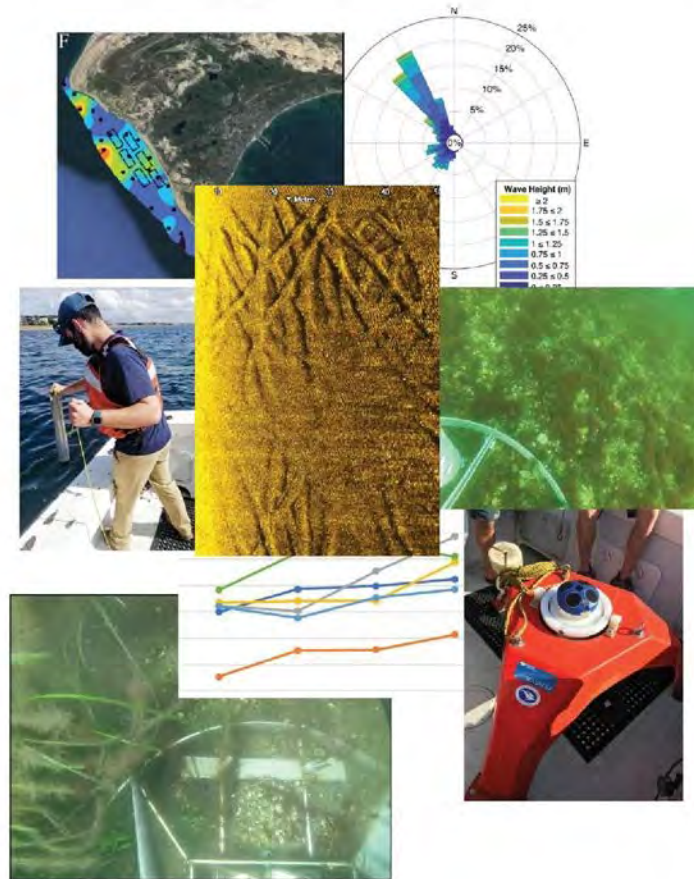




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Coastal Ecosystem Evolution along Cape Cod National Seashore from Long Point to Race Point: Multi-tiered, Science-based Management of Natural Resources and Infrastructure



A report prepared for Cape Cod National Seashore
by

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Legare, B.J., Nichols, O.C., Borrelli, M., 2020. Persistence of Hydraulic Dredge Tracks Following Surfclam Harvesting in Shallow Water. *Journal of Shellfish Research*, 39(2), 331-336.

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1. EXECUTIVE SUMMARY

This project was initiated by the Cape Cod National Seashore to learn more about the processes associated with onshore and offshore sediment transport and the relationship between the two at Herring Cove Beach in particular and the area between Long Point and Race Point in general. At the time the project was developed there was a nearly annual undermining of the north parking lot due to erosion and the old cinderblock bathhouse has been moved landward due to similar erosion problems. The extent and consistency of erosion was not in keeping with the long-term rates of erosion that had been documented by the Massachusetts Shoreline Change Project. In addition, between November 2014 – April 2015 the area from Long Point to Race Point had been extensively impacted by hydraulic clamming. Due to this event, a small distance study was added to the project to better understand the impacts such events could have on the sediment transport in the area as well as the biological impacts on the ecosystem.

At the outset of this project, it was hypothesized that given the nearly annual undermining of the north parking lot, the physical impact (dredge tracks) from an episode of hydraulic clamming would quickly disappear. This has been shown not to be the case. Dredge tracks from the November 2014 to April 2015 episodes were still visible in July of 2017. Some were still present during the last seafloor mapping effort for this project in December of 2018 having persisted between 875 – 1,350 days, including two winter seasons.

It is our belief that the seemingly anomalous erosion seen at the north parking lot was very likely not the result of abnormally high wave energy, intense storms, or the hydraulic clamming event. We believe it is more likely that the north parking lot itself had kept the shoreline from retreating landward for years, perhaps decades, and after the parking lot was removed in 2017 the shoreline re-equilibrated in the form of rapid landward migration or erosion. The erosion and undermining of the north parking lot indicate a dynamic area, but the persistence of dredge tracks below the surf zone reinforces the idea that nearshore subtidal energy regimes should not be assumed based solely upon more visible shoreline processes.

Data on waves and tidal currents were collected off of Herring Cove Beach over 152 days in quarterly surveys between July 2017 and January 2019. Based on data collected, Herring Cove Beach is a relatively low wave energy coast. The mean annual significant wave height at the site is 0.54 m, with a maximum significant wave height of 2.23 m. A hypothesis by an outside reviewer of the project proposal stated that the wave energy from Wood End to Race Point was too great for the establishment and growth of eelgrass beds; this is not the case. The levels of wave energy and current velocities throughout the study area including in the vicinity of Herring Cove Beach are not high enough to prevent the establishment and/or growth of eelgrass.

On November 9, 2017, the Center for Coastal Studies, under a permit from the Massachusetts Division of Marine Fisheries, partnered with a local hydraulic clammer to conduct a limited clamming event within a prescribed area in order to set up an impacted area and a control area to study the physical and biological impacts. In December of 2018, 397 days after the November 2017 impact, <1% of the dredge track lines had persisted, however, as mentioned above approximately 3% of the 2015 dredge tracks were still present during the December 2018 survey.

It has been shown that in the study area dredge tracks that are oriented parallel to shore persist longer than those perpendicular to shore. Also, dredge tracks within coarser substrate such as gravel/cobble or complex/hard bottom persist longer than those in sand. However, given that some of the 2014-2015 persisted longer than the 2017 dredge tracks, both of which occurred in the same orientation and substrate, makes it likely that the intensity with which the 2014-2015 clamming was undertaken was a factor in the persistence of those dredge tracks. This intensity is related to a combination of parameters such as the percent of bottom impacted and the depth of dredge tracks, which is related to gear type and water pressure.

Based on a peer-reviewed journal article published during this project (Legare et al. 2020a), the benthic invertebrate community structure varied significantly between areas of “high”, “low”, and “no” disturbance. Areas of “low” to “no” dredge track impact contained high abundances of organisms associated with a more sedentary life history and lower trophic levels in the food web (e.g. clams, echinoderms, and isopod crustaceans), whereas highly-impacted areas had highest abundances of highly mobile, mostly predatory/scavenging organisms (e.g. polychaete bristle worms and oligochaete worms).

For this study, benthic invertebrate samples were collected in duplicate at 24 stations during four sampling events: Pre-Impact (Oct 2017; “PRE”), Post-Impact (Nov 2017; “POST”), 6 Months Post-Impact (Apr/May 2018; “6POST”); and 12 Months Post-impact (Nov 2018, “12POST”). Pre-Impact samples established a baseline and were compared against POST, 6POST and 12POST samples. In November 2017 the controlled hydraulic clamming harvest occurred in three of six study areas (hereby called boxes) off Herring Cove Beach. A total of 20 dredge passes were conducted covering a linear distance of approximately 11.4 miles. Twelve of the 24 stations within three of the six boxes were subject to hydraulic clamming (impact group). The 12 stations within the other three boxes were not impacted and thus were the control group.

A total of 128,843 individuals belonging to 216 species were identified during the four sampling periods. For statistical analysis, meiofauna were excluded as sampling methods were not geared towards adequately sampling organisms smaller than 1mm. For reasons explained in section 4.6, only data on presence/absence of taxa was used in statistical analysis. Statistical analyses showed that the parameter that most affected species assemblages was presence of algae (% seafloor covered by vegetation as determined by video analysis). Submerged aquatic vegetation provides

shelter and food for many species and is well understood to host higher species diversity than non-vegetated areas.

The controlled 2017 hydraulic clamming harvest was not shown to be statistically significant with regards to species presence/absence in general. The recovery of mobile species presence from the 2017 disturbance, however, was well underway by the last sampling event in December 2018. Conversely, sessile species (or immobile species) biodiversity numbers had begun to recover, but to a lesser extent. It is extremely likely that the high prevalence of vegetation in the area and the adjacent protected areas provided a healthy population of mobile species that were able to colonize impacted areas. After 12 months, pre-impact levels of biodiversity have not been reached. However, given no further disturbances, the continuation of areas of abundant submerged aquatic vegetation and the continuation of the recovery rate that was observed in the first year, it is very likely that biodiversity for both mobile and sessile species, can reach pre-disturbance levels within six years.

2. INTRODUCTION

A multi-disciplinary study from Long Point to Race Point in Provincetown, Massachusetts, was conducted to help managers better understand the short- (seasonal/annual) to medium- (sub-decadal) term ecosystem evolution of this area in general, and Herring Cove Beach in particular (Figure 1). This study integrates a suite of coastal oceanographic, morphological, and sedimentological measurements in addition to benthic habitat data along the 13 km of shoreline within the study area. Data collected include: tidal current velocities and wave measurements; swath bathymetry, sidescan sonar imagery and seismic reflection profiling via vessel-based acoustic surveys; benthic habitat characterization via bottom sampling of macro-invertebrates, sediment grain size and compaction and underwater video; updates to ongoing sediment volume surveys to document short term change; and onshore and offshore shore-normal profiles. In addition, a planned hydraulic clamming event was undertaken to collect before and after data to document impacts.

It is critical to treat coastal ecosystems as one interdependent system rather than a terrestrial system and an adjunct marine system. By studying both sub-systems (terrestrial and marine) and the interactions between those sub-systems, a better understanding of ongoing and future coastal evolution can be developed. Too often coastal science is conducted either on the coast or research vessels. This study treats the onshore/offshore coastal environment as one system.



Figure 1. Upper Left: Locus (NOAA Chart #13249). Time series from 2010 to 2017. The parking lot was repeatedly damaged and repaired. During this period an erosion rate of 4-10 m/yr was seen in the area. Typical long-term rate of shoreline change is ~1m/yr. All images are taken from Google Earth.

The Cape Cod National Seashore receives approximately four million visitors annually with Herring Cove Beach being one of the most highly visited beaches in the Park (Figure 1). Episodic

accretion occurs along the Hatches Harbor spit and consistently at the end of Long Point, however the system as a whole is erosional and the north parking lot has experienced increasing rates of erosion since the 2010s (Figure 1). The net direction of sediment transport is from Race Point to Long Point. The annual rates of net sediment transport in the study area range from 40,000 – 80,000 m³/yr (Giese et al. 2015). For context, the rates of net sediment transport on the open ocean beach are up to 10 times as high with rates reaching over 800,000 m³/yr (Giese et al. 2011). These rates of sediment transport are the *net* annual volumes of material moving along the coastal zone. The volumes of gross sediment transport would be higher still than these net volumes, underlying how energetic these coastal systems are.

One example of these dynamic coastal systems is the formation of ephemeral tidal inlets. Typically, during storm events, new tidal inlets form, and several have formed and filled in the recent past. Ashley (1987) monitored a tidal inlet that opened during the Blizzard of 1978 and remained open for more than a decade, after which it closed naturally, in part due to the volume of sediment moving along the shoreline overwhelming the tidal flow in and out of inlet. McFarland (2019) documented an inlet formation ~1 km (0.6 mi) northwest of the 1978 inlet in 2018 that inlet persisted for several years.

Due to the clear erosional impacts to this area, the Seashore has already begun taking steps to lessen the impacts to Park infrastructure from continuing and intensifying coastal storms, sea-level rise and other natural and human-induced change. Climate change adaptation strategies seen at Herring Cove Beach include the 2012 removal of a cinderblock bathhouse from the 1950s, which was replaced 75 ft landward with a moveable bathhouse. A project to move the north parking lot back ~150 ft and raise its elevation to above the then ‘100-yr flood elevation’ was completed in 2019.

Coastal erosion and accretion in the form of changes in beach width and elevation are directly related to sediment transport in the nearshore. This sediment transport is driven primarily by tidal currents and waves, and this study directly measures those processes while monitoring beach state. Further, sediment transport, tidal currents and waves directly affect physical, biological, and chemical processes on the seafloor, which in turn can create positive (or negative) feedback cycles that can further impact ecosystem evolution. This feedback cycle can be started, altered, stopped, and restarted based on numerous variables. This study documents the links between nearshore sediment transport and coastal evolution.

The disturbance study nested within the larger study was conducted by partnering with a commercial hydraulic clam dredge fisherman to conduct a controlled experiment. Collected data sets related to this episode of clamming were bathymetry, bottom type, sediment compaction, grain size, and benthic habitat characterization in areas along the seafloor with different levels of disturbance related to a hydraulic clamming effort. This disturbance study was conducted to help

better understand a larger commercial hydraulic clamming episode conducted by many fishing vessels from November 2014 through April 2015 (Figure 2) (Borrelli et al. 2019; Legare et al. 2020b). Levels of sediment compaction after such a disturbance may have a direct impact on sediment transport patterns, directions, and volumes, both onshore and offshore in the area, in addition to affecting the way tidal currents and waves interact with the seafloor. Further, sediment compaction has implications for sea clam recruitment, benthic habitat evolution, submerged aquatic vegetation, algal beds, and transitory food sources for marine mammals.

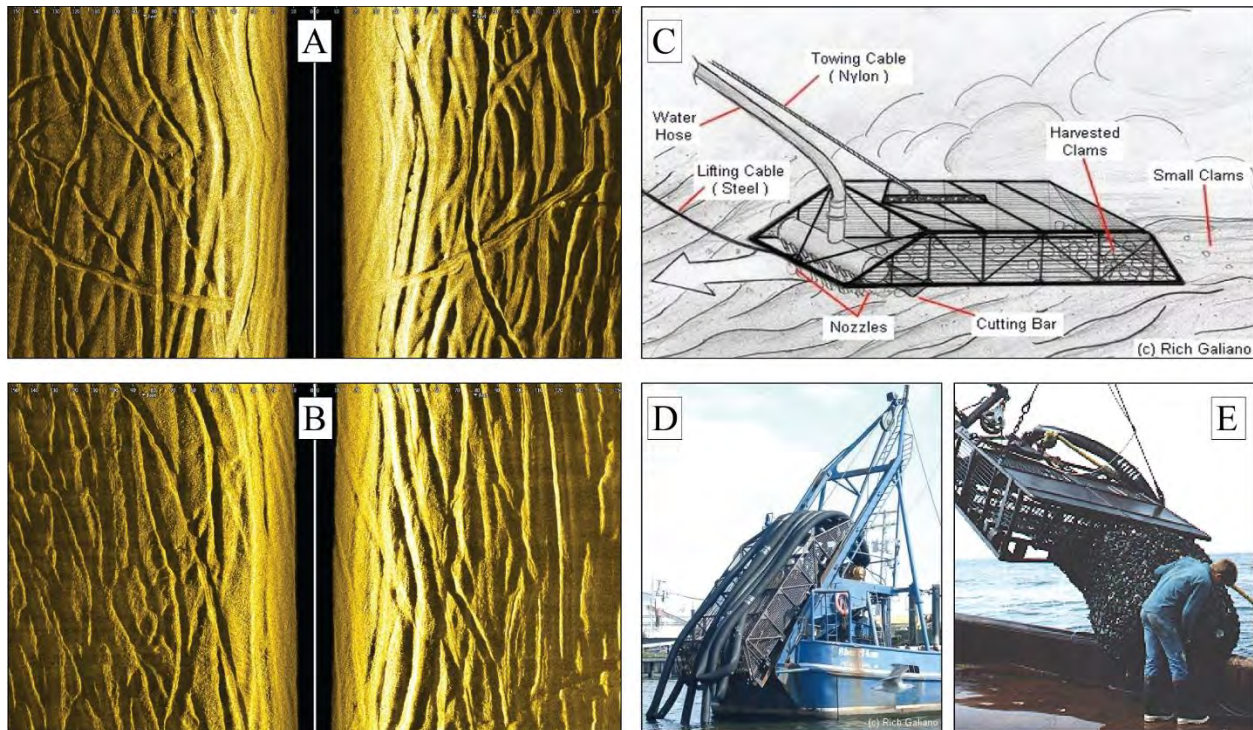


Figure 2. Raw sidescan sonar images collected by the Center for Coastal Studies off of Herring Cove Beach (A) and Hatches Harbor (B) on December 23rd 2014. Most of the seafloor is has dredge tracks from hydraulic clamming. The black bar in the middle of the images is removed during final processing. A drawing of typical hydraulic clamming equipment (C) and two images of a vessel (D) and the basket used to capture the clams (E).

2.1. Hypothesis-driven science

During project development, Seashore staff working with the principal investigator designed the following hypotheses to be tested. It was felt that the rigor associated with hypothesis-driven research would improve the utility of the results and focus project scope to Park priorities. The six hypotheses tested in this study are as follows:

1. A seasonal pattern to tidal current velocities and wave climate in the vicinity of Herring Cove Beach can be documented by quarterly, spring-to-neap Acoustic Doppler Current Profiler (ADCP) surveys.

2. There is a direct relationship between the offshore tidal currents and wave climate and the onshore coastal morphology.
3. There exists a spatial variability of compaction of non-cohesive sediment from Race Point to Long Point for similar-sized sediment.
4. The compaction of similar-sized sediment is different in areas of documented bottom disturbance (e.g., hydraulic clamming) than in areas with no documented bottom disturbance.
5. Providing no further anthropogenic disturbance, the compaction in bottom disturbed areas will increase through time to pre-disturbance levels.
6. The benthic invertebrate communities are different in areas of documented bottom disturbance (e.g., hydraulic clamming) than in areas with no documented bottom disturbance. Providing no further anthropogenic bottom disturbance, the invertebrate communities in disturbed areas of the sea floor will recover through time to pre-disturbance levels.

The first hypothesis, H1: A seasonal pattern to tidal current velocities and wave climate in the vicinity of Herring Cove Beach can be documented by quarterly, spring-to-neap Acoustic Doppler Current Profiler (ADCP) surveys, though seemingly simple, was deemed foundational due to the lack of oceanographic data on the narrow shelf in the study area (Figure 5). It was therefore critical to establish a baseline set of data with regards to waves and tidal currents for this project. These data are used to classify coastal compartments (e.g., low, moderate, or high wave energy coast) and help scientists better design future studies.

The second hypothesis, H2: There is a direct relationship between the offshore tidal currents and wave climate and the onshore coastal morphology, was developed to take advantage of the new oceanographic data to better understand the evolution of the coastal system. The relationship between offshore processes and onshore morphology is a complex one and this hypothesis was designed to aid this work and future studies given the recent and ongoing erosion seen at Herring Cove Beach. According to the Massachusetts Office of Coastal Zone Management's *Massachusetts Shoreline change* project webpage (<https://maps.massgis.digital.mass.gov/MassMapper/MassMapper-CZM-Shorelines.html>), the long-term shoreline change rates along Herring Cove Beach averages ~1 ft /yr. Since the late 1990s, the rates of erosion were reportedly increasing and between 2010 and 2018 Herring Cove Beach in general and, particularly, the north parking lot were undergoing episodes of erosion that required action from the Seashore. Erosion rates in the tens of ft per year were reported by park staff based on GPS surveys (unpublished NPS data) and from semi-quantitative evidence from online imagery such as Google Earth™. In the

late 2010s, the cinderblock bathhouse at Herring Cove Beach, Provincetown, MA, USA, was in danger of becoming undermined due to the increased rates of erosion (Figure 1). The bathhouse was demolished and a new bathhouse, capable of being relocated in the future, was constructed 75 ft behind the old structure. The erosion at the site continued and the north parking lot was undermined to varying degrees and repaired almost annually between 2010 and 2018 when the parking lot was moved 200 ft landward and raised above the then 100-year storm elevation (Figure 3).



Figure 3. A and E: Images of Herring Cove Beach, Provincetown, MA, USA before (2018) and after (2021) the parking lot was moved ~80 m landward. Middle upper (B): Image of asphalt being placed on sand from the 1960s at Herring Cove Beach. Middle Center (C): 2017 coastal erosion undermining parking lot at Herring Cove. This was one of several repaving projects from 2010-2018. Middle Bottom (D): Seashore crew repairing parking lot, circa 2015.

Similar to the lack of oceanographic data in the study area there is a lack of granulometric data which is related to grain size, shape, distribution and other properties, such as compaction. Hypothesis 3, H3: There exists a spatial variability of compaction of non-cohesive sediment from Race Point to Long Point for similar-sized sediment, was developed to understand the sediment transport pathways within the context of the oceanographic and morphological data discussed above.

With the above data and the bottom disturbance caused by the hydraulic clamming between approximately November 2014 and April 2015 (Figure 2) conversation with Park staff produced the fourth hypothesis, H4: The compaction of similar-sized sediment is different in areas of documented bottom disturbance (e.g., hydraulic clamming) than in areas with no documented bottom disturbance. The ability to combine data sets, measure, and track multiple variables ideally allows for the investigator to separate out cause and effect with regards to natural and human-caused drivers. As part of the larger study, a *nested disturbance study* was developed to address the possible impacts of hydraulic clamming in the area and hypotheses 4, 5, and 6 are directly related to bottom disturbances caused by hydraulic clamming.

The fifth hypothesis, H5: Providing no further anthropogenic disturbance, the compaction in bottom disturbed areas will increase through time to pre-disturbance levels, is related to disturbance and recovery after an episode, or episodes, of hydraulic clamming. For the purposes of better understanding system disturbance and recovery, the Center for Coastal Studies worked with the Massachusetts Division of Marine Fisheries in late 2017 to permit a hydraulic clamming vessel to drag the bottom in only prescribed areas off Herring Cove Beach (Figure 4). This was done so the Center could perform a ‘Before-After-Control-Impact’ (BACI) study. BACI studies are the standard for determining impacts and/or changes to a system. While not always conclusive, the BACI method removes as many variables as possible, which is most critical in natural environments which, of course, have many variables.

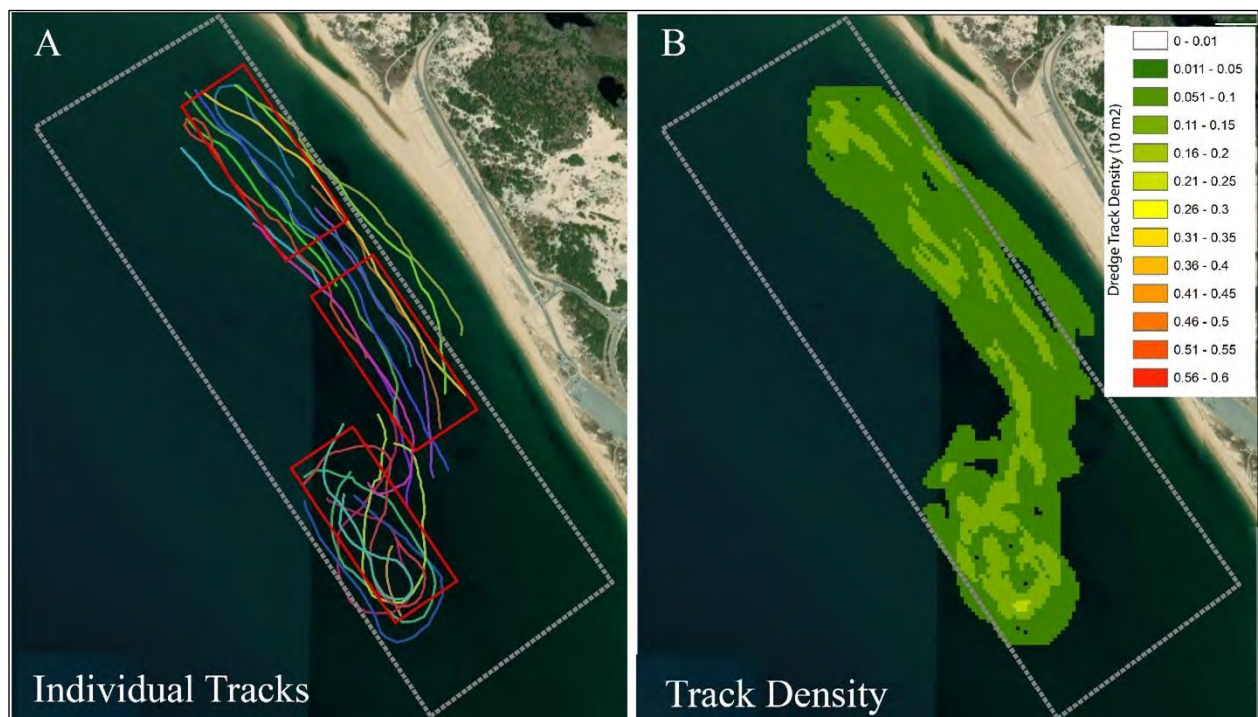


Figure 4. Controlled dredging performed in 2017 as a BACI style experiment. Dredge tracks were obtained from an on-board GPS (A), dredge track density (B) indicated fishing intensity across the study site ranging from 0-6%.

Lastly, in addition to the physical response to bottom disturbance via hydraulic clamming, the ecological impacts of the seafloor biota or benthos were monitored via the collection and identification of the biodiversity of macro-invertebrates immediately before and after the 2017 hydraulic clamming as well as 6- and 12-months after the effort. Therefore, the sixth hypothesis is as follows: H6: The benthic invertebrate communities are different in areas of documented bottom disturbance (e.g., hydraulic clamming) than in areas with no documented bottom disturbance. Providing no further anthropogenic bottom disturbance, the invertebrate communities in disturbed areas of the sea floor will recover through time to pre-disturbance levels.

This study was developed to better understand the links between coastal oceanographic processes (tidal currents and waves) and onshore and offshore sediment transport to provide NPS staff with science-based findings to improve the management of the area.

The following section provides some background on the surf clam fishery and the rationale for the disturbance study and was adapted from Legare et al (2020b). The immediate biological and physical impacts of hydraulic clamming are known to be detrimental across a variety of habitats (Hiddink et al. 2017; O'Neill and Ivanović 2015). This method of fishing affects habitats by physically disrupting the benthic substrate while removing organisms (both target species and by-catch), causing short and long-term changes in benthic communities (Stokesbury et al. 2011; Thorarinsdóttir et al. 2009). Long-term recovery is related to the intensity of harvest, habitat type affected, and hydrographic regime of the area (Gilkinson et al. 2015; Oberle et al. 2016a; Stokesbury et al. 2011). If conducted in substrates containing stable, fragile structures like coral reefs or submerged aquatic vegetation beds, high rates of damage are typical, requiring long periods for recovery (Hiddink et al. 2017; Stokesbury et al. 2011). Management of hydraulic clamming is conducted on both the regional and local scale (Committee 2001). Despite the long-term and widespread use of mobile fishing gear and localized impacts to the substrate, relatively little data are collected on the fine-scale distribution of fishing effort (Demestre et al. 2015).

