Characterizing Spatial and Temporal Trends in Net Sediment Accumulation in Seagrass Meadows

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Abstract

Seagrass meadows are known as hot spots for carbon accumulation, but there is limited field data on the variability of sediment accumulation across time and space. We developed a method to assess spatial and temporal heterogeneity in net sediment accumulation in seagrass meadows using small, inexpensive samplers, allowing for over 200 unique measurements across multiple transects within our study site. Using this method, we assessed sediment accumulation across seagrass meadow edges, and in varying weather conditions. We found the greatest accumulation of sediment 5 m outside of seagrass meadow edges, with sediment accumulation rates averaging just under $100 \text{ g m}^{-2} \text{ day}^{-1}$, though rates were highly variable. Carbon accumulation from settled sediment was generally greater outside of seagrass meadow edges than within the bed, especially at sites undergoing recent expansion. Measurements made during tropical storms showed both scouring of sediment away from sites, and increased accumulation, depending on site properties as well as individual tropical storm characteristics. In the storm that had a measurable storm surge, scouring of sediment was a more dominant mechanism, whereas deposition dominated in the storm that had high winds but no associated storm surge. Our data demonstrate the necessity of including measurements that characterize both spatial and meteorological variability to develop a more holistic understanding of the movement of sediment and particulate organic carbon associated with seagrass meadows, especially as meadow area becomes increasingly fragmented with human activity and global change.

Keywords Sediment accumulation · Edge effects · Organic matter · *Zostera marina* · Spatial heterogeneity

Introduction

Sediment movement in estuaries can be highly variable through space and time (Granata et al. 2001) but influences many components of the estuarine environment, including water clarity (Koch 2001), sediment biogeochemistry (Fraser et al. 2016), and benthic community composition (Olsen et al. 2013). Coastal sediment transport processes may be increasingly influenced by climate change,

particularly increased tropical storm intensity (Walsh et al. 2016). Seagrasses, such as *Zostera marina*, are notable for their influence on sediment and organic matter deposition (Moriarty and Boon 1989; De Boer 2007; Koch 2001). Increased organic matter trapping has been proposed as a mechanism for seagrass expansion, wherein increased nutrients from the water column increase growth, and the removal of sediments from the water column increases light available for plants (Cardoso et al. 2004; De Boer 2007). However, high sediment organic matter also drives microbial production of toxic compounds such as sulfide in the seagrass rhizosphere, posing a potential detriment to seagrass (Canfield et al. 1993; Haviland et al. 2022). Hydrodynamic variables such as exposure and current direction also influence seagrass meadow sediment transport dynamics (Granata et al. 2001). Tropical storms bring greater winds and increased turbulence to coastal ecosystems and thus impact sediment transport in seagrass meadows. The result of these changes varies, with some tropical storms scouring sediment away from seagrass beds (Van Tussenbroek

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1994) and others depositing enough sediment to bury vital seagrass structures (Fourqurean and Rutten 2004). In both cases, seagrass mortality can occur (Cruz-Palacios and Van Tussenbroek 2005), but the impact of storms on seagrass meadows varies depending on hydrological changes associated with the storm (Correia and Smee 2022). Tropical storm severity is predicted to increase as climate change progresses (Walsh et al. 2016) and may present an additional stress on seagrass meadows.

Studies have demonstrated that seagrass meadows are sites of significant carbon burial (Fourqurean et al. 2012), and a portion of this carbon comes from organic matter settling out of the water column (Duarte et al. 2013). While many studies have shown increased sediment trapping by seagrass (i.e., Gacia et al. 2003; Bos et al. 2007), others have shown no significant difference in sediment trapped between seagrass meadows and comparable unvegetated locations (Mellors et al. 2002). Seagrass reduces wave energy by increasing bottom shear stress compared to unvegetated areas, leading to the accretion of fine sediments (Bos et al. 2007), which may increase the chance of survival for plants due to enhanced light and increased sediment nutrient availability (Koch 2001) and potentially increase meadow expansion via higher rates of germination (Van Katwijk and Wijgergangs 2004). Site characteristics (i.e., vegetation density, sediment grain size, location of specific sampling sites) influence the distribution of sediment deposition across a seagrass bed (Ricart et al. 2015; Van Katwijk et al. 2010), and within a meadow, sediment accumulation can vary greatly in space (Zhu et al. 2022). Despite this, many field-based studies are limited to collecting data on a coarse spatial scale, assessing seagrass meadow sediment dynamics at just a few locations within a seagrass bed. Additionally, many studies on seagrass meadows have not used sediment traps, despite their utility for the quantification of sediment accumulation (Duarte et al. 2013; Gacia et al. 1999). Frequently used methods such as ^{210}Pb dating provide useful data, but difficult to implement in regions of high bioirrigation, and many sediment trap designs do not allow sediments to resuspend, limiting analyses to sedimentation, rather than net sediment accumulation. Developing a more holistic understanding of net sediment accumulation will allow a better understanding of patterns driving carbon burial in seagrass meadows over space and time, with implications for understanding their survival under changing environmental conditions such as meadow area loss, sea level rise, and increased storm intensity.

