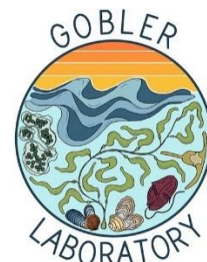


CHANGES (*Creating Habitat, Acidification reduction, Nitrogen bio-extraction, Guarding our shorelines, Erosion control, Sequestering carbon*)

Progress Report for Peconic Estuary Partnership, February 2025



**Stony Brook University
School of Marine and
Atmospheric Sciences**



EXECUTIVE SUMMARY

Coastal communities, ecosystems, and fisheries face multiple concurrent, compounding and complex environmental threats in the 20th century. Sea level rise poses a significant and escalating threat to coastal communities. Habitat loss has resulted in the collapse of critical fisheries. The overloading of nitrogen from anthropogenic sources has degraded water quality and contributed to the decline of fisheries and aquaculture. Ocean acidification represents an additional threat to shellfisheries. Still, creative expansion of bivalve populations and marine habitats offers an opportunity to mitigate these threats, while enhancing fisheries. Oyster, seagrasses, and kelp aquaculture can contribute significantly to coastal economies and economic growth and may offer valuable natural defenses against the storm surge and sea-level rise while also offering opportunities to mitigate ocean acidification. The overarching objective of this project is to utilize combinations of kelp, oysters, and seagrasses to bioextract nitrogen, sequester carbon, mitigate ocean acidification, protect shorelines, enhance fisheries and biodiversity, and improve water quality/clarity. The first phase of the project was designed to identify locations that would be ideal for the development of a living shoreline that would create habitat, combat ocean acidification, actively bio-extract reduction nitrogen, protect shorelines, and sequester carbon. During 2023 and 2024, six locations across the Peconic Estuary were evaluated for water quality (temperature, salinity, dissolved oxygen, light penetration, chlorophyll *a*, total nitrogen), sediment composition (grain size distribution, organic matter content, depth of muds), and growth and survival performance of kelp, seagrass and oysters. The data has combined to provide a clear sense regarding locations that would be ideal for kelp, seagrass, and oysters. Among the sites considered, Menatic Creek was deemed inappropriate as it had poor water and sediment quality (high chlorophyll *a* and total nitrogen, low dissolved oxygen and water clarity, muddy, fine-grained sediments) and yielded poor kelp and seagrass survival and growth, although the oyster population did well at this location. Some other sites were deemed to be marginal for full scale restoration projects including Ganet Creek, Sag Harbor Cove, and the South Ferry/Shelter Island Sound site. These locations had fair water and sediment quality, fair kelp growth, varied seagrass growth, but generally good oyster growth. Sag Harbor Cove was the best among the marginal sites, but may not be appropriate due to the presence of widgeon grass. Two sites that were studied in 2024 that seemed ideal for restoration were the Barcelona Point/Northwest Harbor site and the east side of North Haven. These sites had excellent water quality and sediment quality (low chlorophyll *a* and total nitrogen, high dissolved oxygen and water clarity, coarser grained, low organic matter sediments), had the best kelp growth, excellent seagrass growth and survival, and good oyster growth and survival. For 2025, this project will seek to develop, larger, meso-scale deployments of oysters, kelp and seagrass at these sites, while investigating the usefulness of Sag Harbor Cove.

INTRODUCTION

Oyster, seagrasses, and kelp aquaculture significantly contributes to coastal economies and economic growth in the US (NOAA, 2024). Regarding oyster and kelp, these industries generate revenue through the direct sale of harvested products (Gentry et al., 2017). Kelp also hold promise as a fertilizer and in emerging biostimulant markets (Kim et al., 2019). Seagrasses play a critical role as a nursery habitat for many important shellfish and finfish fisheries (Heck et al., 2003). Aquaculture operations for crops such as oyster and kelp create jobs in coastal communities, spanning farm labor, processing, distribution, and supporting industries like boatbuilding and equipment supply (Jolly and Klontz, 2020). Furthermore, these forms of aquaculture can enhance tourism and recreation by attracting visitors interested in sustainable seafood recreational fishing opportunities associated with restored habitats (Hicks et al., 2004; Jolly and Klontz, 2020). Moreover, restoration of shellfisheries can play a key role in boosting regional economies. For example, the Shinnecock Bay Restoration Program was shown to contribute tens of millions of dollars to the regional economy by restoring the hard clam fishery in Shinnecock Bay (Gobler et al., 2022). By diversifying coastal economies and providing sustainable alternatives to wild-capture fisheries, oyster and seagrass restoration, and kelp aquaculture can support economic resilience and long-term economic growth in coastal regions.

Sea level rise, driven by thermal expansion of warming ocean waters and melting ice sheets, poses a significant and escalating threat to coastal communities. As sea levels rise, inundation of low-lying communities becomes more frequent and severe, leading to coastal erosion, and damage to infrastructure (IPCC, 2021). Furthermore, sea level rise exacerbates the impacts of storm surges, increasing the risk of flooding and destruction during extreme weather events (Kopp et al., 2017). The combined effects of these processes threaten the economic stability, of coastal communities, necessitating adaptation and mitigation strategies to minimize future losses and displacement (Bosello & De Cian, 2014).

Oyster reefs, seagrass meadows, and aquaculture kelp lines can offer valuable natural defenses against the combined threats of storm surge and sea-level rise for coastal communities. Oyster reefs, with their complex three-dimensional structure, act as natural breakwaters, dissipating wave energy and reducing storm surge height (Scyphers et al., 2011). Similarly, seagrass meadows, by stabilizing sediments and creating friction against water flow, attenuate wave action and lessen the impact of storm surge (Paul, 2018). Furthermore, the vertical structure of kelp forests cultivated on aquaculture lines can also provide a similar wave-buffering effect, reducing wave height and energy reaching the shore (Bodycomb et al., 2023). These natural and nature-based features not only offer immediate protection against storm surge but also contribute to long-term coastal resilience in the face of sea-level rise by trapping sediment and building elevation, effectively combating erosion and maintaining critical intertidal habitats (Phillips, 2018). Integrating these ecosystem-based approaches into coastal management strategies offers

a sustainable and cost-effective way to enhance coastal protection and adapt to the challenges of sea level rise.

Finally, seagrass meadows, kelp forests, and to a lesser extent oyster reefs are recognized as "blue carbon" ecosystems that sequester carbon and mitigate the threat of ocean acidification. It is clear that kelp and seagrasses absorb substantial amounts of carbon from the atmosphere and seawater through photosynthesis, effectively reducing the concentration of CO₂ (Duarte and Krause-Jensen, 2017; Duarte et al., 2025). The carbon is then stored in their biomass, as well as in the sediments beneath seagrasses and within the complex three-dimensional structure of kelp forests (Macreadie et al., 2019; Duarte et al., 2025). This process not only sequesters carbon but also helps to buffer against ocean acidification by increasing pH levels in the surrounding waters (Hendriks et al., 2014). By locally reducing CO₂ concentrations and increasing pH, seagrasses and kelp can create refugia for marine organisms that are vulnerable to the impacts of ocean acidification, including oysters (Young et al., 2022). Protecting and restoring these valuable ecosystems is therefore crucial for both carbon mitigation and adaptation strategies in the face of climate change.

OBJECTIVE AND TASKS:

The overarching objective of this project is to utilize combinations of kelp, oysters, and seagrasses to bioextract nitrogen, sequester carbon, mitigate ocean acidification, protect shorelines, enhance biodiversity, and improve water quality/clarity.

Tasks of this project are to: 1. Perform benthic and pelagic site evaluations to assess the suitability of multiple sites across the eastern Peconic Estuary the aquaculture of kelp, the establishment of oyster reefs, cages, and/or balls, and for eelgrass restoration. 2. Perform experimental and pilot scale deployment of aquacultured kelp, oyster reefs, cages, and/or balls, and eelgrass, 3. Quantify carbon sequestration, nitrogen bioextraction, and shoreline protection afforded by sundry experimental and pilot scale approaches, and 4. To estimate carbon sequestration, nitrogen bioextraction, and shoreline protection afforded by full scale deployments.

APPROACH

During year one of this project, water quality and benthic parameter assessments relative to the growth of kelp, oysters and seagrass were made at in-shore and open water sites across North Haven, Sag Harbor, and Shelter Island. In-land sites to be assessed included Gannet Creek in North Haven, Menatic Creek on Shelter Island, and Sag Harbor Cove, in Sag Harbor whereas open water regions included the eastern shore of North Haven, the region near the south ferry site of Shelter Island, and the region north of Northwest Harbor in East Hampton (Figure 1). In year one, water quality was surveyed via continuous temperature, light, pH, and dissolved oxygen measurements whereas discrete measurements of temperature, light, pH, and dissolved oxygen chlorophyll and nutrients were also be made. Sediment surveys included assessments of

sediment type, organic matter content, and sulfide content. Hydrodynamic measurements included water depth and wave height. Experimental scale grow-out of kelp, oysters, and seagrass were executed, and growth rates of organisms were quantified and along with C and N extraction.

Water Quality Monitoring

Water quality was monitored in multiple ways. Firstly, YSI EXO3 multi-parameter sondes was deployed at each of six sites to continuously monitor levels of dissolved oxygen (DO), temperature, pH (NBS scale), conductivity (i.e., salinity), and total chlorophyll *a*. Continuous data was internally logged within sondes every 10 min and will be downloaded from the sondes and stored in cloud storage (Stony Brook University Google Drive) every two weeks. To complement these continuous measurements, discrete samples were collected at each site and region for the measurement of total nitrogen, light levels at depth and chlorophyll *a*. Total nitrogen was collected and quantified in triplicate on filtered (0.2 μm) polysulfone capsule) seawater samples and frozen for later analysis. Light levels were measured using a Secchi disc. Extracted chlorophyll *a* was measured from samples collected on glass giber filters and analyzed fluorometrically (Parsons, 2013).

Kelp

We will collect reproductive sugar kelp from LIS in the fall and induce spore release onto seed strings in the Stony Brook – Southampton marine laboratory’s kelp hatchery employing the methods originally based on Yarish et al. (2017) and refined to maximize yields during the past four years. After five weeks of care in the nursery, the kelp seed strings will be deployed directly onto the horizontal lines at field sites using standard techniques that wrap the seed string around the longline. After seeding, the lines will be checked regularly to ensure that the appropriate depth is maintained in the water column. Kelp lines will be seeded in late November/early December and are expected to be harvested in late May/early June.

Kelp will be monitored on a bi-weekly basis from January through May by collecting triplicate samples from each open-water kelp line deployed at each site. For each sample, all kelp biomass including blade, stipe, and holdfast will be excised from a 15 cm length of line, and the following measurements will be made: wet weight, dry weight, average kelp blade length, blade width, and stipe length. The blades and stipes in each sample of kelp will be separated and dried for the analysis of tissue C and N content (see Section 5.1 below). Analyses of the tissue C and N content coupled with the wet weights and the linear relationship between wet and dry kelp weights we have established with hundreds of kelp samples during the past five years will allow the net amount of N removal to be quantified. When growth ceases and kelp tissues begin to decay in late spring, all kelp will be harvested from lines and brought to the Stony Brook – Southampton campus for drying and/or composting.

Regarding kelp, lines with kelp were installed and seeded at each of the six sites in late December/early January 2023/2024, and harvested in mid to late May. At four of the sites (Barcelona Point, East North Haven, Genet Creek, Menantic Creek), two horizontal lines installed at four of the sites using the staked line method where lines were staked ~0.3 meters above the bottom using screw anchors. At two of the sites (Sag Harbor and South Ferry), lines were deployed off of docks, with four horizontal suspended lines installed off floating docks at the Ship-aShore marina in Sag Harbor, and three vertical drop lines installed off a fixed private dock near the South Ferry in North Haven. All lines were monitored monthly when three samples were collected, removing all biomass in 15 cm segments. For all samples, fresh weight, dry weight, blade lengths, and the Carbon-Nitrogen content of the kelp tissue (CN samples stored for analysis) were measured.

Oysters

Oyster spat-on-shell (SOS) was deployed in triplicate cages at each of the six study sites to monitor survival and growth. The low-profile wire cages (103 cm x 56 cm x 27 cm), typically used by the oyster aquaculture industry, were customized to hold one standard oyster grow-out bag, with 6-inch legs to elevate the bag above the sediments (Figure 2). Oysters were deployed to each cage using two separate methods that differed in the level of predator protection. First, SOS oysters were placed inside mesh grow-out bags inside of the oyster cages, as would typically be done by commercial oyster farmers. Second, SOS oysters were placed in soft Vexar mesh sleeves that were affixed to the outside top of the cages. Vexar mesh sleeves are often used by oyster restoration practitioners to construct shell bags to build oyster reefs, and this deployment method better represented the conditions oyster spat may experience in a restoration setting as opposed to an aquaculture setting, particularly regarding predator exposure. While the aquaculture method (grow-out bags) helps protect small oyster spat from large predators like crabs, whelk, and starfish, the restoration method (Vexar mesh sleeves) does not. Seven shells with known starting quantities and sizes of oyster spat were placed in each replicate bag/sleeve for each treatment at each site. The spat-on-shell was deployed to the field sites on 7/12/24, and monitored every four to five weeks through 10/9/24. At each monitoring time point, the number of live and dead spat were counted on each shell, and the shell heights of live oyster spat were measured. In addition, the shells of dead oysters were inspected for predator damage, and the presence of predators on or in the bags/sleeves was recorded.

Sediment surveys

For sediments, benthic surveys of sites were conducted through transect dives on SCUBA performed by a pair of trained divers. The divers laid three 10m transect with a pre-labeled rope (flagging tape marker at 5m). Sediment cores to 5cm depth were taken for qualitative sediment characteristics, % organic matter and grain size analyses. Organic matter was analyzed through loss on ignition analysis. Duplicate sub-samples were homogenized and dried to a constant weight at 60° of at least 20g, pre-weighed and combusted at 400°C for 12 hours, then re-weighed

for total matter loss (Schumacher 2002). Grain size were analyzed through duplicate subsamples, each at least 40g. Each sample will then be weighed, dried at 60°C for 24 hours, placed in a desiccator to cool, and re-weighed for dry weight. The amount of salt in each sample can be calculated with the amount of water lost during drying and salinity at the site. The samples will then be partitioned into size classes, noting of larger non-sediment presence (clam shell fragments, plastic, etc.), using sieves corresponding to each class: Pebbles >2000 µm (10 mesh), Very course and course sand 500-2000 µm (35 mesh), Medium, fine, and very fine sand 63-500 µm (230 mesh), Silt <63 µm. After being partitioned the samples werere-weighed according to their size classes (Poppe et al., 2000).

Seagrass

Three bottom oyster cages had been previously installed at each site in parallel to the shoreline. The distance from the edge of the first oyster cage to the edge of the last oyster cage was approximately 2 meters. To standardize the location of the eelgrass plantings, a 2-meter distance was measured using a transect tape on the shoreward side of the oyster cages, directly alongside and parallel to the cages. A screw anchor with a 0.5-meter line and small buoy attached was secured into the seafloor at both the beginning and end of the transect line at each site. These screw anchors were used to prevent the oyster cages from being moved from their positions and assist in relocating the transplanted eelgrass. At each of the six transplant locations, three eelgrass sods were transplanted into distinct $\frac{1}{4}$ m² plots (within quadrats during the planting that were then removed), with 0.2 m between each of the plots. The plots were positioned 0.7 meters shoreward from the oyster cages (0.7 meters from the transect tape between then aforementioned screw anchors). The plots were numbered 1 through 3, from left to right, with the observer's back to the shore. A handheld GPS unit was used to record the latitude and longitude of each of the screw anchors. All six transplant locations included this same setup. However, the site off North Haven also included an additional setup that was approximately 10 meters away from the previously described setup, completed in the exact same way, except without oyster cages to the seaward side of the transplant plots. The intention of the addition of these plots without oyster cages was to evaluate the effect of having oyster cages on the seaward side of the eelgrass transplants, specifically to assess whether the cages dampened wave energy from boat wakes that could impact transplanted eelgrass. In other words, the North Haven site included eelgrass transplant plots protected by oyster cages and unprotected (protected and unprotected, respectively). With three eelgrass transplant plots per location (with one having six transplant plots) and six locations, 21 sections of eelgrass sod were used. The final remaining sod was used to supplement a previously planted plot that appeared to have fewer shoots than the others. As each eelgrass sod was being transplanted within each plot at each site, great care was made to ensure that all roots and rhizomes were covered with sediment and were below the surface of the sediment. To minimize further disturbance to the eelgrass transplant plots, no quantitative assessments of the plots were done on the day that transplants were completed.

On a monthly basis after eelgrass was transplanted to each location, SBU personnel returned to complete monitoring assessments of each plot. Monitoring assessments occurred on August 19th, September 12th, and October 17th of 2024. Monitoring assessments involved placing a ¼ m² quadrat around each eelgrass transplant plot. Within each quadrat, the percent cover of eelgrass, widgeon grass (*Ruppia maritima*) and macroalgae within each quadrat was visually estimated and recorded. Widgeon grass was included since it was clearly present in the general area at the Sag Harbor Marina location. The number of eelgrass shoots and the number of shoots with exposed roots and rhizomes within each quadrat was quantified and recorded. Any exposed roots and rhizomes were pushed back underneath the surface of the sediment. The length of five eelgrass shoots were measured (to the nearest cm) within each quadrat including the shoot closest to each corner of the quadrat and the shoot closest to the center.