Fisheries management plans for Atlantic surf clams (*Spisula solidissima*), state that the effects on the benthic communities are short lived (hours to months) in sand-dominated, high-energy environments, as the adverse effects on the benthic community would be greater from strong currents and storm events (Mid-Atlantic Fishery Management Council, 2016; Fuller and Cameron, 1998). Physical disruption of the substrate can cause localized sedimentation and reduce substrate compaction (Eigaard et al. 2015; O'Neill and Ivanović 2015; Tuck et al. 2000). If conducted in an area of fine-grained sediment (silt or clay) impacts to the surrounding area are more problematic than in areas of coarser grained sediments (Lambert and Goudreau 1996). The immediate impacts include large changes to the bathymetry of the substrate, creating troughs and mounds, and the destruction of burrows, tubes, and shells through burial or physical impact (Gilkinson et al. 2003). The trough walls will erode as wave and tide action act upon the substrate caused by slumping, sediment transport and bioturbation (Gilkinson et al. 2003). The combined action of the dredge and hydraulics change the benthic community long after contact (Gilkinson et al. 2015; Oberle et al. 2016b; Sköld et al. 2018).

Originally a modification of a “dry” dredge, a hydraulic clam dredge uses water pumped into the substrate to access the resource beneath the surface, improving efficiency and reducing mortality of the targeted catch (Parker 1971). This method fluidizes the sand, allowing the cutting knife of the dredge to dig up to 0.25 m below the surface, creating wide troughs that have been shown to persist for extended periods of time (years) in deep water (>30 m), low energy environments (Gilkinson et al. 2015; Johnson 2002; Mercaldo-Allen et al. 2016; Oberle et al. 2016a). Tow speed,

weight, and orientation of the gear all influence the initial impacts on the substrate and the longevity of the impact (Depestele et al. 2015).

The shallow nearshore waters (0-10 m) off the Provincetown Hook from Race Point to Long Point have a long history of surf clam harvest. Belding (1909) noted that fishermen thoroughly dredged the beds in their search for bait as one of the principal surf clam fisheries in the state (Belding 1909). Shifting from dory-based tongs and rakes and “dry” dredges, used prior to World War II, hydraulic clamming became the standard harvest method in Massachusetts (Parker 1971; Smolowitz 1982) by the late 1950s (Pol and Carr 2000). Situated between Race Point and Long Point, Herring Cove has been well-known for a rich bed of surf clams, and hydraulic clamming was a common sight off Provincetown for decades (Anonymous 1957). In 2007, a town moratorium was put in place on hydraulic clam dredging in depths shallower than 40 feet (14.9 m), although this moratorium was not endorsed by the Massachusetts Fisheries Management Agency (Myers 2015).

In November 2014, hydraulic clam dredging began in the study area. Despite town opposition, clamming continued through the end of April 2015. A typical vessel engaged in this fishery in state waters employs a dredge with a 48-inch (1.2 m) wide cutting knife set at 4-6 inch (10-15 cm) depth, with nozzle water pressure ranging from 30 to 60 psi (207-417 kPa) (Nichols, unpublished data). After April 2015, no dredging of any kind was observed or reported in this area. Although anecdotal, given the contentious nature of the effort (including local enforcement and legal actions) (Ward 2017) and the proximity to shore, the reported cessation of the clamming activity through the end of our study seemed very likely.

3. METHODS

The techniques, instruments and data sets used for this project are detailed here. Many data sets are used for multiple purposes within the study and are discussed in several sections of this report.



Figure 5. Study design for quarterly survey data within the study area (red), including offshore (acoustic) and onshore (beach) profiles (white). Sediment/compaction/bottom video sampling at the transect sediment sample locations (yellow). Acoustic Doppler Current Profiler (Orange Triangle). Location of BACI sampling area in gray.

3.1. Acoustic Doppler Current Profiler

To accurately measure the waves and currents influencing the study area, a Teledyne RDI Sentinel V20 Acoustic Doppler Current Profiler (ADCP) was deployed six times throughout the duration of the study, with deployments ranging from 18-35 days. The ADCP records binned current data throughout the entire water column, beginning approximately one meter from the seafloor.

3.1.1. Acoustic Doppler Current Profiler – Field Work

The ADCP was deployed from R/V Marindin at approximately $-42.043488^{\circ}\text{N}$, $70.227404^{\circ}\text{W}$ (Figure 5; Figure 10), with an average water depth at deployment of 8 m. The ADCP was deployed with Teledyne's Sea Spider seafloor platform (Figure 6), which secures the ADCP on a gimbal such that the sensors can continue to point vertically even if the mount is not level on the seafloor and remain approximately 0.6 m above the seafloor.

3.1.2. Acoustic Doppler Current Profiler – Processing and Analysis

ADCP data was processed using Teledyne's Velocity software, adjusting for magnetic variability as indicated in **Table 1**. To determine relative accuracy, wave values were compared to NOAA buoy data in Cape Cod Bay (Buoy #44090; 41.840°N , 70.329°W) and north of Provincetown (Buoy #44018; 42.203°N , 70.154°W).

Table 1. ADCP deployment dates, durations, and calibration constants. Times are given relative to local time.

Deployment	Start Time	Stop Time	Duration	Magnetic Variation
LR201707	2017-07-27 12:00:00	2017-08-14 06:06:28	18 days	14.936
LR201710	2017-10-26 22:00:00	2017-11-30 14:44:59	35 days	14.921
LR201802	2018-02-27 10:30:00	2018-03-20 06:30:00	21 days	14.900
LR201805	2018-05-16 11:00:00	2018-06-16 11:00:00	31 days	14.887
LR201808	2018-08-06 12:00:00	2018-08-24 16:17:57	18 days	14.874
LR201812	2018-12-11 10:00:00	2019-01-09 23:00:00	29 days	14.852

For analysis, U- and V-velocities were converted into longshore (+ northwest) and cross-shore (+ on shore) velocities using a counter-clockwise rotation of 123° . Wave data was filtered to remove erroneously high wave periods calculated from very small wave heights. As such, wave periods over 14 seconds, wave periods that exceeded 7 seconds while the corresponding wave height was less than 0.35 m, and wave periods that exceeded 6 seconds while the corresponding wave height was less than 0.1 m were excluded from analysis.



Figure 6. Teledyne RDI Sentinel V20 Acoustic Doppler Current Profiler (ADCP) mounted on a Teledyne Sea Spider seafloor platform.

To determine if the currents in the study area were sufficient to initiate the motion of sediment, the Turbulent Kinetic Energy (TKE) method was used. The TKE method relates fluctuations in velocities to the bed stress such that:

$$\text{TKE} = \frac{1}{2} \rho (\overline{u'^2} + \overline{v'^2} + \overline{w'^2})$$

where u' , v' , and w' are deviations from mean velocities in the x, y, and z directions, respectively, and ρ is the density of seawater. From now commonly used experimental values (Kim et al. 2000), we know that bed shear stress (τ_b) is related to TKE by a constant value of 0.19:

$$\tau_b = C_1 \text{TKE}$$

With an estimate for bed shear stress, we can use modified versions of the Shields Diagram to assess initiation of motion. Miller et al. (1977) compares friction (or shear) velocity (U_*) to grain size, where friction velocity can be calculated as:

$$U_* = \sqrt{\frac{\tau_o}{\rho}} \text{ cm/sec}$$

Friction velocities can be thus calculated for the entire deployment period and compared to grain size using the relationships in the Shields Diagram modified by Miller et al. (1977); see Figure 7.

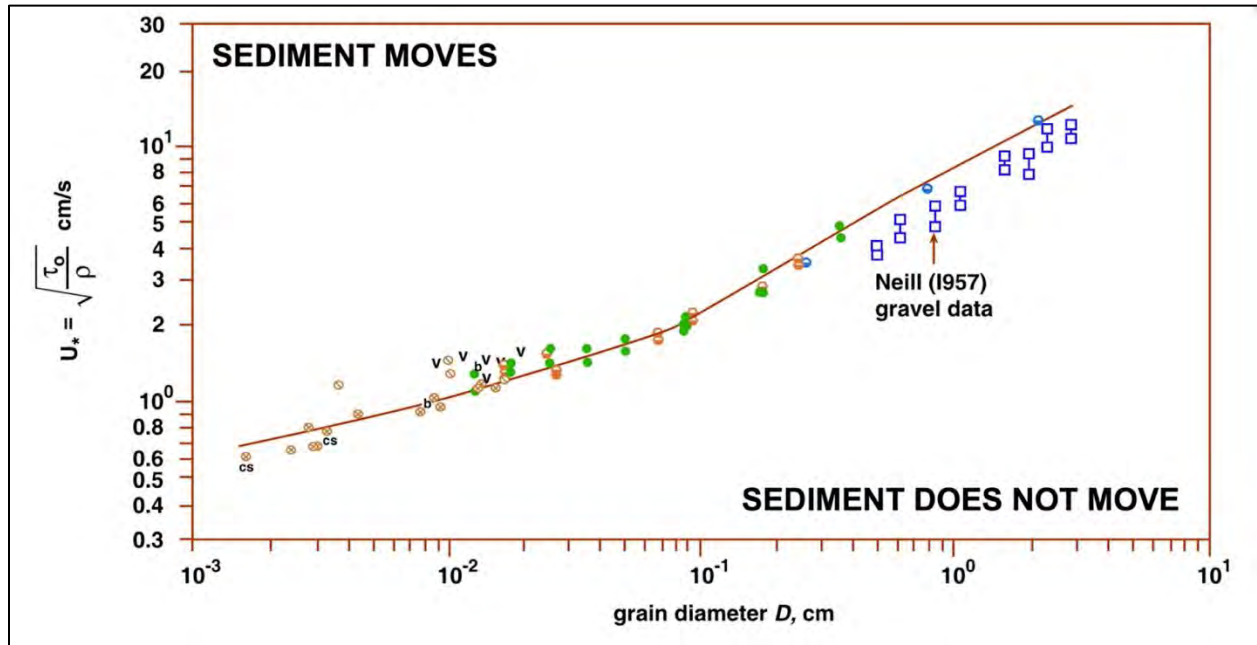


Figure 7. Modified Shields Diagram, adapted from Miller et al. (1977) and Southard (2006).

3.2. Penetrometer

A free-fall penetrometer, Bluedrop® (Figure 8) from *blueCdesigns Inc.*, was used for in-situ characterization of sediment compaction and shear strength. The Bluedrop was chosen due to its rapid and simple hand deployment, allowing for large areas to be repeatedly surveyed. Accelerometers within the unit measure the speed through the water column and into the seafloor. This instrument is deployed by attaching a tether line, holding the instrument from a vessel just below the water line, and releasing it. The instrument then falls through the water column until impact with the seafloor. This process of deployment will be referred to herein as a *drop event*. Once a drop event has been completed, the instrument is then brought back onto the vessel with the tether line. The rate at which the instrument decelerates upon impact and the magnitude of

penetration provides vital information including the quasi-static bearing capacity (QSBC), which is a proxy for sediment compaction. The deceleration and penetration the instrument records have been shown to adequately characterize both the physical and geotechnical characteristics of the seafloor in part through analyzing QSBC values (Stark and Wever 2008). For example, the deceleration and penetration of the instrument would vary greatly between a high-energy, sandy environment and a low-energy, muddy setting. Upon impact with the seafloor, the penetrometer decelerates rapidly with relatively little penetration in sandy environments with the opposite being true in muddy environments.

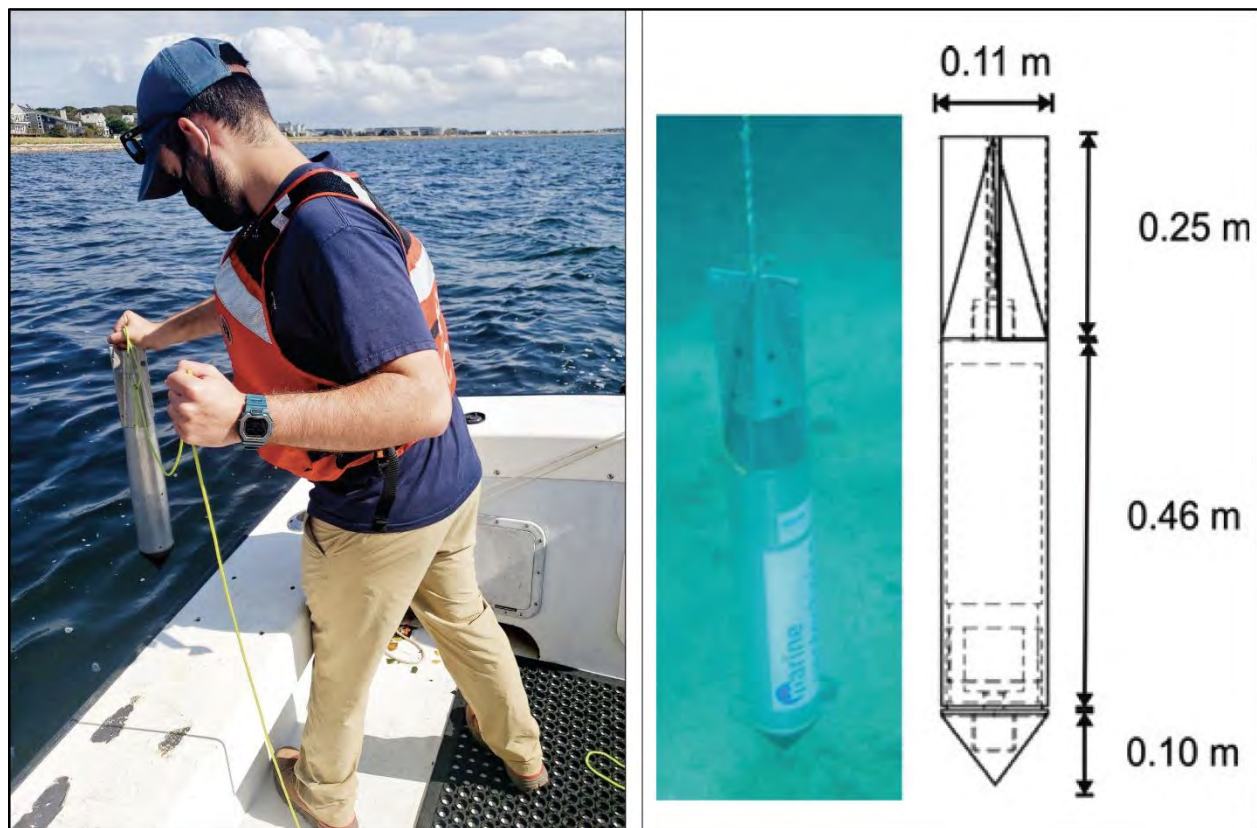


Figure 8. Left: The technician lowers the penetrometer to just below the water line and then releases the line. Right: Image and schematic taken from Stark et al. (2011).

The Bluebird is comprised of four main sections of the body: nose, battery module, electronics module, and a tail section. The nose acts as the impact surface of the instrument. Directly behind the impact cone, there is a pressure sensor behind a porous ring that aids in the characterization of the seabed and processing of the data. The battery module simply houses the battery of the instrument. The electronics module houses five accelerometers measuring vertical acceleration in g (gravitational acceleration) which includes a $\pm 1.7g$, $\pm 18g$, $\pm 55g$, $\pm 200g$, and $\pm 250g$ accelerometer. These accelerometers measure the acceleration in the direction of travel of the instrument when being deployed through the water column. Along with the accelerometers in the vertical (Z) direction, there is also a dual-axis $\pm 55g$ accelerometer that measures acceleration in

each of the horizontal X and Y directions to record the tilt of the instrument throughout a drop event. All of the accelerometers operate at a sampling frequency of 2 kHz, i.e. collecting 2,000 data points every second. The tail section has four vertical wings to stabilize the instrument in the water column during a drop event. There is also an eye bolt at the end of the instrument to act as a tether point for a deployment line, in this case paracord was used for all drop events (Figure 8).

3.2.1. Penetrometer – Field Work

The Bluedrop was deployed in various locations using two different methods. First, it was deployed according to manufacturer's specifications, where the penetrometer was hung over the side of the vessel, released below the water line allowing for a 'free fall' to impact the sediment, and recovered via an attached line. Ideally, the probe reaches terminal velocity, which allows for consistent amounts of kinetic energy to be recorded during impact. A second method of deployment was developed to better control the penetrometer as it relates to the seafloor near a bottom sediment grab. A 1.5-m perforated PVC chute (Figure 9) was attached to the Young-modified Van-Veen used for sediment and invertebrate sampling. This chute allowed for more precise data to be collected adjacent (~10 cm away) to the sediment sample. As terminal velocity is only achieved in falls >5 m and in the absence of drag created by the retrieval line and currents, consistent maximum velocity was not achieved while using the second method of deployment. To allow for comparisons between the two different methods of deployment, the QSBC was standardized to the maximum velocity of the free-fall drop events in the same study area.

3.2.2. Penetrometer – Analysis

Data was processed by utilizing *DropView ver. 1.5* software, which was created by the manufacturer for the viewing, processing, and exporting of data from the Bluedrop penetrometer. This software plots acceleration through time, allowing for the visualization of the drop event. For each drop event, integration points selected by a technician can be used to calculate the acceleration, speed, and depth of penetration, as well as other factors associated with seabed characterization, such as the abovementioned QSBC, which was chosen as the primary metric because it is a proxy for sediment shear strength and compaction (Stark et al. 2011). The metrics taken from the penetrometer data were then correlated with the individual sample sites based on GPS positions taken during the sampling. For each drop event, these metrics include maximum QSBC (kPa), acceleration at maximum QSBC (g), depth at maximum QSBC (cm), and velocity at maximum QSBC (m/s).

3.3. Vessel-based Acoustic Surveys

All vessel-based acoustic surveys were conducted on board the R/V Marindin, a customized 8.3-m Eastern® mono-hull research vessel. The vessel was fitted with a bow-mounted EdgeTech 6205 phase-measuring sidescan sonar, which yields co-located, dual-frequency sidescan backscatter

imagery and swath bathymetry. The operating frequencies are 550 and 1600 kHz for sidescan backscatter and 550 kHz for bathymetry. The sidescan backscatter resolution and horizontal beamwidth are 1 cm and 0.5° at 550 kHz, and 0.6 cm and 0.2° at 1600 kHz. The bathymetric range and vertical resolution are each 1 cm (Edgetech 2014). Motion data were collected with a Teledyne TSS DMS-05 motion reference unit mounted onto the sonar housing, measuring heave to 5 cm and roll and pitch to 0.05° (TSS 2006). Position was collected using Trimble® R8 or R10 GNSS systems utilizing Real-Time-Kinematic GPS (RTK-GPS). For more information on this sonar, ancillary instruments and survey methods see Borrelli et al. (2021).

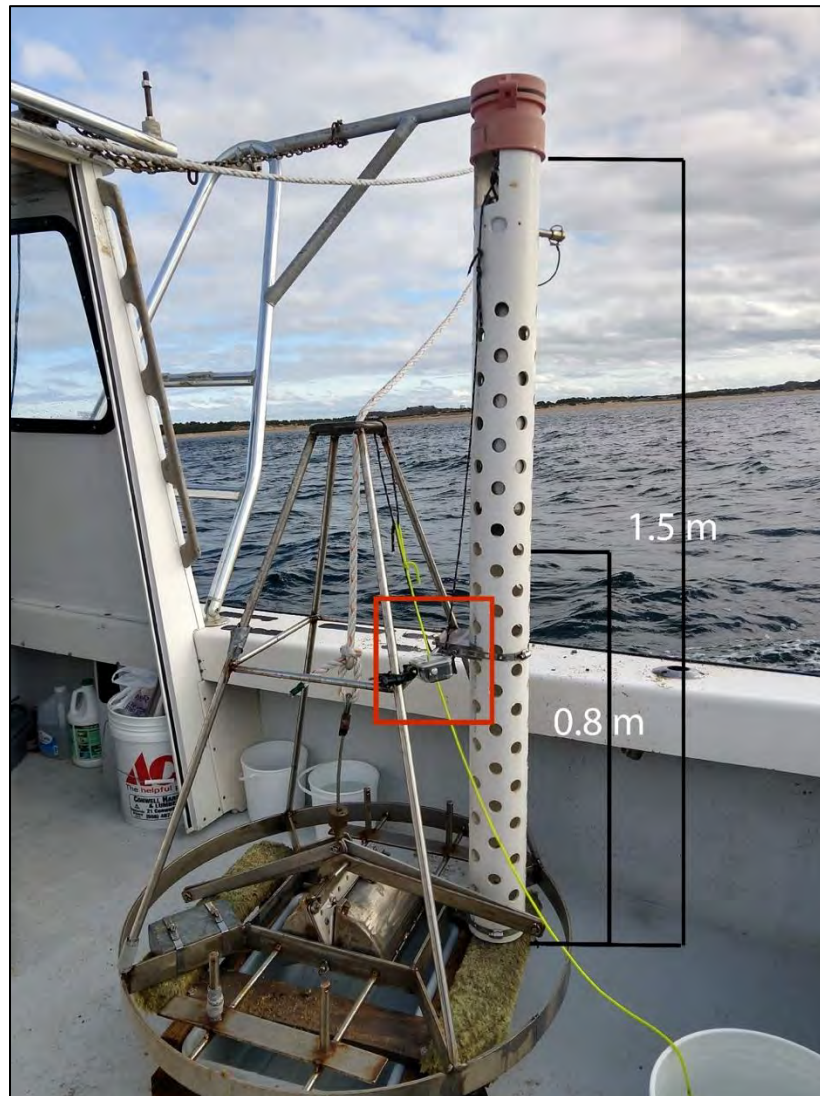


Figure 9. Young- modified Van Veen grab with PVC tube to deploy the BlueDrop adjacent to the bottom sample location and a GoPro Hero5 ® positioned (red box) for habitat assessment.

Incoming acoustic data were monitored and settings controlled (gain, range) in EdgeTech Discover Bathymetric® software and surveys were planned and acquisition performed in Hypack Survey® software. Survey lines were spaced to ensure that all sidescan backscatter was collected with a

minimum of 200% overlap, reducing the likelihood of misidentification as dredge tracks were ensonified from multiple angles. Data were collected by both Discover Bathymetric (.JSF format) and Hypack Hysweep® (.HSX) software. JSF data were imported into SonarWiz6® where a combination of automated and manual data processing was undertaken including bottom tracking, slant range correction, offset entry and gain setting adjustments. Outputs were exported as a mosaicked Geotiff at a pixel resolution of 0.5 m (0.25 m²).

3.3.1. Acoustic Survey – Field Work

Swath bathymetry and sidescan sonar imagery were collected off Herring Cove Beach, pre- and post-disturbance, as described below. These surveys were conducted along parallel lines to ensure enough overlap for complete coverage (Figure 5). The surveys themselves were also oriented parallel to shore. This is typical as adjustments must be made to the instruments as depth changes. Further, by aligning the surveys alongshore, the boat captain can conduct safer, more predictable surveys in shallower waters, which can be hazardous. The survey starts in deeper waters allowing the technician, to view the seafloor that the boat will be occupying on the next survey line. If a large rock or other hazard is present it can be noted and avoided. Swath bathymetry was also collected quarterly from 2017 – 2018 on shore-perpendicular transects and is discussed in section 3.4.1 below.

3.3.2. Acoustic Survey – Processing and Analysis

Dredge tracks were hand digitized from individual sonar files in the SonarWiz digitizer extension. Results were exported to raster format (geotiff) at a pixel resolution of 1 m, the approximate width of observed dredge tracks. To understand the spatial distribution of the dredge tracks, or bottom disturbance, within the study site, track density was calculated. Dredge tracks were converted from raster to point data, with each point representing 1 m² of seafloor. The point-density analyses were conducted with the Spatial Analyst extension in ArcGIS Desktop, which produced a heatmap of point densities, in this case *dredge track density*. The study area was divided into grid cells of 10 x 10 m and the aggregated count of dredge tracks in each cell is displayed as a heat map across the survey area (Bokuniewicz and Jang 2018). As the spatial units are in meters, heat map units are in meters squared. In this study, the minimum mapping unit of a dredge track is 1 m²; thus, an output grid resolution of 10 m (100 m²) was selected. A 10-m grid provides the finest resolution heat map while maintaining the original mapping unit (1 m²) and minimizing over- or underestimating the density of points. This also produces density data that is equivalent to percent cover, for example 0.13 dredge tracks per m² is equivalent to a percent cover of 13%, making the data comparable to other study locations.

To quantify factors that determine the longevity and persistence of dredge tracks, a series of variables were calculated and a model of persistence was developed using “Random Forest” algorithms in the open-source computer program R. First, fishing intensity was quantified by the

density of dredge tracks for the 2014–2015 and 2017 dredge events, together and separately. These dredge tracks were examined within the confines of the BACI study area and mapped via acoustic survey.

To better understand how present conditions determine the persistence of dredge tracks, the sampling conducted within the dredge boxes was utilized for analysis. First, at each time point—Pre-disturbance (PRE), Post-disturbance (POST), 6 months post-disturbance (6POST), and 12 months post-disturbance (12POST), each individual variable of interest was utilized to create a continuous surface within these 10-ha boxes. Between sampling stations, grain size (D_{50} mm), habitat percent cover from bottom video analysis (e.g. V_Sand, V_Gravel, algae), and QSBC from the free-fall grid survey were interpolated using the “spline with barriers” tool in ArcGIS Desktop 10.7. The 10 m² dredge track density raster was then used for each time point to align the data surfaces for grain size, habitat (bottom video data), depth, and QSBC for the development of a model of dredge track persistence across all bottom habitats present. Separate models for both 2014 – 2015 and 2017 dredge events were developed and used to determine which variables influence the persistence of the dredge tracks.

To demonstrate how the track orientation affects the persistence, the directionality of the dredge tracks was examined. To do so, the proportion of dredge tracks present during each survey event were tabulated and normalized to the total proportion present. The direction of each dredge track was quantified. If the track direction was within 22.5° of the shore direction, these segments were considered alongshore. If they exceeded 22.5°, they were considered cross-shore. The majority of dredge tracks were parallel with the shoreline. Hydraulic clam dredging operations are typically conducted along a single bathymetric contour when harvesting in the nearshore; in this case it was also parallel to shore. Operations stay along a single contour so as to reduce the need for adjusting the line out during dragging.

To understand the recovery of the substrate following hydraulic clamming, a multi-scaled approach was undertaken. First, physical and geological parameters were monitored quarterly for two years to identify seasonal trends in the area between Race Point and Long Point, second, a BACI (Before-After Control-Impact) style study was performed for one year to monitor the impacts of hydraulic clamming on a finer spatial scale at Herring Cove (Figure 5, Figure 10).