In this study, we use a novel method to characterize the extent of small-scale heterogeneity in sediment transport using a dataset consisting of almost 200 individual measurements of net sediment accumulation, focusing on carbon accumulation, over a series of transects along *Z. marina* bed edges. Additionally, we assess meteorological variability in sediment accumulation within seagrass meadow interiors over the course of two tropical storms of varying intensity. We hypothesize that there will be a high degree of spatial variability in sediment and carbon accumulation along seagrass meadow edges and that tropical cyclones will impact sediment accumulation by increasing movement of sediment, with some areas seeing greater-than-baseline accumulation, and other regions seeing less.

Methods

Study Site

We carried out our experiments in West Falmouth Harbor (WFH), a shallow lagoon (average depth at mean high water of 1.9 m) adjoining Buzzards Bay on Cape Cod, Falmouth, MA, USA. The harbor consists of several basins, two of which support extensive seagrass meadows (monospecific *Zostera marina*). The most seaward vegetated basin is the Outer Harbor (OH) and is characterized by high relative exposure and sandy, low-organic sediments, while the more inland vegetated basin is the Middle Harbor (MH), characterized by moderate to low relative exposure, tall seagrass, and highly organic, high sulfide sediments (Haviland et al. 2022).

Each transect site was characterized by the height of its canopy, dominant sediment characteristics, and relative exposure to wind and currents. Canopy height was calculated as the average height of mature, adult shoots (second- and third-oldest blades) of seven plants sampled from the site closest to the transect location (Fig. 1). Seagrass edges were delineated based on where vegetation cover became < 10% in a ~5 m^2 area. The dominant sediment grain size was determined based on the majority grain size of the sediments along the transect at each site, using stainless steel sieves with 4-mm mesh (#5), 2-mm mesh (#10), and 250-µm (#60) and 63-µm (#230) mesh. Relative exposure of each site was categorized as high, medium, or low based on the position of the harbor relative to the mouth and dominant tidal flows. Table 1, below, shows this information for each site, along with transect orientation.

Sampler Design

In the summers of 2020 and 2021, we used a new method to assess net sediment accumulation in seagrass meadows. The sample collection with this methodology is different from those using a typical sediment trap design due to the positioning of the sampler, which sat directly on the sediment surface, and with the capacity for sediment to fall into the sampler as well as resuspend back into the water column. This results in a measure of net sediment accumulation,
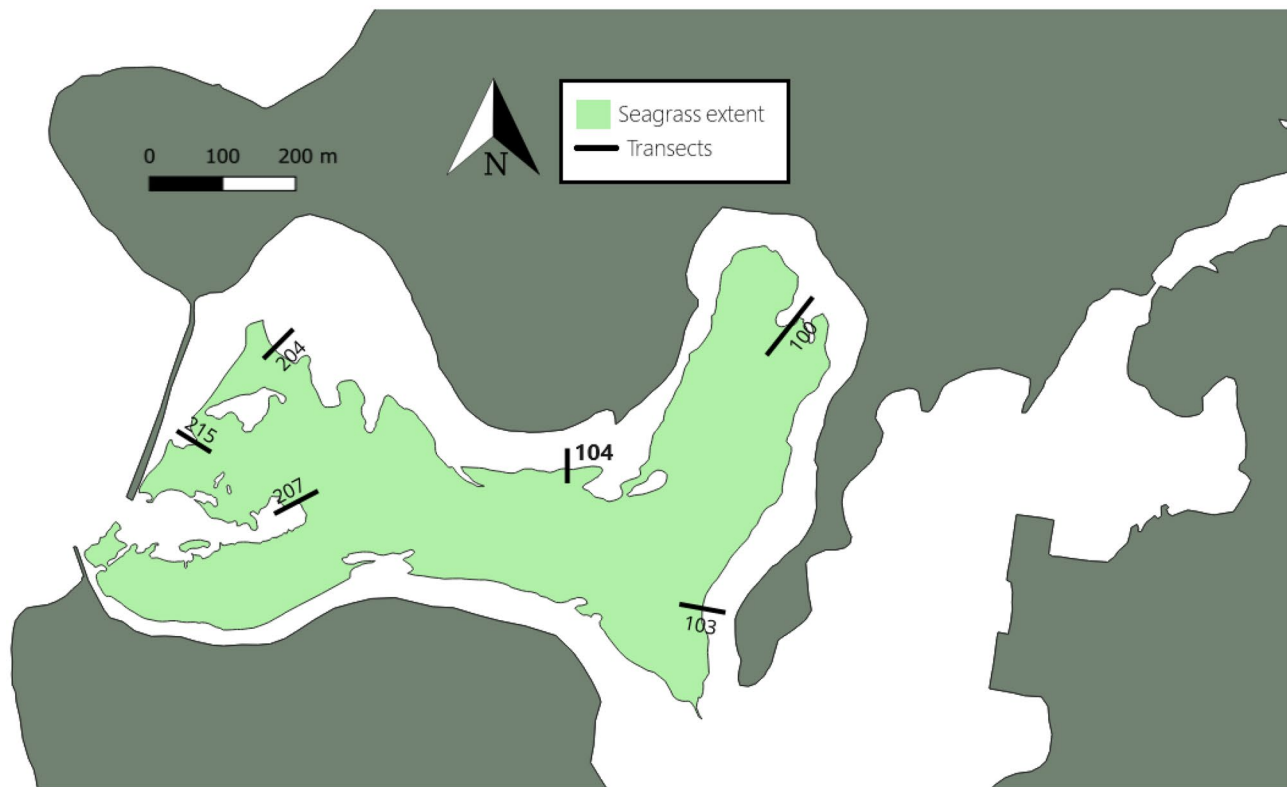
Fig. 1 Approximate transect locations in WFH—Note that because mapped seagrass extent is from 2017, and transects were deployed in 2020 and 2021, exact transect locations have been altered slightly for demonstrative purposes due to minor annual changes in seagrass edge location. For true transect coordinates, see supplementary information

