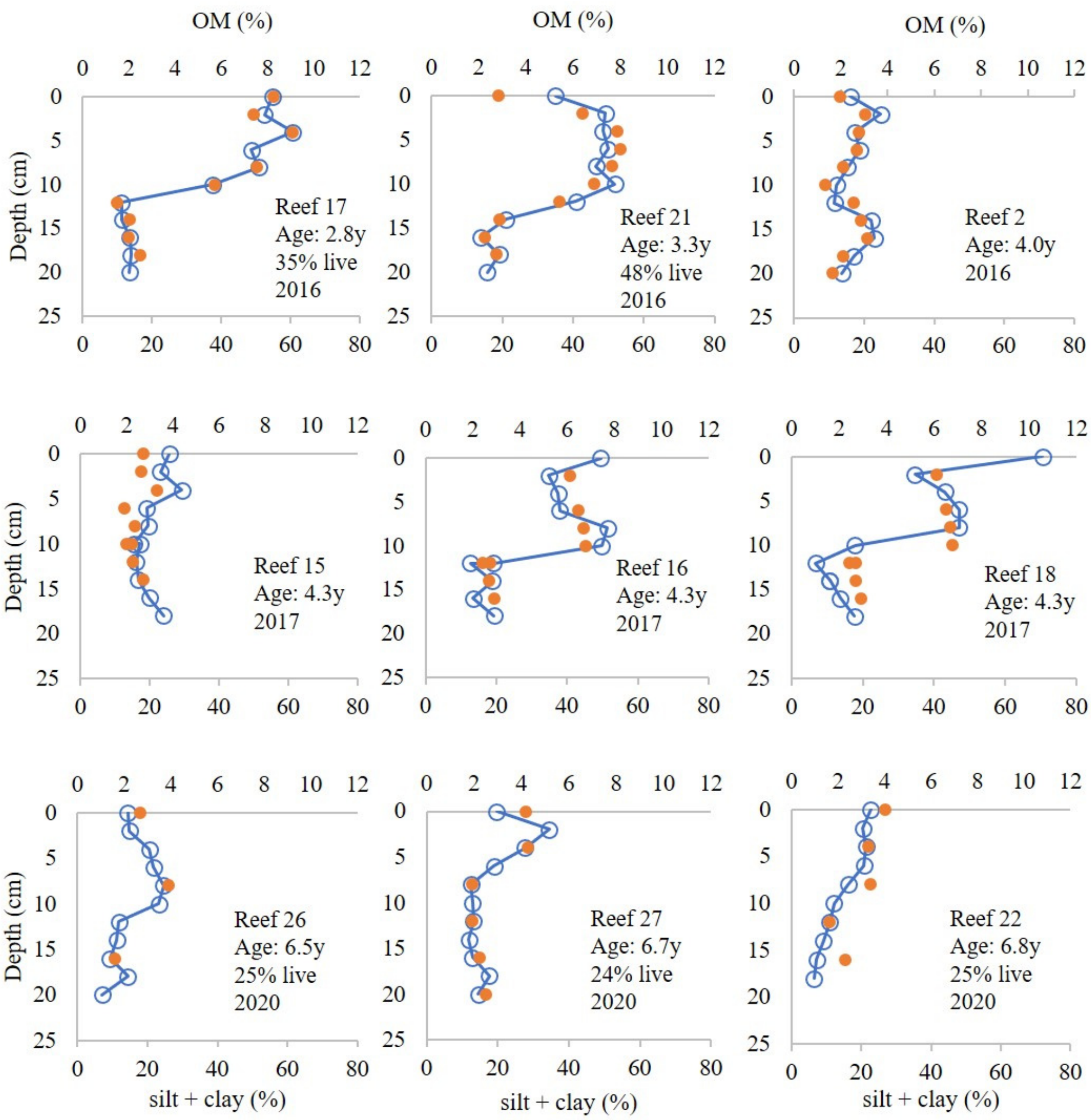


Figure 3. Vertical profiles of organic matter (OM) (open blue circles, blue line) and silt + clay (filled orange circles) for 9 reef sediment cores, 2016–2020. Percent cover of live oysters is provided from the GTM Research Reserve monitoring database, used with permission. Panels without percent cover values indicate that percent cover was not measured for that reef in that year. Silt + clay data from 2016 and 2017 cores are from [44].