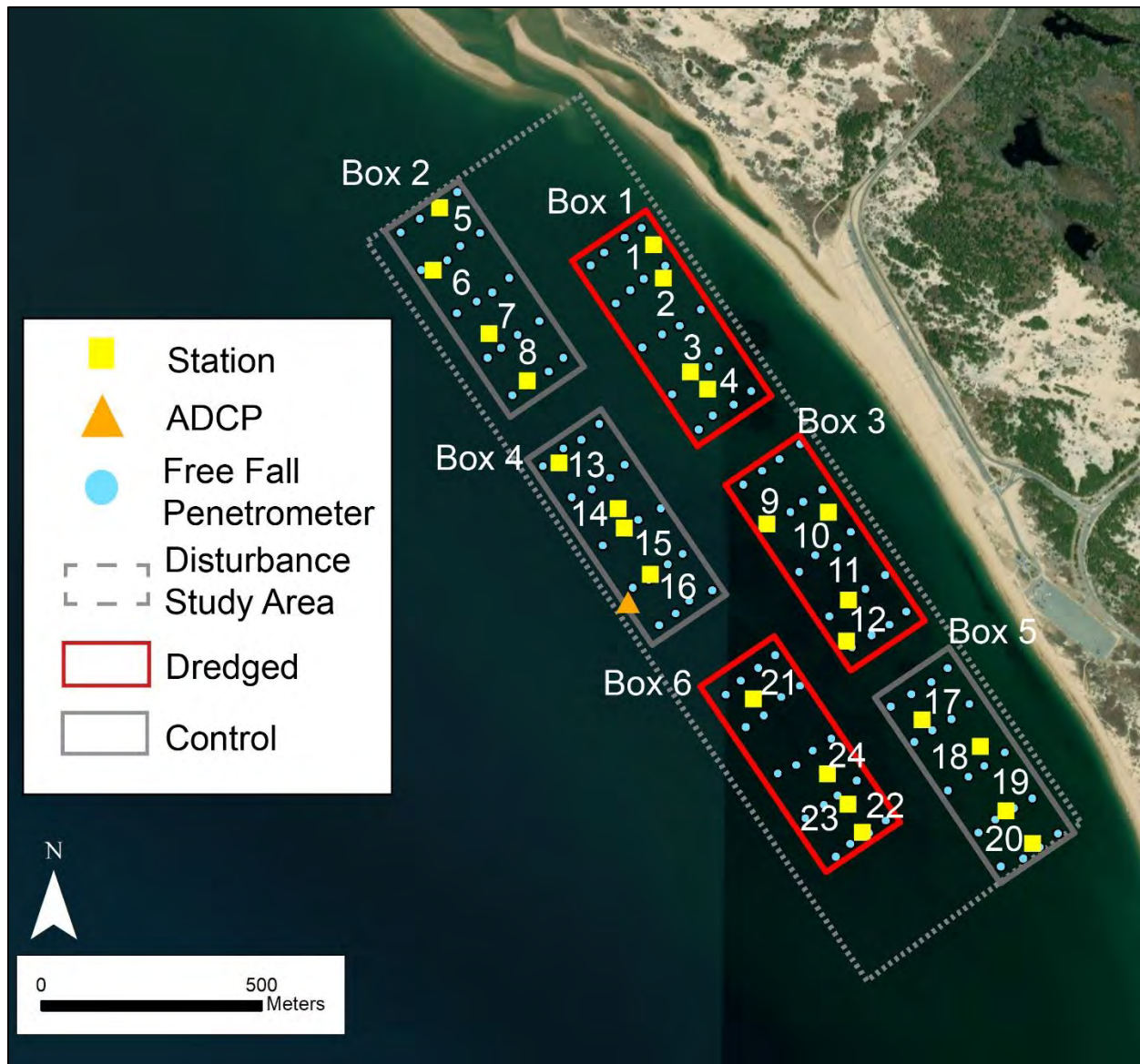


Figure 10. Study design for BACI study with impacted dredged areas (red) and un-dredged areas (Dashed. Sampling for invertebrate, compaction, sediment, and video occurred temporally across four time periods (Pre- disturbance, Post- disturbance, 6 months after disturbance, and 12 months after disturbance). Orange triangle is location of ADCP

3.3.3. Seismic Reflection (Sub-Bottom) Survey

Seismic reflection profiles were collected using a StrataBox sub-bottom profiling system, operated at a frequency of 10 kHz with a minimum vertical resolution of ~6 cm (SyQuest 2006). Towfish height was maintained approximately 1 m below the surface of the water on a fixed pole mount. Survey lines were run at a speed of ~1.5 m/sec. Spatial location was embedded into the sub-bottom files using a serial output from a Trimble RTK-GPS, the same system used for the acoustic surveys described above. Depth to reflectors was calculated using an acoustic velocity of 1,500 m/sec.

Chesapeake Technologies SonarWiz™ was used to process survey lines. The seafloor was manually tracked in SonarWiz's bottom tracking section, allowing the images to be accurately corrected for time varied gain and contrast to maximize visibility of internal reflectors. Time-varied gain accounts for the inherent differences in intensity between returning signals down the profile. Automatic Gain Control was used to better distinguish internal reflectors. Horizontal image resolution was speed corrected to produce a horizontal resolution of 0.25 m/pixel. Vertical image resolution was set to 0.025 m/pixel, producing a vertical exaggeration of 10X. The sub-bottom profiles are displayed in an inverse medium yellow-orange known as a Klein color scheme. Interpreting seismic reflection profiles is done by identifying seismic facies. Seismic facies are sedimentary packages, distinguishable from adjacent units based on internal characteristics, (i.e. the intensity, spacing, continuity, and internal geometry of seismic reflectors), external geomorphic form, and stratigraphic relationship to other units (Roksandic 1976; Vail et al. 1977).

3.4. Onshore and Offshore Profiles

To better understand the links between the onshore and offshore sub-systems, 33 shore-normal transects, spaced 300 m apart, were established throughout the study area. These transects started onshore and continued past the 'shelf break' where water depths rapidly change from 8-10 m to 30-40 m. Quarterly surveys were conducted from 2017 to 2018 for both offshore and onshore profiles.

3.4.1. Offshore Profiles

The offshore profiles were collected via vessel-based surveys with the same instruments, methods, and platform used for the bathymetric surveys discussed above. Surveys started near high tide and the vessel navigated to the shallowest waters that were safely navigable, positioned itself on the transect, and began to collect the profile. After processing the bathymetry, a raster file was created. Point data along the transect were extracted every 2 meters slightly off center to minimize noise associated with the near field (nadir) which is typical in swath bathymetry from Phase Measuring Sidescan Sonars, as well as the far field which is typical with all swath bathymetric systems.

To calculate slopes for the offshore profiles, we utilized a rigorous and repeatable quantitative method. The slope of offshore profile was calculated between MLLW (or the most landward point) out to the inflection point of the 'shelf break'. This was defined as the minimum of the second derivative of the whole bathymetric profile (Figure 11).

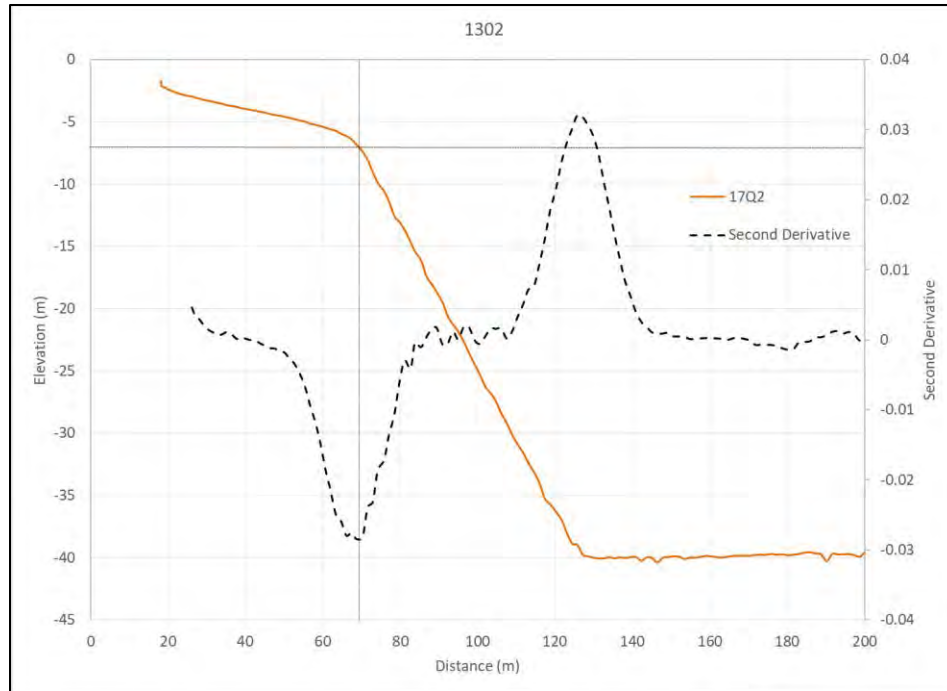


Figure 11. Example from transect 1302 of the method used to determine of the seaward most point to consider when calculating slope.

3.4.2. Onshore (Beach) Profiles

Onshore profiles were collected using an RTK-GPS along the 33 transects. Typically, the field team navigated to a single, pre-determined starting point for each transect behind the crest of the most seaward dune. The technician then collected points that reflect the topography of the dune/beach system. These surveys occurred at or near low tide to map as much of the beach as possible. Technicians waded into ~2-3 ft of water to collect point data. The slope was calculated for the onshore (beach) profiles considering the intersection of the beach profile with the MHHW and MLLW elevations.

3.5. Disturbance Study

3.5.1. Before – After – Control - Impact

Before-After Control-Impact (BACI) studies are designed to study the effects of human activities and predicted natural changes by establishing data collection beforehand to gather baseline information that can be compared to data collected during and after the predicted change (e.g. predicted storms, construction of wind farms, changes in ship routing, and restoration projects) (Clarke and Tully 2014; Seger et al. 2021). Results of BACI studies are often used to minimize the environmental impact of future activities and can provide information on the resiliency of individuals, populations, and ecosystems in response to change.

Here we describe four survey events (PRE- disturbance, POST- disturbance, 6 month POST-disturbance and 12 months POST- disturbance) of directly impacted and adjacent, natural areas. A total of 24 locations were randomly stratified across six 10-ha rectangular boxes (three disturbed and three controlled; Figure 10). A benthic grab sampler fitted with a GoPro Hero 5™ and a chute for the BlueDrop penetrometer (Figure 9) was used to collect benthic infauna samples, sediment characteristics (including sediment compaction and grain size), and bottom attributes via video at the PRE, POST, 6POST and 12POST time points. In addition, acoustic surveys were conducted, and 20 evenly spaced sediment compaction samples were taken per box at each time point.

For this study, hydraulic clam dredging was conducted in three of the six rectangular boxes to document the impact to the ecosystem immediately after as well as six months and 12 months post disturbance. The other three boxes were left undisturbed to serve as a control. The clam dredge was a standard commercial design, 61 inches wide (outside width including shoes), with a 48-inch cutting bar set to 4 inches of depth. The dredge was equipped with 13 nozzles (0.75 inches internal diameter) and manifold pressure was set to 42 psi. Bar spacing of the dredge cage was 2 inches, and the attached ring bag consisted of 2.5 inch x 3.5 inch oval rings. The dredge was equipped with rock chains spaced ~12 inches apart, and an ~8 inch ‘rock drop’ between the cutting bar and the bottom of the cage that could be stitched closed or left open to reduce the number of rocks retained by the dredge

3.6. Benthic Invertebrates

To determine the biological and physical structure of the benthic habitats, field surveys were conducted for invertebrate and sediment characterization, water column structure and video imagery during four sampling events: pre- disturbance (PRE; 10/21 and 10/22/2017), post-disturbance (POST; 11/15, 11/18, and 11/28/2017), 6 months post-disturbance (6POST; 4/30 and 5/1/2018), and 12 months post-disturbance (12POST; 11/15 and 11/16 2018). Sampling stations were arranged in six groups of four (see red and grey boxes in Figure 10). Three of the six groups, or boxes, underwent a disturbance even by a hydraulic clamming dredge on 11/9/2017. Dredging methods and tracks were chosen to represent commercial clam dredging as closely as possible (see section 4.5).

3.6.1. Benthic Invertebrates – Field Work

All samples were collected aboard the R/V Marindin using a Young-modified Van Veen grab sampler (Figure 9). An EXO2® sonde was used for the collection of water column data (pH, dissolved oxygen, temperature, and salinity), and a Garmin GPSMAP® 78 was used to obtain horizontal and vertical coordinates for each sample. A GoPro Hero 5™ was attached to the Van-Veen grab sampler, and high-resolution video was collected for each sample to aid in bottom characterization and documentation. At each station, two biological replicates and one sediment sample were taken. Each waypoint was recorded and labeled by system name, station name,

replicate number and date, (e.g. HC03.2_120_18). All GPS data points were downloaded to a .csv file and imported into ArcGIS for subsequent mapping.

The anchor line was let out approximately 1 meter between each grab sample replicate to ensure that no previously disturbed areas were resampled. The Van Veen grab samples a surface area of 0.04 m² to a depth of 0.1 m below the seafloor for a total volume of 0.004 m³ (4 liters). It is well-suited for sand- to mud-sized samples (≤ 2 mm) but does not function as well in areas with coarser grain sizes. A sample was deemed successful when the two scoops of the Van Veen grab were fully closed, at least 2 liters of material were sampled, and the surface of the sample was level—indicating that the Van Veen grab did not sample the seafloor at an angle. The sampler has viewing plates allowing the user to view the top of the sample without disturbance for verification or further sub-sampling. When unsuccessful sampling was encountered due to rocks or shells interfering with the jaws closing, four attempts were made to sample with the Van Veen before the station was rejected. In this case, the nearest next randomly selected station replaced the original station. The contents of the Van Veen were then emptied into a bucket; a low energy wash of seawater was used to rinse any substrate adhering to the Van Veen into the bucket. Any large bivalves, crabs, or vertebrates (fish) were measured, counted, and identified (or photographed for later identification) before being returned to the water. Larger, mobile organisms collected by this method are considered ancillary data, as benthic grab sample gear cannot provide quantifiable estimates of their abundance or density. In the laboratory, the contents of the bucket were prepared for invertebrate analysis.

3.6.2. Benthic Invertebrates – Processing and Analysis

To determine the benthic invertebrates found in each biological grab sample, the contents of each grab sample were sieved through a 1-mm mesh (Fox et al. 2009; Hemery et al. 2017; Mittermayr et al. 2022; Souza and Barros 2015) to retain organisms, detritus, and substrate greater than 1 mm in size. A low energy wash and gentle manual agitation were used to sieve the sample to reduce damage to biological specimens. The material retained on the sieve was transferred to triple-labeled glass jars and preserved with 95% ethanol with Rose Bengal to dye invertebrates. Date of field sampling, preservation, processing, and identification were all recorded on sample tracking data sheets as well as any notes about samples.

To sort out or “pick” the invertebrates from the substrate, the preservative was drained from the sample and disposed of according to CCS hazardous waste management plan. The sample was gently spread out into a large white plastic tray and water was added. The sample was visually inspected using 3-fold magnification on a magnifying LED lamp. All invertebrates were picked out of the sample and sorted into general categories as discerned by the unaided eye (i.e. worms, shellfish, amphipods etc.). All personnel and volunteers were trained by the project biologist on proper picking technique and on general visual cues to find invertebrates. Quality control for each sample was performed by the project biologist according to CCS Quality Assurance Project Plan

for Invertebrate Sampling Projects. Specimens were then preserved in 70% ethanol in 20 ml glass scintillation vials.

Specimens were identified by the project biologist using a dissecting microscope. All initial and final identifications, counts, and any notes were recorded on the identification data sheet. Specimens were identified to species level when possible or to genus, families, or orders depending on the difficulty of identification (Appendix A). All identified specimens were counted. Pictures were taken of representative specimens of each species using a digital microscope camera.

All PRE samples and four 6POST sample replicates were analyzed in-house at CCS. The remaining samples were analyzed at Cove Corporation (Lusby, MD). Following Gallagher et al. (1997), two taxa drop rules were applied to these data. First, all generic taxonomic designations at taxonomic levels higher than family were dropped if there were more than two valid lower-level designations for that group. Second, all known meiofaunal taxa were dropped from analysis as the sampling methods used do not adequately capture taxa smaller than 1 mm (Giere 2009).

Table 2. Complete list of environmental factors collected. (*) indicates factors not included in statistical analysis

Environmental variables	Environmental variables
Organic Matter (%)	Depth
Median	Total initial impact 2017
Mode	*Total 2017 impact at timepoint
Sorting	*QSBC Max [kPa]
Skewness	*V_Sand (%)
Sand (%)	*Disturbance
Mud (%)	*Gravel (%)
ph	*Mean
Surface temperature	*Kurtosis
Algae (%)	*4mm %
Shell (%)	*Salinity
V_Gravel (%)	*Penetration at NqsbcMax (cm)
Total impact 2015	*Velocity at NqsbcMax (m/s)
L Slope	* Deceleration at NqsbcMax (g)

PRIMER7 (Clarke and Gorley 2015; Clarke and Warwick 2001) was used for statistical analysis. To examine the relationship between physical variables (Table 2, Appendix B) and benthic species composition, bioenv stepwise procedures (BEST), distance-based linear modelling (DistLM), constrained divisive clustering (LINKTREE), and similarity profile permutation tests (SIMPROF) were conducted using the PERMANOVA+ extension on PRIMER (Anderson et al. 2008). The

DistLM analyzes the relationship between a multivariate data set (benthic community), as described by a resemblance matrix (Bray Curtis dissimilarity) and a set of one or more predictor variables (Table 2) using distance-based redundancy analysis (dbRDA). The routine allows for e.g. sediment characteristics to be considered individually or grouped together in specific sets and obtains p-values testing the null hypothesis (no relationship) using the appropriate permutation methods (Clarke and Warwick 2001). All predictor variables used for this analysis were checked for correlations and excluded if $R^2 > 0.95$. The remaining variables are indicated by an asterisk (*) in Table 2. All analyses were for each sampling event individually and an all-inclusive data set spanning 12 months.

3.7. Grain Size

To characterize the sediment substrate of the benthic habitat for each sample location, sediment samples were processed for organic matter content and sediment grain size analysis.

3.7.1. Grain Size – Field Work

In addition to the two biological samples taken at each station, a third sample was used to document the grain size of the sediment. This sample was taken between the first and the second biological replicate to ensure that the sediment sample was generally representative of the substrate sampled by the biological replicates. The surface sediment was transferred to a 100-ml Whirl-Pak®, and later dried at the lab for future analysis.

3.7.2. Grain Size – Processing and Analysis

Grain size analysis was conducted following one of two methods. For coarse grain size ($> 64 \mu\text{m}$), sediment samples were split and organic material was burned off in a muffle furnace at 550°C for four hours. Samples were then sieved between $64 \mu\text{m}$ and 4 mm according to manufactures instructions before processing with a Horbia Camsizer at the Woodruff Lab, within the University of Massachusetts, Amherst, MA. Processed sediments were retained. All grain size results were saved to .csv files. All data were reported using Wentworth grain size thresholds and classes (Folk 1974).

For fine grain size ($< 1 \text{ mm}$), sediment samples were split and organic material was burned off in a muffle furnace at 550°C for four hours. Sediment was then gently washed with tap water to remove salt and potential ash before processing with a Beckman-Coulter laser diffraction particle size analyzer at the University of Massachusetts, Amherst, MA. All grain size results were saved to .csv files. All data were reported using Wentworth grain size thresholds and classes (Folk 1974).

To determine organic matter content of sediments for each sample (organic matter content by Loss On Ignition; LOI); 20-30 grams of sediment were placed on pre-weighed aluminum trays, and the

wet weight of the sample was recorded before being placed in a drying oven at 105°C for 24 hours (Heiri et al. 2001; Mittermayr et al. 2022). Dried samples were removed from the oven and placed in a desiccator. Each sample was weighed, and the dry weight was recorded. After recording the initial dry weight, all samples were broken using either a clean spatula for sandy samples or a clean mortar and pestle to grind finer samples. After a sample was ground, it was re-dried and reweighed to account for any lost material. To determine the proportion of organic matter, the homogenized samples were placed in a muffle furnace at 550°C for four hours (Legare et al. 2020c; Snyder et al. 2004). After ignition, the samples were re-weighed, and the percent organic matter as loss on ignition was determined by the following calculation:

$$\text{LOI (\%)} = (M_{\text{dry}} - M_{\text{dish}}) - (M_{\text{ignite}} - M_{\text{dish}}) / (M_{\text{dry}} - M_{\text{dish}}) * 100$$

Where M_{dry} is the weight of the dried sample (at 105° C) plus the aluminum dish, M_{ignite} is the weight of the ignited sample (at 550° C) plus the aluminum dish, and M_{dish} is the weight of the aluminum dish. LOI data were then corrected for salt content by using salinity data from CTD casts.

3.8. Video Assessment of Bottom Types

A GoPro Hero 5™ was mounted to the Van Veen grab and recorded video each time it was lowered into the water. The camera was mounted facing downward to collect data on seafloor habitat characteristics. Still images were captured from the video using Adobe Premier CCTM for each time the Van Veen contacted the seafloor, which was multiple times during the collection of some samples.

The still images were captured at a point during the sampling video that yielded the best image clarity typically achieved by taking the still image the moment the Van Veen contacted the seafloor or after the sediment settled. These still images were used for two main purposes. First, they were used to document the sampling location when a successful sample was collected so the two data points, the grab sample and still images, could be used in conjunction to better document the seafloor where a sample was collected. Second, all still images were used, whether or not a successful sample was captured, in order to document the seafloor throughout the study area.

3.8.1. Video Footage – Processing and Analysis

Digital video footage was reviewed for habitat characteristics and heterogeneity such as presence/absence of algae or gravel. Digital still images were obtained from videos. The entire frame of the image was analyzed by trained reviewers.

Percent cover of sand, gravel, shell, algae, and eelgrass (for definitions see Table 3) were visually quantified using a random point overlay on still images with the program Coral Point Count with Excel Extensions (CPCe) (Kohler and Gill 2006). Visual cues such as size, shape, texture, and color of substrates, as well as the presence of bedforms were used to differentiate between substrate categories (Table 3). If an object needed to be measured, a measuring tool in CPCe® was used, calibrated by a known length of the Van Veen’s metal frame. Individual macrofauna and algae were identified to the lowest practical taxon and noted on the spreadsheet. Percent cover (%) was determined by overlaying 25 random points on the image and identifying the material underneath each point (Figure 12). A total of 25 points was chosen because 10 points were insufficient for analysis and the differences between 25 and 50 points and 25 and 100 points were minor (Terrill 2021). To avoid confusing video assessed descriptors with descriptors of the same name (gravel and sand) assessed by grain size analysis, we chose to use the terms “V_Sand” and “V_Gravel” for video derived information.

Table 3. Benthic categories for video analysis

Category	Definition	Reference
V_Sand	Fine unconsolidated material <2mm	Wentworth 1992, FDGC 2012
V_Gravel	Coarse unconsolidated material >2mm	Wentworth 1992, FDGC 2012
Shell	Shell hash and rubble (living or non-living) >2mm	FDGC 2012
Algae	Filamentous, sheet and/or leafy/leathery benthic macroalgae	FDGC 2012
Eelgrass	<i>Zostera marina</i>	

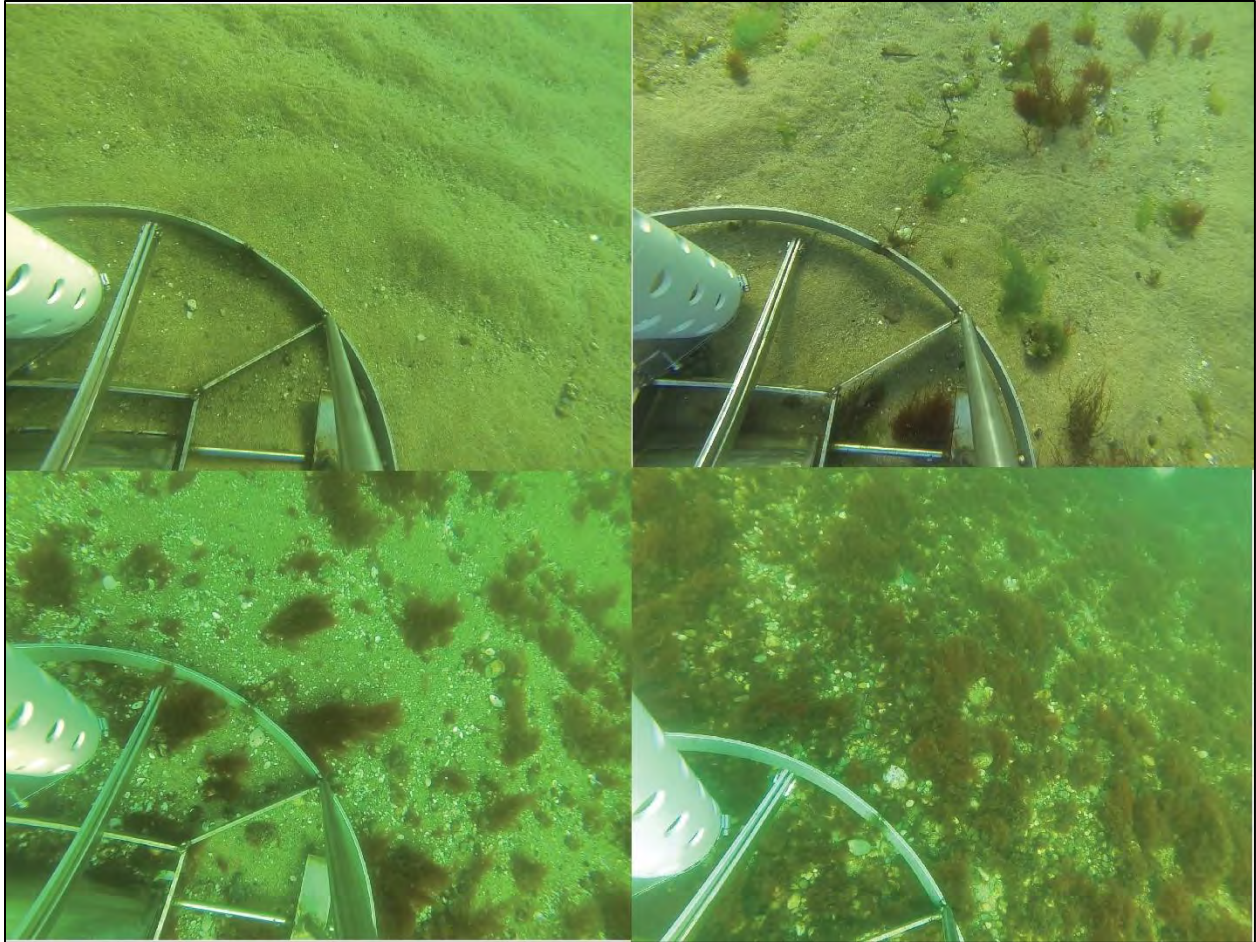


Figure 12. Representative examples of habitats seen throughout the study site with V_Sand (in the upper right) to ~100% cover of V_Gravel and algae (in the lower left).