rather than sedimentation alone. The sampler is inexpensive and easy to install, allowing for the collection of data on a fine spatial and temporal scale.

The 3-D printed sampler was designed in collaboration with EP Oceanographic, LLC (Bourne, MA). The design (Fig. 2) included a circular base segment 7.6 cm in diameter, with 0.3-cm-thick walls, 1.9 cm high (height to width ratio of 0.25, cross-sectional area ~48 cm^2), and a flexible cap designed to seal the sampler prior to extraction. The base had four legs to be pressed into the sediment surface for

extra stability. A stainless-steel hex nut can be attached to the fastenings on the bottom of the base to maintain negative buoyancy where necessary. Additionally, a small joint attached to one side of the sampler fits a bamboo skewer with attached flagging tape, for locating the sediment sampler in dense seagrass meadows or turbid locations. Each sampler was fitted with an appropriately sized tin weigh dish and a 3-D printed flexible lid to prevent loss of sediment during transport from the sediment surface to the boat. Samplers were always deployed and collected by SCUBA

Table 1 Characteristics of transect sites

Transect site	Approx. canopy height (cm)	Transect Orientation	Average depth at MHHW (m, approximate)	Dominant sediment grain	Relative exposure
Northern MH (100)	24	N-S	2.9	Very fine sand (VFS)	Low
Western MH (103 and 104)	29	N-S, NW-SE	2.7	VFS	Moderate
Northern OH (204)	25	N-S	2.7	Medium sand (MS)	Moderate
Eastern OH (207)	23	NNE-SSW	2.8	Fine sand (FS)	High
Western OH (215)	25	N/A	2.9	FS	High

While the site numbers (in brackets under transect site) used in this research match site numbers for previous work done in West Falmouth Harbor (i.e. Haviland et al. 2022), sites for sediment accumulation do not match the exact location of previous sites with the same number, but instead, the seagrass bed edge nearest to the given site. See Table S1 for details on analyses carried out at each site
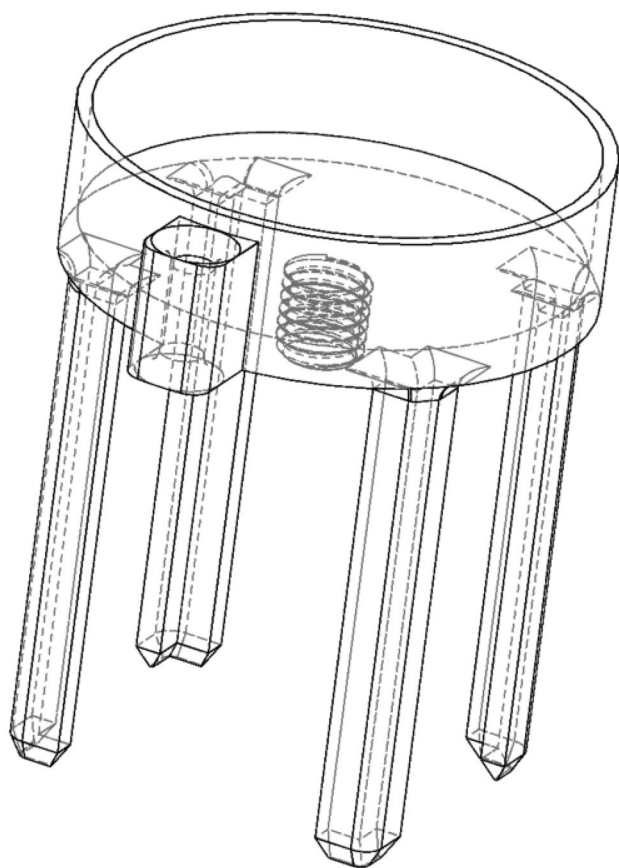
Fig. 2 A schematic showing the 3-D printed sampler design base. To download and print the design files, visit https://github.com/kah334/3DSedimentAccumulation

divers. Divers attached the lid before removing samplers from the sediment, so that minimal sediment was lost while transporting samplers from the sediment surface to the boat. Tins were tested in seawater and found not to gain or lose significant weight due to corrosion over periods of less than 14 days. Because of this, all deployments were carried out for 6–7 days. For longer deployments, the tin can be omitted or replaced with a different material. We tested the performance of the design against a sediment accumulation method used in salt marshes developed by French and Spencer (1993), wherein a 10-cm-diameter petri dish fitted with a glass-fiber filter was attached to a bamboo stake and placed on the sediment surface (Fig. S2).