RESULTS AND INTERPRETATION

Water quality

Across all sites, on average, light penetration to the bottom varied by site (Fig 3). The Northwest Harbor/Barcelona Point site, Sag Harbor Bay/Artist Colony and South Ferry site in Shelter Island Sound had the greatest degree of light penetration (80-90%), whereas Genet Creek, Menantic Creek, and Sag Harbor Cove had lower light levels (60-70%; Fig 3). These outcomes were generally consistent with the general locations, as the lower light sites were more enclosed compared to the open water sites that all that greater light levels and penetration. All of these light conditions by themselves would be permissive of seagrass growth, although higher light levels will favor more robust seagrass growth (NYSDEC 2009).

Across all sites, on average, chlorophyll *a* concentrations varied by site and displayed a pattern inverse to light penetration (Fig 3) as the Northwest Harbor/Barcelona Point site, Sag Harbor Bay/Artist Colony and South Ferry site in Shelter Island Sound had the greatest lowest levels of chlorophyll *a* (6 – 8 µg L⁻¹), whereas Genet Creek, Menantic Creek, and Sag Harbor Cove had higher levels (10 – 25 µg L⁻¹; Fig 3). Among the later sites, Menantic Creek stood out as having chlorophyll *a* concentrations that were more than double all other sites (25 µg L⁻¹; Fig 3). These concentrations are generally indicative of eutrophic conditions in estuaries and can contribute to hypoxia and low light levels; these levels also exceed guidance levels provided by USEPA (USEPA, 2001).

Bottom dissolved oxygen (DO) levels measure during the day were generally high across all sites (Fig 5). Menantic Creek stood out as having the lowest average bottom DO levels (5.5 mg L⁻¹; Fig 5). This site almost certainly experienced nocturnal hypoxia (Wallace et al., 2014, 2021), a condition well-known to endanger estuarine fish and shellfish (Clark and Gobler, 2016; Morrell and Gobler, 2020; Tomasetti et al., 2022).

Total nitrogen (N) trends largely paralleled those seen for chlorophyll a (Fig. 6). Northwest Harbor/Barcelona Point and Sag Harbor Bay/Artists Colony had the lowest levels ($\sim 0.3 \text{ mg L}^{-1}$; Fig 6), while Shelter Island Sound and Sag Harbor Cove displayed mean levels of less than the former PEP standard of 0.4 mg L^{-1} while Ganet Creek were at that level (Fig. 6). Menantic Creek stood out as having the highest average TN levels (0.7 mg L^{-1} ; Fig 6) a level likely to contribute to poor water quality and ecological outcomes at this site.

Discrete water quality measurements were made using a handheld YSI multiparameter sensor, including temperature, salinity, and dissolved oxygen during the 2024 kelp season revealed only minor differences among sites (Figure 7). Temperatures rose from $< 5^\circ\text{C}$ in February to $\sim 20^\circ\text{C}$ by May (Figure 7) with the final levels exceeding optimal temperatures for kelp growth, accounting for decreases in kelp biomass during this time (*see below*). Salinity levels were all generally 26 – 28 PSU (Figure 7), a good level for kelp, seagrass, and oysters. Salinity dropped to 21 ppt in Genet Creek in May (Figure 7), the lowest salinity reading of the study. Dissolved oxygen slowly dropped as temperatures rose at all sites although was generally DO high throughout kelp growing season at all sites (Figure 7).

In summer, temperature records across sites demonstrated small differences across sites strong diel variance across all sites during the summer of 2024. The Barcelona Point and Sag Harbor Cove sites were the warmest of the sites and experienced two, one-week periods of temperatures above 25°C (Fig 8), a level known to be stressful to seagrass when sustained for more than one week (NYSDEC, 2009). In contrast, the Sag Harbor Bay / East North Haven site and Ganet Creek site experienced slightly more moderate temperatures (Figure 8).

In sum, with regard to water quality, Menantic Creek is highly eutrophic (low DO, high chlorophyll a, low light levels) location and is likely not suitable for oysters and seagrass. Ganet Creek, and Sag Harbor Cove had some concerning water quality trends (extended temperatures above 25°C , elevated chlorophyll a, or low light) although none that would be fully disqualifying for work with seagrass, oysters, and kelp. The Northwest Harbor, Shelter Island Sound, and Sag Harbor Bay were cooler, had high oxygen, nearly full light at the bottom, enough chlorophyll a to be supportive of continued work with seagrass, oysters, and kelp.

Sediment surveys

Sediment surveys were performed at all six locations during which sediment samples from 20 sites from each location were obtained and analyzed for grain size distribution, organic matter content and mud depth at each site. Among the sites, the two creek sites were the similar to each other as were most of the open water sites (Northwest Harbor, Shelter Island Sound, and Sag Harbor Bay) with Sag Harbor Cove being a blend of the sites. To highlight these differences, on one extreme the Northwest Harbor/Barcelona Point site was dominated by

sediments that were 90 – 500 μm (Figure 9) and had a low level of organic matter content (<0.5%; Figure 10). In contrast, Menantic Creek was dominated by sediments that were < 90 μm (Figure 11) and were comprised of had a high level of organic matter, in some cases exceeding 9% (Figure 12). Across all sites, on average, Menantic Creek and Genet Creek had high levels of organic matter in sediment (4-6%), while Sag Harbor Bay and Sag Harbor Cove had lower level (~1.5%), and Northwest Harbor/Barcelona Pont and Shelter Island Sound/South Ferry had the lowest levels (<0.5%; Figure 13). Regarding grain size distribution, Menantic Creek and Ganet Creek were distinct as they were dominated by fine grain sediment (>60% of sediments < 90 μm ; Figure 12). Sag Harbor Cove contained roughly 20% of sediments < 90 μm , whereas all other sites contained 1 – 2% (Figure 14). The depth of soft mud at each site generally paralleled trends in fine grain sediments with Menantic Creek being distinguished as having more than 1.5 m of mud (Figure 15). Genet Creek had nearly a half meter of mud while Sag Harbor Cove was ~0.4 m (Figure 15). In contrast, Sag Harbor Bay/Artist Colony, Northwest Harbor/Barcelona Pont and Shelter Island Sound/South Ferry all had no mud (Figure 15).

Collectively, the sediment analyses demonstrate that the three more enclosed sites, Menantic Creek, Ganet Creek, and Sag Harbor Cove, were dominated by fine grain, organically enriched, muddy sediment. In contrast, Northwest Harbor, Shelter Island Sound, and Sag Harbor Bay were dominated by sandy, low organic matter, coarse-grained sediments. The extreme depth of muds and organic matter content and fine grain sediments at the two creek sites make them unsuitable for seagrass and on-bottom oyster planting, as these sediments will have high levels of sulfides which are toxic to seagrasses and these sites lack the firmament necessary for building oyster reefs; shell bags and oysters will sink into the muds and die (NYSDEC, 2009). While Sag Harbor Cove had some areas of high organic matter content and muds, there were zones that were more suitable (Figure 16), suggesting there was potential at this site as well.

Kelp grow outs

Kelp lines were seeded in late December / early January and growth on some lines was first detectable in February (Figure 17). For two of the sites, Barcelona Point/Northwest Harbor and East North Haven (Sag Harbor Bay) kelp growth was robust with kelp at Barcelona Point reaching ~0.28 m long blades and peak biomass were 0.14 kg per meter of line (Figure 17). East North Haven reached similar blade lengths with a maximum line yield of about 0.08 kg per meter (Figure 17). While there was some growth at other sites, it was minor compared to Barcelona Point and East North Haven. One significant issue for all sites was the emergence of *Ectocapus* sp. seaweed (aka ‘Slip gut’) on the kelp lines. This brownish slimy seaweed, can be problematic as it biofouls lines and competes for space with kelp on the lines. Once kelp is established, it can fend off slip gut and other biofouling organisms. But if slip gut takes hold first, it can outcompete the kelp. Kelp lines for the 2024 grow-out season were seeded in late December / early January. Observations from other locations (i.e. Greenwave farm in Long

Island Sound) suggest earlier seeding can lead to better growth, possibly due to higher nitrogen availability providing an early nitrogen boost.

Given the results obtained in 2024, a novel kelp approach was used in 2025 specifically using sporophyte kelp lines. Presently, the timing of kelp deployment is dependent upon the annual collection of reproductive kelp tissue from the ocean during the fall when ‘sorus tissue’ develops as temperatures cool. These reproductive tissues are used to spawn kelp onto seed strings which, after several weeks of laboratory based-cultivation, are deployed. Regarding climate-related barriers, one of the stronger climate change signals in downstate NY has been seasonal warming trends, with summer and fall water temperatures increasing at three-times the global average. This has had a trickledown effect on the kelp industry, as the sugar kelp only generates reproductive sorus tissue needed for the generation of kelp seed strings once fall temperature becomes cool enough, an event that has occurred later over time. Over the years, we have discovered that early deployment of kelp maximizes yields as early kelp growth during late fall allows the kelp to reach a size threshold that minimizes and restricts fouling by other algae. The growth of all seaweeds is temperature dependent. In fall, while temperatures are cooling but are still in a range that facilitates modest kelp growth, typically in the absence of competitive growth of other algae, perhaps due to the minimal photoperiods. As such, kelp that is deployed earlier is less fouled and grows more robustly, increasing the quality and quantity of the product upon harvest. Alternatively, the significant warming of fall water temperatures in NY during the past two decades has necessitated a later collection of kelp reproductive tissues. The trending of warming waters in summer and fall, therefore, is effectively shortening the growing season for kelp and decreases the likelihood of success as early season kelp growth has been correlated with larger later season yields. While these findings might suggest kelp farming will not be resilient to climate change, there are advances in kelp culturing that can help overcome these obstacles, specifically the development of gametophyte kelp cultures. Just as land farmers do not rely on their current crops to provide seeds for the following season, the development gametophyte kelp cultures will allow kelp farmers to not be reliant upon ecosystem-collected reproductive kelp for their farms. This advance will also allow kelp to be deployed in the early-to-mid fall, maximizing final yields and minimizing fouling.

For 2025, therefore, we cultivated gametophyte kelp cultures at Stony Brook University. Using previously established methods gametophytes were cultured and in early fall were transitioned to sporophytes that will be then set on seed strings that will be deployed on oyster farms. In parallel, traditionally spawned kelp from recently collected reproductive kelp tissue were collected in fall spawned and deployed later for comparative purposes. While it is still early in the growing season, early signs indicate that the gametophyte kelp lines are growing well at all locations and are growing much faster than the traditionally spawned sporophyte lines. This new method should allow for more robust kelp growth at all sites for this project.

Oyster grow outs

Oyster survivorship and growth

On 10/9/24, 89 days after deployment to the field sites, survival of SOS ranged among sites between 47% and 80% for oysters inside grow-out bags (Figures 18A,B), and between 35% and 61% for oysters in Vexar mesh sleeves on the outside of cages (Figures 18A,B). The lowest survival was found at the South Ferry site, for both oysters inside and outside of cages. The highest survival was found at Barcelona Point and Sag Harbor for SOS inside grow-out bags in cages (Figure 19). Differences in survival among sites, however, were not significant for SOS inside cages (ANOVA, $F=2.54$; n.s.) or SOS outside cages (ANOVA, $F=2.57$, n.s.). At five of the six sites, survival of SOS placed inside grow-out bags was slightly higher than that of SOS placed in Vexar mesh sleeves, suggesting that the grow-out bags may provide some level of protection against predators (Figure 19). The main predator observed was oyster drills, which were particularly abundant at the South Ferry site and may explain the higher mortality there. The grow-out bags did not completely exclude oyster drill predators.

Oyster spat grew at all sites, with growth rates from 7/12/24 to 10/9/24 ranging between 0.30 to 0.57 mm d⁻¹ among sites and treatments (Figures 20-22). Growth significantly differed among sites for SOS inside (ANOVA; $F=12.88$; $p<0.001$; Figure 22a) and outside (ANOVA, $F=11.02$; $p<0.001$; Figure 22b) of cages. Growth was significantly lower at South Ferry than other sites for SOS inside and outside of cages (Tukey HSD tests; $p<0.05$ for significant differences). The highest growth rates were observed for SOS inside cages at Barcelona Point and Sag Harbor, where survival was also highest, and the lowest growth rate was observed at South Ferry where survival was also the lowest. At five of the six sites, growth was higher for oyster spat placed in grow-out bags than oyster spat placed in Vexar mesh bags (Figure 23).

In sum, with oyster growth and survival was quite good across sites, East North Haven/Sag Harbor Bay, Barcelona Point/Northwest Harbor, and Sag Harbor Cove has the fastest growth rates and the highest survival rates.

Seagrass

Shoot counts varied across sites and over time. The eelgrass transplant plots at the North Haven site had the highest initial shoot counts, following by Barcelona Point, Sag Harbor Marina, South Ferry, and Ganet Creek (Figure 24). At the time of the first monitoring event in August, all eelgrass that had been transplanted into plots at the Menantic Creek site had died and was decomposing. Given the complete mortality of transplanted eelgrass at the Menantic Creek site, the decision was made to exclude it from furthering monitoring (Figure 24). There was an exceptionally high amount of macroalgae during this monitoring event compared to the other sites during the time (Figure 27) along with low water clarity. Other than the Menantic Creek site, most other sites experienced a decline in the average number of eelgrass shoots within each

transplant plot between August 19th and September 12th (Figure 24). The exception to this were the transplant plots that were not protected by oyster cages (unprotected) at the North Haven site. On average, the shoot count in these unprotected plots increased slightly over the same time-period (Figure 24). Excluding the Menantic Creek site, eelgrass persisted throughout the duration of the sampling events. The average shoot count in transplant plots increased in all but one site (Ganet Creek) between September 12th and October 17th. The average shoot count continued to decline at the Ganet Creek site between September and October (Figure 24). Barcelona Point, North Haven, and South Ferry all had average shoot counts in October that exceeded the shoot counts in August. The average shoot count at Sag Harbor Marina increased between September and October and returned roughly to the equivalent shoot count as August (Figure 24). Again, there was nothing to assess for the Menantic Creek site for live eelgrass.

Across sites that eelgrass persisted during the duration of the sampling events, average shoot length followed a similar pattern to shoot count where it fell to a minimum in September and increased into October (Figure 25). Three sites experienced maximum average shoot length in October including Sag Harbor Marina, South Ferry, and Ganet Creek. The others experienced maximum average shoot length in August including North Haven (both protected and unprotected transplant plots) and Barcelona Point. Out of all the sets of transplant plots, the unprotected North Haven site was the only one to experience a decline in average shoot length during the entire period (Figure 25).

While the average percent cover of eelgrass in the transplant plots at most locations (Ganet Creek, South Ferry, and both protected and unprotected North Haven plots) increased between August and September, the increase was minimal at both South Ferry and Ganet Creek. The relatively large increase in average eelgrass percent cover in the North Haven transplant plots may have been a product of differences in current intensity between sampling events. While the average percent cover of eelgrass remained the same between August and September for Barcelona Point, it declined slightly over the same time-period (Figure 26). Only in Sag Harbor Marina did percent cover fall from August to September, and from there stayed even into October. For all other sites, the average eelgrass percent cover declined between September and October. However, overall, the average percent cover between August and October remained relatively stable across all sites that eelgrass persisted at (Figure 26).

Across all eelgrass metrics, the highest-performing sites appear to be Barcelona Point and North Haven (both protected and unprotected transplant plots). These sites had the highest average shoot counts across the sampling period (Figure 24). North Haven and Barcelona Point also had among the highest eelgrass percent cover of all the sites, with Sag Harbor Marina also at a similar level to Barcelona Point (Figure 26). The average eelgrass shoot lengths were observed at the Sag Harbor Marina site in October, with what appeared to be the highest growth in shoot length over the course of the monitoring period (Figure 25). South Ferry had relatively long

shoot lengths as well. Other sites were all clustered around an average of 20 – 30 cm in average shoot length throughout the monitoring period (Figure 25). The plantings at Ganet Creek and South Ferry fared worst overall. South Ferry showed some of the longer shoot lengths (Figure 25), but in all other metrics the values for these sites were noticeably lower than the others throughout the monitoring period (Figures 24, 26).

The measurement that showed the least consistent overall patterns was the percent cover of macroalgae. Most sites recorded relatively low macroalgae coverage early in the monitoring period, except for Menantic Creek, which had an average macroalgae coverage of about 75% in August (Figure 27). From there, most sites experienced an increase in macroalgae coverage going into September, with the Sag Harbor Marina site jumping drastically from approximately 20% to 90% coverage. In October though, the pattern diverged, with half of sites ending the monitoring period below 25% average macroalgae coverage, and the North Haven sites dramatically increasing to join Sag Harbor Marina with over 75% coverage (Figure 27).

When directly comparing the protected and unprotected eelgrass transplant plots at the North Haven site, there was very little difference, if any, in the average eelgrass shoot counts, shoot lengths, and percent cover across the sampling period (Figures 24-26). Furthermore, the average macroalgae percent cover was also very similar (Figure 27).

Finally, it should be noted that certain data is missing which is not obvious in the figures. On the second monitoring date, in September, visibility was particularly low in Sag Harbor Marina and one of the eelgrass patches could not be found. Data from that site on that date is averaged using the data from only two quadrats instead of three. Furthermore, also in September, miscommunication between field personnel resulted in some quadrats having only four eelgrass shoot length measurements recorded instead of five. This condition applies to one quadrat from Sag Harbor, two quadrats from North Haven Unprotected, and one quadrat each from South Ferry and Ganet Creek sites for that date.