4. RESULTS AND DISCUSSION

All data sets collected for this project are reported here, as are their spatial and temporal parameters. The descriptions are based on either the method used to collect the data and/or analysis done with them.

4.1. Acoustic Doppler Current Profiler

The ADCP was deployed off Herring Cove Beach in approximately 8 m of water. Over six deployments between July 2017 and January 2019, 152 days of wave and current data were recorded. There is relatively good agreement in significant wave height between our ADCP data and the relevant NOAA wave buoys in Cape Cod Bay and of off Provincetown on the open ocean side (Figure 13).

Per Bird (2008), mean annual significant wave height for a coast can be used to determine if the coast is classified as high, moderate, or low wave energy, where high wave energy coasts exceed 2 m, moderate wave energy coasts range from 1-2 m, and low wave energy coasts fall below 1 m. Significant wave height is calculated using WaveWatch III data from the model sites closest in proximity to our study site and averaging in our wave data, we can classify the study site as a relatively low wave energy coast. The mean annual significant wave height at the site is 0.54 m, with a maximum significant wave height of 2.23 m.

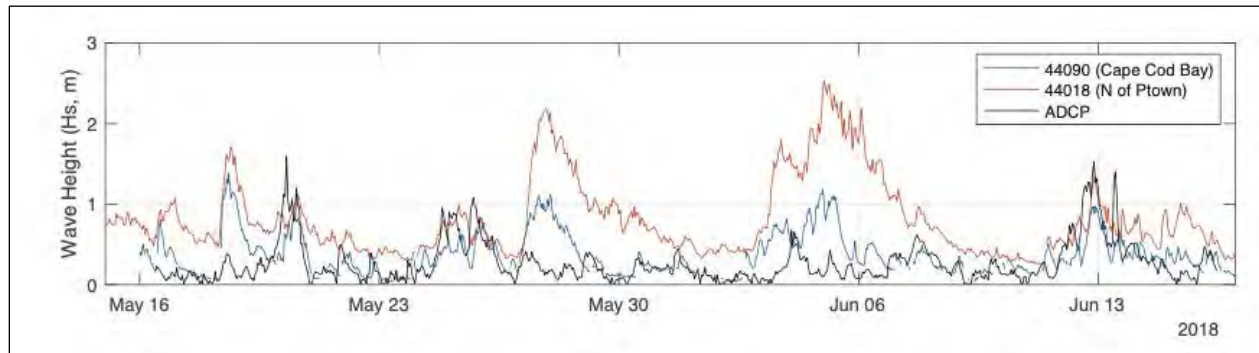


Figure 13. Comparison of ADCP wave height data to NOAA wave buoys in Cape Cod Bay (44090) and north of Provincetown (44018). Note strong event correlation though lower magnitude given ADCP was in much shallower water.

Wave direction was largely seasonal. Fall and winter deployments recorded the largest wave heights, with most waves from the northwest, whereas spring and summer deployments recorded smaller wave heights from a larger distribution of directions (Figure 14).

Currents at the site showed significant tidal influence in the cross-shore direction. Depth-averaged cross-shore velocities were rarely greater than 0.25 m/s in either the onshore or offshore direction, and maximum depth-averaged along-shore velocity was 0.5 m/s in the northwest or southeast direction. Bottom velocities were regularly smaller than surface velocities, which is typical, with bottom velocities rarely greater than 0.25 m/s in either direction.

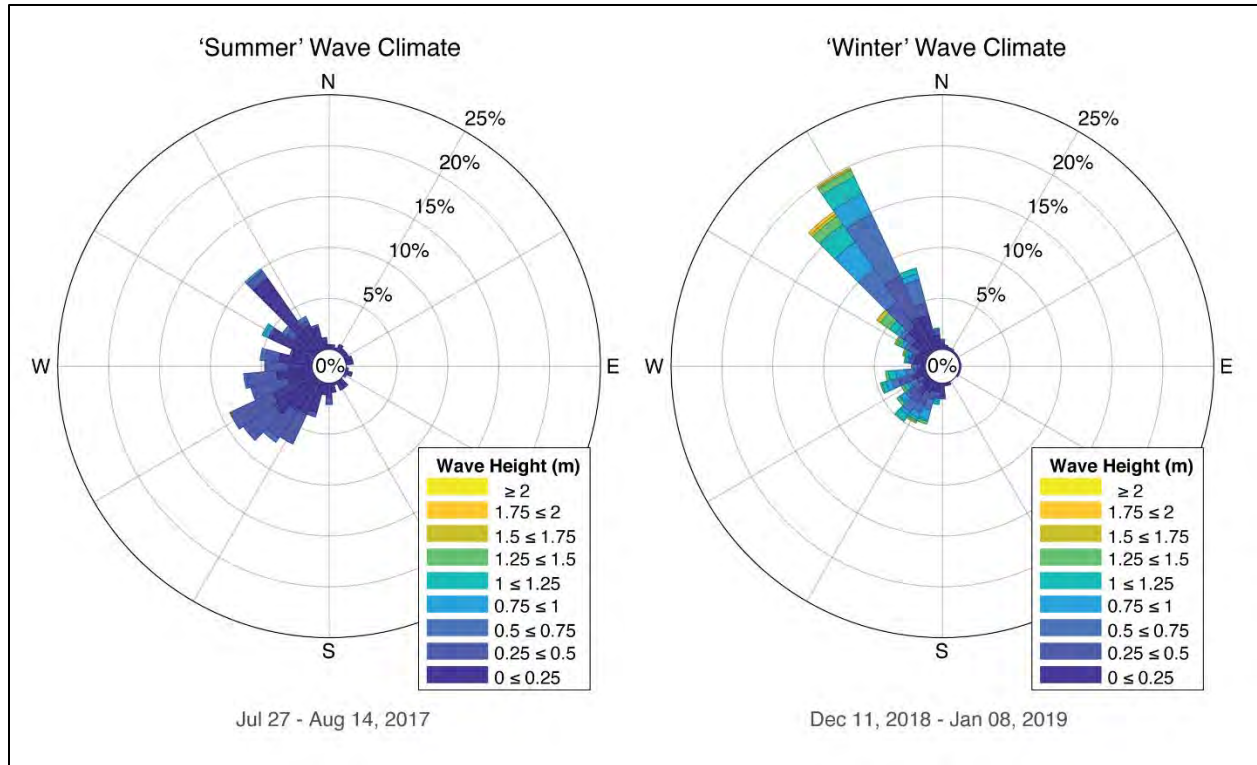


Figure 14. Results from two of the six ADCP deployments demonstrating the seasonality of waves with regards to wave heights and directionality.

4.1.1. Initiation of movement

The median grain size (D_{50}) across all study sites was 0.12 cm. The modified Shields' Diagram (Figure 7) indicates that for the initiation of movement of the averaged-sized sediment in the study site, the shear velocity must be greater than ~ 2.3 cm/s. Using the TKE method discussed in section 3.1.2, shear velocity at the site exceeded 2.3 cm/s during 82% of deployment time points, indicating that the system is capable of moving sediment most of the time (Figure 15). Shear velocity is not a 'true' current velocity value but is used to characterize the shear stress between layers of water, and sediment, other layers of water, or solid structures and therefore much smaller values are needed to initiate the movement of sediment than current velocities.

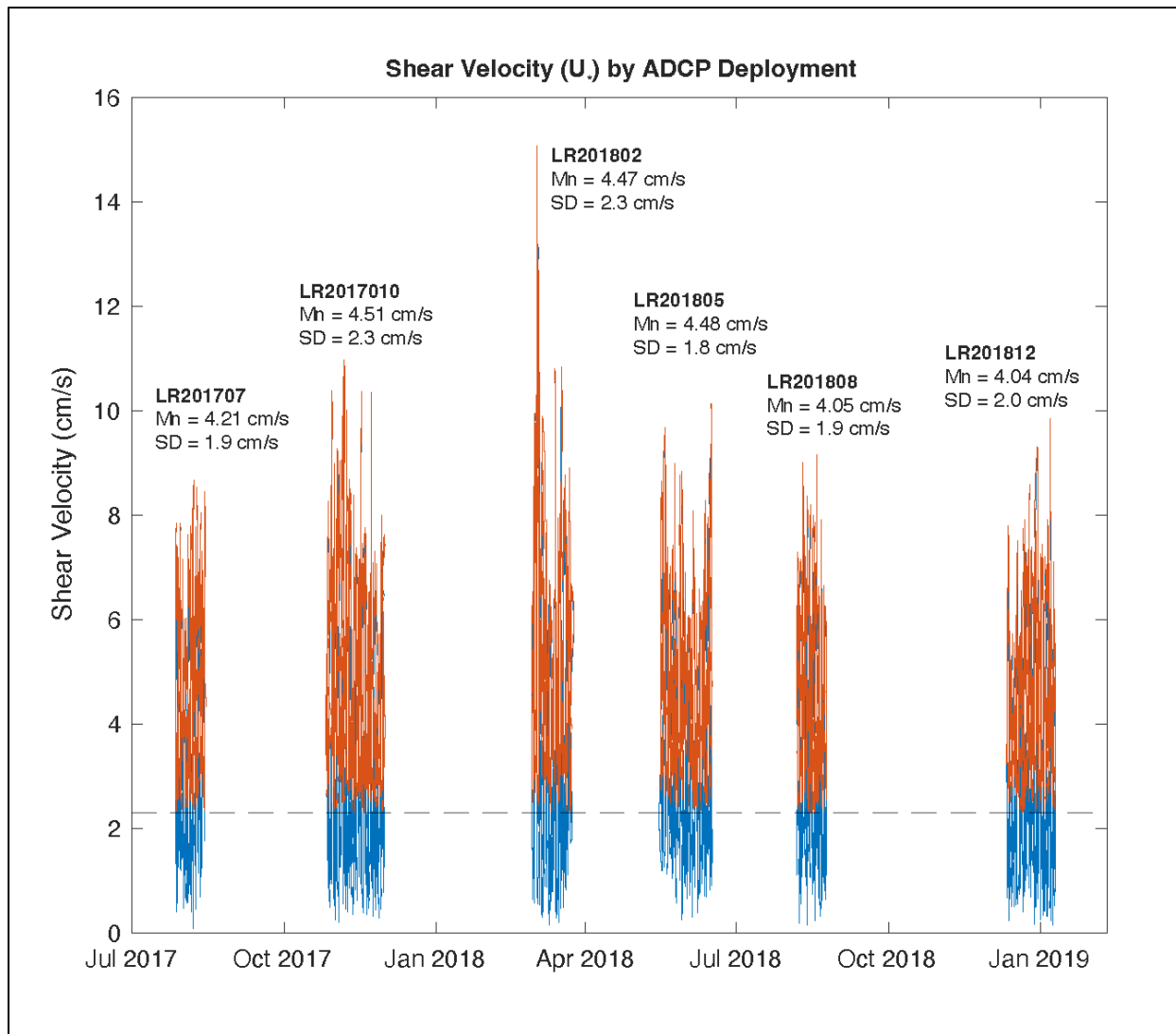


Figure 15. Computed shear velocity (U_*) using the TKE method. Shear velocity > 2.3 cm/s is generally capable of moving sediment in this system. Times when the computed shear velocity is greater than the threshold for initiation of movement is indicated in red.

4.2. Penetrometer

As described above, the penetrometer collected data ($n = 952$) via two deployment methods: free fall and mounted onto the Van Veen. The freefall data were collected within the impact study boxes. Van Veen-mounted penetrometer data were collected along the 33 transects, while collecting sediment samples, as well as within the impact study boxes when collecting data for invertebrate sampling.

Table 4. Breakdown of penetrometer results by dataset for the study.

Data set	Box #	QSBC Average (kPa)	SD	Avg + (2*SD)	# of drops	% of total drops	Outliers	N
Free Fall	1	67.02	27.25	121.53	80	17%	4	76
	2	52.89	8.91	70.71	80	17%	3	77
	3	69.29	30.65	130.60	80	17%	4	76
	4	68.10	26.29	120.67	77	16%	3	74
	5	64.35	16.82	97.99	80	17%	4	76
	6	76.03	32.55	141.12	80	17%	6	74
	Total	66.27	25.97	118.20	477	100%	24	453
Invert	1	67.58	27.37	122.32	47	17%	0	47
	2	56.10	21.68	99.46	37	14%	2	35
	3	70.97	23.53	118.03	43	16%	2	41
	4	81.62	36.66	154.94	40	15%	3	37
	5	77.04	36.01	149.06	52	19%	1	51
	6	79.61	25.82	131.25	55	20%	1	54
	Total	72.15	28.51	129.18	274	100%	9	265
Transect	-	61.80	23.52	108.84	201	-	11	190
All Data	-	68.65	25.93	120.50	952	-		908

The data collected with the Van Veen-mounted penetrometer along the 33 shore-normal transects (Figure 16) occurred over six surveys between May 2017 and September 2018 (**Table 4**, Appendix E). Seasonal trends are notable throughout the study area, though are most pronounced in the area off of Herring Cove Beach. The highest QSBC values occur in October 2017 and March 2018. These time periods mark the beginning and end of the most energetic waves seen in the area. These increased values may be a function of the thinning of the sand layer in these areas. The underlying gravel would generate higher values of QSBC therefore the thinner the sand layer the higher the QSBC values. This is further corroborated since the gravel is most prevalent in these areas as shown by the bottom video analysis.

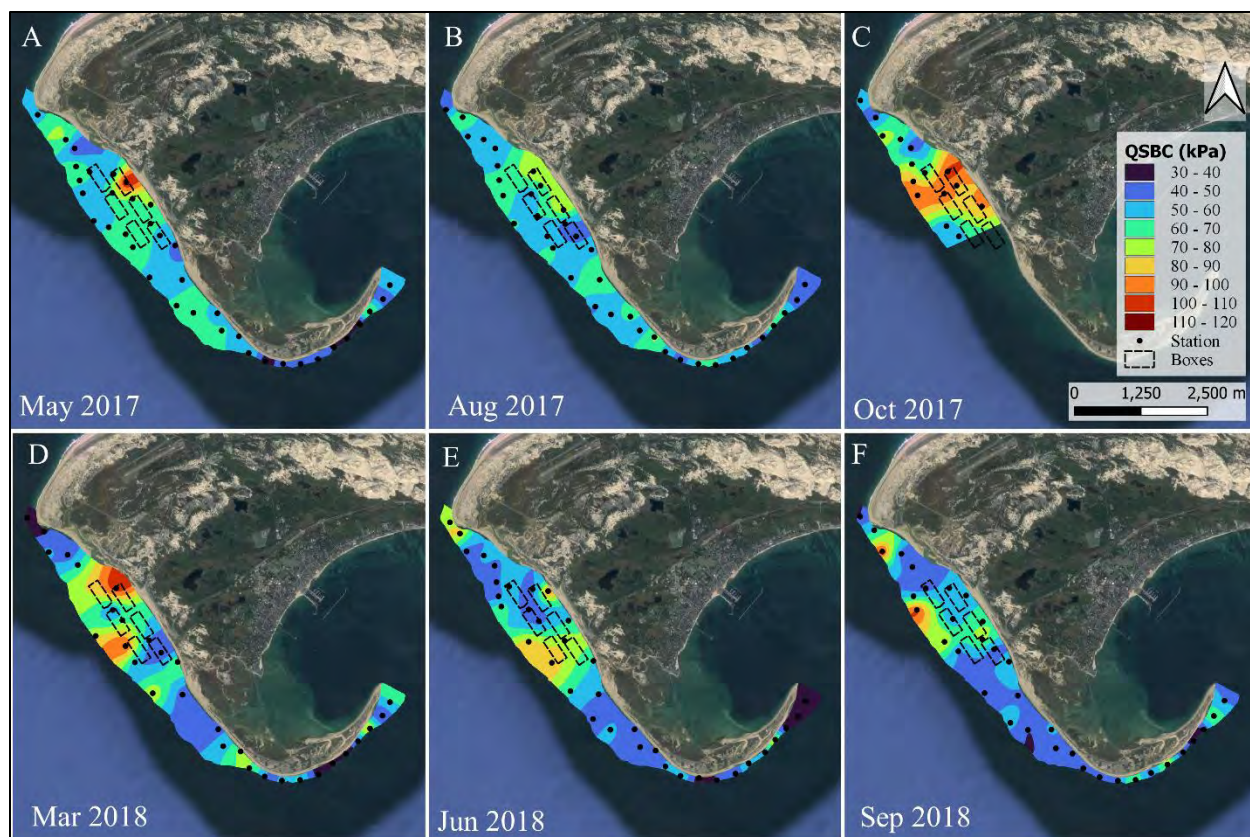


Figure 16. Interpolation of compaction data (QSBC) sampling along the transects from Race Point to Long Point. During the October 2017 penetrometer survey the instrument was not retrieved after a cast. Thus, only a partial dataset was collected and is shown here. The instrument was later recovered.

Though QSBC values have some utility in determining seasonality, the QSBC values of the seafloor near the invertebrates were documented to better characterize the benthic habitat and document relationships between the invertebrate community and QSBC (Appendix E). Freefall penetrometer data were collected at 20 sites within each of the six impact boxes ($n = 120$) to document the entire box (Figure 17) rather than the sparsely data density that were collected with the invertebrate samples.

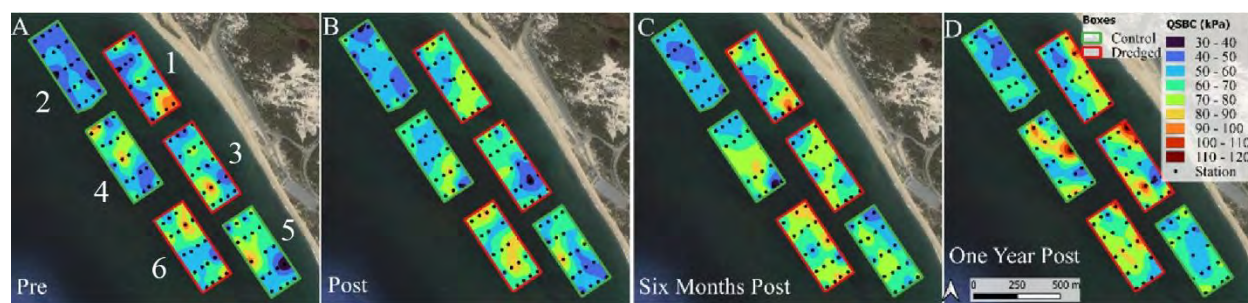


Figure 17. Freefall penetrometer data were collected at 20 sites within each box for a total of 120 data points for pre-impact, post-impact, 6 months post-impact and 12 months post-impact.

An overall pattern of increasing QSBC values can be seen at each impact box over the course of the study (Figure 17). However, boxes 1, 2, and 6 show a clear increase in QSBC between the Pre- and post-impact period. Boxes 3, 4 and 5 show only slight changes relative to 1, 2 and 6. Although the boxes are arbitrarily drawn the relationship between the pre- and post- changes in QSBC correlate well with the presence/absence of gravel shown in the QSBC data collected along transects as well as the bottom video analysis. In areas where gravel is present, we see smaller changes in pre- vs post-impact QSBC values. This would be consistent with a thin sand layer over a gravel bottom, typical in the higher energy wave climates between fall and early spring. It should be noted that while the patterns are clear, the magnitudes of the changes do not allow us to conclusively state this with absolute certainty. More work is needed to directly address this phenomenon.

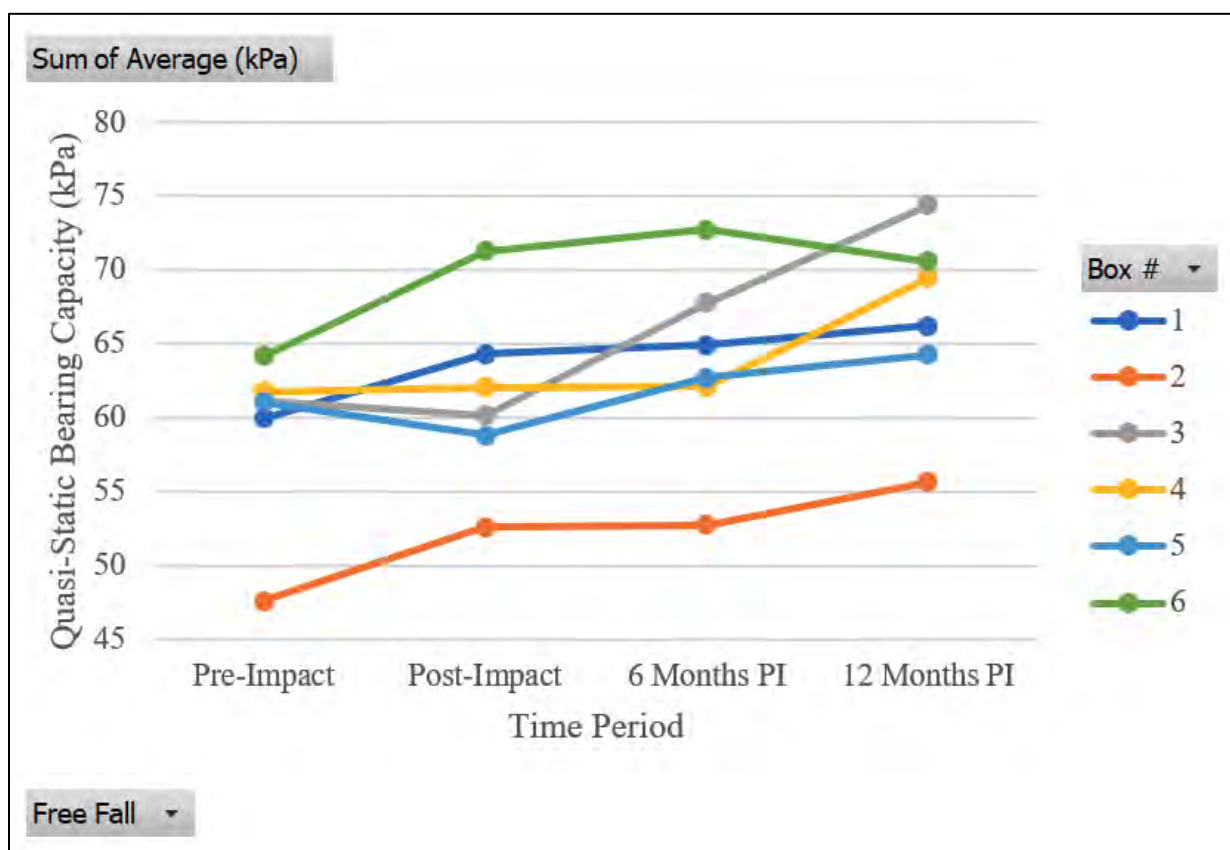


Figure 18. The Quasi-static Bearing Capacity (QSBC) is given in kilopascals (kPa) for the six impact boxes for 4 time periods. Data points for each box is an average for all 20 data points within a single box for the time period.

4.3. Acoustic Surveys

In 2015, as part of a project to develop benthic habitat maps within the Park, the seafloor from Long Point to Race Point was mapped (Borrelli et al. 2019). A total of 5.1 km², consisting of 324 km of survey lines, with an average depth of 6.97 m, were mapped between June 6 and August 6. The study documented 402,309 m² of seafloor that were disturbed during the hydraulic clamming

that occurred between 01 November 2014 and 30 April 2015 in the area (7.8% of the 5.1 km² area were covered in dredge tracks ranging in density from 0-53%; Figure 19).

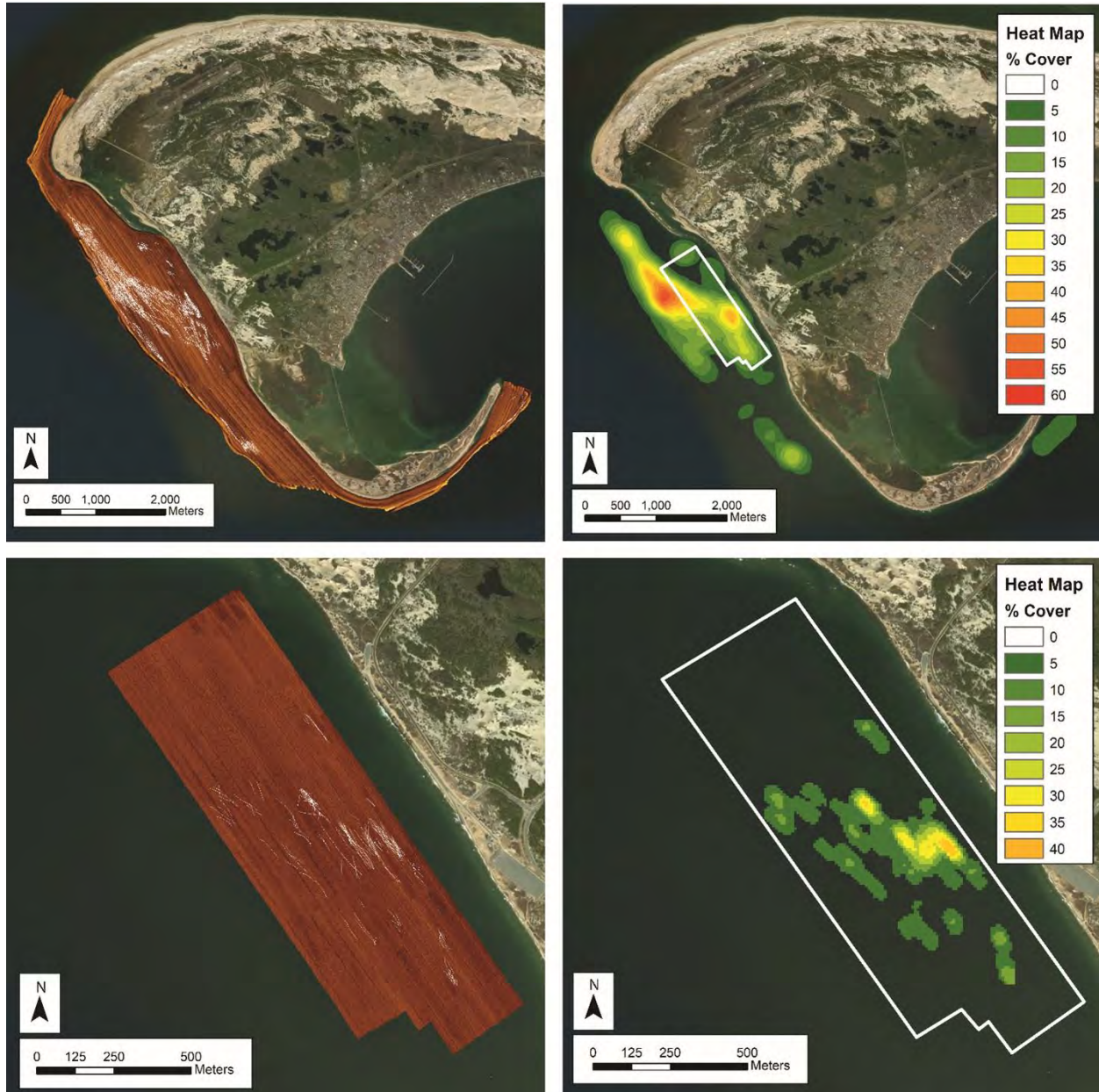


Figure 19. Sidescan backscatter data from acoustic surveys (left) in 2015 (top) and 2017 (bottom) with digitized dredge tracks (white). Density of dredge tracks and study area outlined (right) (From Legare et al. 2020b).