Seagrass Transect Experiments

We measured sediment accumulation in transects laid out across seagrass bed edges in the summers of 2020 and 2021. In 2020, we sampled transects in July and August, with three sediment samplers located every 2 m from 2 m outside of the seagrass bed edge to 6 m within the bed (8 m). For these

2020 transects, which included sites 100, 103, 204, and 215 (Table 1), we collected sediment cores at each station in addition to accumulated sediment samples. We extruded and homogenized the top 6 cm of the sediment cores, dried the sediments at 100 °C for 48+ h, and assessed for % organic matter as above. Accumulated sediment samples were processed as described above. We sampled longer (26 m) transects during peak seagrass biomass months (June–August) in 2021 traversing from 10 m outside the seagrass bed to 16 m inside the seagrass bed. Along each transect, three replicate sediment samplers were located at each station. Stations were situated 10 m outside the bed, 5 m outside the bed, at the bed edge, and 2, 4, 6, 11, and 16 m within the seagrass bed (seven stations per transect). Transects were located near sites 100, 104, 204, and 207 within WFH (Fig. 1). For a breakdown of sites and transects sampled in 2020 and 2021, see Table S1.

Transects were laid out using pre-measured lengths of rope to determine the exact distances between stations. We then placed sediment samplers in a triangle formation about 0.1 m apart from each other at each station. Divers took care to ensure that seagrass was undisturbed by sampler placement, and minimal sediment was suspended during deployment and collection. All samplers within a transect were deployed and taken in at the same time, and each transect was out for 6–10 days. Data from the transect at site 204 is incomplete due to an anchor dragging through the transect at ~6 m prior to collection.

After bringing the sediment samplers to the lab, we removed the tin from the sampler body, and carefully suctioned seawater off the tins using a syringe filter to prevent loss of sediments. We flushed sediments twice with DI water and siphoned the water as above to remove residual seawater and associated salts that would influence sample weight. Tins were then placed directly into the drying oven at 100 °C for 48+ h. Samples were cooled completely in a desiccator cabinet and then weighed on an analytical balance. Sediment from all three reps at each station was homogenized into a pooled sample and assessed for % organic matter using loss on ignition (450 °C for 4 h), along with one station randomly selected for each transect where the three replicate samples were assessed separately (unpooled) to assess the replicability of the method.

Tropical Storms

To determine the impact of tropical storms Isaias (August 2020) and Elsa (July 2021) on net sediment accumulation in seagrass meadows, two sites in WFH were selected: site 207, a sandy site with high relative exposure, and site 100, a more protected site characterized by low exposure. Baseline data were collected during calm conditions at these sites in July of 2020 and June of 2021. During the tropical storms, sediment

samplers were deployed at one location 30 m inside the bed edge at each site (five at each site in 2020, 6 in 2021). Samplers were deployed two days prior to each storm's projected landfall and collected two days after peak winds.

While Isaias made landfall as a stronger storm than Elsa, Isaias's eye tracked further west of Buzzards Bay as compared to Elsa, where the eye passed directly over Buzzards Bay. Tropical storm Isaias had gusts of up to 53 knots over Buzzards Bay, sustained winds of 43 knots (41.40 N 71.03 W), and no rainfall, occurring August 4–5, 2020 (Latto et al. 2021). Tropical storm Elsa occurred July 9–10, 2021, and resulted again in some significant winds, with gusts approaching 44 knots in Buzzards Bay, sustained winds of 37 knots (41.40 N 71.03 W), and minimal precipitation (Cangialosi et al. 2022). Isaias resulted in a 0.6–0.9 m storm surge, while Elsa had no associated storm surge. Predominant wind direction during Isaias was out of the SE as the tropical storm approached, and then the SW, while wind during tropical storm Elsa varied from E early in the storm, SW, then to W by the end of the event (National Data Buoy Center (NDBC) for station BUZM3).

Statistical Analysis

We analyzed transect data using simple linear models, after assessing data within each variable for normality, with the transect site included as a fixed block factor. Linear models include distance along transect against accumulated sediment % OM; distance along transect against organic matter accumulation rate; and core sediment organic matter against accumulated sediment organic matter. For sediment accumulation rate against distance on the transect, we fitted a locally estimated scatterplot smoothing (LOESS) curve for visualization purposes, carried out a polynomial regression using the R package caret (Kuhn 2008), and calculated the mathematical peak value (location along transect at which the peak sediment accumulation value is found) along the curve for all sites, and then each site individually. All model residuals were tested for normality using the R package olsrr (Hebbali 2020); see supplementary information for details. Data collected at sites 100 and 207 during baseline conditions and during tropical storms were assessed using Tukey's multiple comparison of means. The two sampling methods described above were compared to each other using t-tests, after assessing for normality (Fig. S2).