The general trends discussed above are mostly in line with expected growth patterns for *Zostera marina* at this time of year. Eelgrass responds negatively to heat stress, and historically in this region the time of greatest heat stress is in August through September. It is not unexpected, therefore, that metrics like shoot count and shoot length would experience their lowest values during that month. Temperatures fall as summer turns to fall, and this allows for another period of growth at the end of the growing season, as was visible in October.

The one metric that did not exhibit this trend was percent cover of eelgrass. It should be noted, however, that among the measured variables percent cover is less refined than other metrics given that it is a visual estimation rather than a defined count or measurement, such as shoot counts or lengths, respectively. This method is commonly used due to its speed in estimation,

but is also influenced by current and observer bias. Generally, shoot counts and shoot length are more exact measurements. The spike in percent cover in the North Haven transplant plots during September appears to have been likely driven by differences in current strength between August and October given the high level of current observed at the location during a changing tide. The monitoring events during August and October occurred close to slack tide at the North Haven site, while the September monitoring event took place between tides when the current was moving relatively quickly, likely causing the grass to lean over.

While macroalgae coverage was generally relatively low in August at all sites, except for Menantic Creek, Sag Harbor Marina experienced a drastic increase in average macroalgae percent cover between by September while South Ferry, Ganet Creek, and the unprotected transplant plots at North Haven had more modest increases in macroalgae. Sag Harbor Marina had a high level of macroalgae coverage in the general area as well from September through October, with the level of macroalgae remaining high into October. The high amount of macroalgae at the Sag Harbor Marina site makes it a challenging location for larger scale transplanting.

It should also be noted that the macroalgae cover at the North Haven sites increased drastically between September and October. While there was very little submerged aquatic vegetation at the North Haven site, with the bottom generally composed of open sand, it appears that macroalgae was caught up in the eelgrass transplant plots moving by in the current.

There was a lack of notable difference in any of the eelgrass monitoring metrics between the protected and unprotected eelgrass transplant plots at the North Haven site. This appears to indicate that the presence of oyster cages did not have an appreciable effect on the eelgrass transplants. However, the oyster cages used at these sites were relatively low-lying and it is certainly possible that a larger structure or different orientation of the oyster cages with respect to eelgrass transplants could affect the grass in a different manner. For instance, a larger structure may be able to dampen wave energy, especially from boat wakes, more effectively than the cages that were used. Furthermore, the potential wave dampening effects of the cages, if present, may take longer to be observed than a 4-month time span.

The South Ferry and Ganet Creek sites both had a high amount of cobble and pebbles in the sediment. The sediment composition made it very difficult for SBU personnel to plant eelgrass shoots into the sediment at this site. Furthermore, the South Ferry site has large boulders throughout the area, presenting additional challenges to planting at a larger scale at this location. Both sites are also near a busy boat channel through which vessels move at high speed. Wave action from boat wakes was very apparent to SBU personnel while at these locations. Given these stressors, it was not surprising that the transplants at these sites fared relatively poorly compared to other locations. The Menantic Creek site had the opposite issues. This area was

shallower than other sites, with soft, muddy sediment and virtually no current whatsoever due to its position in a very sheltered section of Menantic Creek on Shelter Island. The water at the Menantic Creek site was likely too warm and turbid to allow eelgrass to persist, with all eelgrass completely dead by the time the first monitoring event occurred.

One site that did show surprising results was the Sag Harbor Marina location. Given how far back into Sag Harbor Cove the site is, we had assumed that it would become too warm and turbid to allow eelgrass to persist. Furthermore, the sediment is relatively soft and muddy with Widgeon grass already present in close proximity to where the eelgrass transplant plots were situated. Given that Widgeon grass generally outcompeted eelgrass at warmer temperatures, it appeared unlikely that eelgrass would survive at this location. Furthermore, it is close to a marina and a boat channel (no wake zone) and is deeper than the Menantic creek site. In spite of these stressors, plus a consistently high macroalgae coverage, the eelgrass at this site grew well and even had the longest shoot lengths of all sites on average. However, the soft sediment and presence of Widgeon grass makes this area a challenging site for concerted large-scale eelgrass restoration efforts. Furthermore, given the abundance presence of Widgeon grass at this site, also a native seagrass species, attempted restoration of eelgrass in this area may not be appropriate.

In terms of potential for large-scale restoration efforts, Barcelona Point and North Haven area clearly the most suitable candidate sites out of the six that we evaluated. Both sites are characterized by sand bottom with low macroalgae coverage and suitable depth for eelgrass to grow. Furthermore, they are both areas that were once home to eelgrass meadows. The data shows these to have the highest average shoot counts in the transplant plots consistently over the course of the monitoring period. Barcelona Point generally has low current as well. The North Haven site has a moderate amount of tidal current and this would have to be considered when designing strategies to facilitate eelgrass restoration at this location. These locations also have relatively clear water compared to the other locations. Both of these sites are also very accessible by water and from shore. Overall, Barcelona Point and North Haven appear to be viable locations for future eelgrass restoration efforts.

Wave Energy

Wave energy was quantified at each location using RBRsolo³ sensors that measure wave height, wave energy, and wave period (average height and period of the largest 1/3 of the waves in the burst). In 2024, tandem, two-week deployments occurred for all six research sites, with wave sensors placed in open waters and behind oyster cages to assess the ability of the cages to dissipate wave energy. Data analyses are ongoing but Figures 29 and 29 provide an example of the data output. For all six sites, we have continuous records of depth at each site (Figure 28) that is subsequently converted in wave height for each site (Figure 29). For most, but not all sites, the parallel deployments revealed lower maximal wave height behind the oyster cages

compared to unprotected sites. This data help explains the improved eelgrass coverage behind the cages as compared to the open water site at the North Haven site (Figure 26). Work is ongoing to assess the complete wave energy profile of all sites.

Next Steps

This first phase of the project was designed to identify locations that would be ideal for the development of a living shoreline project that could creating habitat, combat ocean acidification, actively bio-extract reduction nitrogen, protect shorelines, and sequester carbon. The guidance for evaluating the suitability of individual sites was based on water quality, sediment composition, and growth and survival performance of kelp, seagrass and oysters. The data has combined to provide good agreement across sites with regard to locations what would be ideal for kelp, seagrass, and oysters. Among the sites considered, Menatic Creek was deemed inappropriate as it had poor water and sediment quality (high chlorophyll *a* and total nitrogen, low dissolved oxygen and water clarity, muddy, fine-grained sediments) and yielded poor kelp and seagrass survival and growth, although the oyster population did well at this location. Some other sites were deemed to be to marginal for full scale restoration projects including Ganet Creek, Sag Harbor Cove, and the South Ferry/Shelter Island Sound site. These locations had fair water and sediment quality, fair kelp growth, varied seagrass growth, but generally good oyster growth. Sag Harbor Cove was the best among the marginal sites, but may not be appropriate due to the presence of widgeon grass. Two sites that were studied in 2024 that seemed ideal for restoration were the Barcelona Point/Northwest Harbor site and the east side of North Haven. These sites had excellent water quality and sediment quality (low chlorophyll *a* and total nitrogen, high dissolved oxygen and water clarity, coarser grained, low organic matter sediments), had the best kelp growth, excellent seagrass growth and survival, and good oyster growth and survival. For 2025, this project will seek to develop, larger, meso-scale deployments of oysters, kelp and seagrass at these sites, while investigating the usefulness of Sag Harbor Cove.

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Figures

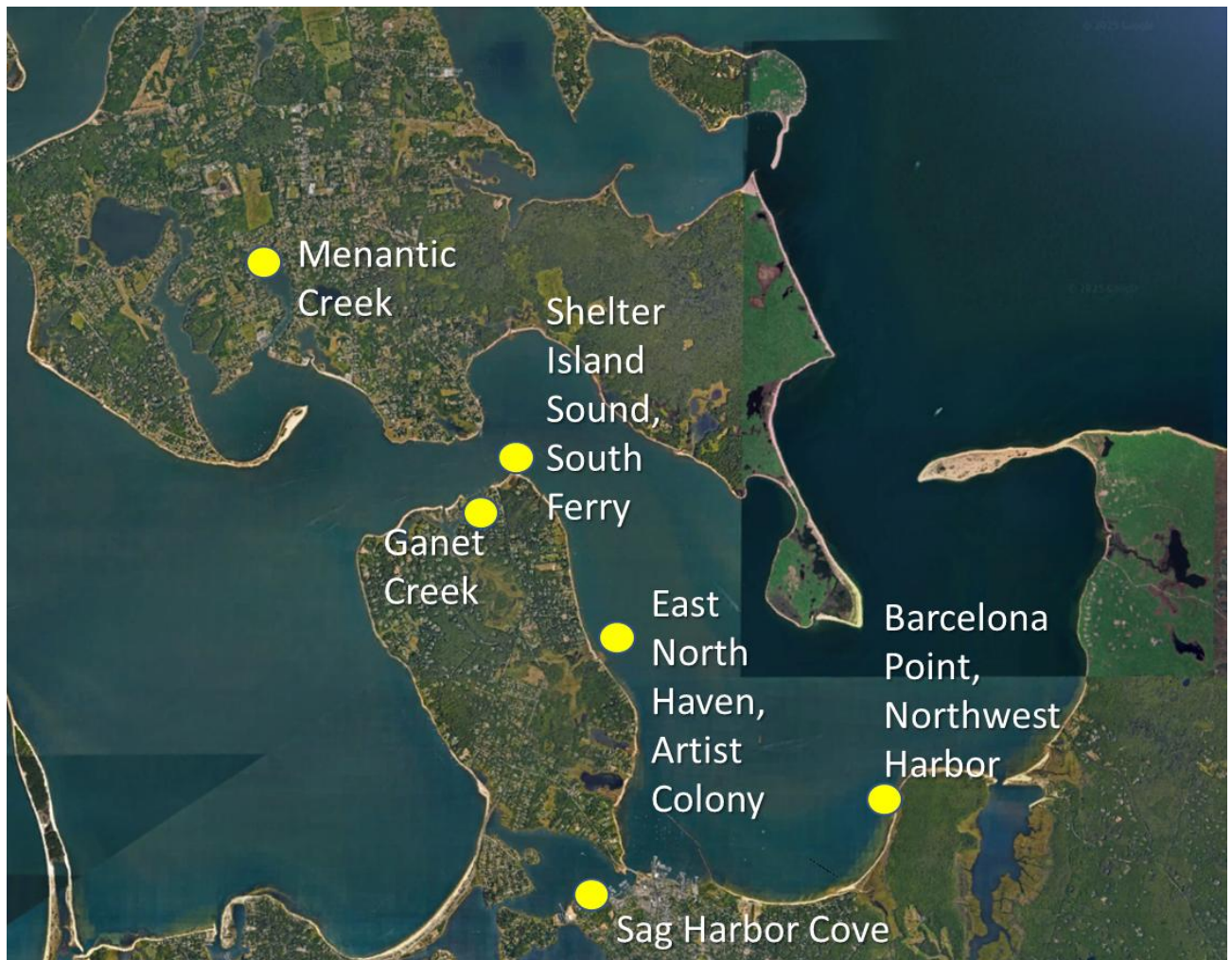


Figure 1. Sampling sites for the CHANGES project.

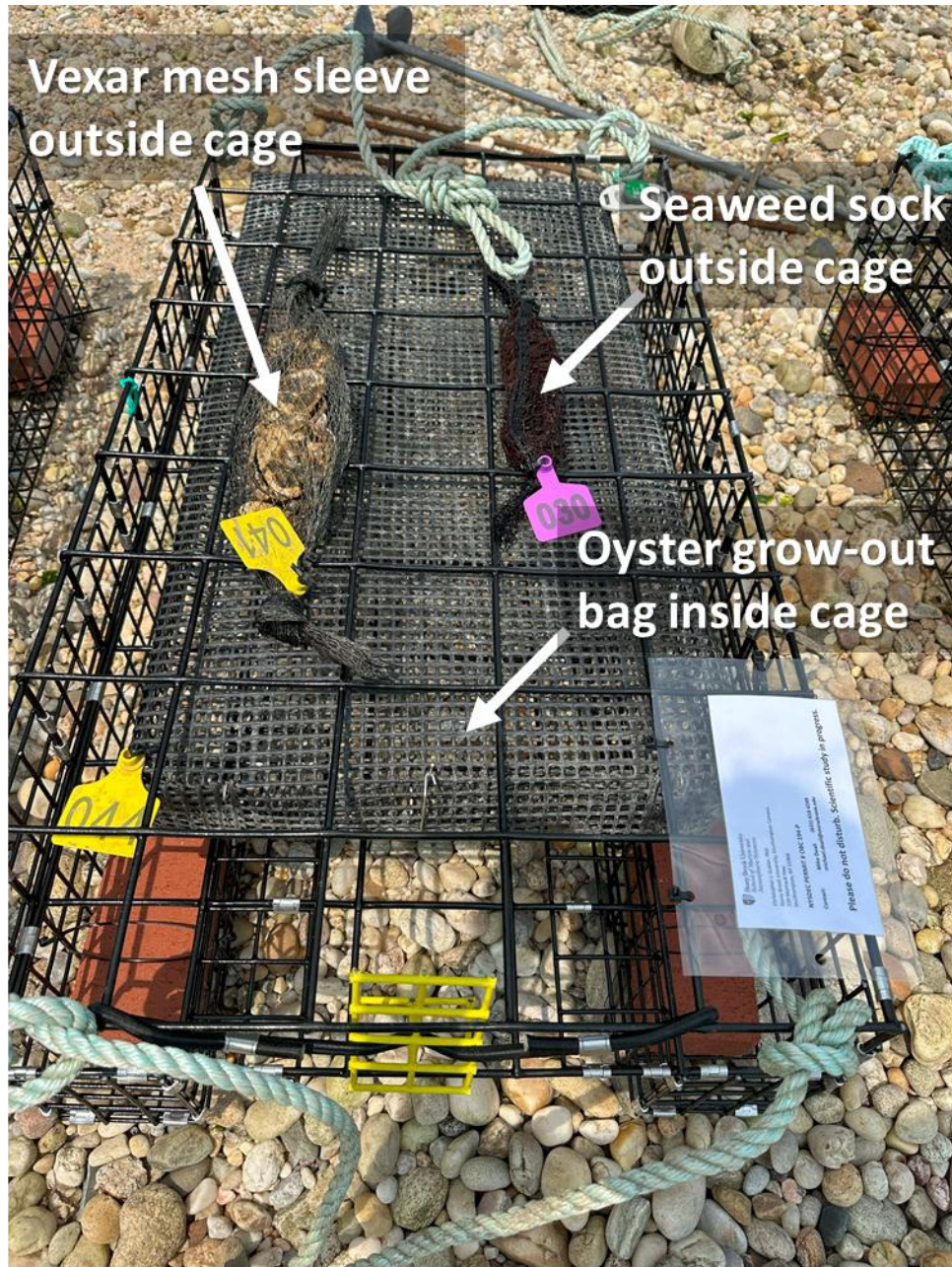


Figure 2. Photo of the oyster cages deployed at the six study sites. Oyster spat-on-shell was placed in a grow-out bag inside the oyster cage (predator exclusion), and also in a Vexar mesh sleeve on the outside of the cage (exposed to predators). Mussel socks filled with red-branching macroalgae were also attached to the tops of cages. Three cages with this design were deployed at each of the six sites.

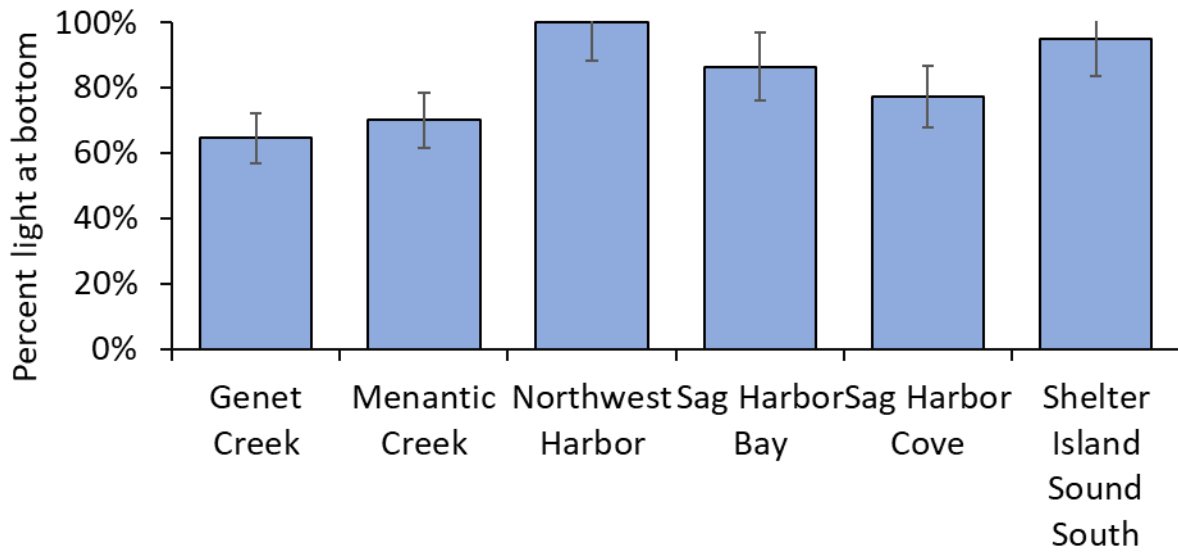


Figure 3. Mean percent light at bottom across sites.