Acoustic surveys for this study were performed around a controlled, experimental hydraulic clamming event during four time periods: Pre- disturbance (PRE), Post- disturbance (POST), 6 months after disturbance (6POST) and 1 year after disturbance (12POST).

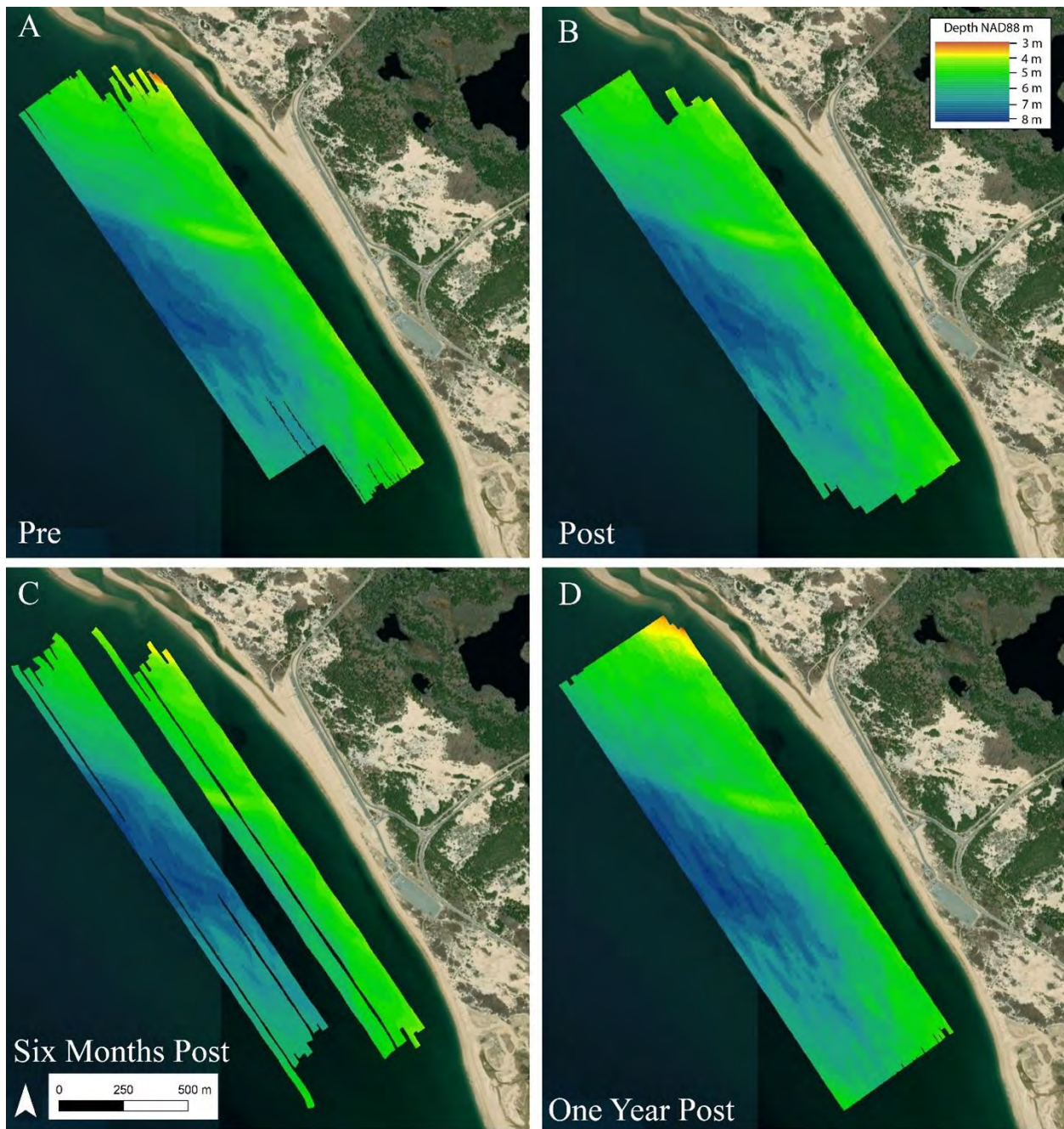


Figure 20. Bathymetric coverage at each time point across the study area.

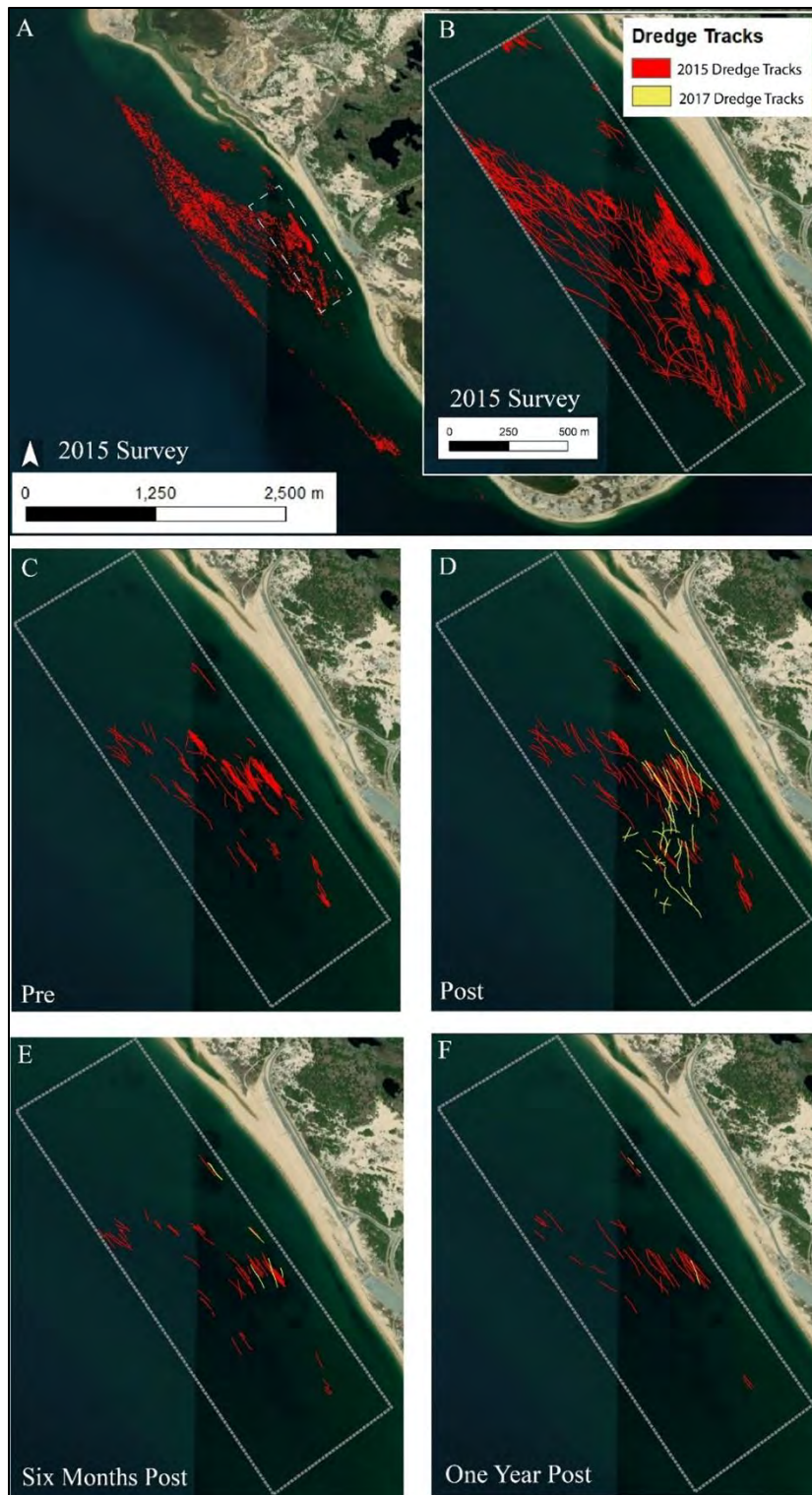


Figure 21. Digitized dredge tracks from acoustic surveys. Dredge tracks for 2015 (red) are identified in surveys in 2015 (A:B), and in each of the surveys and make up the majority of the DT though the end of the study period. Dredge tracks from the 2017 controlled disturbance event are identified in yellow. These were only acoustically surveyed after the disturbance (Post) and were monitored for 1 year (D-F).

4.3.1. Acoustic Surveys Dredge Tracks for the 2014 – 2015 dredge event

Vessel-based acoustic surveys were conducted between June 6 – August 6, 2015 and mapped an area of 5.10 km² (324 km of survey lines), with an average depth of 6.97 m (Borrelli et al. 2019). A Geotiff mosaic of the sidescan backscatter was created with 0.5 m cell size. A three-dimensional surface was generated using the bathymetric data with 0.5 m cell size. A total area of 402,309 m² of dredge tracks were digitized, from the 5.10 km² area (or 7.8%), and dredge track density ranged from 0-53% (Figure 19).

While the majority of the dredge tracks were off Herring Cove, there were also a set of dredge tracks that were present between Wood End and Long Point (Figure 21). These solitary dredge tracks that were present off Long Point were of particular concern because they impacted an expansive eelgrass bed (Figure 22). These dredge tracks were digitized in the 2015 survey and were subsequently surveyed in 2017, 2018 and 2019. They were present in the 2017 survey but had largely disappeared by the 2018-2019 surveys.

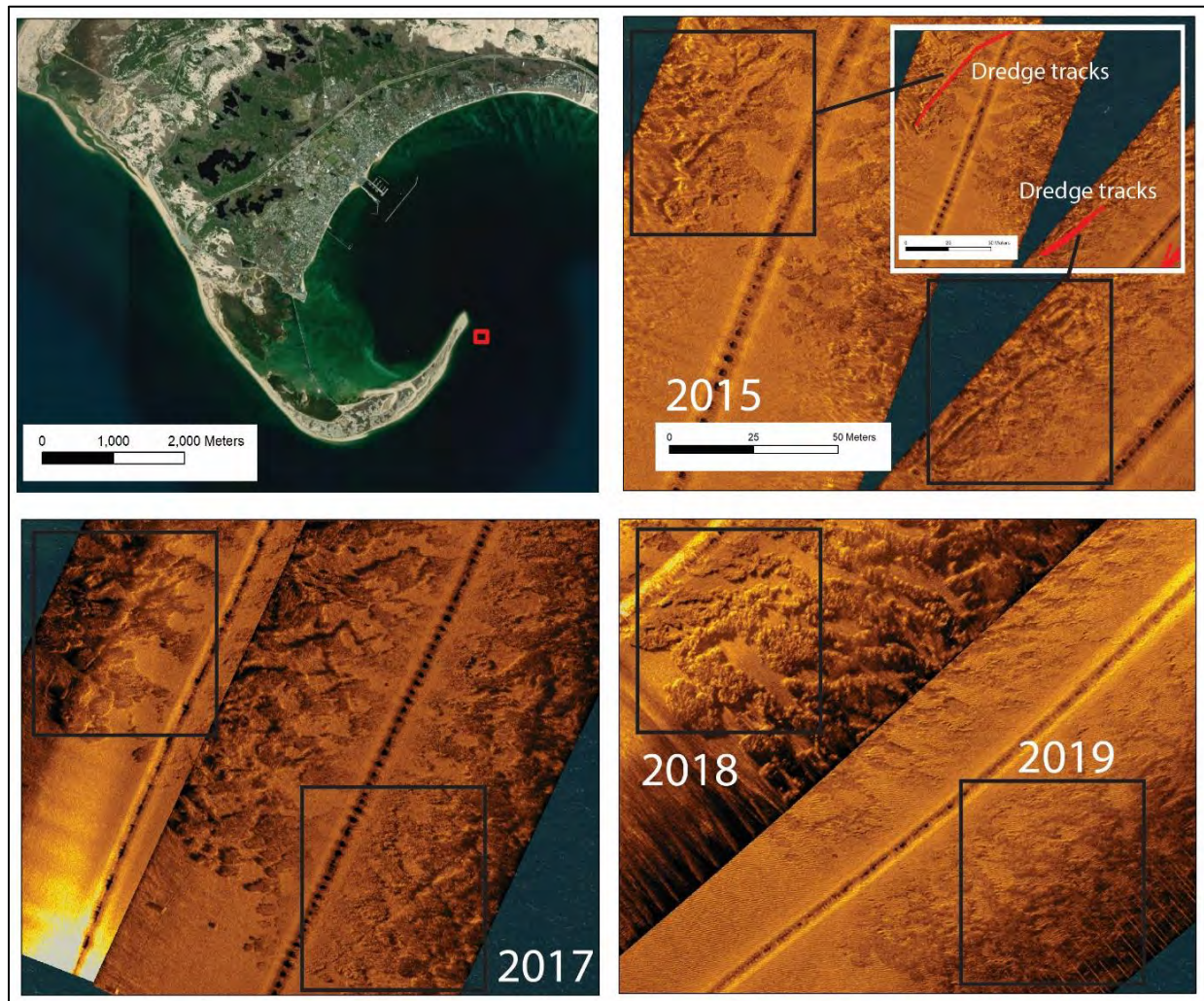


Figure 22. Side scan sonar surveys in 2015, 2017, 2018 and 2019 showing the evolution of two dredge tracks where the hydraulic clamming dredge impacted the eelgrass beds off Long Point.

4.3.2. Acoustic Survey Dredge Tracks 2017-2018

On October 23, 2017 (PRE) an area covering 1.05 km² (Figure 19) was mapped via vessel-based acoustic surveys on the same platform with same suite of instruments. This 1.05 km² survey is within the 2015 survey area (Figure 19) and will be used for the remaining analysis. Digitized dredge tracks totaled 9,784 m² (or 1%) and dredge track density ranged from 0-24% (Figure 21). The same 1.05 km² area contained 145,454 m² of digitized tracks in 2015, with dredge track density ranging from 0-39%. Comparing point density results, between 2015-2017 areas containing no dredge tracks changed from 3.8% to 74% km². Areas impacted between 1-10% in 2015 had almost fully recovered by 2017. Areas with dredge track density >10% were proportional in their recovery; since the dredge track density was high, the recovery was low (linear regression; $r^2=0.95$; $F=110.6$; $df=1,7$; $p<0.001$; std error=0.206) (Figure 21 and Appendix F) (Legare et al. 2020a). Prior to the linear regression, data was checked for normality via Shapiro-Wilks test ($p=0.862$). In 2015 the areas with the highest dredge track density (35-40%) occupied 0.023 km², and 0.016 km² remained in 2017, a 28% reduction (Table 1; Figure 21). Although the dredge tracks were still present in 2017, bathymetric data indicated the troughs were less steep (Figure 24) when comparing 2015 to 2017.

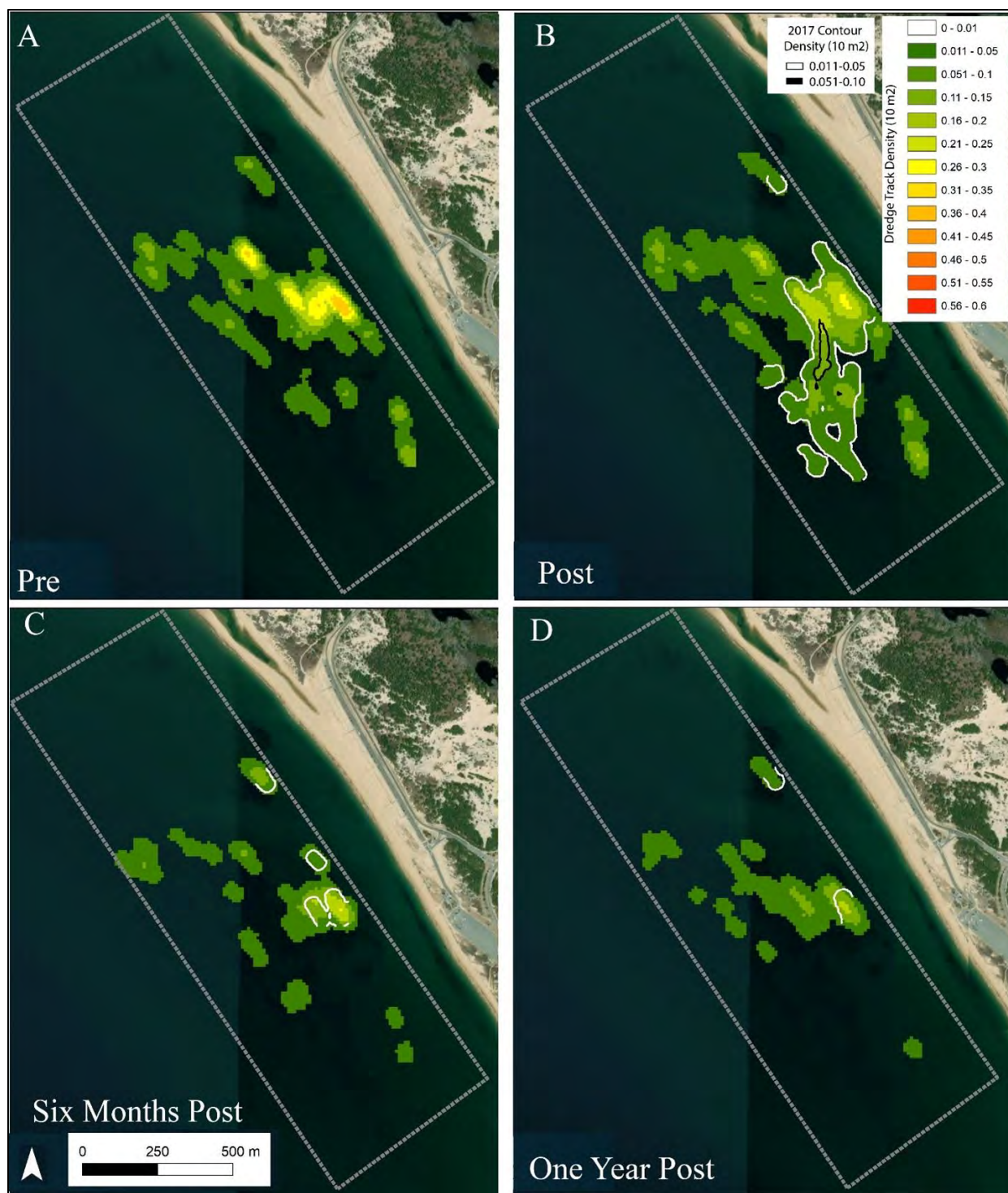


Figure 23. Total dredge track density from both dredging events in 2015 and 2017. Dredge tracks density ranges from 0-17%. The areas re-disturbed by the 2017 dredge event are contoured in white and black.

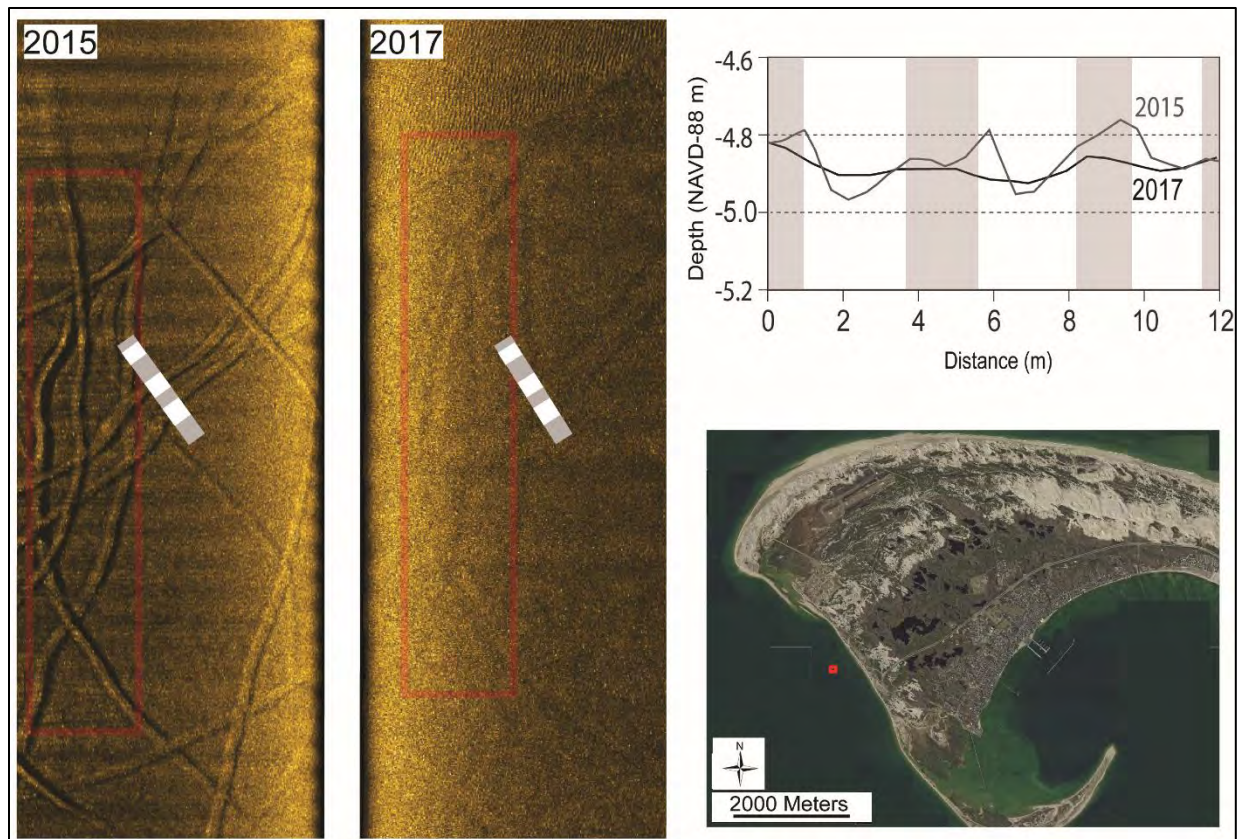


Figure 24. Port channel of sidescan backscatter data of the same area from 2015 to 2017 with persistent dredge tracks. Bathymetric profiles for 2015 and 2017. Dredge tracks are identified in white for the profile in the sidescan waterfall imagery and white on the graphed profiles.

4.3.3. Acoustic Survey Dredge Tracks Controlled Study

On November 9, 2017 a controlled hydraulic clamming harvest occurred across three of six experimental areas off Herring Cove (Figure 10). A total of 20 dredge passes were conducted covering a linear distance of approximately 18.350 km. The initial disturbance had dredge track densities between 0-11% within the experimental areas. Between initial disturbance and POST event mapping (12/3/2017), dredge densities reduced from 11% max to dredge track densities between 0-6% throughout the experimental areas. Subsequent mapping at the 6 months (5/9/2018) showed that dredge tracks were reduced to a max density of 3%. After a year (12/11/2018), the only dredge tracks left were at a density of 2% (Figure 25).

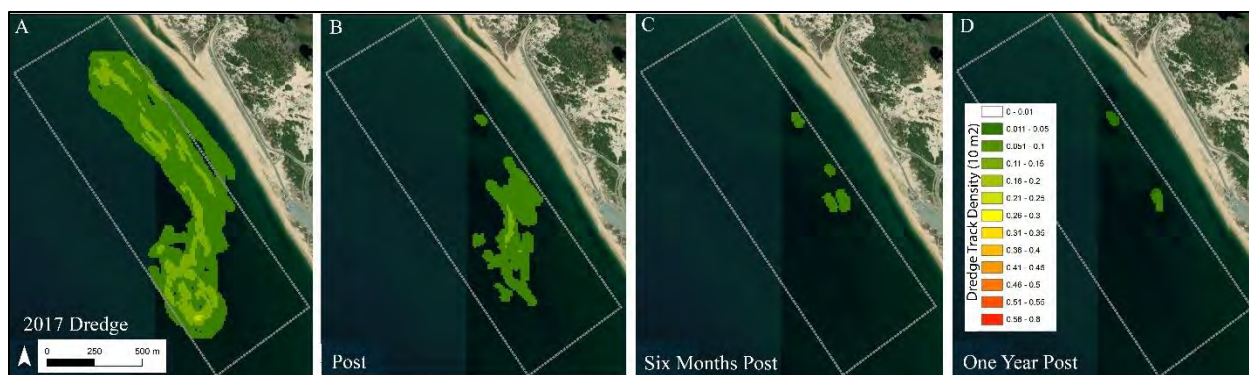


Figure 25. Dredge track density for the 2017 dredge event. Dredge tracks density range from 0-11% initially (panel A) and are almost completely recovered over the course of 1 year (panel D).

4.3.4. Seismic Reflection (Sub-bottom) Surveys

A total of 13 km (7 nautical miles) of survey lines were collected offshore of Herring Cove in June 2021 (Figure 26). Overall penetration of the seismic signal of the SyQwest® StrataBox in this location was limited to ~ 2 m. Penetration in some portions of the study area may have been deeper, but because of the relatively shallow water depths for much of the study area, the seismic multiples obscured the reflectors >2m below the seafloor.

Five seismic facies identified within the study area are summarized below. A *sedimentary facies* is simply a categorization that geologists use to quickly describe a body of sediment based on the likely depositional environment and the physical, chemical, and biological characteristics that associated with that environment. For example, a *coastal dune facies* quickly tells the reader that the material within this sediment body was likely deposited in a coastal dune setting, dominated by winds, and may or may not have evidence of the coastal beach environment, such as an erosional dune scarp. Seismic facies discussed here are based on the acoustic data collected during the seismic reflection surveys (discussed above) and are more general than sedimentary facies. Individual reflectors representing depositional layers within the facies described below could be further identified and described with additional mapping and/or sediment coring.