Results

Seagrass Bed Edge Transects

Across bed edge transects, we saw a prominent edge effect, with peak sediment accumulation values at all sites

occurring between 5 m outside of the seagrass bed and the bed edge. Sediment accumulation peaked outside the bed and then decreased with increased distance inside the seagrass bed ($p < 0.001$, Fig. 3A). At the same time, the % organic matter of the accumulated material increased over the course of the transect when assessed across all data points ($p = 0.01$, Fig. 3B). This pattern was consistent at sites 100, 104, and 204 but did not occur at site 207, a high-exposure site where the majority of captured material was low-organic, coarsely grained sand. The combination of decreased sediment accumulation and increased % organic matter led to no change in total trapped organic matter (g m^{-2} day^{-1}, Fig. S4) over the transect length at all sites ($p = 0.32$). At one site (100), the total organic matter accumulation decreased across the length of the transect ($p < 0.01$). Notably, this is a low-energy site and was in the
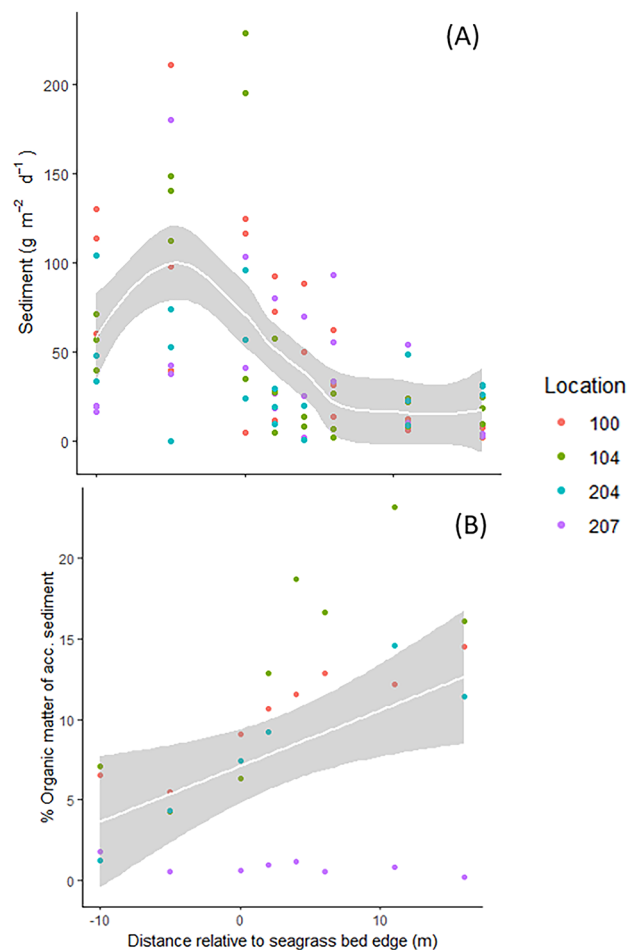

Fig. 3 **A** Extended transects sampled in 2021. On the x-axis, 0 represents the seagrass bed edge, while negative numbers denote distance outside the bed, and positive numbers denote distance inside the bed. Solid line and 95% CI calculated using locally estimated scatterplot smoothing (LOESS). See supplementary information for details on polynomial regression. **B** Percent organic matter of accumulated sediments over the transect length ($p = 0.01$). Solid line and 95% CI calculated using linear regression

most sheltered location of all sites; this is also the only site seagrass has expanded in WFH in recent years.

Accumulated organic matter and top 6 cm sediment organic matter followed each other closely ($p < 0.001$, $R^2 = 0.58$, Fig. 4). The % organic matter of newly accumulated sediments was ~1.5 times higher on average than sediment core organic matter (top 6 cm). There was no significant change in sediment grain size of any class (silt and clay, very fine sand, fine sand, medium sand, and coarse sand) along any transect ($p > 0.1$ for all).

Tropical Storms

Sediment accumulation values averaged across both sites during the 2021 event, Elsa, did not differ from baseline conditions across both sites ($p = 0.4$) but resulted in greater sediment accumulation compared to Isaias, the 2020 event ($p < 0.001$; Fig. 5). Sediment accumulation during tropical storm Isaias did not differ from baseline values across all sites ($p = 0.1$). When assessed at a finer spatial scale, Isaias differed from the baseline in the Outer Harbor, closer to the harbor channel, where sediment accumulation was significantly below background conditions at the site ($p = 0.02$), possibly due to increased scouring and movement of sand away from the site, which experiences stronger wave action than the other tropical storm site (100), which is more protected. Similarly, Elsa saw higher sediment accumulation rates than baseline only in the Middle Harbor ($p < 0.001$).