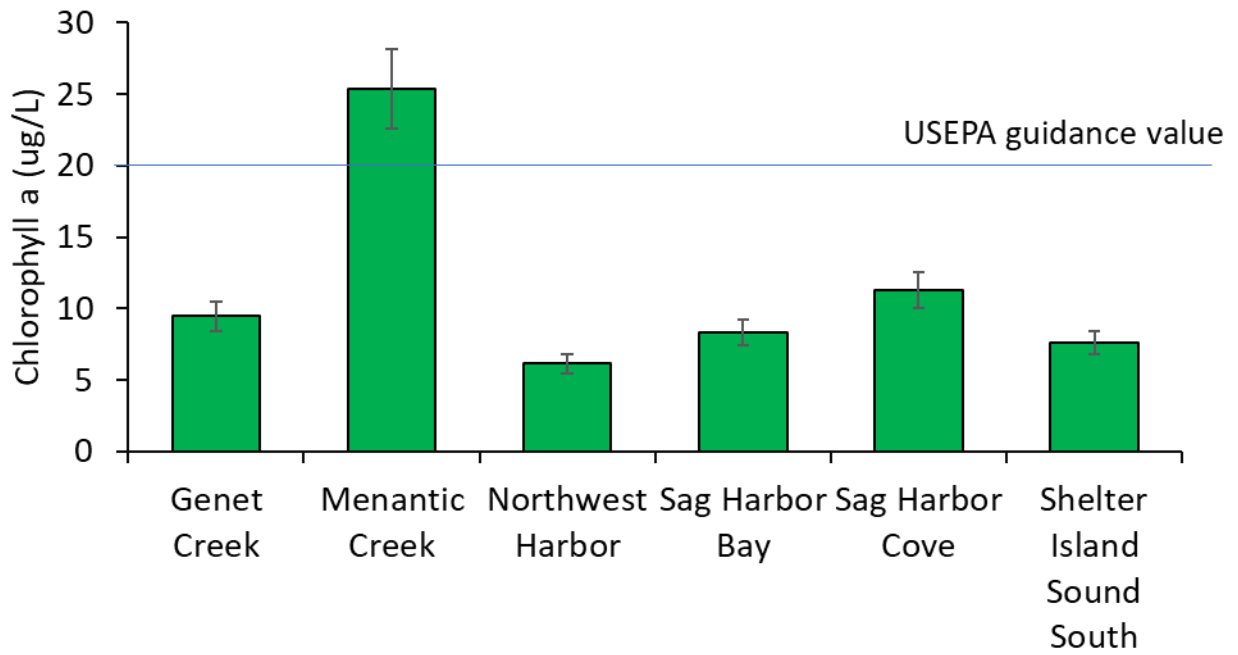


Figure 4. Mean chlorophyll a concentrations across sites with NOAA guidance value noted.

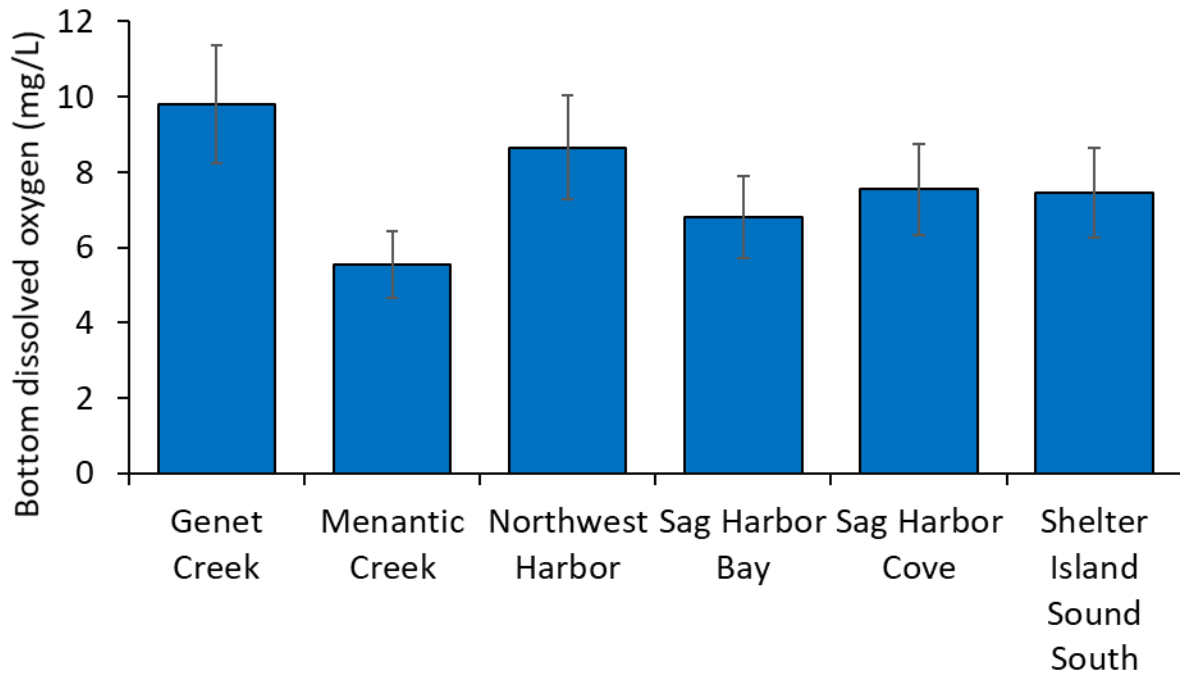


Figure 5. Mean bottom dissolved oxygen across sites.

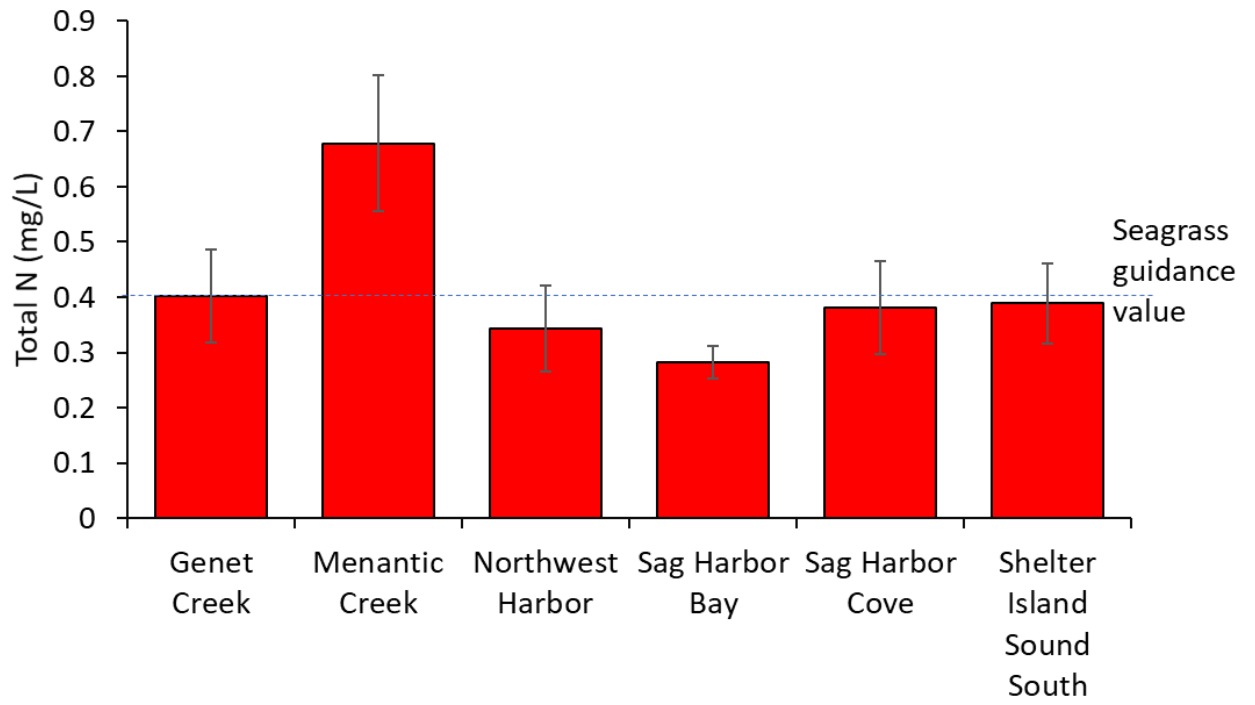


Figure 6. Mean total nitrogen in the water column across sites with seagrass guidance value noted.

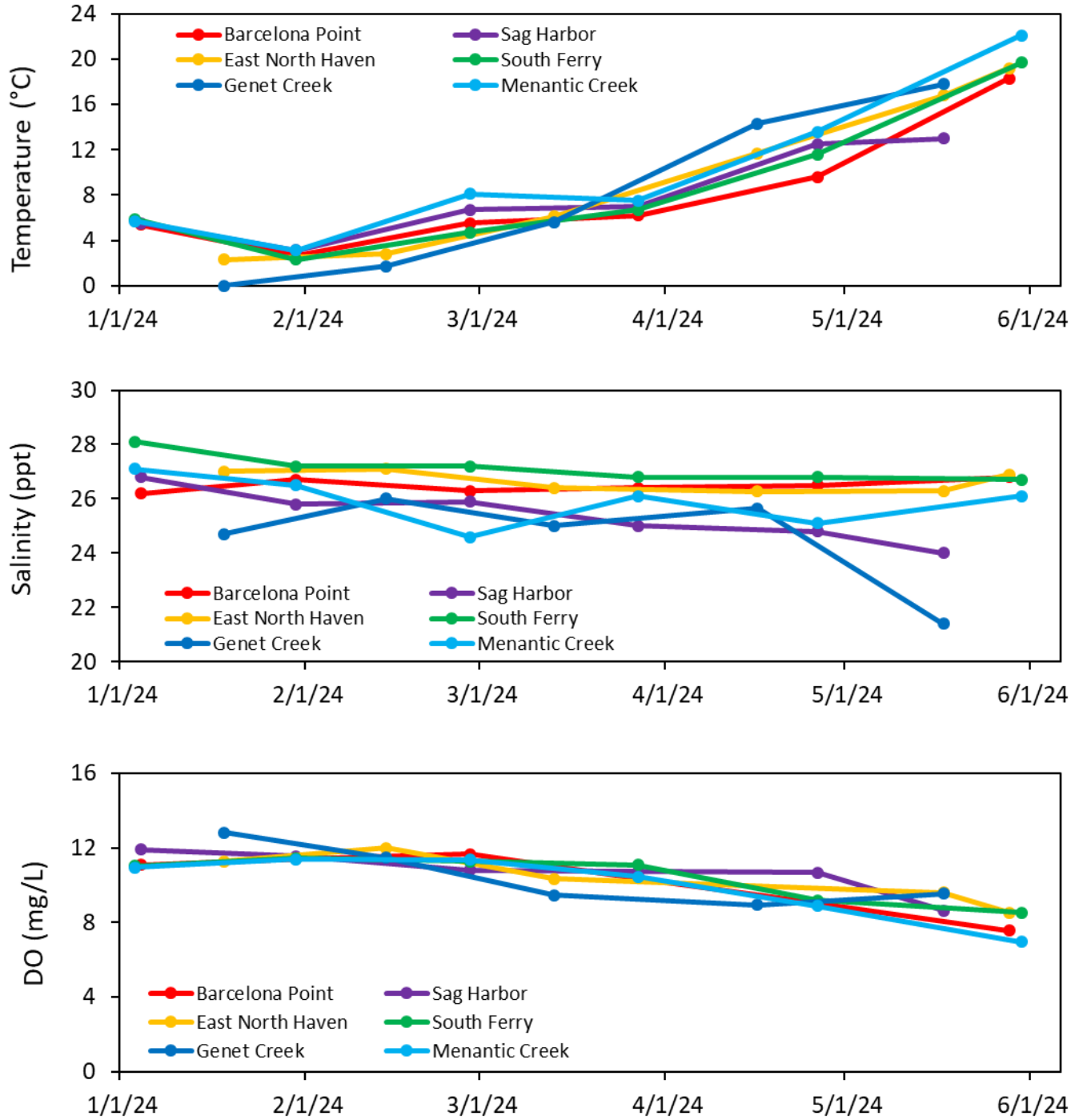


Figure 7. Temperature, salinity, and dissolved oxygen measured across sites during the 2024 kelp grow out season.

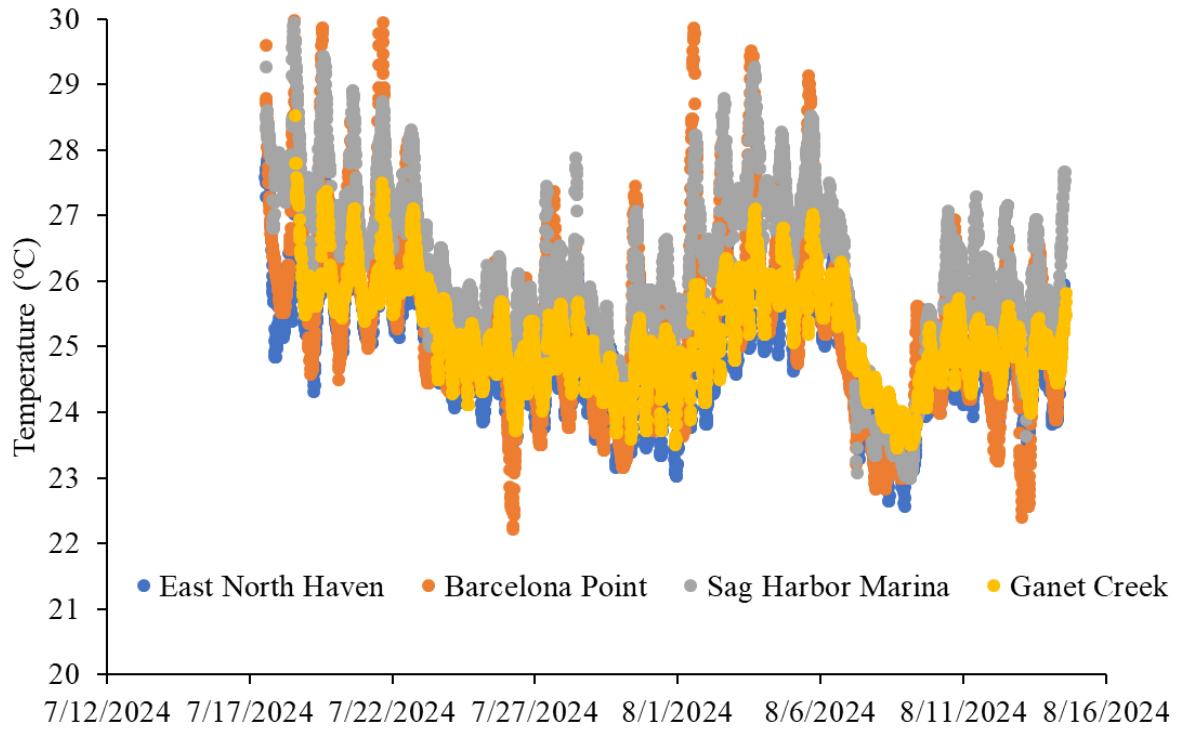


Figure 8. Temperatures measured across sites during the summer of 2024.