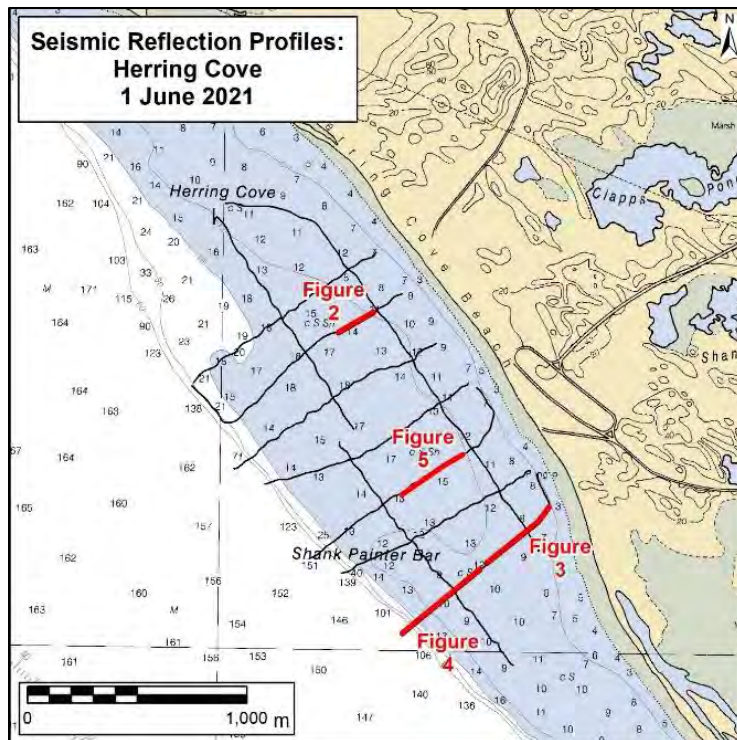


Figure 26. Portion of NOAA Chart 13249 showing the location of seismic reflection profiles collected on 1 June 2021.

Facies 1: Facies 1 is located at the seafloor and is characterized by a convex surface expression with an underlying reflector that is relatively flat and dips slightly offshore. Maximum measured thickness is 1.1 m (Figure 27). This facies is interpreted as shore oblique bars and coincides with features identified on both 2018 USACE Topobathy LiDAR and bathymetry from this study.

Facies 2: Facies 2 was mapped from the nearshore limit of the survey offshore out to a water depth of approximately 6 m and a maximum distance offshore of approximately 300 - 400 m. Maximum thickness was < 1m and was largely acoustically transparent (Figure 28). This facies is interpreted to be a depositional platform, the offshore extension of the active profile.

Facies 3: Facies 3 was identified in and around the topographic feature referred to as Shank Painter Bar. This facies is characterized by a reflector with an apparent dip towards the northwest. This reflector has a slope of 1:200 and begins at or near the seafloor in approximately 6.5 m of water (Figure 29). The surface expression of this facies has a slightly convex shape and thickens towards the edge of the platform with a slight shoaling. The maximum thickness of this deposit is >2 m, however seismic multiples obscure the reflector, and the actual maximum thickness is not known. The basal reflector is overlain by sediment with reflectors also dipping towards the northwest, however with a steeper angle (gradients of 1:100 - 1:50). The presence of seismic multiples and limited penetration of the seismic system restricts the ability to map the continuity of the basal

reflector, however it appears to continue to the steeper slope extending down to the deeper water of Cape Cod Bay (Figure 29).

Facies 3A: Facies 3A was mapped adjacent to facies 3 on two seismic lines adjacent to facies 3. This facies is characterized an acoustically transparent layer with a relatively flat surface expression, although small undulations may represent facies 1. Maximum thickness was <0.75 m (Figure 30). Facies 3A was located offshore of and was not contiguous with facies 2. Facies 3A is contiguous with facies 3, but it is unclear if this represents a different unit or is a continuation of that unit. Facies 3A is differentiated from facies 3 by the offshore dip of the seafloor, which is different from the thickening offshore configuration of facies 3.

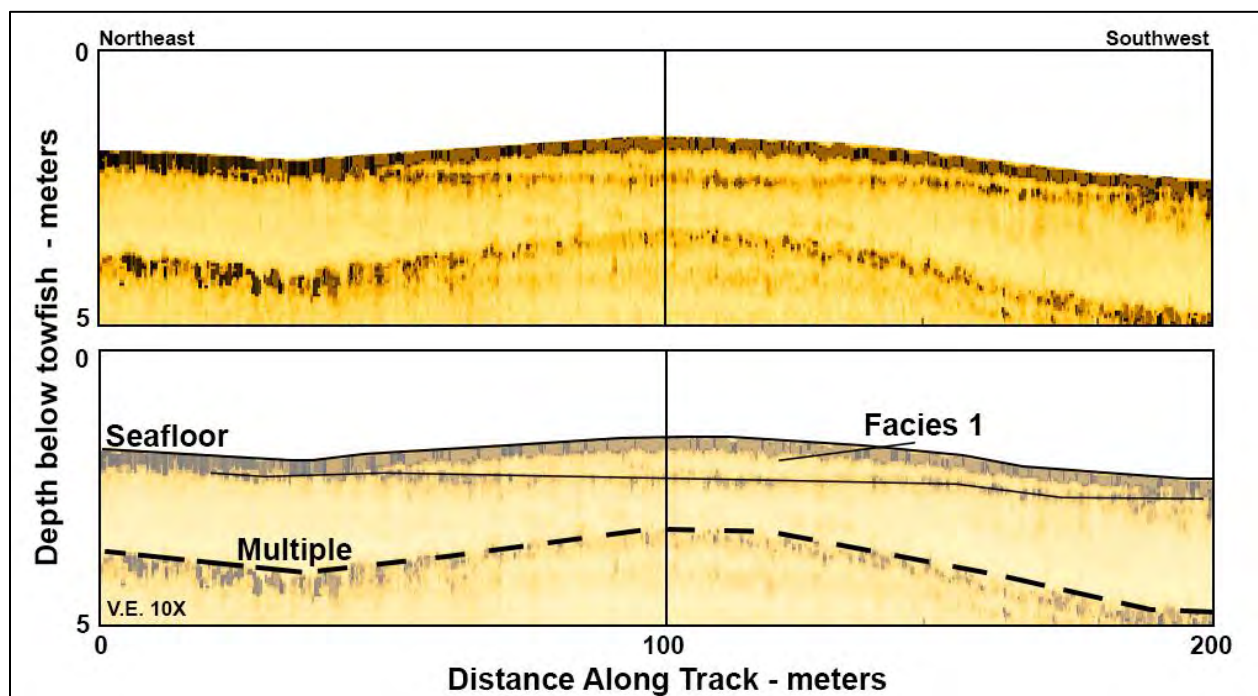


Figure 27: Top - Seismic reflection profile offshore of Herring Cove. Bottom - Interpreted seismic reflection profile showing an example of facies 1. See figure 26 for the location of the image.

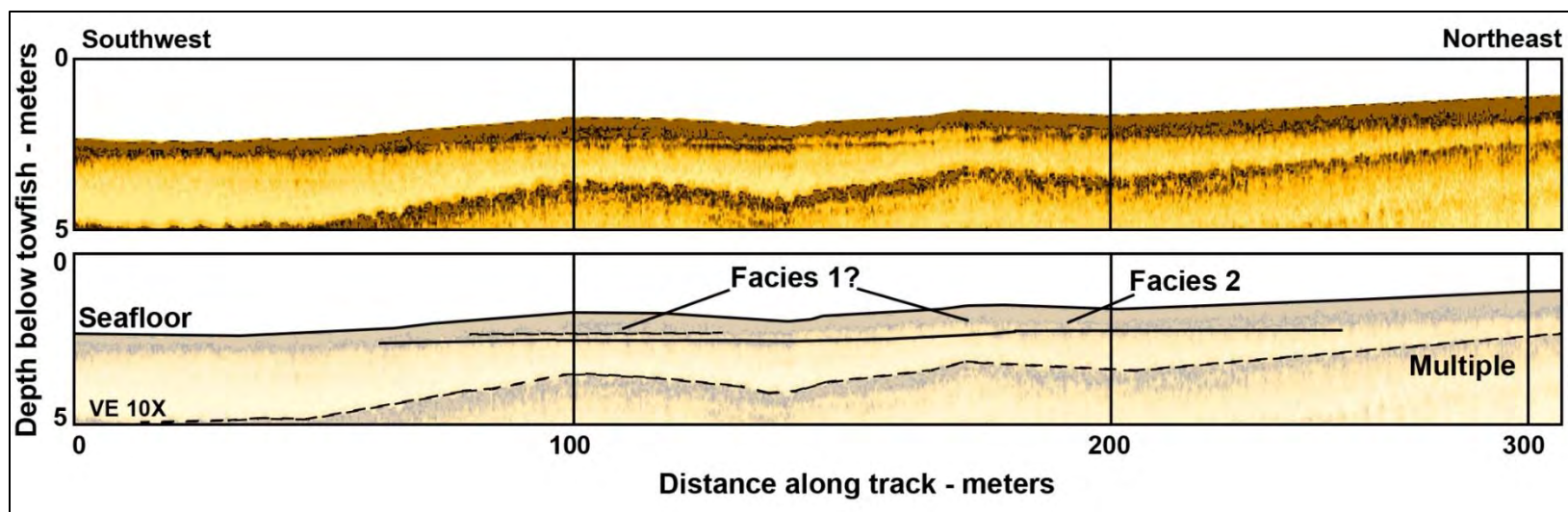


Figure 28. Top - Seismic reflection profile offshore of Herring Cove. Bottom - Interpreted seismic reflection profile showing an example of 2 and possibly facies. 1. See figure 26 for the location of the image.

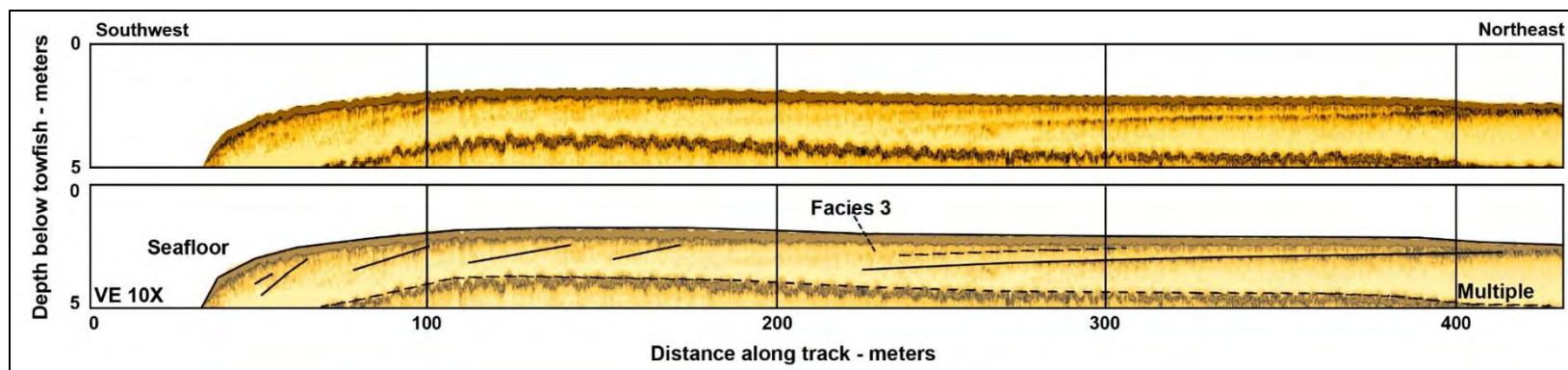


Figure 29. Top - Seismic reflection profile offshore of Herring Cove. Bottom - Interpreted seismic reflection profile showing an example of facies 3. See figure 26 for the location of the image.

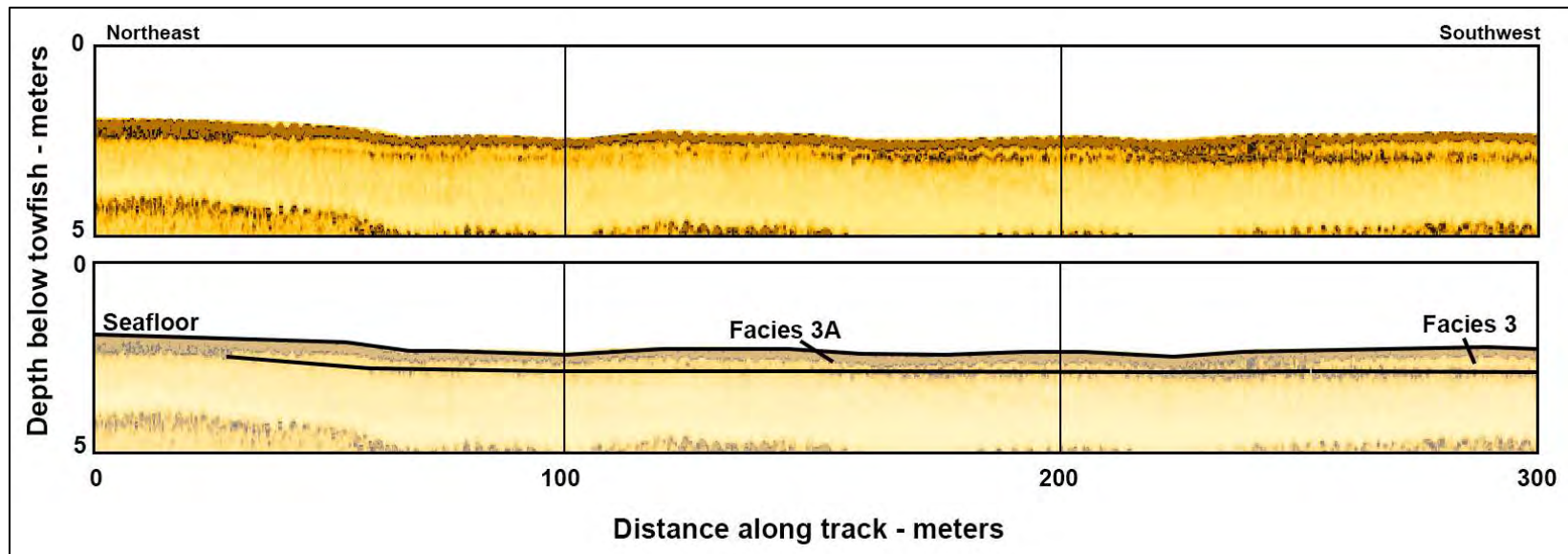


Figure 30. Top - Seismic reflection profile offshore of Herring Cove. Bottom - Interpreted seismic reflection profile showing an example of facies 3 and facies 3A. See figure 26 for the location of the image.

It should be noted that in areas where gravel has been mapped using video analysis, penetration of the acoustic signal was very limited, which is typical for these types of instruments. While this does limit our ability to image the subsurface in these areas it does corroborate the findings of the video bottom analysis with regards to the presence of gravel (V_Gravel) using a different method – seismic reflection as discussed below. In fact, the results from the areas where the seismic data was collected corroborate the overall findings with regards to grain sizes in general and habitats related to grain size, such as the relationship among sand, gravel, and algae, since algae attaches to gravel.

4.4. Onshore and Offshore Profiles

Seven quarterly onshore and offshore profiles were collected along 33 shore-normal transects from May 2017 through December 2018. Coastal sediment transport in general can be divided into alongshore (or longshore) and cross shore sediment transport: the former is the primary type of transport, by volume, and the latter can be considered somewhat seasonal. Longshore sediment transport occurs as waves impact the beach at an angle and slowly move sediment ‘downdrift’. Due to the seasonal patterns of waves discussed above, the predominant direction of sediment transport in the winter months is from Race Point toward Long Point and is relatively higher than in the summer. During the summer, the rates of sediment transport are relatively low and move material from Long Point to Race Point. The ‘net’ annual direction of sediment transport is from Race Point to Long Point. This is most clearly seen along sand spits such as those at Hatches Harbor and Long Point. The tips of the spits point in the direction of longshore sediment transport.

The trends between the onshore and offshore profiles during this study varied based on seasonal and annual trends. In general, the majority of onshore (beach) profiles (60.6%) increased in slope during the survey period and a larger majority of offshore profiles (72.7%) decreased in slope. As beaches erode, the slope decreases, and beaches become low and flat. This is most clearly seen in seasonal changes. Winter beaches have lower slopes due to the wave energy removing material from the beaches. During fairweather conditions, the sediment is returned to the beach and the slope increases. Long-term patterns of changes in slope can indicate shifts in the coastal system.

The stretch of shoreline that saw the most consistent decrease in offshore slopes were those facing south near Wood End Light. With the narrowest inner shelf, this area has some of the longest fetches in Cape Bay. Longer term datasets would be needed to determine if this was an ephemeral phenomena or part of a trend that could indicate a change in coastal response to wave energy.

In the study area, there is a pattern of onshore decrease and offshore increase in slope from the north parking lot to the south parking lot. These patterns are not unexpected given the recent change to the onshore system, i.e. the removal and relocation of the north parking lot further inland. It is likely that the north parking lot had kept the shoreline from retreating for years, perhaps

decades, and after the parking lot was removed the shoreline re-equilibrated, and the decrease in slope was a result of that erosion and re-equilibration.

4.5. Hydraulic Clamming: 2017

On November 9, 2017, 20 dredge tows were conducted over seven hours in the three experimental boxes on board the fishing vessel F/V Kimberly Ann. Tows were done in a manner consistent with standard commercial fishing practices. The vessel towed the dredge at an average speed of 1.5 knots with an approximately 3:1 towing warp to depth ratio. At the end of each tow (Figure 31) the contents of the dredge were emptied on deck, the catch of surf clams was estimated by volume (bushels), and all dredge contents were deposited in similar habitat away from the study area. The vessel's position was recorded continuously using a Garmin® GPS 78X by Center staff onboard the vessel, collecting track location between the start and end of each haul (Figure 4, Figure 32).



Figure 31. Surf clams about to be offloaded during one of the experimental tows.



Figure 32. Vessel based GPS dredge tracks during 2017 clamming event showing total number of surf clams quantified per tow. The abundance of clams collected was standardized per meter of track. This indicates that clam densities were more abundant on the landward side of the study area.

GIS-based analysis documented a fishing impact of 0-6% dredge track coverage per 10m² (Figure 25) and landings of 0.2 to 24 bushels of clams (Figure 32) and an estimated 0 to 7 bushels of shell an rocks. The majority (75%) of dredge tracks were longshore with the remaining 25% being cross shore (Figure 34). For the 2017 disturbance cross-shore tracks disappeared faster than the longshore tracks (Figure 25). This was also evident in the evolution of the tracks that were created in the 2014-2015 disturbance event (Figure 33, Figure 35). It should be noted again, however, that our analysis of the 2014-2015 tracks begins with the July 2015 acoustic data that was collected for a different project (Borrelli et al. 2019).

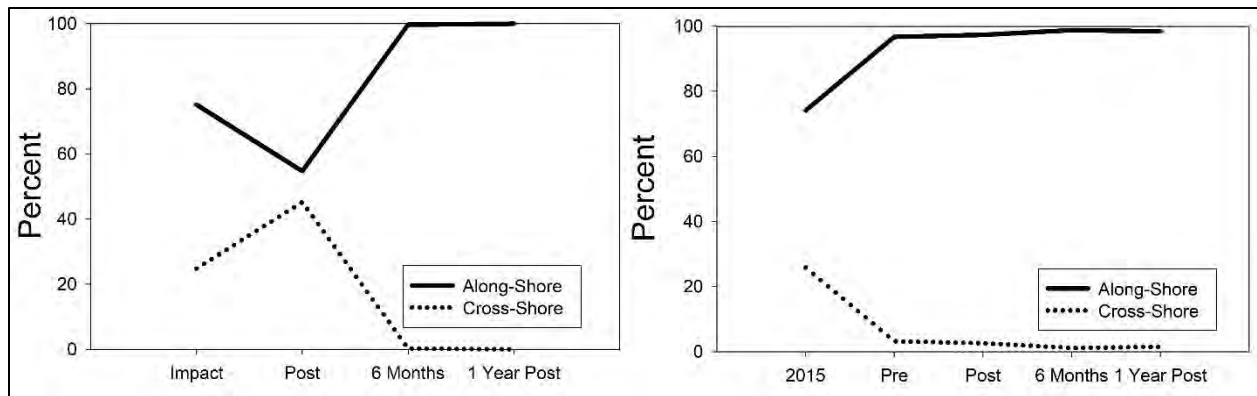


Figure 33. Percent of dredge tracks categorized as along-shore or cross-shore direction with 2017 (left) controlled dredging events and 2015 (right) uncontrolled dredging events across each acoustic survey from POST, 6POST, and 12POST.

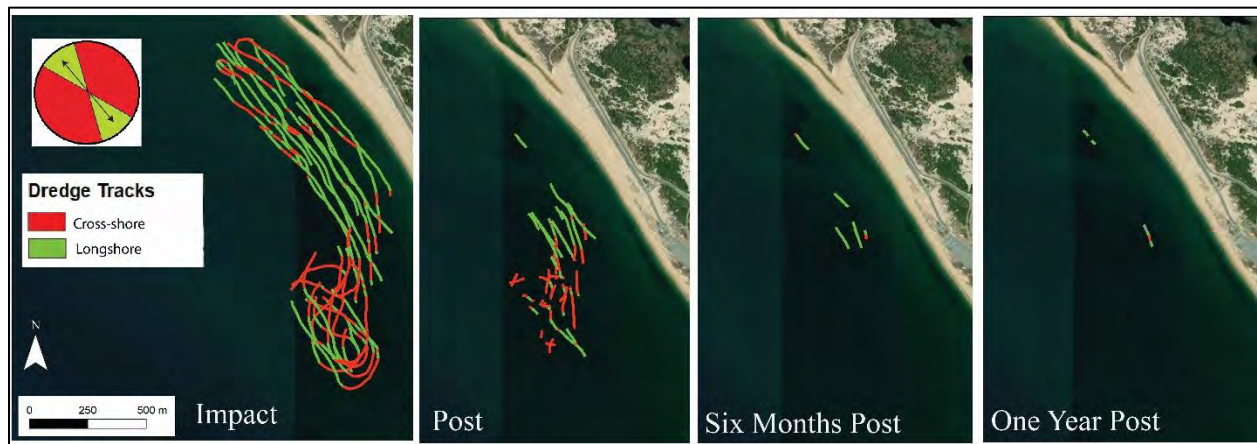


Figure 34. 2017 controlled dredge tracks (DT) categorized as long-shore or cross-shore. The progress from the disturbance event (A) to Post (B) shows the majority of the 2017 DT were recovered within the time between dredging and the post acoustic survey. Within 6 months (C) almost all the cross-shore tracks had been recovered within and only a few segments of long-shore remain. After 1 year post disturbance all but two segments remain, with a small segment of cross-shore remaining.

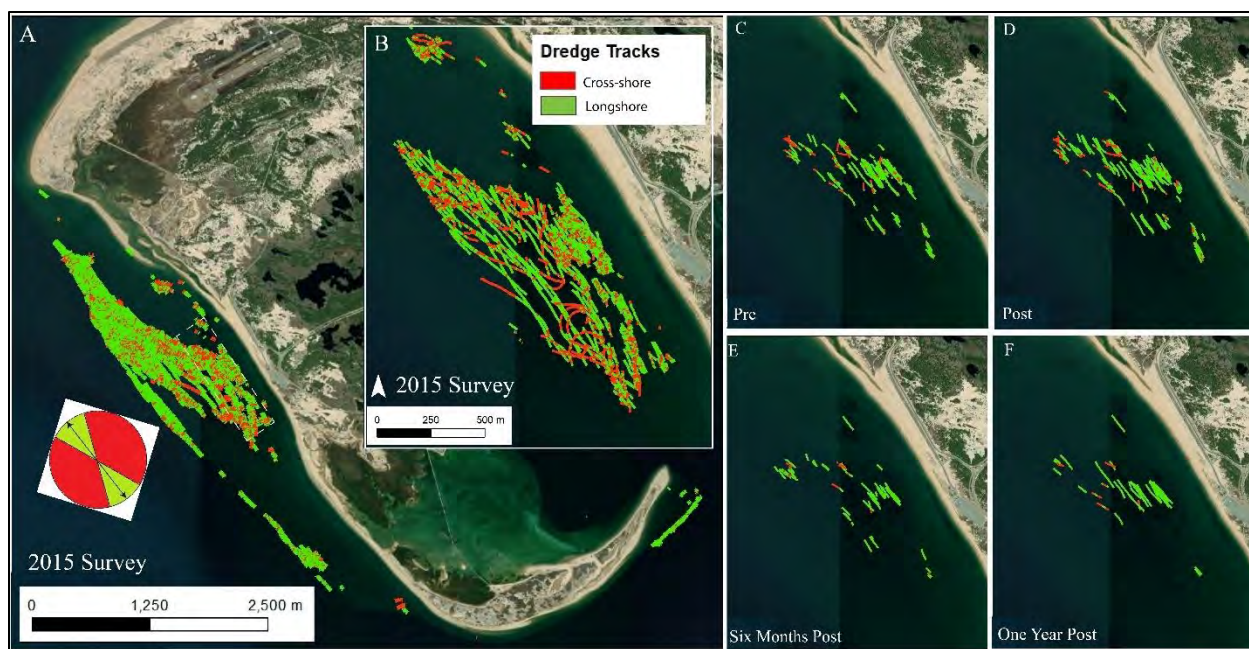


Figure 35. The 2015 uncontrolled dredge tracks (DT) categorized as long-shore or cross-shore. The progress from the 2015 acoustic survey indicates the minimum extent of the disturbance (A:B) to the substrate, and shows the progress in 2017 to follow a similar path where cross shore lines are lost faster than long-shore (C-F).

4.6. Benthic Invertebrates

Samples taken during the PRE disturbance sampling event (October 21-22, 2017) were analyzed at the CCS. 6POST samples were partially analyzed at CCS with the remaining samples analyzed at Cove (Cove Cooperation, Lusby, MD). POST and 12POST samples were analyzed entirely at Cove. Four replicate samples (Stations 1-4) from the 6POST sampling events were analyzed at Cove, the other four were analyzed at CCS. Discussing and comparing results with Cove, it was determined that methods preparing samples for analysis varied between the two laboratories. Excluding meiofauna, a common practice in studies such as this, mitigated the effect the two methodologies had on quantifying invertebrates. Using these four samples for an inter-lab comparison, the invertebrate abundances remained non-comparable, with Cove significantly undercounting invertebrate abundances by up to 10-fold compared to CCS. Cove and CCS did, however, identify comparable species richness data (Figure 36). Thus, the results and statistical analysis of benthic invertebrate response to disturbance is therefore limited to species richness. Datasets on species richness derived from CCS and Cove analyses are used here.