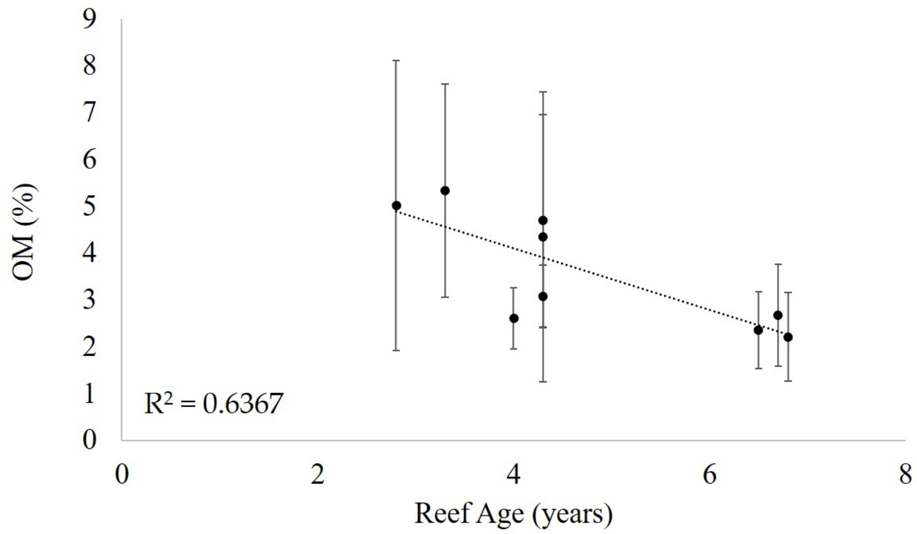


Figure 4. Average OM in the top 20 cm of each core (black circles) versus reef age at the time the sediment core was obtained. Error bars are standard deviations of the individual core layers. The dotted line indicates a linear regression line with an R^2 value of 0.6367.

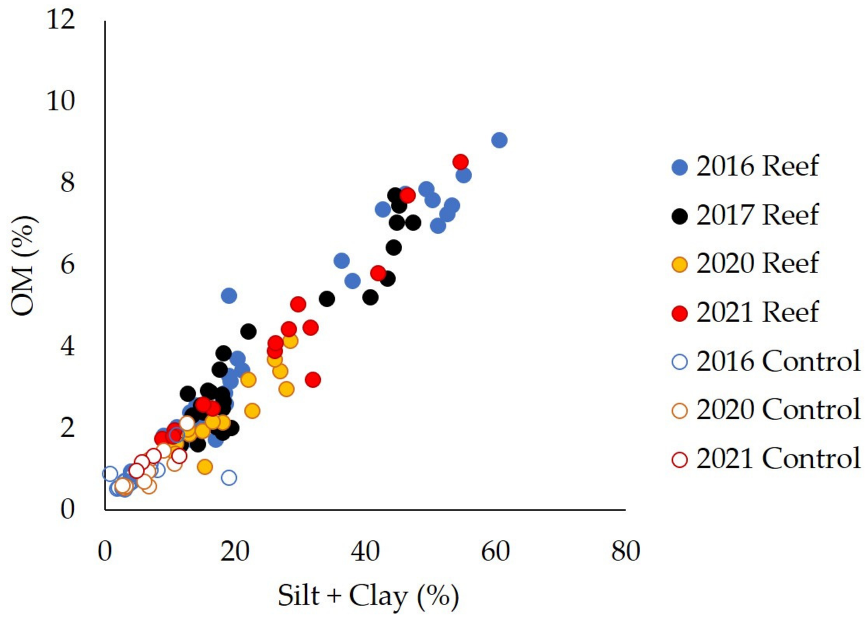


Figure 5. Correlation between silt + clay and OM in all samples for which both analyses were carried out.