Discussion

Seagrass Bed Edge Transects

As demonstrated by the variability in our high measurements of sediment accumulation rates, which sometimes
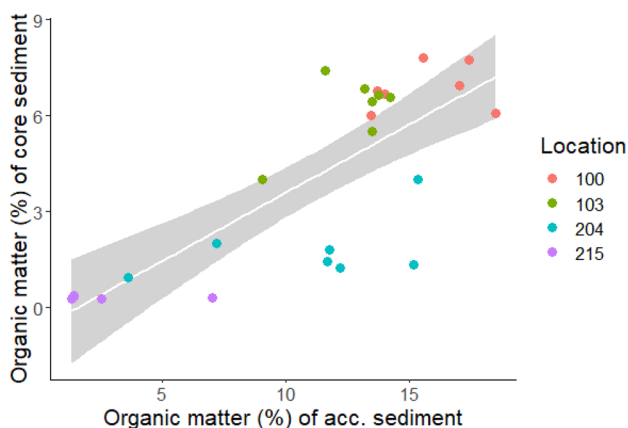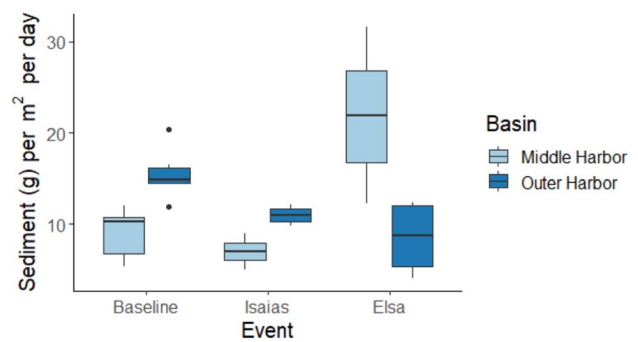
Fig. 5 Net sediment accumulation under baseline and storm conditions from two sites in West Falmouth Harbor, each located ~30 m inside seagrass meadows

exceeded 200 g m^{-2} per day, some of our data likely represent "hot spots and hot moments" (McClain et al. 2003) of sediment accumulation, rather than baseline conditions. Previous research has shown significant spatial heterogeneity in carbon storage across seagrass meadows, depending on environmental conditions (McHenry et al. 2023). Across all variables and all sites, the best predictor of sediment accumulation and percent organic matter of accumulated sediment was position relative to the meadow edge ($p < 0.001$ for sediment accumulation, $p = 0.01$ for percent organic matter). Sediment accumulation adjacent to and outside of the bed edge is as much as seven times greater than accumulation within the bed. This is likely due to the influence of edge effects on particle transport, as currents slow when they reach the edge of a seagrass bed due to the increased roughness of the bottom of the vertical profile (Granata et al. 2001), leading to particles reaching settling velocity (De Boer 2007). This is especially the case when the seagrass canopy occupies more than 10% of the vertical space in the water column (Nepf and Vivoni 2000), which is the case for all our sites at low tide (all exceed 10%), and most of our sites at high tide (all between 8 and 11%). The increased settling of sediment just outside of the seagrass bed may promote meadow expansion, as increased sediment settling promotes water clarity, which would increase the light available to seagrass seedlings (Adams et al. 2016; De Boer 2007).

While sediment accumulation decreased as distance into the bed increased, organic matter (% of accumulated material) increased, with lower values found outside of the seagrass bed. These two trends balance to result in roughly equal levels of total organic matter (g per m^2 per day) accumulation both outside and inside of seagrass beds. The exception to this is low-energy site 100, where total organic matter decreases over the course of the transect, with higher values outside of the bed compared to inside. Notably, site 100 is the only site where the seagrass meadow area has recently increased, with significant

Fig. 4 Organic matter of core versus accumulated sediments sampled at the short transect sites 100, 103, 204, and 215 (Table 1)

northward expansion of the seagrass bed noted since 2015. The accumulation of organic matter in the sediments outside of the seagrass bed may play a role in this expansion.
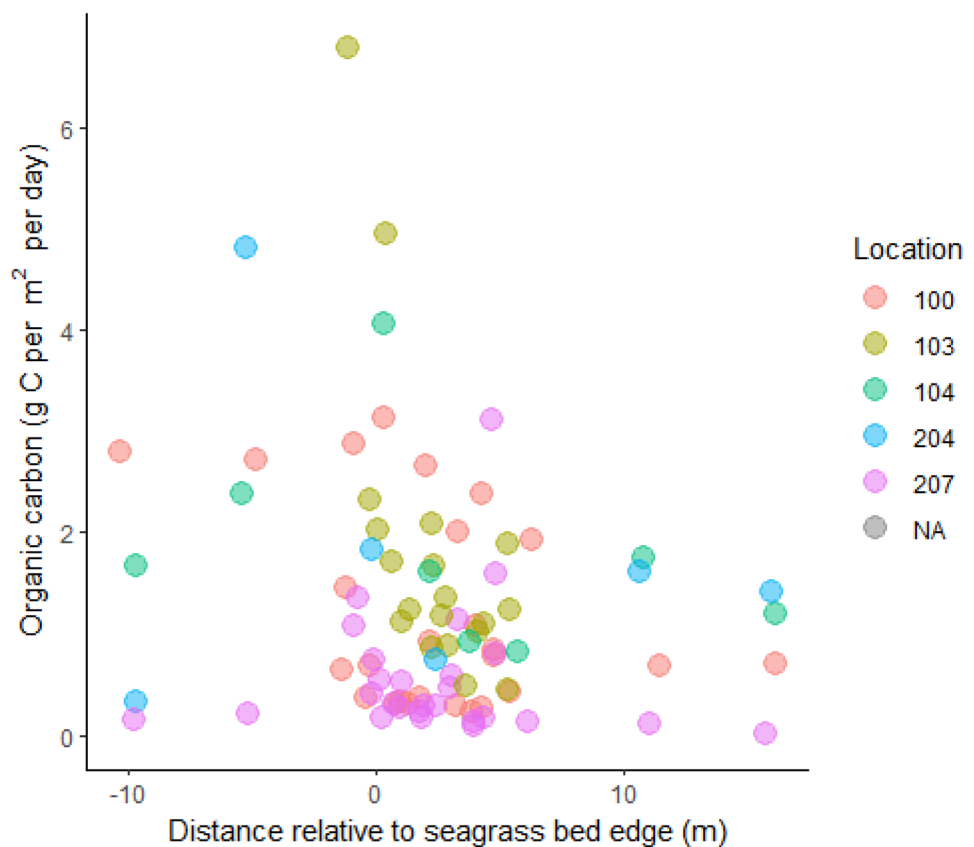
Carbon