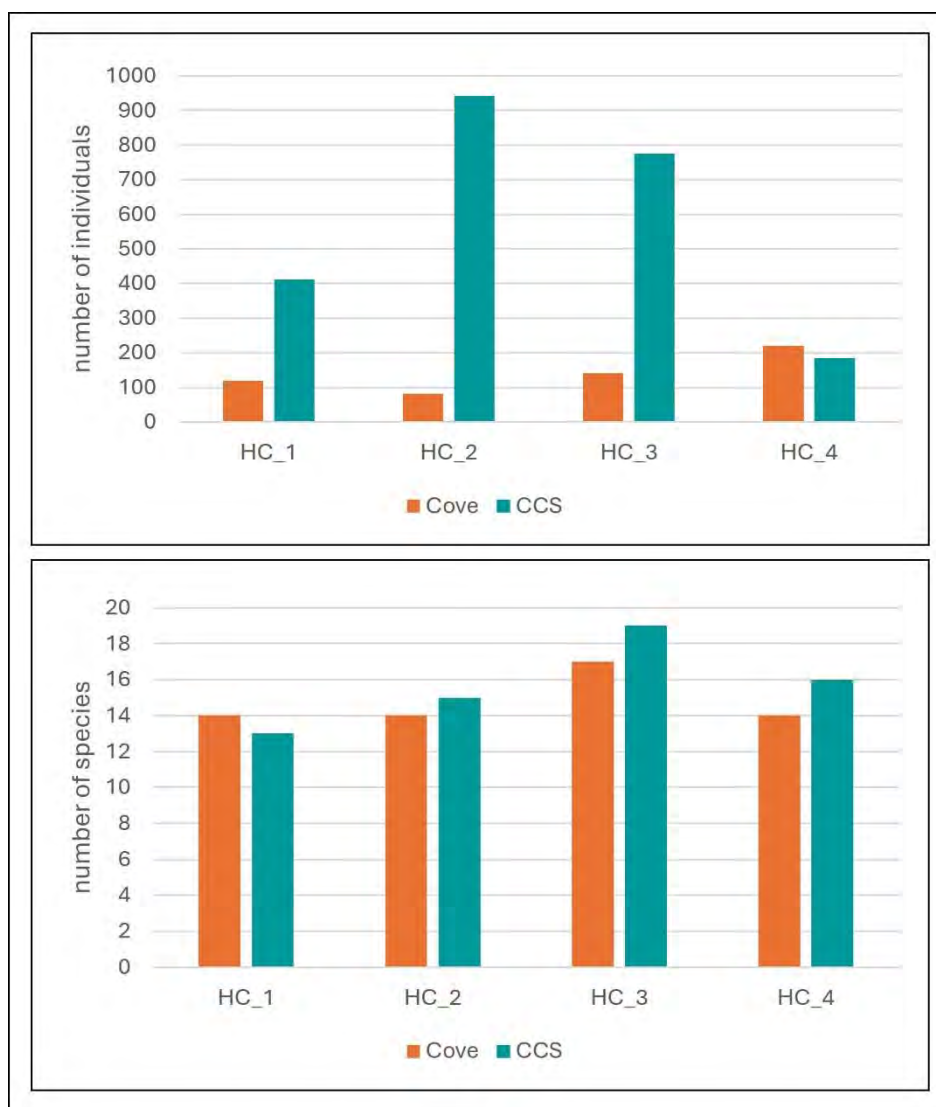


Figure 36. Comparison of replicates (stations 1-4 of 6POST) analyzed at CCS (green) and Cove (orange), after excluding meiofauna from the analysis.

On October 21-22, 2017 (PRE), November 15, November 18 and November 28, 2017 (POST), April 30 and May 1, 2018 (6POST), and November 15 and November 16, 2018 (12POST), benthic invertebrate samples were collected, in duplicate, at 24 locations as described above. On average, replicate samples were 6.7 meters apart. Overall, 225 taxa (see species list Appendix A) were identified, and 128,843 individuals were counted. According to drop rules described in section 3.6.2, 58,214 individuals belonging to 110 taxa were used in statistical analyses. Of 28 environmental factors (Table 2) considered, five were excluded due to incomplete datasets (QSBCmax., deceleration at NQSBCmax., velocity at NQSBCmax., penetration at NQSBCmax., total 2017 disturbance at timepoint), four were excluded due to ecological redundancy (salinity, pH, 4mm, kurtosis) and four were excluded due to correlation (V_Sand, mean, disturbance, gravel) leaving 16 factors to be considered in statistical analyses. While the water column in the study area is well mixed and surface temperature does affect the benthic habitat, this factor was excluded

from analyses within sampling events (due to ecological redundancy) but not from analyses between sampling events which occurred across seasons. See Appendix A for

A note on how to read and interpret nMDS and DistLM/dbRDA plots as shown in this report.

Where regular scatter plots use symbols to represent values for two different numeric variables and focus on the position of each symbol in relation to the horizontal and vertical axis, nMDS plots are **non-metric, multidimensional scaling** scatter plots and focus only on the position of the symbols relative to each other. nMDS plots can be “arbitrarily *scaled, located, rotated* or *inverted*.” (Clarke and Warwick 2001). Two close symbols indicate high similarity between the underlying datapoints, whereas symbols that are far apart (e.g. symbols 10 and 20 in Figure 39) indicate dissimilar or different underlying datapoints. When symbols in an nMDS plot are visually evenly distributed it can be assumed that the underlying datapoints (e.g. species diversity per station) are also evenly distributed. The opposite is true when symbols cluster into groups (see Figure 37 – unpublished data A. Mittermayr). Groups may cluster tightly (orange stars in Figure 37) or loosely (blue triangles in Figure 37), thus indicating high or low similarity between samples respectively. Since nMDS plots aim to depict multiple dimensions in a 2D graph, a certain amount of distortion, or stress, is associated with each plot. According to Clarke and Warwick (2001), stress should be interpreted following Table 5.

Table 5. Interpretation of stress associated with nMDS plots according to Clarke and Warwick 2001.

nMDS stress	Interpretation
< 0.05	Excellent representation with no prospect of misinterpretation
< 0.1	Good ordination with no real prospect of misleading interpretation
< 0.2	Potentially useful
> 0.3	Points are close to being arbitrarily placed

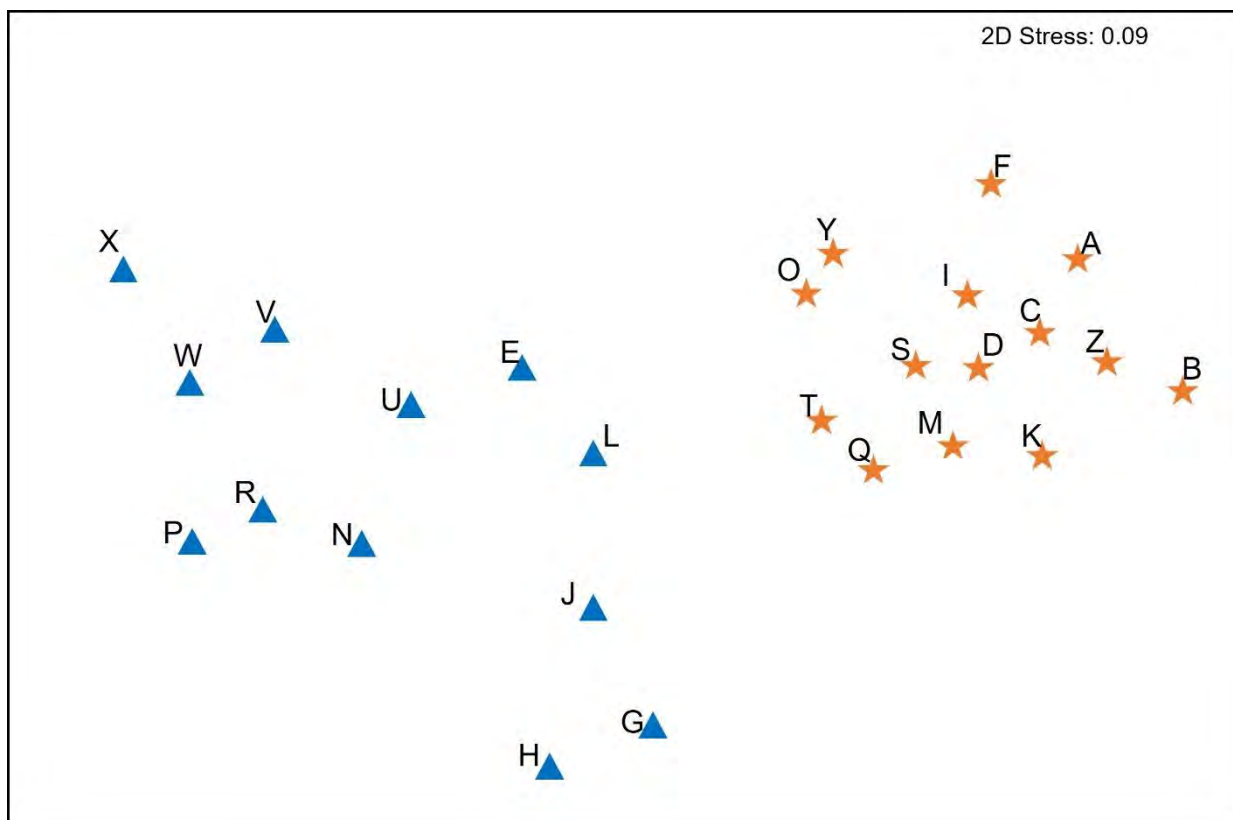


Figure 37. An example for an nMDS plot generated with PRIMER. Two groups, or communities, appear to be separate, with no overlap. One community (stars) appears to be clustered more tightly than the other (triangles) indicating more similarity within the first than the second community.

Analysis of Similarity (ANOSIM) can be interpreted similarly to ANOVA (Analysis of Variance), however, instead of differences the focus lies on similarities between data sets. ANOSIM is run in PRIMER and results in an R-value (describing the degree of similarity) and an associated p-value (describing the significance of the R-value). See Table 6 for guidelines on how to interpret R-values. ANOSIM between two data sets (e.g. control and disturbed) will result in one R-value; analyses between multiple data sets (e.g. PRE, POST, 6POST, 12POST) will result in a global R-value summarizing the R-values of each comparison.

Table 6. Interpretation of ANOSIM R-values

R-value	Interpretation
0.5 – 1.0	High dissimilarity between data sets
0.25 – 0.5	Different, but overlapping data sets
0 – 0.25	Very similar data sets
< 0	More dissimilarity within than between data sets

A distance based linear model (DistLM) in PRIMER is a routine for analyzing and modeling the relationship between a multivariate data set and one or more predictor variables (e.g. grain size

metrics) (Anderson et al. 2008). The underlying question is: *does variable X explain a significant portion of the variation in a given data set?* This is answered in the form of multiple tables (as can be seen here: tables 7-10). To visualize a DistLM output, a distance-based redundancy analysis (dbRDA) plot can be used. Like the nMDS plots described above, distances between symbols in dbRDA plots indicate similarity when close together, or dissimilarity when far apart. Also, depending on the number of predictor variables contributing to the variation in the data set, dbRDA plots are most often a 2D representation of three or more-dimensional data sets. As an example, the plot below (Figure 38 - unpublished data A. Mittermayr) shows four species communities clustering together and four overlaid vectors of different directions and length. The clustering of the four communities indicates that there are similarities within every community and no overlap between communities. The vectors represent four predictor variables (light availability, temperature, and latitude) calculated by the DistLM to contribute to the variation of the data set.

Generally speaking, “the longer the vector, the bigger the effect that variable has had” on the data set (Anderson et al. 2008). The location of symbols in relation to the direction of vectors indicates a relationship between the variable represented by a vector and the underlying data set. In Figure 38, “light availability” is the longest vector, thus this variable has the biggest effect on the data set. The spread of symbols along the vector “light availability,” points towards data on coral reef communities being associated with one end of the range covered by this variable, while deep sea communities can be associated with the other end of the range. Since this applies to all symbols on the plot, it can also be concluded that tide pool communities are more similar to coral reef communities in terms of light availability and sea ice communities are more similar to deep sea communities. Focusing on the deep sea communities, the plot shows a cluster at the opposite end of “light availability” compared to coral reef communities. Additionally, the cluster is situated along the length of the vector “latitude” (deep sea communities are not limited to certain latitudes) and the end of the temperature range used as variable in the model.

While dbRDA plots are a fairly straightforward way to visualize data sets and associated variables, the actual thresholds of these variables (e.g. what is the light availability that separates coral reef communities from sea ice communities?) have to be calculated separately, using e.g. the LINKTREE function in PRIMER.

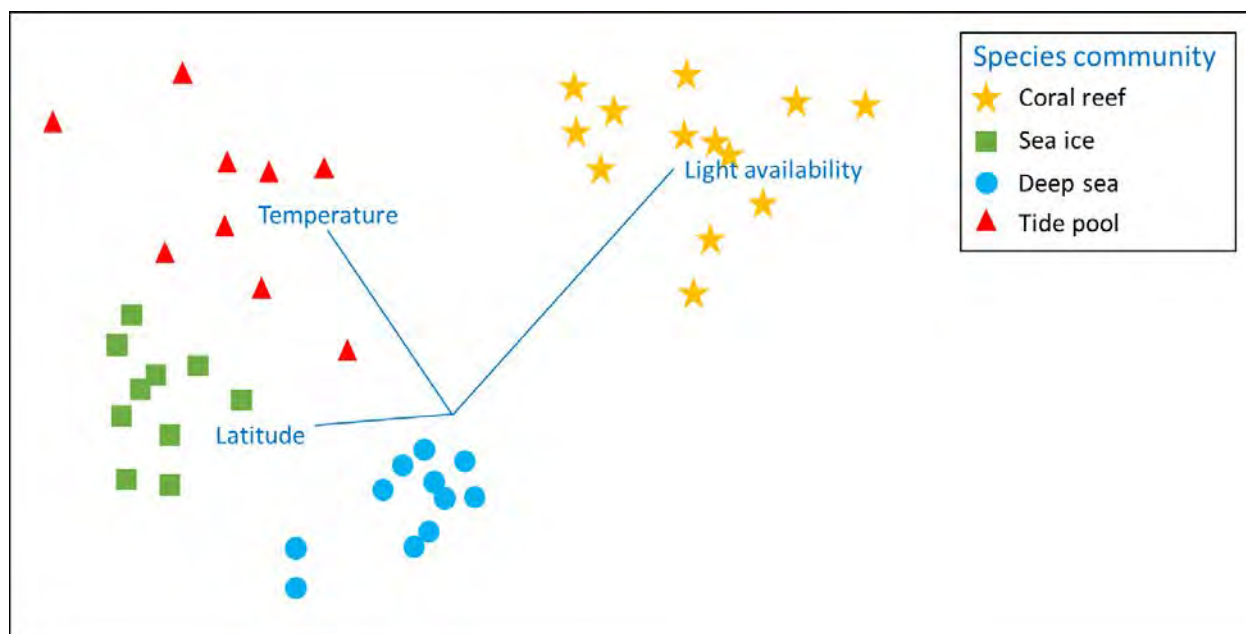


Figure 38. Distanced-based redundancy analysis plot based on results of a previously run distance-based linear model. Three vectors represent three variables that best explain the variation in the data set.

4.7. Benthic Invertebrates – Pre-Disturbance

Samples collected pre-disturbance resulted in 94,136 individuals belonging to 130 species, with polychaetes, oligochaetes, and nematodes contributing 88.9% of individuals and 42% of species, followed by molluscs (33% and 6%) and crustaceans (17% and 3%). After applying drop rules, 34,882 individuals belonging to 79 families remained for statistical analysis. When running initial ANOSIMs (analysis of similarities) to detect differences between control and disturbance locations, no significant results could be found in terms of species diversity ($R = -0.013$, $p\text{-value} = 0.523$) (Figure 39) or abundance ($R = 0.021$, $p\text{-value} = 0.266$). Negative R -values indicate more difference within groups than between groups; R -values <0.25 indicate similarity between samples. Additionally, an ANOSIM for location (onshore vs. offshore) was run and yielded significant similarities between stations in terms of species diversity ($R = 0.242$, $p\text{-value} = 0.009$). The most important factors (Table 2) driving differences between boxes were calculated to be algae and depth, which explain 25.9% and 7.4% of variability in species composition (Table 7) with the remaining 14 factors explaining an additional 66.7%.

Table 7. Results from PRIMER's distance based linear model (DistLM). Percentage of PRE variation explained by individual axes based on selection criterion: AICc and selection procedure: Best.

Axis	% explained variation out of total variation	
	Individual	Cumulative
Algae	25.97	25.97
Depth	7.4	33.37

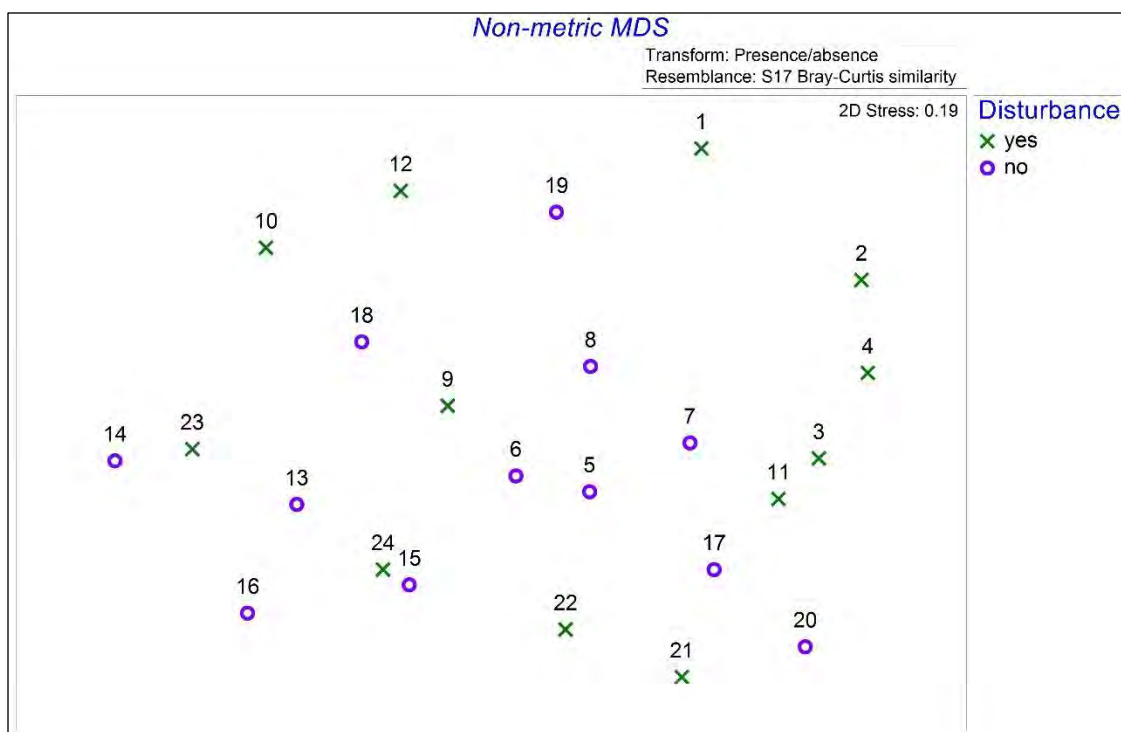


Figure 39. A non-metric multidimensional scaling (nMDS) plot showing stations 1-24. Colors indicate stations to be subjected to disturbance (green x) and stations to act as no-disturbance control locations (purple circles). No significant patterns are apparent, indicating evenly distributed species communities. Distance between points indicates similarity (e.g. stations 4 and 14 are more different than station 2 and 4). Stress could be reduced to 0.13 in a three-dimensional plot.

4.7.1. Benthic Invertebrates – Post Disturbance

Samples collected post-disturbance resulted in belonging to 90 species, with Molluscs contributing 44.7% of species, followed by polychaetes, oligochaetes and nematodes (35%), and crustaceans (19%). After applying drop rules, 60 families remained for statistical analysis. When running initial ANOSIMs (analysis of similarities) to detect differences between control and disturbance locations, no significant results could be found in terms of species diversity ($R = -0.067$, $p\text{-value} = 0.887$) (Figure 40). The most important factors (Table 2) driving differences between disturbed areas and control areas were calculated to be algae and depth (Table 8).

Table 8. Results from PRIMER's distance based linear model (DistLM). Percentage of POST variation explained by individual axes based on selection criterion: AICc and selection procedure: Best

Axis	% explained variation out of total variation	
	Individual	Cumulative
Algae	25.63	25.63
Depth	9.83	35.46

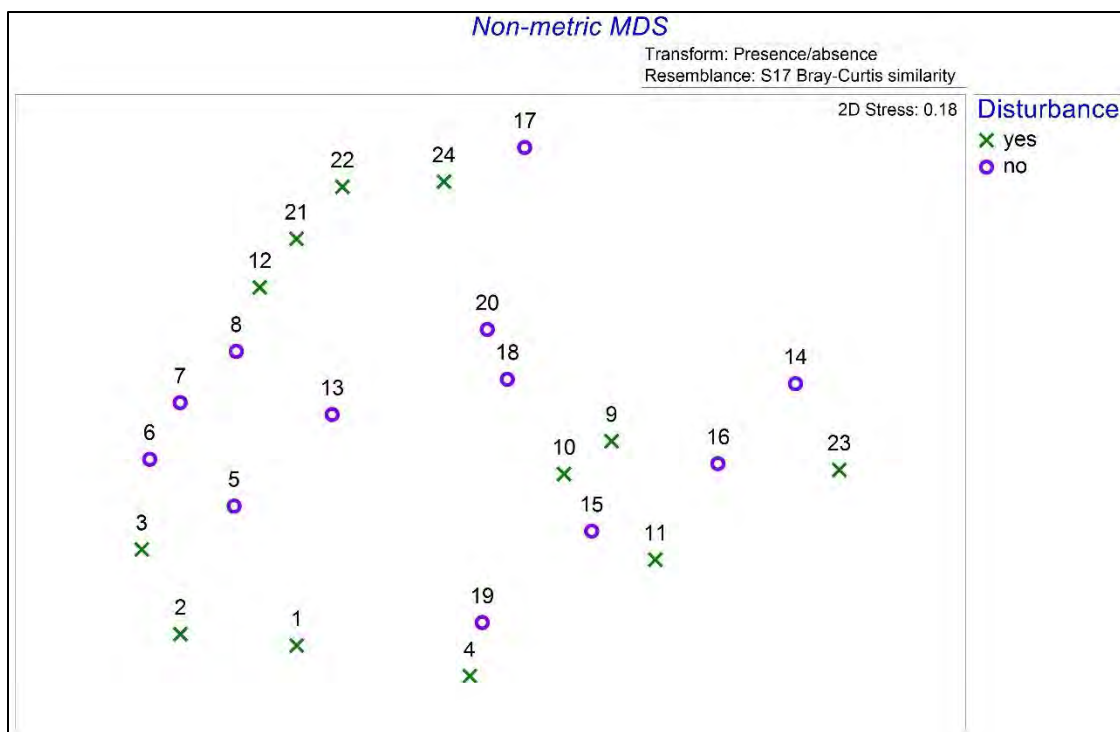


Figure 40. A non-metric multidimensional scaling (nMDS) plot showing stations 1-24 post disturbance. Colors indicate stations subjected to disturbance (green x) and stations to act as no-disturbance control locations (purple circles). No significant patterns are apparent, indicating evenly distributed species communities. Stress could be reduced to 0.09 in a three-dimensional plot

4.7.2. Benthic Invertebrates - 6 Months Post Disturbance

Samples collected six months post-disturbance resulted in 107 species, with polychaetes, oligochaetes, and nematodes contributing 39.3% of species, followed by molluscs (35%) and crustaceans (21%). After applying drop rules, 73 families remained for statistical analysis. When running initial ANOSIMs (analysis of similarities) to detect differences between control and disturbance locations, no significant results could be found in terms of species diversity ($R = 0.025$, $p\text{-value} = 0.26$) (Figure 41). The most important factor (Table 2) driving differences between disturbed areas and control areas were calculated to be algae and depth (Table 9).

Table 9. Results from PRIMER's distance based linear model (DistLM). Percentage of 6POST variation explained by individual axes based on selection criterion: AICc and selection procedure: Best

Axis	% explained variation out of total variation	
	Individual	Cumulative
Algae	39.14	39.14
Depth	6.56	45.70

Figure 41. A non-metric multidimensional scaling (nMDS) plot showing stations 1-24 6-month post disturbance. Colors indicate stations subjected to disturbance (green x) and stations to act as no-disturbance control locations (purple circles). No significant patterns are apparent, indicating evenly distributed species communities. Stress could be reduced to 0.1 in a three-dimensional plot.

4.7.3. Benthic Invertebrates - 12 Months Post Disturbance

Samples collected 12 months post-disturbance resulted in 95 species, with polychaetes, oligochaetes, and nematodes contributing 39.3% of species, followed by molluscs (39%) and crustaceans (13%). After applying drop rules, 62 families remained for statistical analysis. When running initial ANOSIMs (analysis of similarities) to detect differences between control and disturbance locations, no significant results could be found in terms of species diversity ($R = 0.107$, $p\text{-value} = 0.52$) (Figure 42). The most important factor (Table 2) driving differences between disturbed areas and control areas were calculated to be algae and depth (Table 10).