4. Discussion

4.1. Sediment Cores

Our sediment cores and surface samples provide complementary perspectives on this site: the surface samples provide a snapshot in time of all surface sediments and their neighboring reefs, whereas the cores show changes in vertical profiles of a subset of locations over a longer period. This is important because, while surface sediments might be quite dynamic in response to short-term events, the deeper sediments should be more consistent. The organic-rich, finer layer in the top 15 cm of the cores from Reefs 17 and 21 (Figure 3) has been documented previously at this site [25,27] and has been interpreted as evidence of the altered depositional environment after the reefs were installed. Similar oyster restoration enhancement of sediment OM has been reported by others [32,34,48]. This OM is thought to be derived from a combination of biodeposits from oysters as well as the trapping of fine material due to the attenuation of wave energy by the reef structure. Oysters produce 0.98–1.53 g of biodeposits per oyster per week (for *C. virginica*) that are consistent with the material in this layer: 9.0–22% OM and primary particle sizes within the silt + clay size class [35]. However, trapping of fine allochthonous particles by the reef structure is also possible, and the relative importance of these two mechanisms is difficult to parse [22]. Furthermore, benthic nutrient fluxes from this OM-rich sediment can support enhanced primary production from benthic algae, which could contribute to additional OM [25]. Sedimentary organic carbon deposition associated with oyster restoration can generate significant carbon burial with rates rivaling that seen in other coastal vegetated systems (i.e., "blue carbon") [27,32,49]. These changes have been linked to increases in microbial respiration, benthic nutrient fluxes, and high rates of denitrification [28,31,33,34]. The sediment biogeochemistry of oyster restoration/living shorelines is, therefore, of tremendous interest, with potentially significant effects on carbon and nutrient budgets.

Our previous work at Wright's Landing had shown the OM-enriched upper sediment layer to be very pronounced and present at all reefs tested. At the location our current samples were obtained, Veenstra et al. [27] measured a layer with a thickness of 10–25 cm, suggesting a sediment deposition rate of up to 6 cm/yr and a carbon deposition rate of approximately 100–200 $gC/m^2/yr$ over the first four years after construction. If those deposition rates had stayed constant, we would expect the fine layer to be twice as thick (20–50 cm) by 2020. However, the cores in this study show the OM-rich layer to be <15 cm thick, more variable over space and time, and apparently diminishing between 2016 and 2020 (Figures 3 and 4). Silt + clay content decreased in a similar manner (Figure 3). This could suggest that the high deposition rates measured during the 2012–2016 interval are no longer in effect and that fine material was lost. However, our practice of not coring the same reef more than once (to avoid sampling a previously disturbed area) confounds our ability to conclude there was OM loss over time based on these data alone. In addition to the possibility of spatial variability, the 2016 cores were obtained in summer, whereas the later cores were obtained in winter. This raises the possibility of seasonal influence on oyster biodeposit rates and/or benthic algae [35,50]. However, if seasonality were a key control on OM, we would expect a spring/summer enrichment in OM concentrated at the top of the core. Yet, the June 2016 cores show no such enrichment and, in fact, show slightly lower OM at the surface layer. Further, the highest surface OM values were seen in the December 2017 cores (Figure 3). There are several variables potentially influencing the sediments, so we cannot conclusively calculate a rate of OM loss over time. Nevertheless, inspection of the vertical profiles, comparison of these data with OM values from past studies [25,27], together with field observations of sediment color and texture, all broadly support OM loss.

This apparent OM loss, and the near-disappearance of an enriched layer in the 2020 cores, call into question the stability of the carbon burial previously measured at Wright's Landing. Remineralization of OM in situ could explain some of the decreases, especially if labile biodeposits constitute a large component of the OM-rich material [35,49]. As oyster percent cover has decreased over time here, we might very well expect to see a decrease in sedimentary OM as the labile fraction of previously deposited OM becomes remineralized. However, if organic matter were simply remineralizing within the sediment, we would expect to see changes only in OM content, not particle size. Yet, our data show that the relationship between OM content and silt + clay remains relatively consistent across time, core depth, and even reef versus control samples (Figure 5). This evidence supports remobilization with associated loss of fine particles, rather than remineralization in situ, as the primary loss mechanism. Nevertheless, remobilization would still be relevant for the carbon budget because exposure to sunlight and oxygen during resuspension events can increase sedimentary OM bioavailability [51–53].