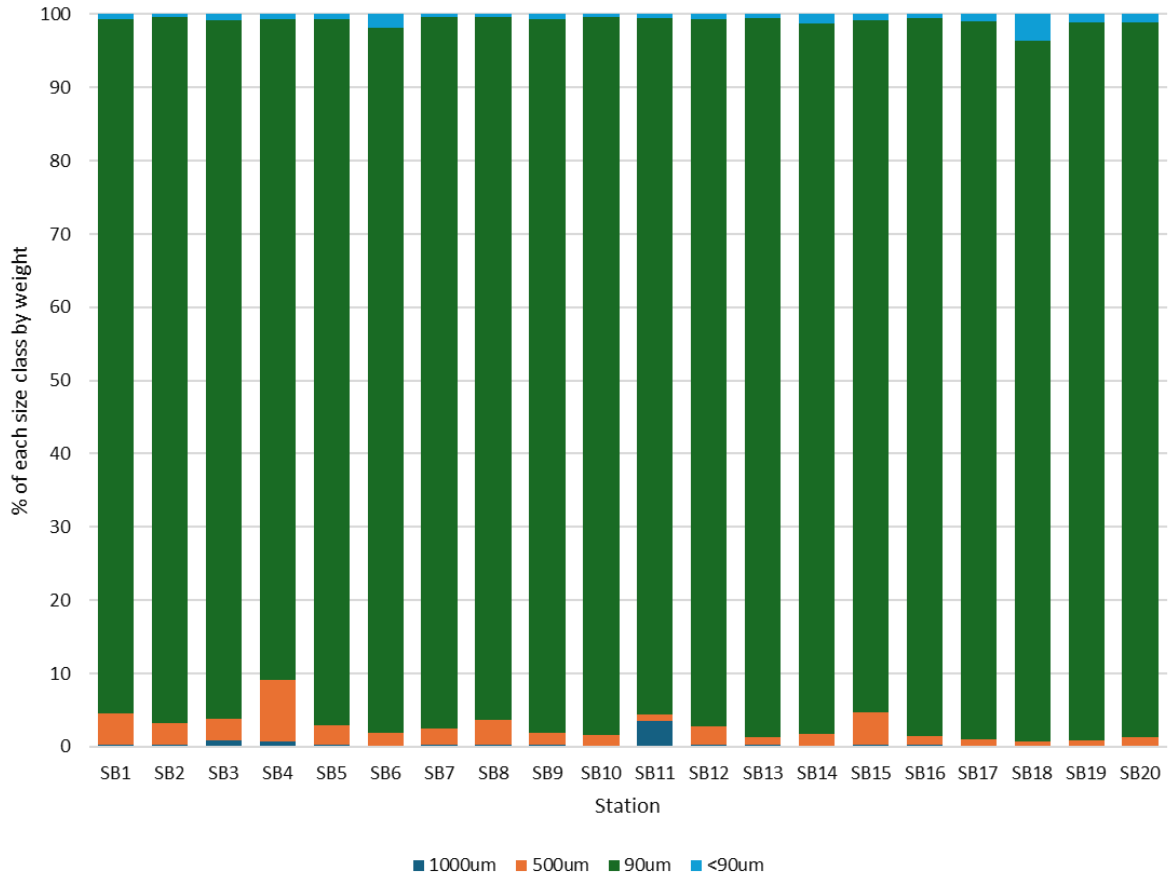


Figure 9. Northwest Harbor sediment grain size distribution

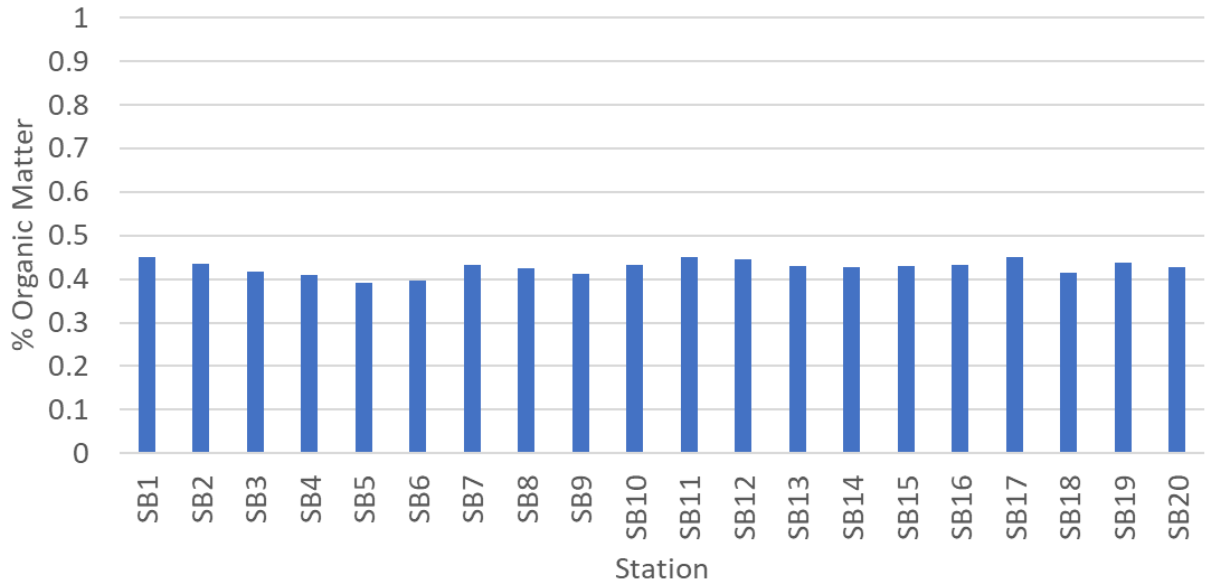


Figure 10. Northwest Harbor, percent organic matter of sediments.

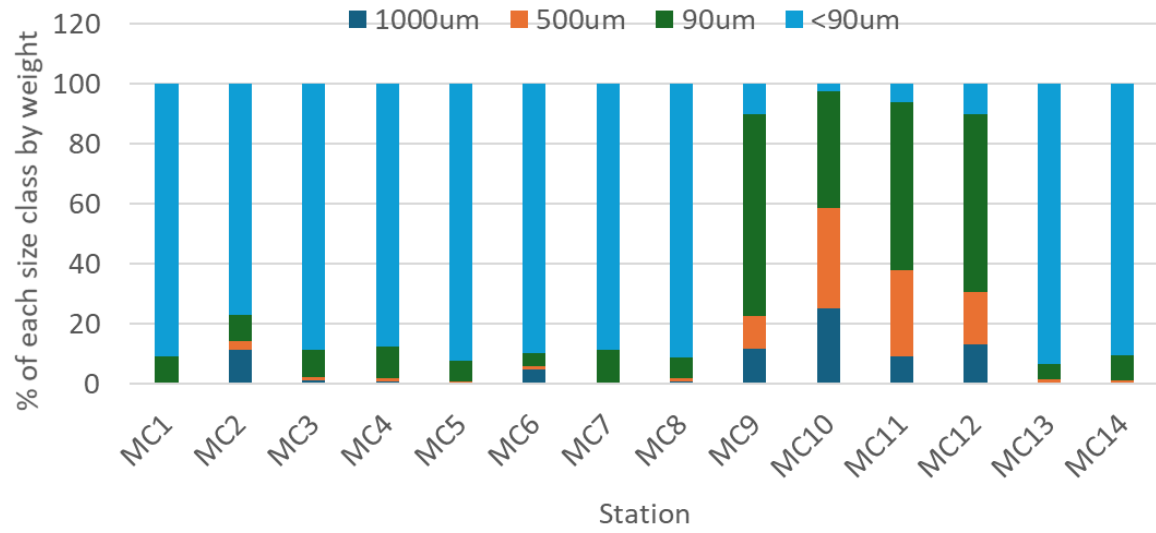


Figure 11. Menantic Creek sediment grain size distribution

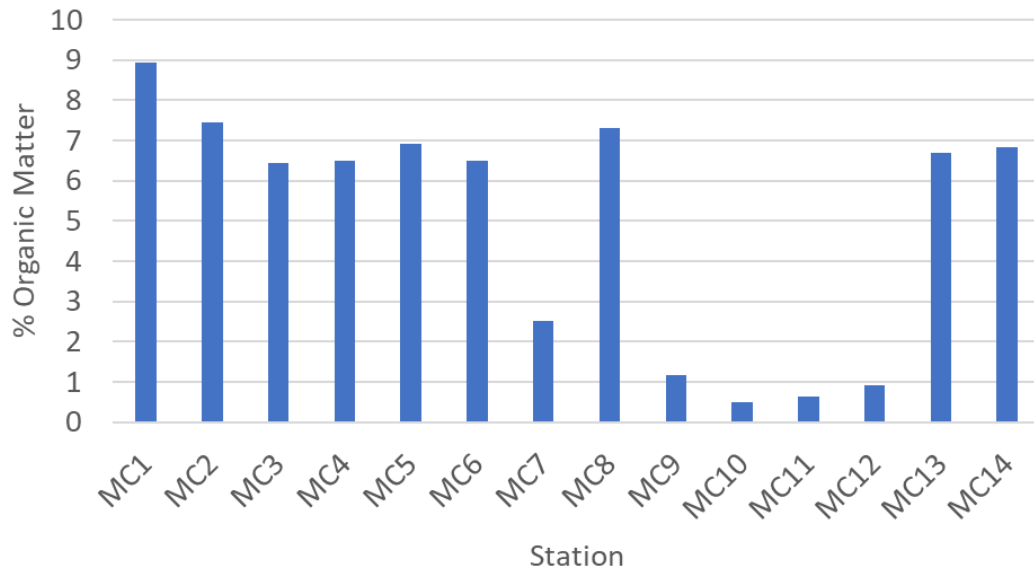


Figure 12. Menantic Creek, percent organic matter of sediments.

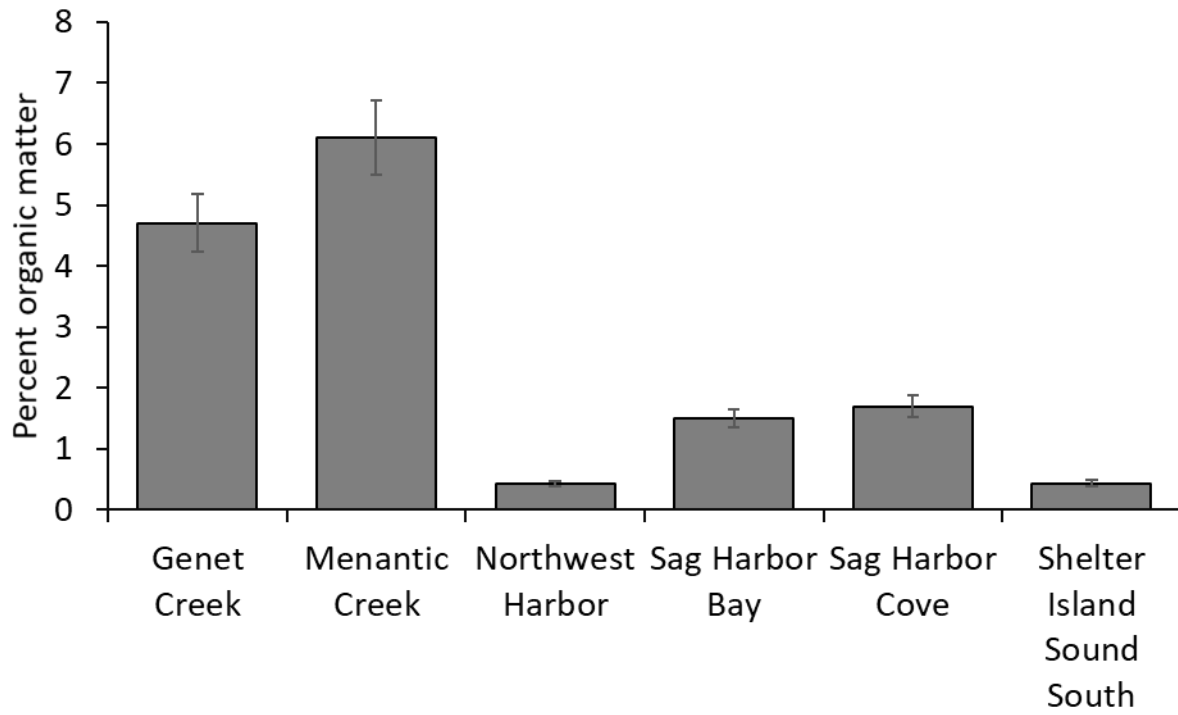


Figure 13. Mean percent organic matter of sediments across sites.

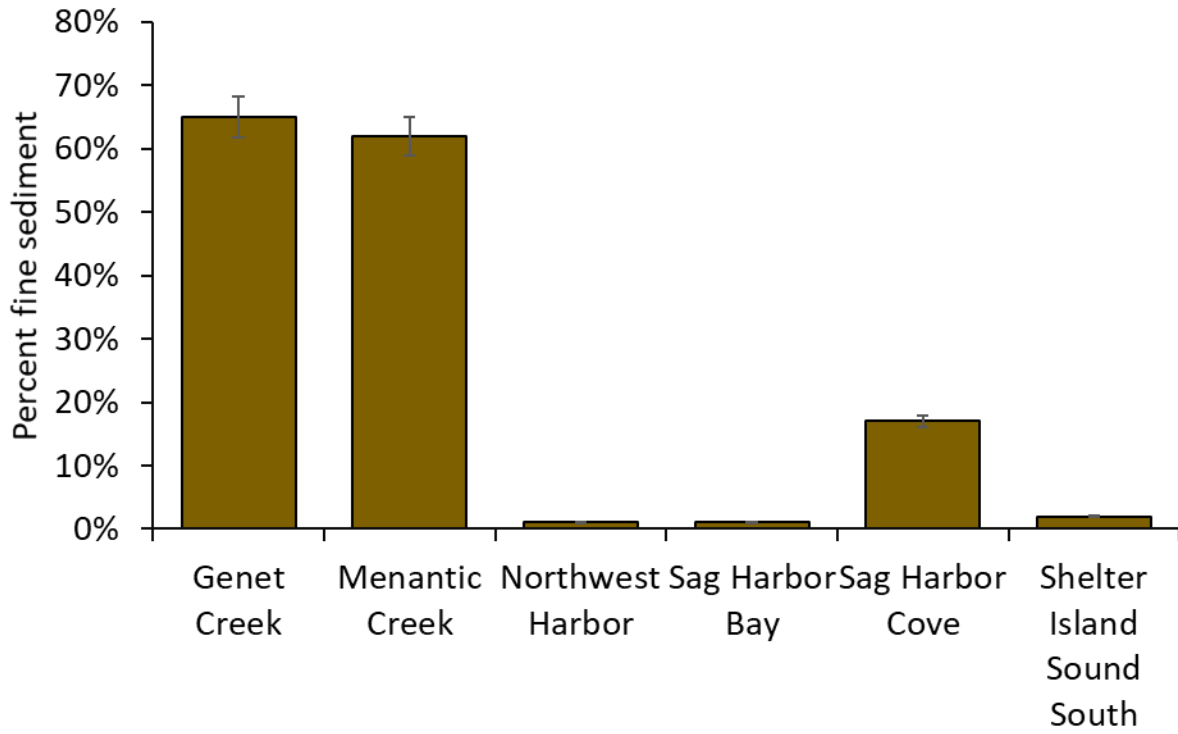


Figure 14. Mean percent fine grained sediments (< 90μm) across sites.

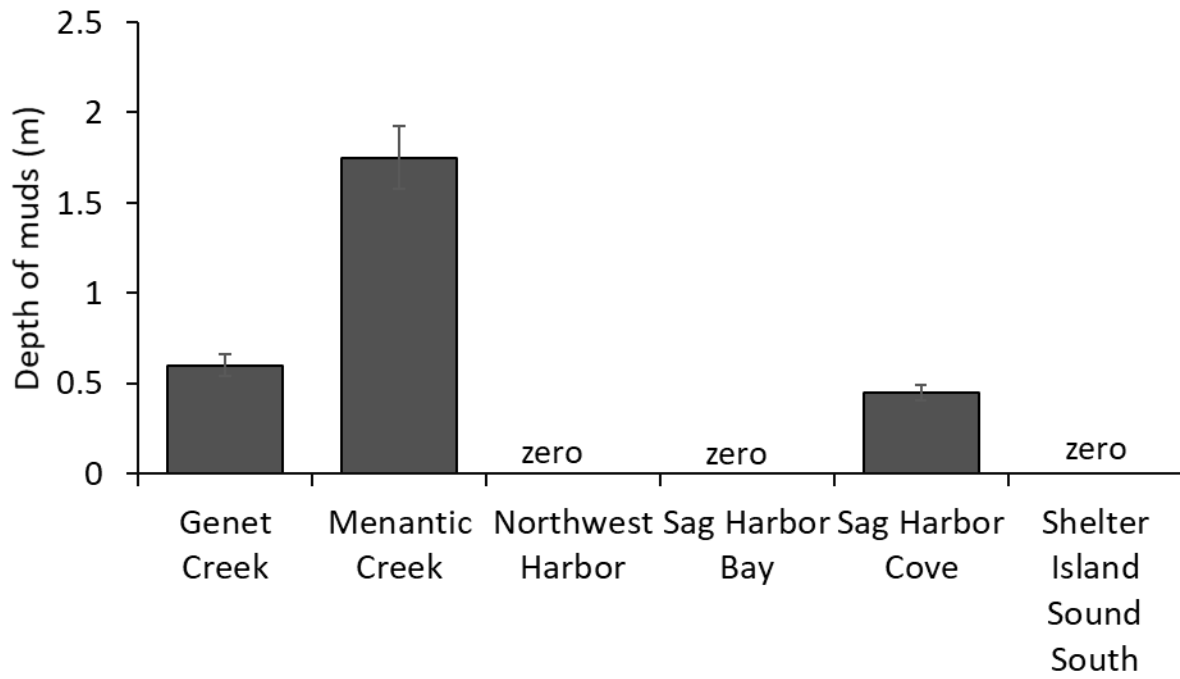


Figure 15. Mean depth of mud across sites.