In shallow WFH sediments, roughly 42% of the organic matter is composed of organic carbon (Haviland et al. 2022). We can use this and the organic matter accumulation data to estimate that at site 100, for example, organic carbon accumulation decreases from 3 g C per m^2 per day at a point 10 m outside the bed to less than 1 g C per m^2 per day 16 m within the bed (Fig. 6). At sites 104 and 204, organic carbon accumulation was consistent across the transect, averaging 1.8 g C per m^2 per day at both sites. Site 207 saw very low organic C accumulation, at less than 0.15 g C per m^2 per day along the transect. Across all measurements, the average C accumulation was 1.2 g C per m^2 per day and ranged from 0 to 4 g C m^{-2} day^{-1}. These values are in line with what others have found, with Gacia et al. (2002) seeing rates of 0.1 to 1.8 g C per m^2 per day settling out in seagrass meadows; and Barrón et al. (2004) seeing average deposition of 1.9 g C per m^2 per day, both in Mediterranean *Posidonia oceanica* meadows (reviewed by Duarte et al. 2013).

Tropical Storms

We saw greater net sediment accumulation during tropical storm Elsa in 2021 than we measured during tropical storm Isaias in 2020. Winds impacting Buzzards Bay were slightly higher during Isaias as compared to Elsa, which may have contributed to increased scouring of sediment away from sites. Isaias had a 0.6–0.9 m storm surge reported in Woods Hole and New Bedford, MA (Latto et al. 2021), but there was no associated storm surge reported in MA with Elsa. Storm surges are highly turbulent (Cheikh and Momen 2020), so this activity during Isaias may have contributed to the greater scouring of sediment away from the site near the channel (OH) relative to baseline conditions. We found opposite trends in the site between the two storms, with greater deposition in MH during Elsa, and more deposition (though lower than baseline) in OH during Isaias. With its impact being high winds alone (no storm surge), Elsa may have reduced sediment accumulation rates from baseline only in the more wind-exposed OH. This suspended material may have then settled out in the more sheltered MH region. Isaias's storm surge impacted both basins' sediment dynamics, with lower sediment accumulation than baseline. While there are interesting patterns suggested from these data, these two storms represent a very small sample size, and more data on net sediment accumulation from future

Fig. 6 Estimated accumulated organic carbon. On the *x*-axis, 0 represents the seagrass bed edge, while negative numbers denote distance outside the bed, and positive numbers denote distance inside the bed

storms is needed to determine what controls erosion versus deposition in seagrass meadows in New England.

Studies in Australia and the Caribbean suggest two major impacts of storms on seagrass beds: sediment removal which can lead to exposure of belowground structures, and seagrass burial (Cruz-Palacios and Van Tussenbroek 2005). In many cases, as with the impact of Hurricane Georges on seagrass meadows in Florida, both mechanisms can happen at once in different areas within a vegetated embayment (Fourqurean and Rutten 2004). The Category 2 storm resulted in one study site buried in 50 cm of sediment, while others received significant erosion, and others still saw limited impacts (Fourqurean and Rutten 2004), demonstrating the spatially heterogenous nature of impacts that tropical storms can have on sediment transport. Work by Browning et al. (2019) assessed this spatial heterogeneity on a fine scale following the impacts of Hurricanes Irma and Maria on Coral Bay in the US Virgin Islands, where net sediment accumulation ranged from −0.8 m (erosion) to +0.8 m (burial). At our sites, sediment accumulation within the sampling devices rarely exceeded the height of the sampler wall (~2 cm), and these two tropical storm events had no observable impact on seagrass mortality, likely due to the limited strength of the tropical storms as compared to hurricanes such as Georges (Category 2), Irma (Category 5), and Maria (Category 5). Tropical cyclones are less typical of the New England coastal environment than Florida and the Caribbean, with only thirty-nine storms impacting New England since 1900, and only nine of these making direct landfall on the coast of New England (Northeast States Emergency Consortium). Intense storms that bring more than 2 m of flooding are even less common, with 30 significant storm events identified over 2000 years in the sediment record of New England salt marshes (Boldt et al. 2010). Models predict increased tropical cyclones reaching New England and other high-latitude coastlines under climate change (Vellarini and Vecchi 2013; Studholme et al. 2022). Further studies, and more data in the coming decades, are needed to understand the variable impacts of these low-intensity events on seagrass meadows in the North Atlantic.