In considering the possibility of sediment remobilization, our cores from December 2017 are of particular interest because they were obtained soon after two hurricanes impacted the area: Matthew (2016) and Irma (2017). Though neither storm directly hit the area, both Matthew (Category 2) and Irma (Category 3) brought tropical-storm-force winds and storm surge more than 4 ft. above normal high tide [54]. The December 2017 cores exhibit substantial variability within the top 10 cm that could be related to erosion and/or deposition during these hurricanes. However, a previous study at this site did not find significant changes in particle size associated with Matthew and Irma [44]. Overall, the storms do not appear to fully explain the OM decrease, as it continued to decline after December 2017. Rather, the loss correlates significantly with reef age, presumably because of changes in the reef structure and/or oyster populations over time.

4.2. Surface Sediments

Surface sediment OM and reef characteristics varied widely in 2021 (Table 1), and we can use this natural variation to gain insights about the reef characteristics that most influence the sediment. In our analysis, the relative elevation of the reef crest and the percent cover of bare sediment were the only independent variables in the model with the best fit for both sediment OM and fine particle content. It is logical that reef crest elevation is highly significant, as this parameter encompasses the net effects of several important processes, such as settling of shell bags, new oyster growth, and loss of cultch over time. Conversely, the presence of "bare sediment" at a reef indicates near-complete destruction of that structure. It is somewhat surprising that reef height was not significant ($p = 0.13$), but sediment erosion and/or deposition along the front edge of the reef might confound that measurement. Interestingly, live oyster cover was not correlated with sediment OM, even though live oysters are reported to deposit OM-rich material in the sediment [35]. Nevertheless, it appears that physical parameters were more important here.

Some authors have highlighted a trade-off between designs that serve the different restoration goals of coastal protection versus increasing oyster populations [8,16,55]. This may be especially important at sites with higher physical energy, such as the current study. The Wright's Landing reefs lost an estimated 75% of their height since construction, with oyster clumps eventually becoming dislodged and scattered (Figure 2). Scyphers et al. reported similar flattening and spreading of reefs when using plastic mesh in a breakwater configuration in the Gulf of Mexico [8]. However, other oyster restoration projects have reported improved physical and biological metrics with the age of the reef [56], even for projects similarly constructed with plastic mesh bags and sited along the ICW [57]. Many oyster restoration projects have successfully used plastic mesh bags, which have advantages in their low cost and availability [37]; however, in this case, the new oyster growth did not produce a cohesive structure capable of withstanding the physical energy of the system. We suggest that sediment particle size can be a time-integrated indicator of physical energy and may be of use for managers evaluating sites for oyster restoration or enhancement projects. We also noted the presence of plastic mesh detritus, which represents most of the "other" category that comprised 10% of the reef cover (Table 1). Ultimately, managers must weigh these considerations of durability against many others in their choice of materials.

5. Conclusions

Our results suggest changes in the depositional environment have occurred, leading to the loss of the fine, OM-rich layer previously observed at Wright's Landing. Given the influence of physical reef structure on the characteristics of surface sediment, we likewise interpret the apparent decline in OM content in our cores as a function of the structural degradation of the reefs as they aged. The production of fine, organic-rich particles from biodeposits is inevitable wherever there are live oysters; however, its localized deposition is not. Ultimately, the sediment characteristics and its associated biogeochemical services may be constrained by the physical energy of the system. Broadly, our data highlight the importance of physical controls on sediment characteristics both in the surface sediments and downcore. Previous research indicates that the protective function of oyster reefs is context-dependent [14,55,58], and our Wright's Landing site is heavily impacted by boat wakes [39]. In this, the site is certainly not unique, as boat wakes have been identified as a major driver of coastal erosion in many locales [59–61]. Therefore, it is all the more important to identify lessons from this project's outcome. This study underlines the potential for sediment and organic carbon deposition associated with oyster enhancement and restoration while highlighting the need for site-specific reef construction materials for long-term sediment stability.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su151612584/s1, Table S1: Construction dates of individual reef segments; Figure S1: Vertical profile of sediment OM from cores in the control area.

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