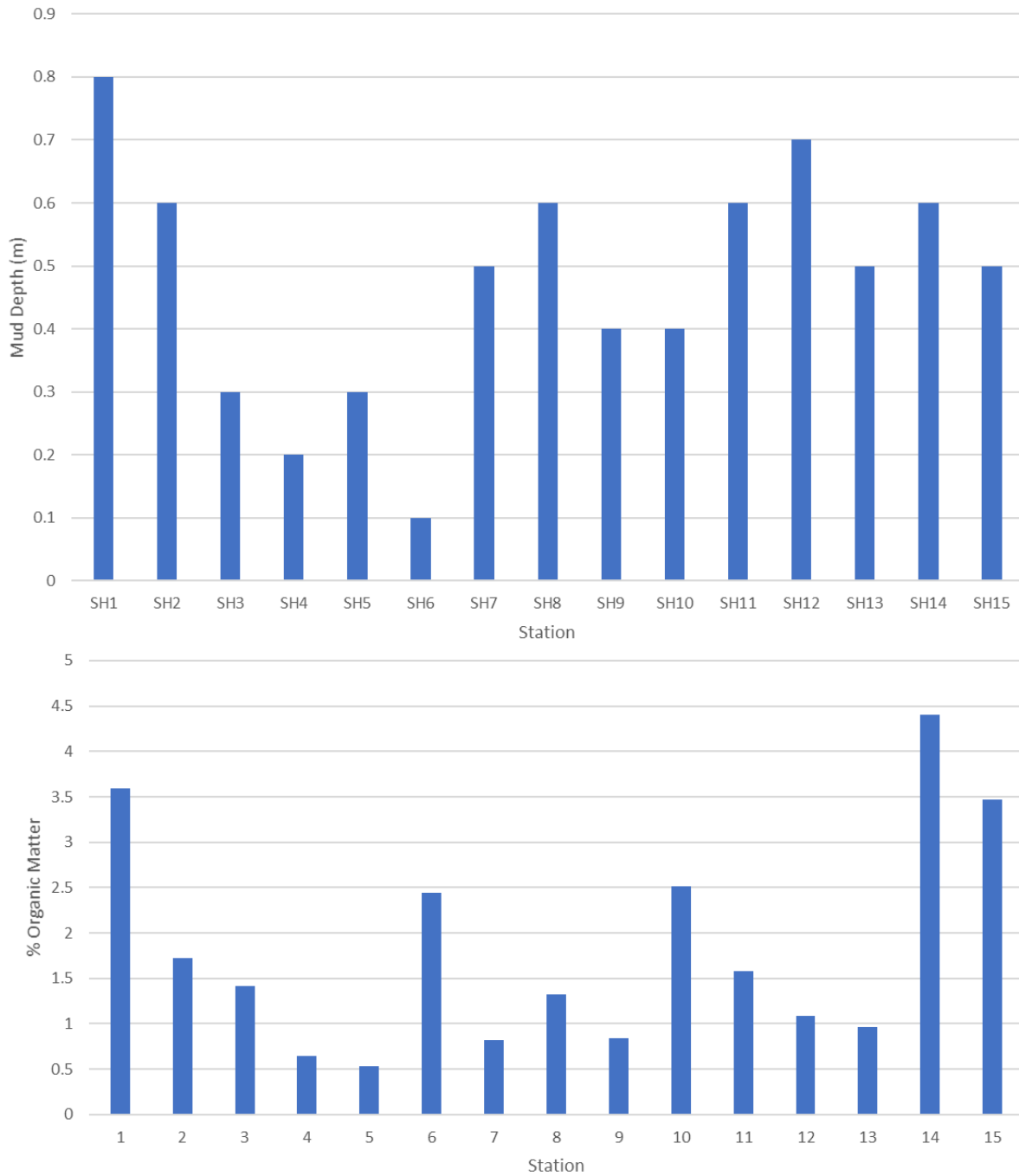


Figure 16. Mean depth of mud and percent organic matter across sampling locations in Sag Harbor Cove.

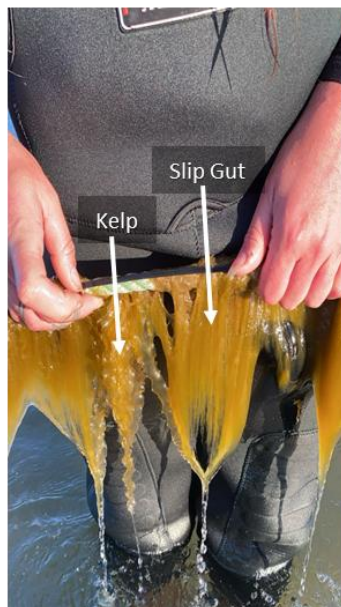
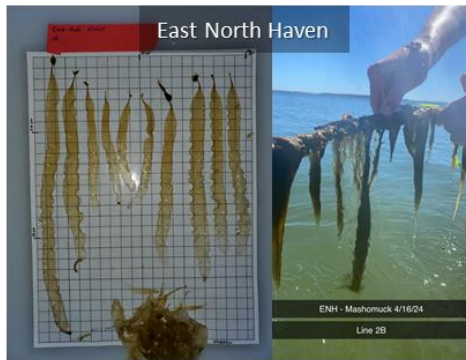
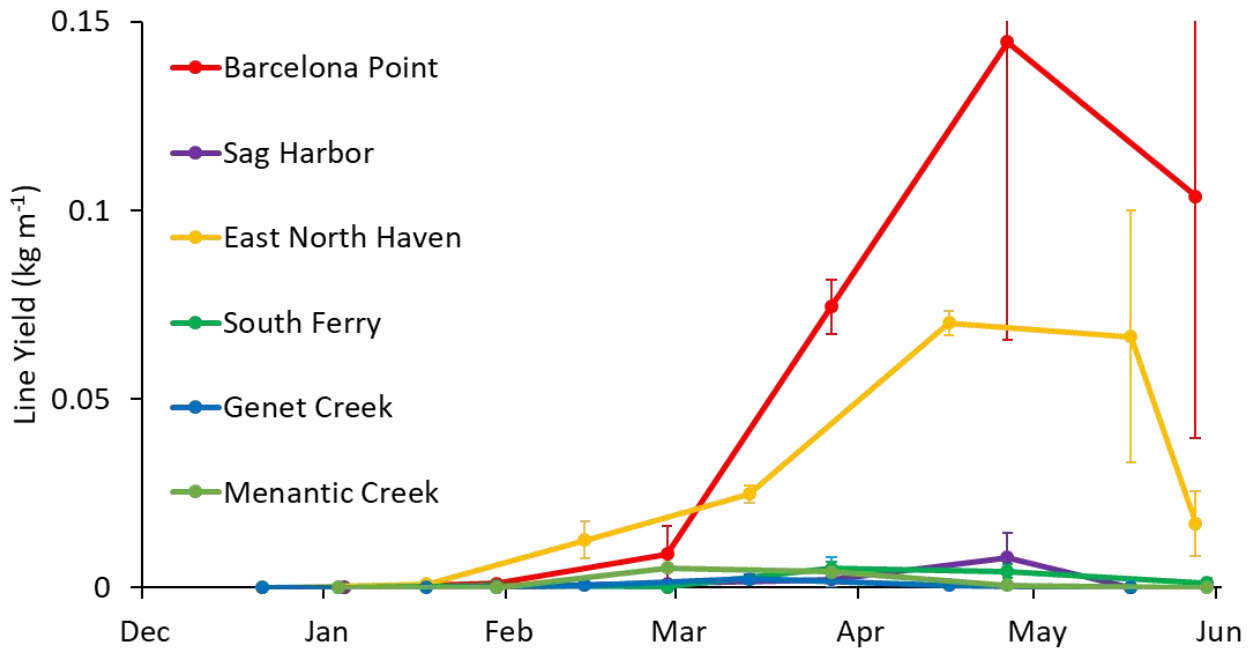
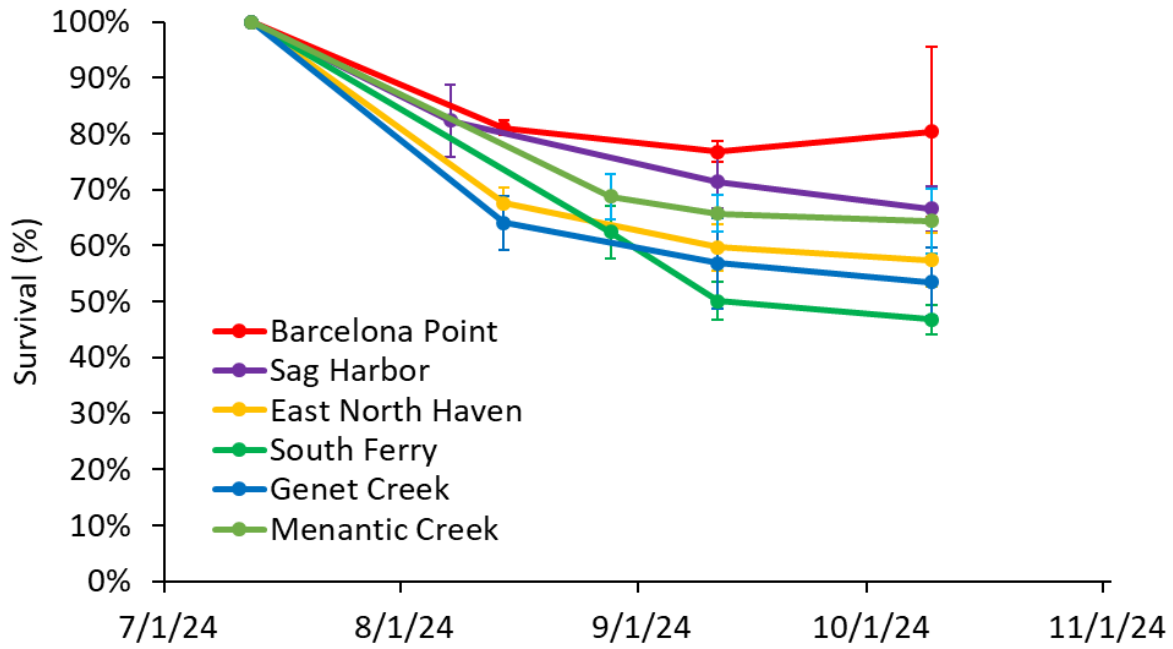


Figure 17. Line yields of kelp across the six locations and images of kelp blades from North Haven and Barcelona Point as well as the appearance of slip gut on kelp line.

A. SOS inside cages



B. SOS outside cages

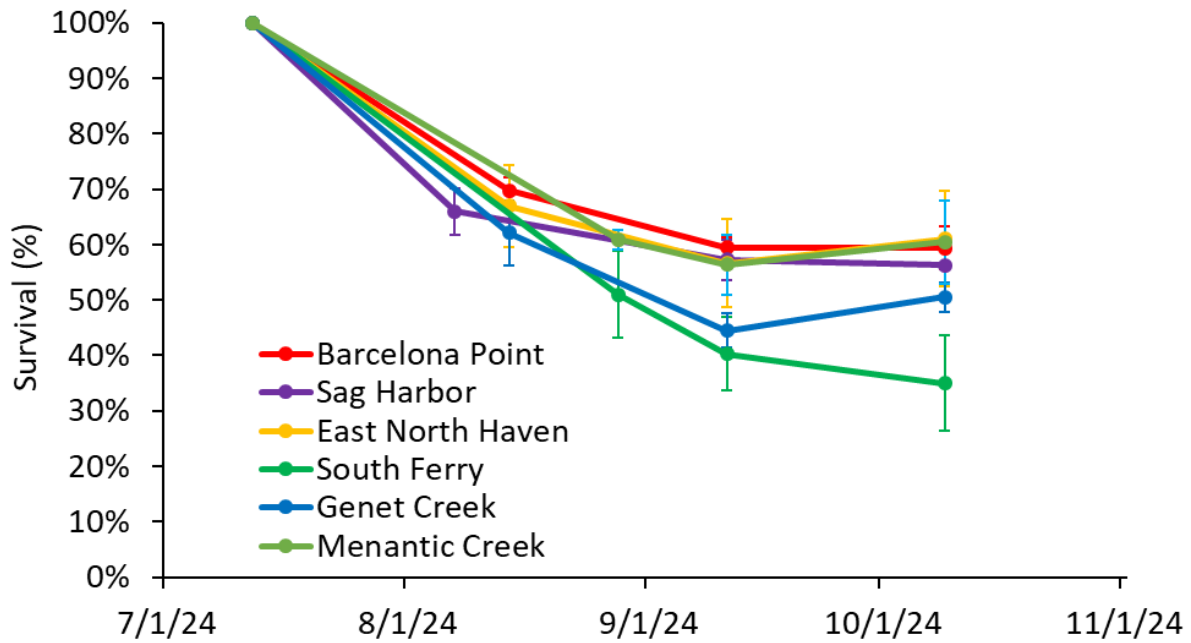
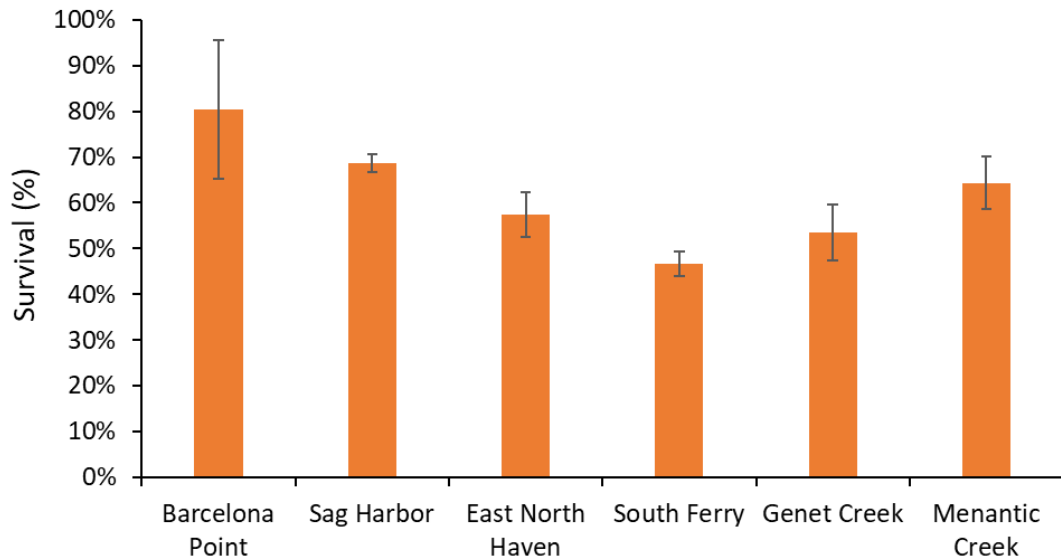


Figure 18. Survival over time of oyster spat-on-shell (SOS) placed **(A)** in grow-out bags inside cages, and **(B)** in Vexar mesh sleeves affixed to the outside of cages, at the six study sites. Survival is expressed as the percentage of the initial oysters deployed that were alive. Error bars are standard errors.

A. SOS inside cages



B. SOS outside cages

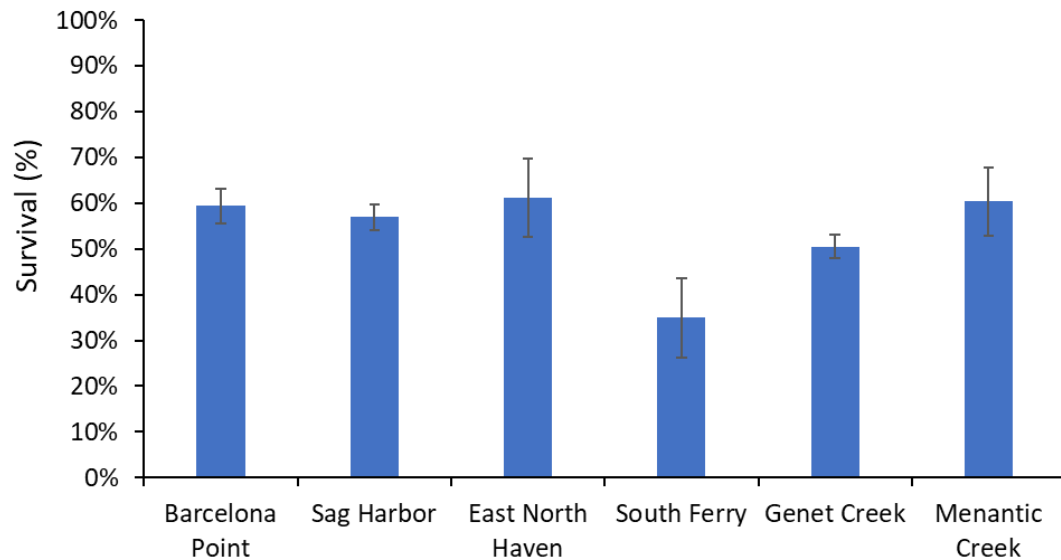


Figure 19. Survival of oyster spat-on-shell (SOS) at the six study sites on 10/9/24, 89 days after deployment to the field sites, for SOS placed **(A)** in grow-out bags inside cages, and **(B)** in Vexar mesh sleeves affixed to the outside of cages. Survival is expressed as a percentage of the initial oysters deployed that were alive on 10/9/24. Error bars are standard errors.