Comparison to Other Methods and Studies

Most studies assessing sediment accumulation in seagrass meadows use either ^{210}Pb dating or assess sedimentation rates using water column sediment traps. We would expect our approach to have lower values than data collected using sediment traps and higher values than data collected using ^{210}Pb. Sediment traps measure gross sedimentation and do not allow for sediment resuspension, while our method does; thus, we expect our method to produce lower values. ^{210}Pb dating measures net sediment accumulation

on a much longer time scale and is generally reported on a per year basis. Because we only measured sediment accumulation during summer time, when water column primary productivity is higher, scaling our values to per year will result in an overestimation of annual sediment accumulation rates.

Novak et al. (2020) assessed sediment accumulation at eleven seagrass meadows across New England, including WFH, using both sediment traps and ^{210}Pb dating methods. With sediment traps, across all sites, they found a range between ~30 and 550 g C m^{-2} over 14-day deployments, or ~2.1 to 39 g C per m^{-2} per day. They found an average of ~215 g C m^{-2} in vegetated regions of WFH or 15 g C per m^{-2} per day over the 14-day deployment. Like us, they saw higher values in unvegetated areas. Their sediment trap values are higher than our overall average of 1.2 g C per m^2 per day, but comparable; this is probably due to the difference in sediment trap design between the two studies, as their traps were specifically designed to prevent resuspension of sediment. Their ^{210}Pb data ranged lower, between 8 and 230 g C per m^{-2} per year, or ~0 to 0.6 g C per m^{-2} per day at all sites. ^{210}Pb dating from cores taken in both vegetated and unvegetated areas of WFH showed negligible sediment accumulation on an annual basis (Novak et al. 2020). Our method found sediment accumulation rates in between these two methods (sediment trap designed to prevent resuspension and ^{210}Pb dating).

Oreska et al. (2017) demonstrated an increase in sediment organic C moving away from the meadow edge and into the meadow over distances of 1200 m in South Bay, Virginia. The authors found much of this organic C to be derived from allochthonous sources, such as sediment transport, in some areas. While we did not see a pattern of increasing C accumulation across our shorter transects, Oreska et al. (2017) posited that meadows with different morphologies, such as slower currents and a lower canopy height to water depth ratio, may see a pattern opposite to theirs. Seagrass in WFH receives a similar magnitude of bottom shear stress, between 0 and 0.12 N m^{-2} within the seagrass bed (Ganju et al. 2012), to seagrass at the Virginia coastal reserve (Hansen and Reidenbach 2012). However, WFH is about twice as deep (average depth 1.4 m at mean water; Hayn 2012) as South Bay (average depth 0.76 m at mean water; Oreska et al. 2017), but with similar canopy heights at most sites (i.e. a lower canopy height to depth ratio), which may contribute to the different pattern we see, as Oreska et al. (2017) predicted. Additionally, South Bay is oligotrophic, while WFH is meso- to eutrophic due to N-enrichment (Howarth et al. 2014); recent work has demonstrated reduced carbon sink capacity in nutrient-enriched seagrass meadow sediments as compared to meadows without eutrophication (Qin et al. 2021).

Conclusions

Edge effects greatly contribute to small-scale spatial heterogeneity in net sediment accumulation in seagrass meadow habitats, with up to 400 times greater sediment accumulation reported only 20 m apart across the bed edge. Because of this heterogeneity, researchers should use caution when scaling up sediment accumulation measurements from a limited number of observations. For example, if we scale up our measurements from vegetated stations at two different sites (104 and 207) to the full meadow area in WFH, we would come up with values disagreeing by three orders of magnitude across the harbor.

Our study showed the greatest accumulation of sediment and C along seagrass meadow margins. The meadow edge represents the most vulnerable part of the meadow, where interactions with strong currents (Fonesca et al. 1983), grazers (Statton et al. 2015), and other stressors result in greater potential for mortality. However, monitoring efforts tend to focus on meadow interiors, with many standard seagrass monitoring protocols calling for sites to be located at least 30 m from an edge. Depending on site morphology, a lack of data on bed edges may have implications for our understanding of whole-meadow dynamics and result in incorrect estimates of carbon accumulation when scaled up. Human influence leads to increased fragmentation in seagrass meadows (Unsworth et al. 2015), meaning that edges are making up a greater proportion of seagrass meadow area in smaller, patchier meadows. This will lead to changing dynamics in seagrass meadows, with potentially greater settling out of sediment along these new edges. Additionally, our results suggest an influence of meadow-edge sediment dynamics on bed expansion or reduction. Though our data is limited, we saw the most organic matter accumulation along the edge (100) of a site experiencing active meadow expansion, and the least organic matter accumulation (207) along the edge of a site that saw meadow area recession the year following this data collection. Thus, understanding the dynamics of meadow edges may be increasingly important in understanding meadow resilience and stability under global change. With tropical storms impacting northern regions of the US east coast more frequently with increased sea surface temperatures (Studholme et al. 2022), understanding how features of a storm—such as storm surge, and wind—impact seagrass meadow sediment accumulation in New England will become increasingly important. Inexpensive, simple methods like the ones presented in this paper can be used at scale to address spatial (position within meadow) and meteorological (tropical storm events, etc.) variability within seagrass meadows, allowing us to better support and protect these ecosystems.

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