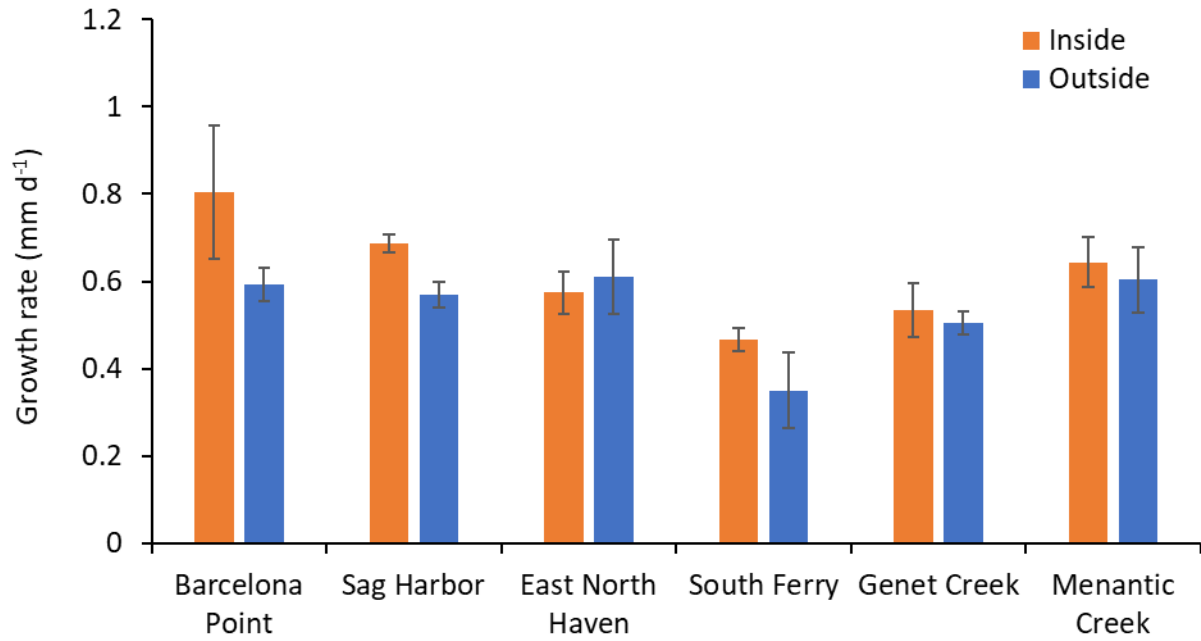
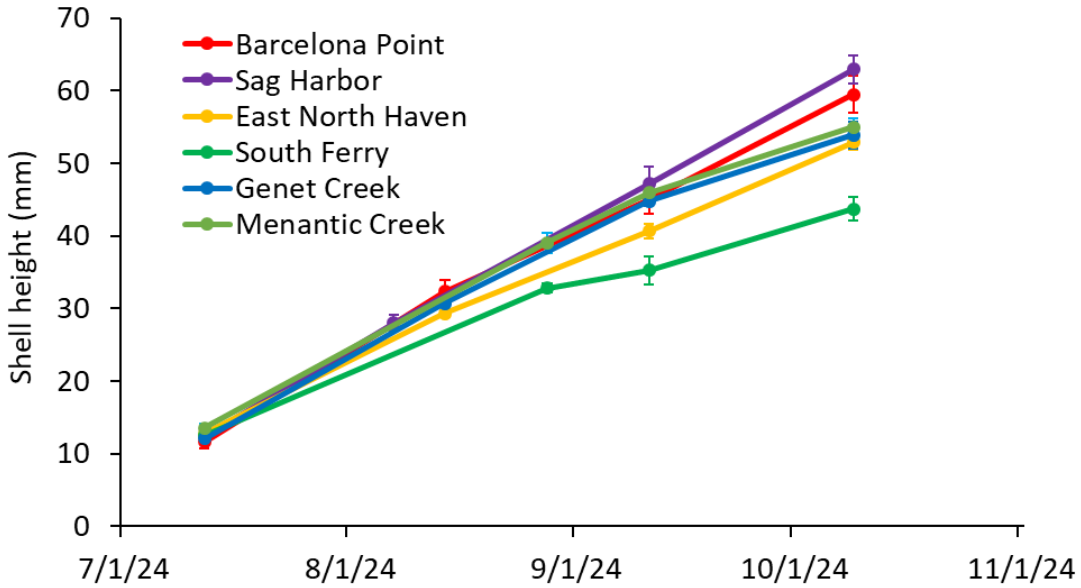


Figure 20. Survival of oyster spat-on-shell (SOS) at the six study sites on 10/9/24, 89 days after deployment to the field sites, for SOS placed in grow-out bags inside cages (orange bars), and SOS placed in Vexar mesh sleeves affixed to the outside of cages (blue bars). Survival is expressed as a percentage of the initial oysters deployed that were alive on 10/9/24. Error bars are standard errors.

A. SOS inside cages



B. SOS outside cages

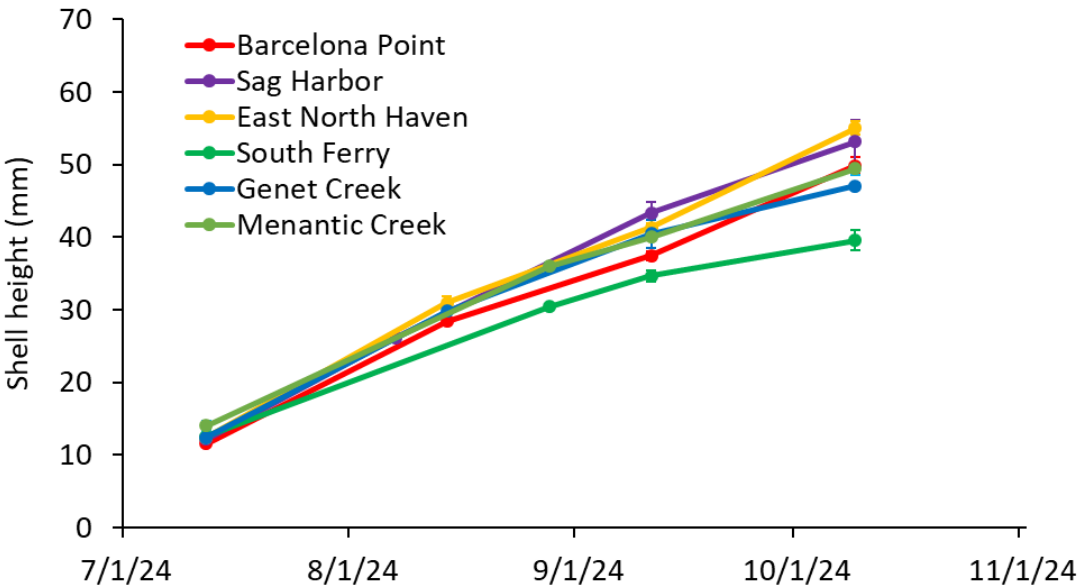
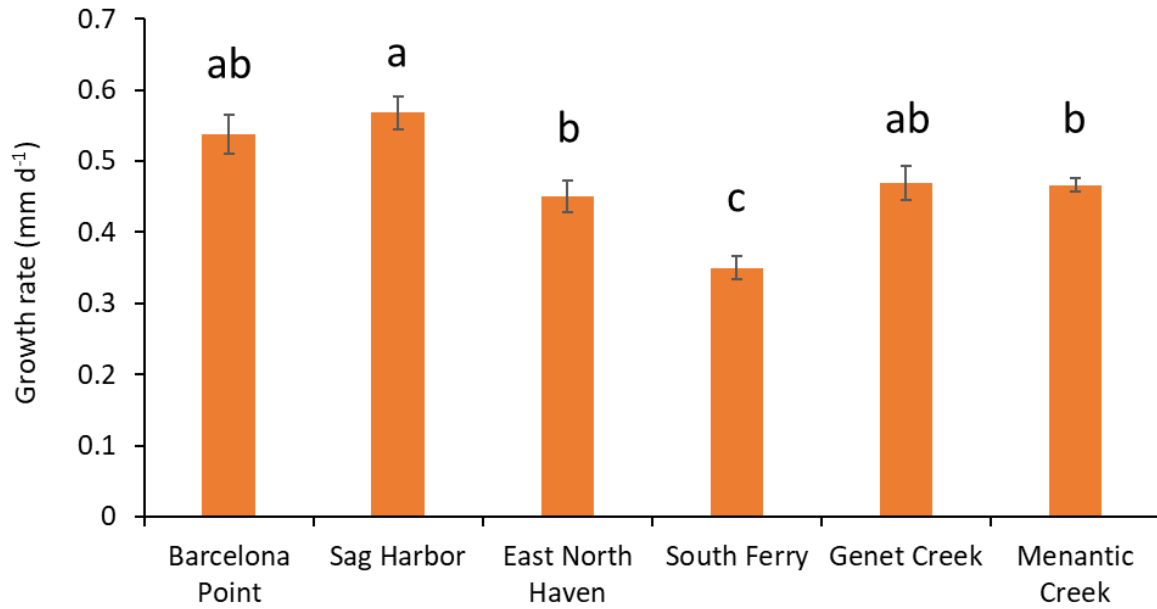


Figure 21. Growth of oyster spat-on-shell (SOS) placed **(A)** in grow-out bags inside cages, and **(B)** in Vexar mesh sleeves affixed to the outside of cages, at the six study sites. Error bars are standard errors.

A. SOS inside cages



B. SOS outside cages

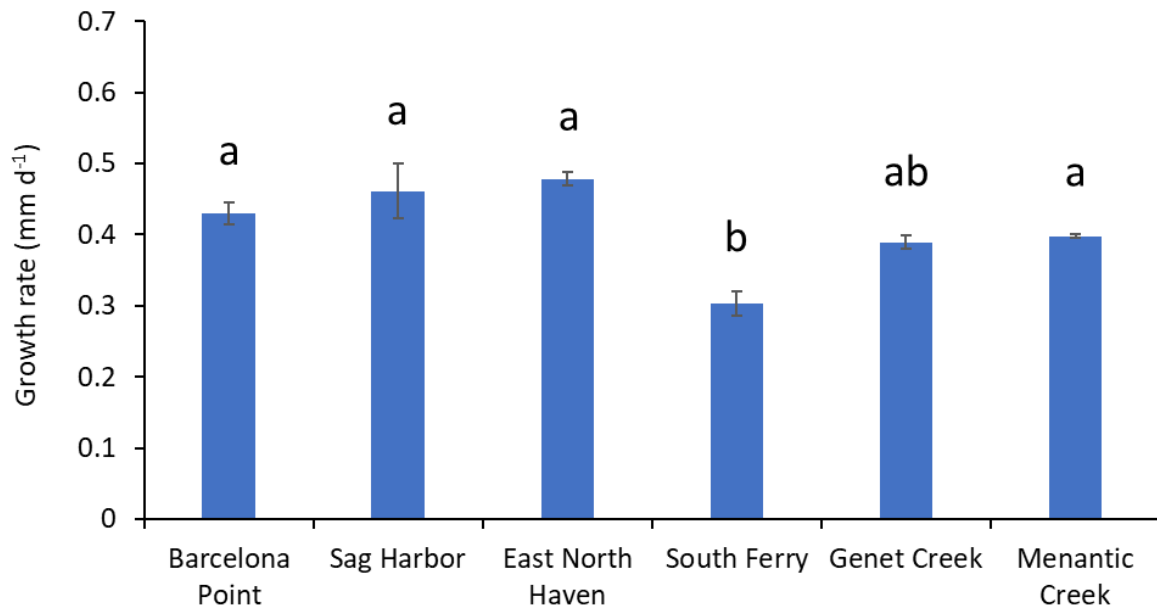


Figure 22. Growth rates (mm d⁻¹) of oyster spat-on-shell (SOS) over an 89 days period between 7/12/24 and 10/9/24 at the six study sites, for SOS placed **(A)** in grow-out bags inside cages, and **(B)** in Vexar mesh sleeves affixed to the outside of cages. Error bars are standard errors. Letters indicate significant differences.

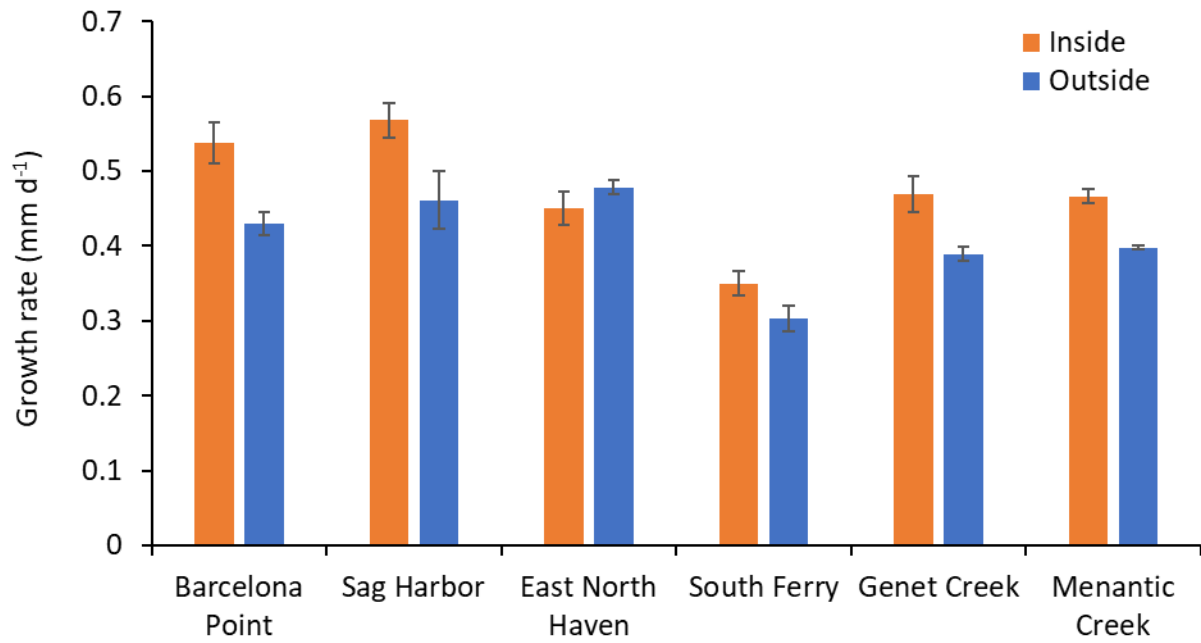


Figure 23. Growth rates (mm d⁻¹) of oyster spat-on-shell (SOS) over an 89 days period between 7/12/24 and 10/9/24 at the six study sites, for SOS placed in grow-out bags inside cages (orange bars), and **SOS placed** in Vexar mesh sleeves affixed to the outside of cages (blue bars). Error bars are standard errors.

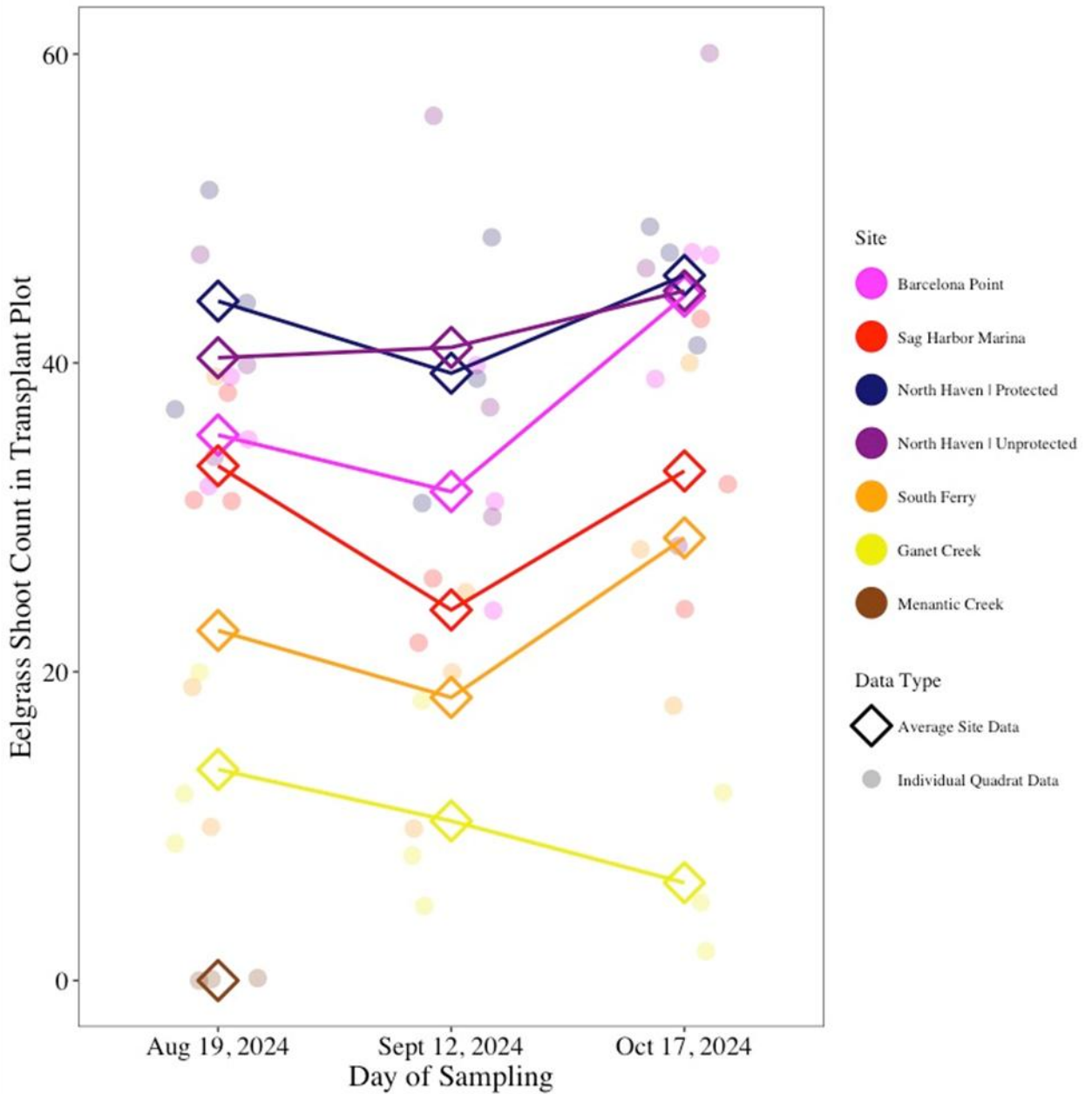


Figure 24. *Zostera marina* shoot count per site over time. Sites are identified by color, and individual quadrat data is represented by small circles. Individual quadrat data was combined to create averages for each site, which are represented by the larger diamonds.

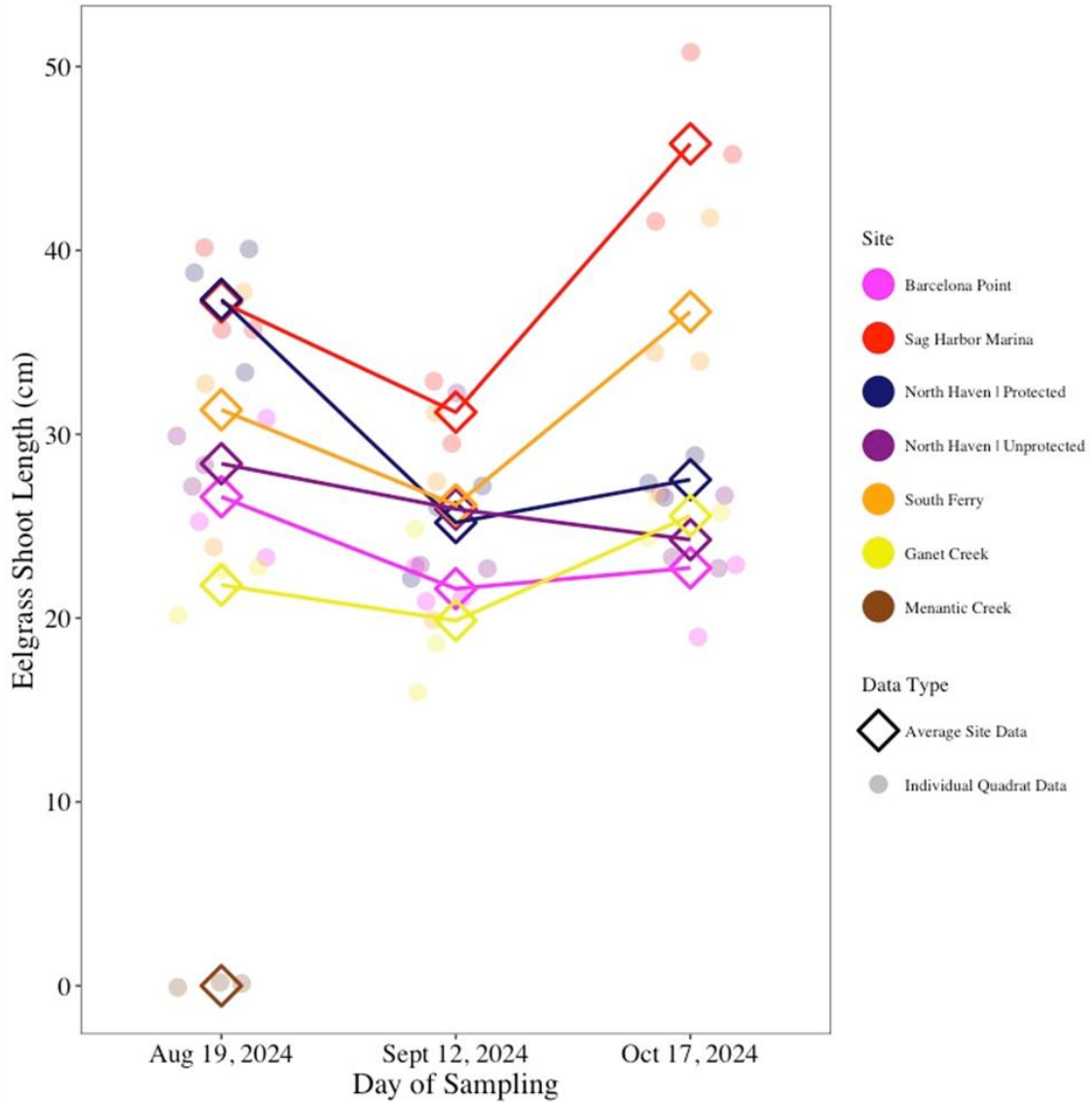


Figure 25. *Zostera marina* shoot length per site over time. Sites are identified by color, and individual quadrat data is represented by small circles. Each data point represented by a small circle was created by averaging the shoot lengths of 5 shoots per quadrat. Individual quadrat data was combined to create averages for each site, which are represented by the larger diamonds.

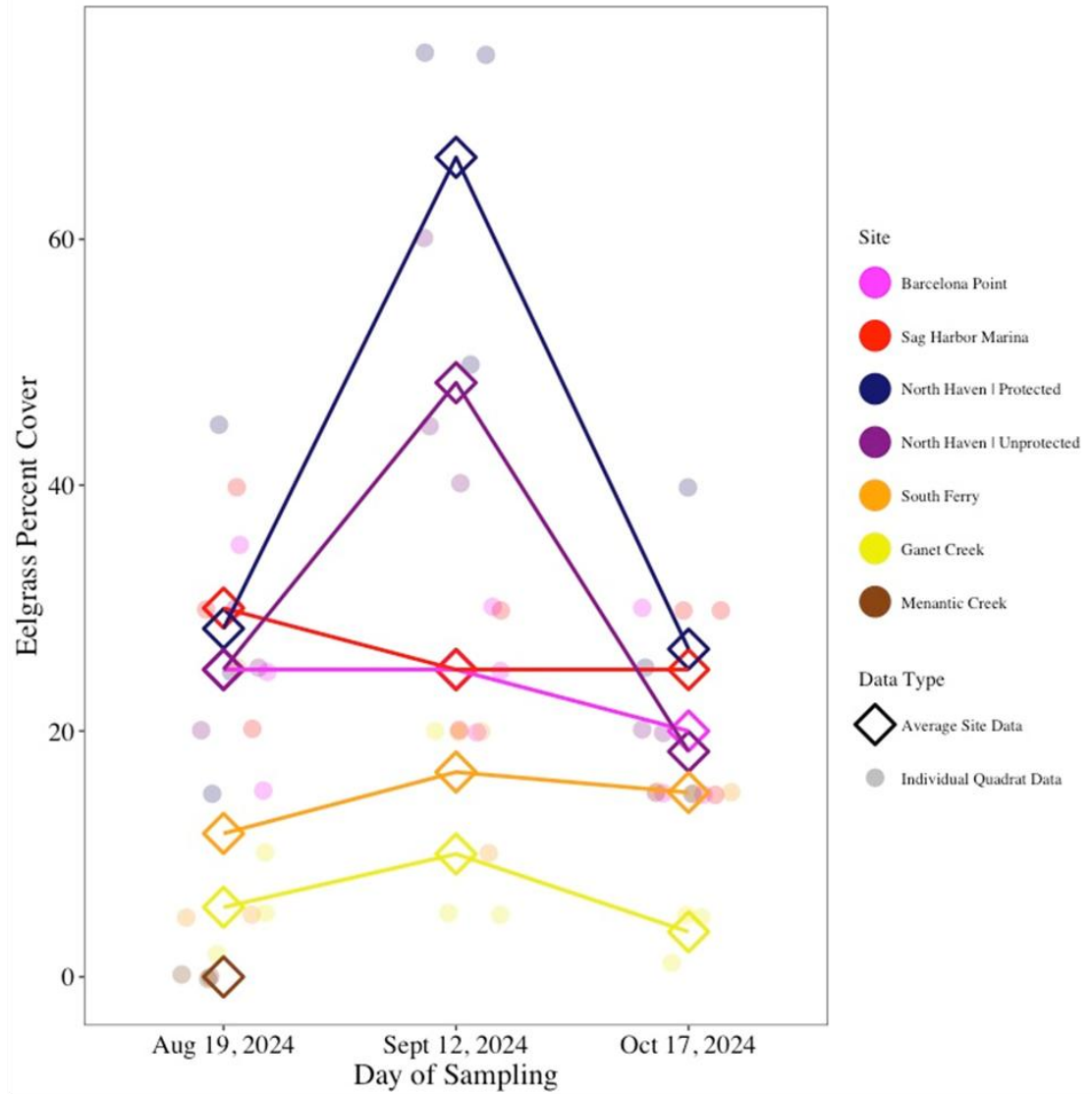


Figure 26. *Zostera marina* percent coverage per site over time. Sites are identified by color, and individual quadrat data is represented by small circles. Individual quadrat data was combined to create averages for each site, which are represented by the larger diamonds.

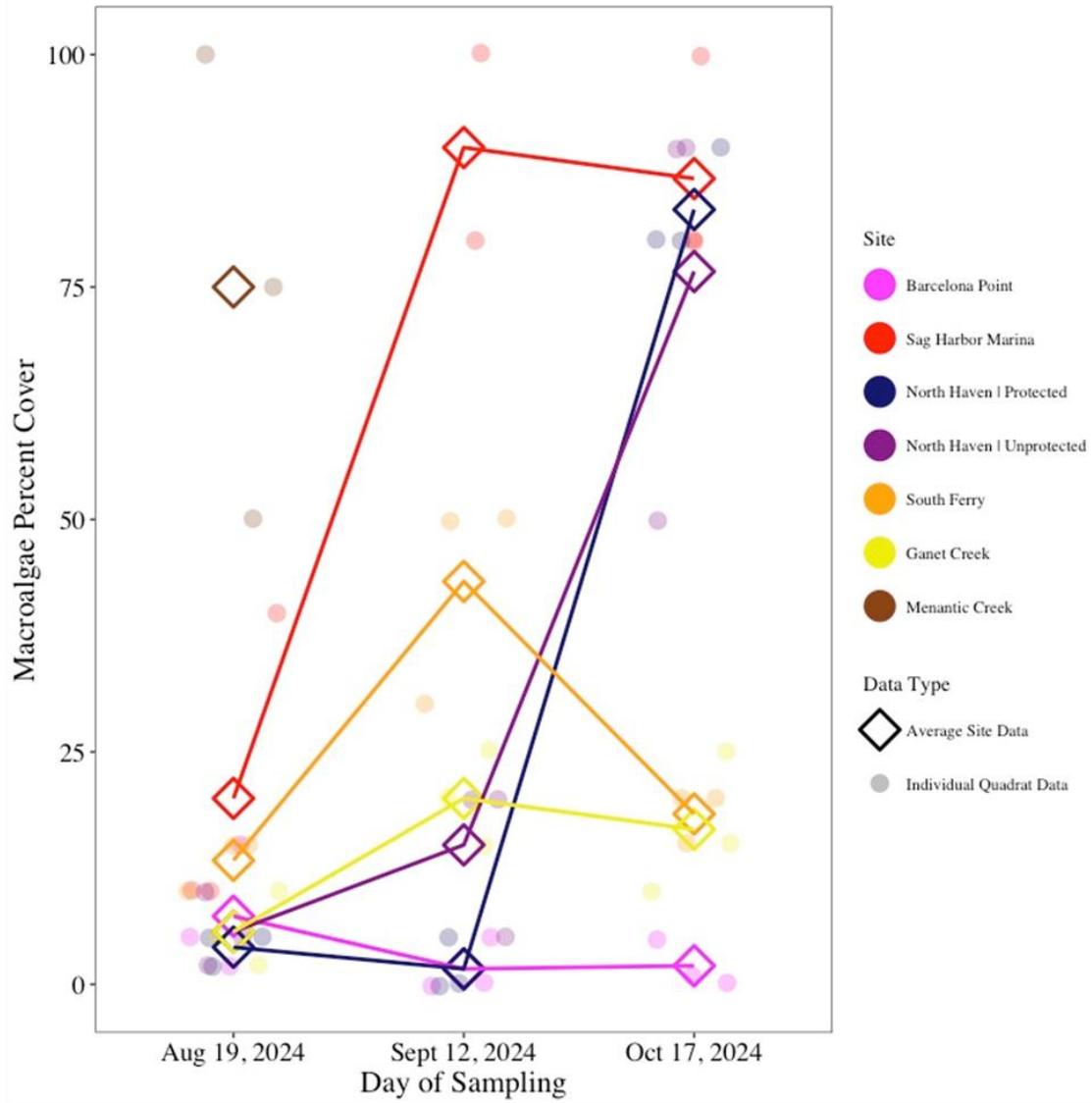


Figure 27. Percent cover of macroalgae per site over time. Sites are identified by color, and individual quadrat data is represented by small circles. Individual quadrat data was combined to create averages for each site, which are represented by the larger diamonds.

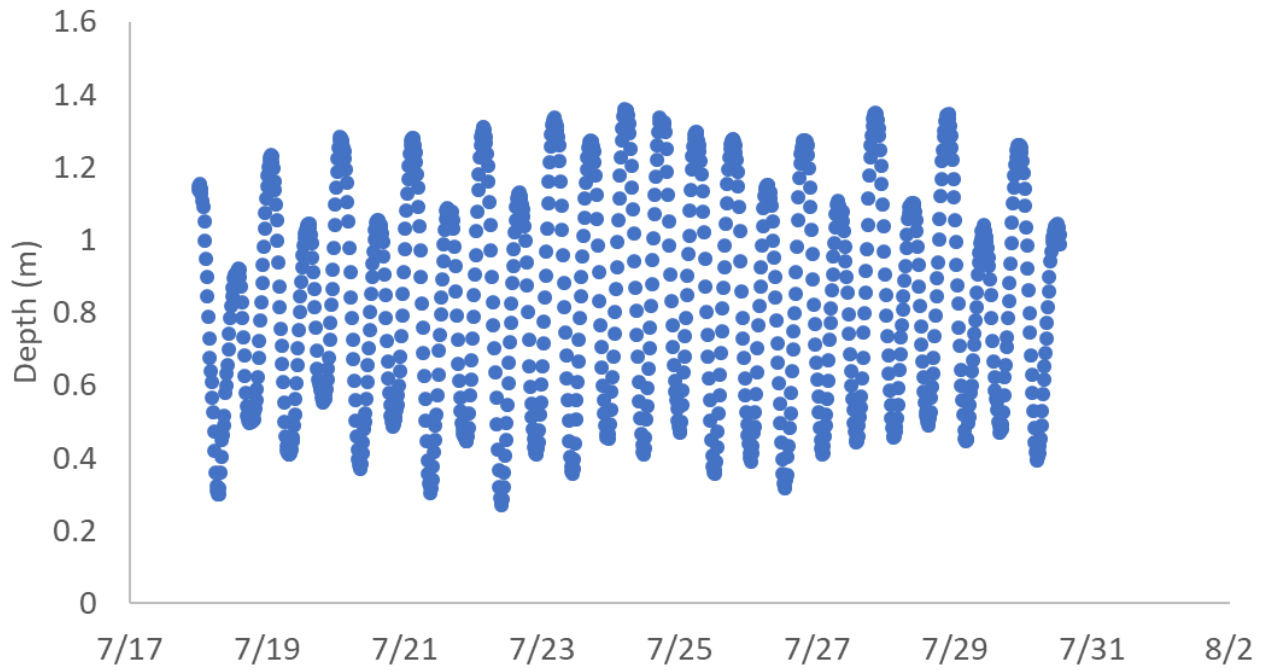


Figure 28. Variance in water depth during the deployment at the North Haven site, July 2024.

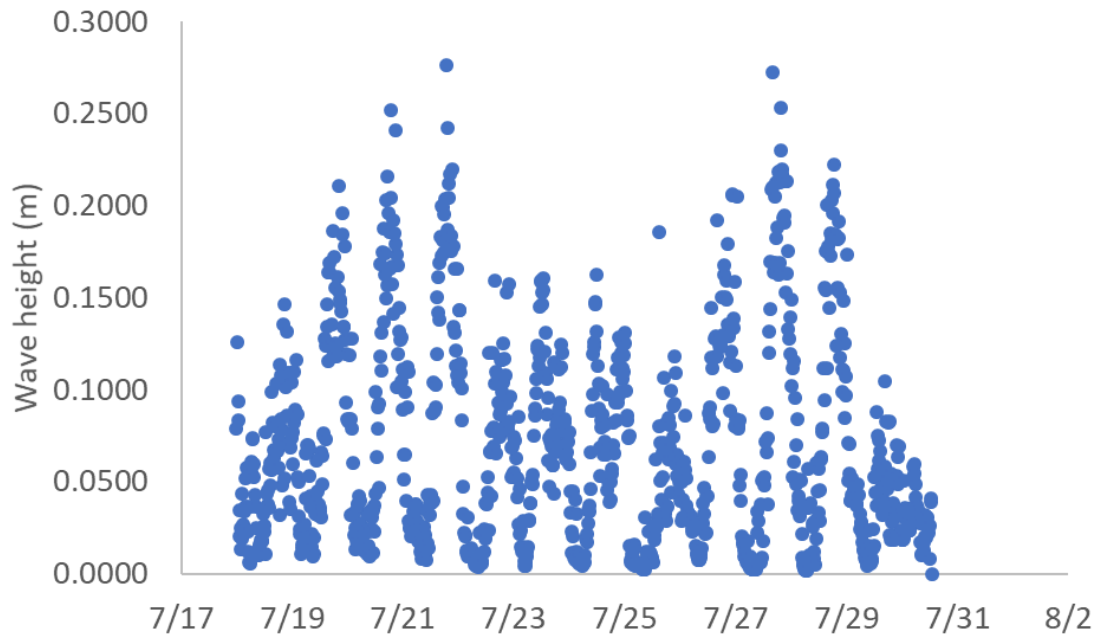


Figure 28. Variance in wave height during the deployment at the North Haven site, July 2024.