Table 10. Results from PRIMER's distance based linear model (DistLM). Percentage of 12POST variation explained by individual axes based on selection criterion: AICc and selection procedure: Best

Axis	% explained variation out of total variation	
	Individual	Cumulative
Algae	21.55	21.55
Depth	4.52	26.06

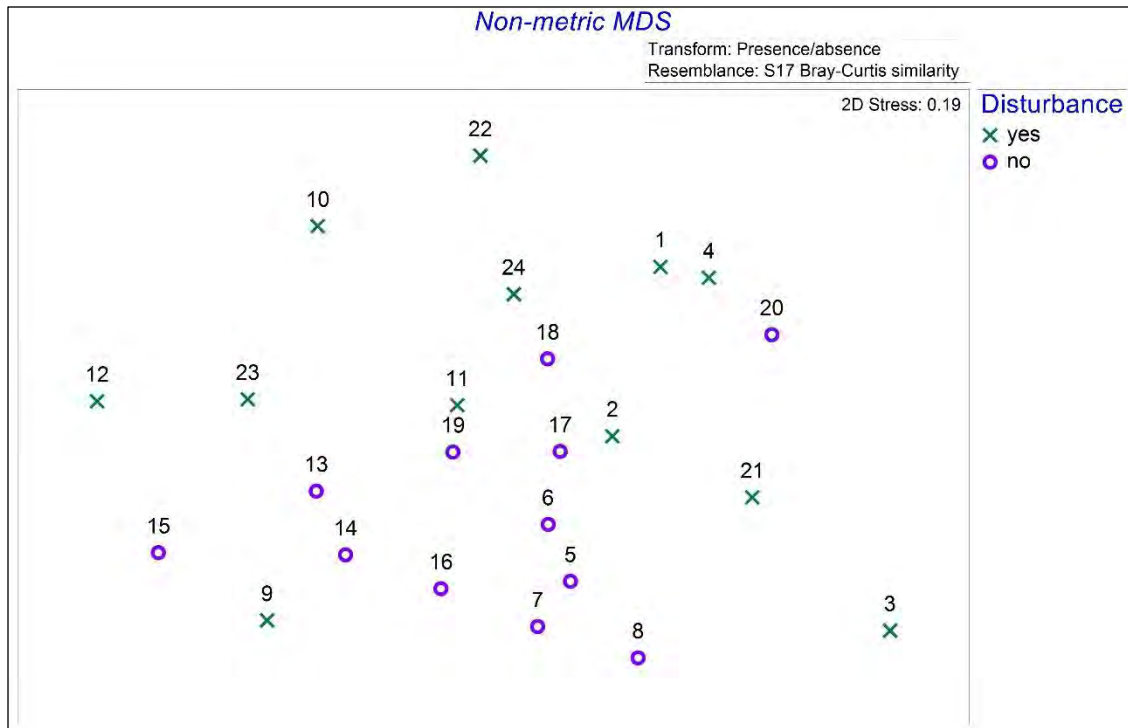


Figure 42. A non-metric multidimensional scaling (nMDS) plot showing stations 1-24 12 month post disturbance. Colors indicate stations subjected to disturbance (green x) and stations to act as no-disturbance control locations (purple circles). No significant patterns are apparent, indicating evenly distributed species communities. Stress could be reduced to 0.12 in a three dimensional plot

4.7.4. Analysis across time points

The four data sets (PRE, POST, 6POST and 12POST) were combined to track changes throughout the sampling period. An initial ANOSIM run to detect differences between the four data sets showed highly significant results (global $R = 0.279$, $p\text{-value} = 0.01$; Table 11, Figure 43). All ANOSIMs including the PRE data set resulted in significantly different but overlapping R -values, while ANOSIMs show that POST vs 12POST and 6POST vs 12POST are significantly similar in terms of species richness.

Table 11. ANOSIM results for comparison between PRE, POST, 6POST and 12POST data sets.

Groups	R-value	p-value
PRE, POST	0.43	0.001
PRE, 6POST	0.45	0.001
PRE, 12POST	0.492	0.001
POST, 6POST	0.061	0.49
POST, 12 POST	0.102	0.003
6POST, 12POST	0.202	0.001

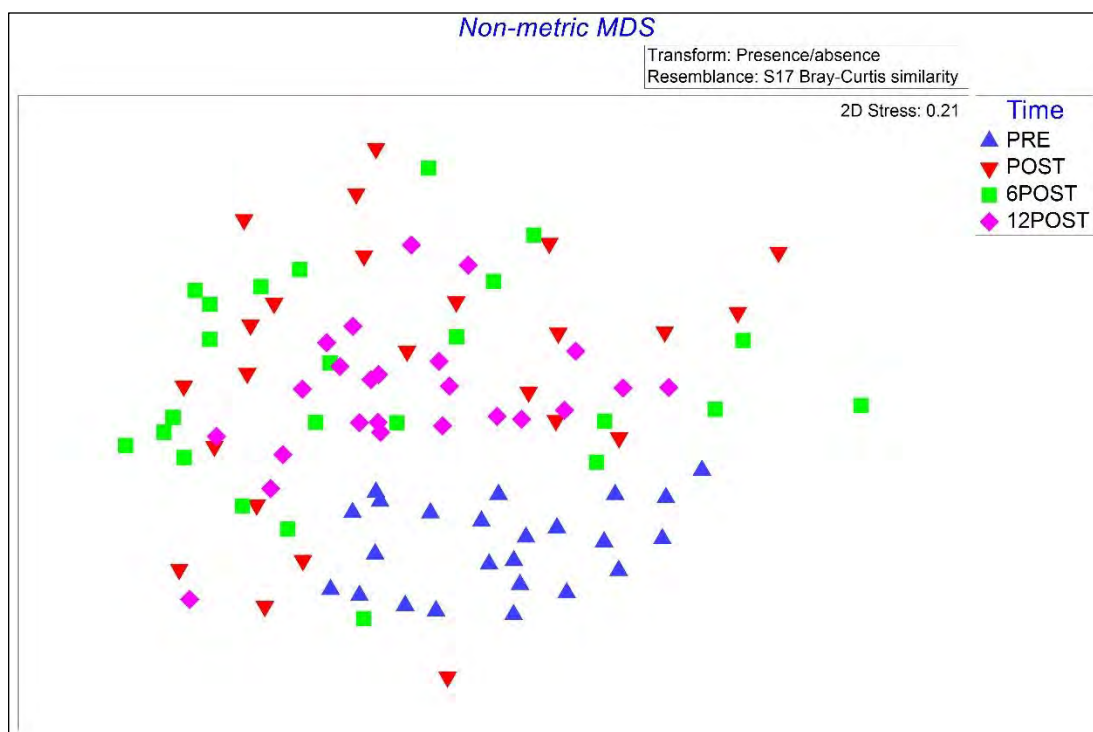


Figure 43. A non-metric multidimensional scaling (nMDS) plot showing stations 1-24 at all four sampling events. Colors indicate time. No significant patterns are apparent, indicating evenly distributed species communities. Stress could be reduced to 0.16 in a three dimensional plot

Looking at which factors (Table 2) affect species diversity across the four sampling events, distance based linear model run in PRIMER showed that seasonality, as represented by water temperature, becomes apparent as a driver (Figure 44). Surface temperature was highest during PRE sampling ($14.49^{\circ}\text{C} \pm 0.24$) compared to POST ($10.6^{\circ}\text{C} \pm 0.84$) 6POST ($8.5^{\circ}\text{C} \pm 0.48$) and 12POST ($9.5^{\circ}\text{C} \pm 0.67$). To determine non- seasonal causes for variation in species diversity, surface temperature was excluded from subsequent analysis and resulted in four factors (depth, algae, V_Gravel and L_Slope) explaining 29.24% variation of a highly overlapping data set (Figure 44, Table 12).

Table 12. Results from PRIMER's distance based linear model (DistLM) excluding surface temperature. Percentage of variation between sampling events explained by individual axes based on selection criterion: AICc and selection procedure: Best

Axis	% explained variation out of total variation	
	Individual	Cumulative
Algae	21.87	21.87
V_Gravel	4.07	25.93
Slope	2.59	28.52
Depth	0.73	29.24

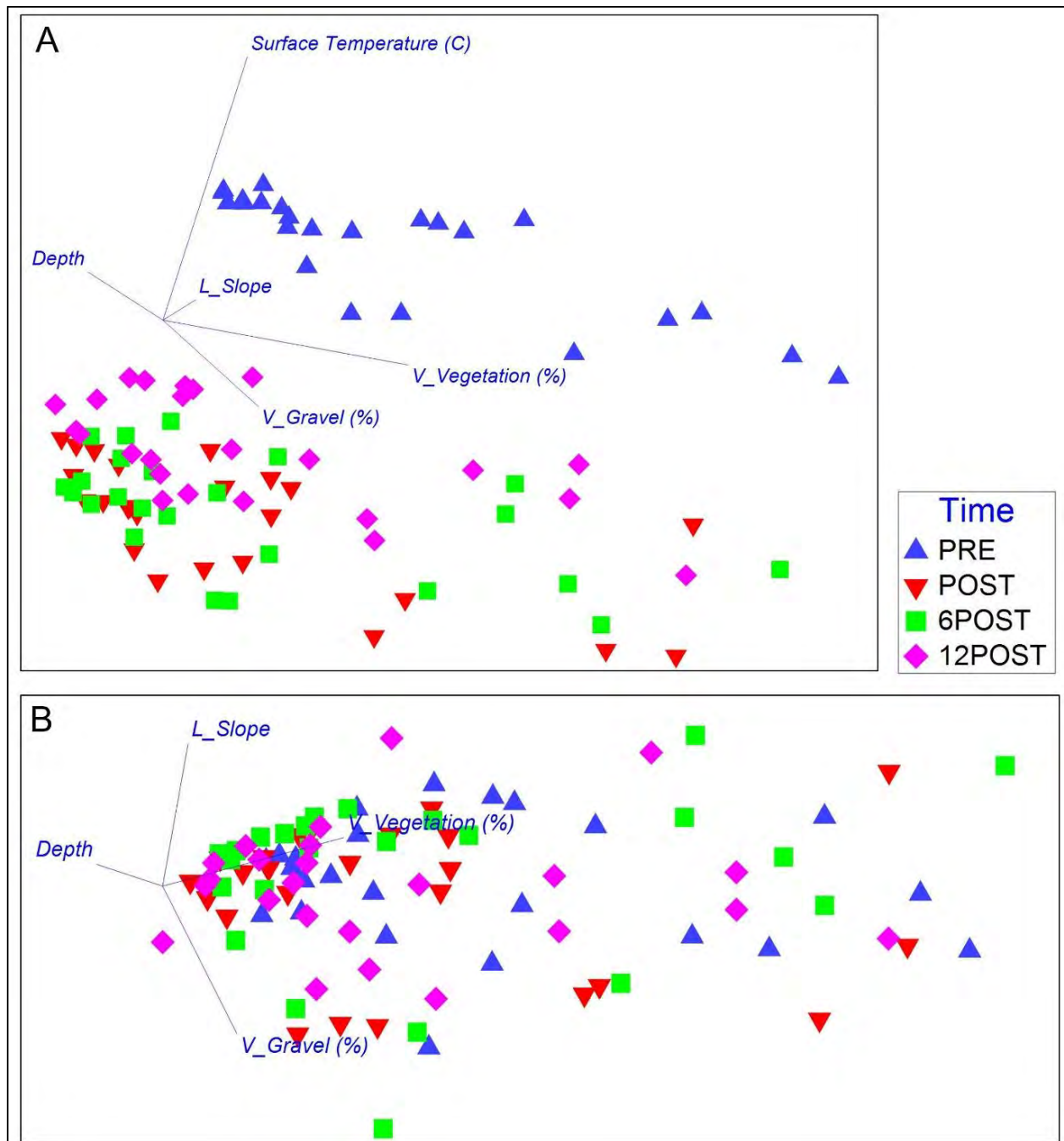


Figure 44. dbRDA plot based on DistLM of stations. Selection criterion: AICc, selection procedure: Best. Panel A shows plot including “surface temperature”, panel B shows plot with forced exclusion of “surface temperature”.

Running LINKTREE and SIMPROF functions in PRIMER we could determine that algae was responsible for the first splits (A in Figure 45), separating stations into locations with >84.6% vegetation (station 14 at 6POST) and locations with <71.5%. Followed by a split of stations into locations with >51.5% gravel and locations with <40.7% gravel. Since these splits are based on observed values, apparent “holes” (e.g. between 84.6% and 71.5% vegetation or between 51.5%

and 40.7% gravel) can be explained by no observations of these values in these ranges at any stations.

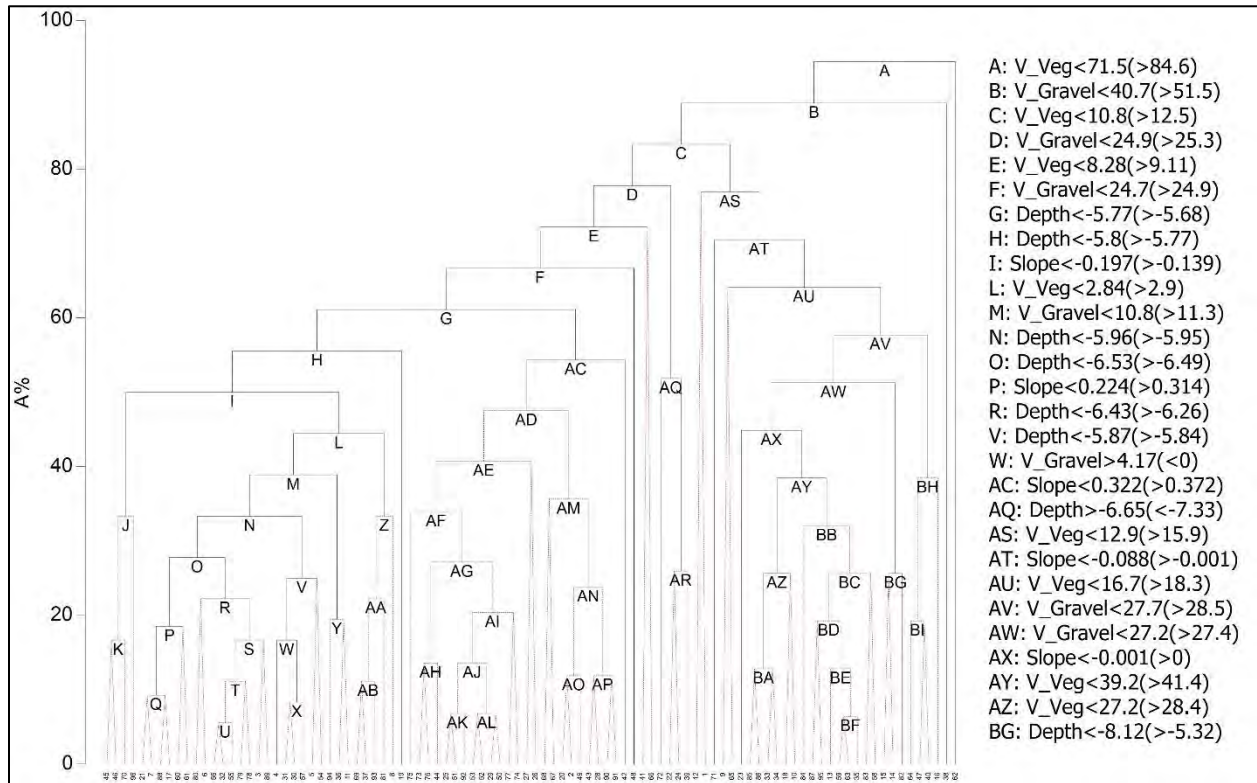


Figure 45. LINKTREE graph based on factors: Algae, V_Gravel, Slope and Depth. Red lines indicate no significant differences between stations. Letters A though BI indicate factors responsible for the split as can be seen in list on the right (only significant splits are listed).

Separating benthic invertebrate species into groups of mobile (e.g. most polychaeta worms) and sessile (e.g. most bivalves) showed that while both mobile and sessile species diversity decreased after the disturbance, mobile species numbers increased following seasonal changes, while sessile species numbers remained low (**Table 13**).

Table 13. Number of mobile and sessile taxa in disturbed areas at 4 different sampling events

Groups	PRE	POST	6POST	12POST
Mobile	137	95	112	102
Sessile	85	51	57	55

Impacts from benthic fishing, particularly hydraulic dredging, are one of the most widespread impacts on the benthic environment (Hiddink et al. 2017; Legare et al. 2020a; Oberle et al. 2016a). The physical disturbance of the substrate and the removal and/or damage of organisms can cause short and long term changes in benthic communities (Johnson 2002; Legare et al. 2020a; Mercado-

Silva 2005). The recovery of the impacted area is correlated to the intensity of the disturbance, the season during which the disturbance occurred, prevalent habitat type in and around the area, and the hydrographic regime (Gilkinson et al. 2003; Oberle et al. 2016a; Sköld et al. 2018; Stokesbury et al. 2011). Fisheries management plans for Atlantic surf clams (Mid-Atlantic Fishery Management Council, 2016; Fuller and Cameron, 1998) state that in sand dominated environments, the effects of dredging on benthic communities are short lived (hours to months), and that, in comparison, disturbances caused by strong currents and storm events would be more severe.

4.8. Grain Size

Sediment samples were collected between Race Point and Long Point (n = 310) twice. Samples were collected along the 33 shore-normal transects during 6 episodes between October 2018 and September 2018 (n = 214). Sediment samples were also taken after 2 invertebrate replicates were collected at each of the 24 stations for four time periods (n = 96) to document the benthic invertebrate community (Table 14).

Table 14. Bottom grab samples collected via Young-Modified Van Veen.

Sample: Time Period	Collection Date(s)
Invertebrate: PRE	10/21/17, 10/23/17
Invertebrate: POST	11/15/17, 11/18/17, 11/28/17
Invertebrate: 6POST	4/30/17, 5/1/17
Invertebrate: 12POST	11/15/17, 11/18/17
Transects: 1st	5/10/17
Transects: 2nd	8/14/17
Transects: 3rd	10/28/17, 11/03/17
Transects: 4th	3/29/18
Transects: 5th	6/16/18
Transects: 6th	9/5/18

The sediment samples exhibited very consistent characteristics across all time periods. The median grain size (D_{50}) at the invertebrate stations was 1.29 mm, or *very coarse sand* according to the standard Wentworth scale. The sorting of the samples was similarly consistent with the majority well- to moderately-well sorted. Samples were collected in 10 out of the 12 calendar months, and yet they remained remarkably similar, showing little to no seasonality. Although wave direction and magnitude showed seasonal relationships (see section 4.1), such little variability in grain size characteristics is indicative of a single source of sediment with minimal variation. Unlike the open ocean, shoreline erosion along the beach and dunes between Race Point and Long Point provides a fraction of the sediment to the system. Most of the sediment source for this area is the material entrained in the longshore sediment transport system that moves material from as far south as Coast Guard Beach in Eastham northward around Race Point continuing to Long Point.

4.9. Video Assessment of Bottom Types

A total of 798 bottom videos were collected during this study, 479 during invertebrate benthic grab sampling and 319 during quarterly sediment sampling. From these videos, still images were extracted, and habitat metrics were classified using 25 random points in Coral Point Count with Excel Extensions (CPCe). Microhabitats were dynamic and varied throughout the study location.

The only samples that included eelgrass (*Zostera marina*) were those found off Long Point at transect 1332 (Figure 46). The remaining areas were primarily bare sand or dominated by algae or gravel (Figure 48, Figure 50).

For video assessments within the disturbance study, the mean habitat metrics across all drops and time points (Pre, Post, 6-post and 12-post) were 59.3% cover of sand, 14.5% cover of gravel, 22.2 % cover of algae, and 3.4 % cover of shell material within the study area. (Table 15, Appendix C**Table 15**). For the video assessment across the quarterly sediment sampling surveys, results from all drops were on average of 60.0% cover of sand, 16.0% cover of gravel, 14.0 % cover of algae, 2.3% cover of shell material, and 0.1% Eelgrass. (Table 16, Appendix C).

Seasonal patterns in algae and bare sand fluctuations were present in the benthic habitat analysis. (Figure 47). The area within the disturbance areas and boxes 3 and 4 were the most dynamic with the highest variability both seasonally (Figure 49, Figure 50) and between the different constituents (Algae, V_Sand, V_Gravel, Shell). This is likely due to the presence of gravel beds which are either exposed during higher energy periods or buried with a thin layer of sand during lower energy periods. Compared to the areas north to Race Point or south toward Wood End, the habitat off Herring Cove within this experiment is a complex habitat (Figure 47, Figure 51).

Table 15. Summary habitat statistics for all drops collected within the benthic invertebrate disturbance study.

Habitat	Mean	St.dev.	Min.	Max.
V_Sand	59.3	36.2	0.0	100.0
V_Gravel	14.5	15.7	0.0	81.0
Algae	22.2	26.7	0.0	100.0
Shell	3.4	7.4	0.0	52.9

Table 16. Summary habitat statistics for all drops collected during the quarterly sediment sampling.

Habitat	Mean	St.dev.	Min.	Max.
V_Sand	60.0	36.0	0.0	100.0
V_Gravel	16.0	20.0	0.0	95.0
Algae	14.0	23.0	0.0	100.0
Shell	2.3	6.0	0.0	47..
Eelgrass	0.1	2.0	0.0	35.0



Figure 46. Eelgrass (*Zostera marina*) was found at transect 1332 Long Point, outside of the disturbance area.

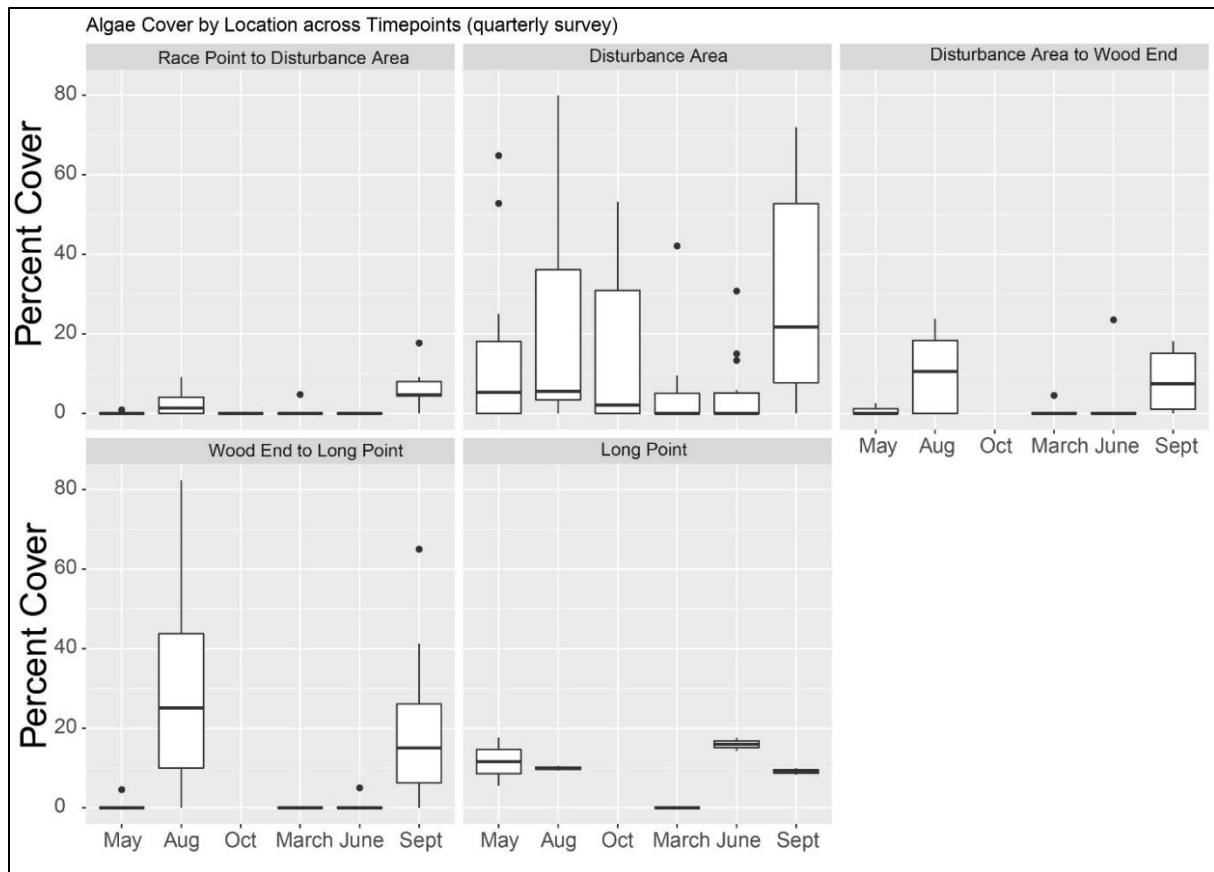


Figure 47. Algae cover from all drops in each area from Race Point to Long Point from the Video assessment analysis.

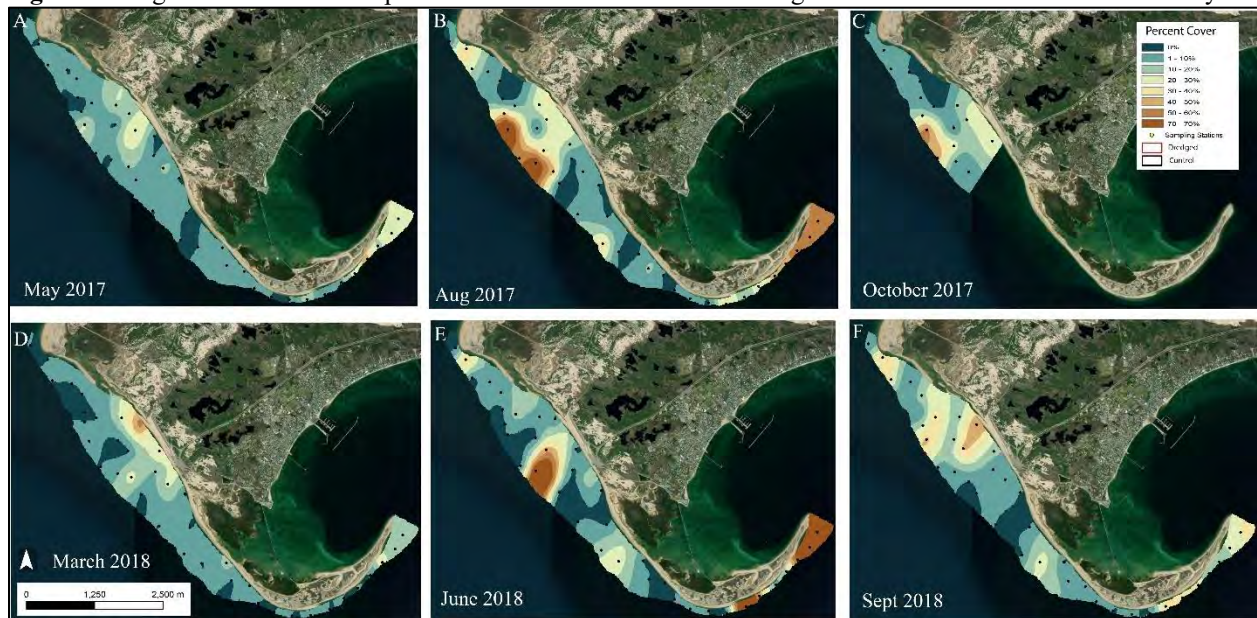


Figure 48. Interpolation of percent cover of gravel derived from quarterly video sampling along transect from Race Point to Long Point.

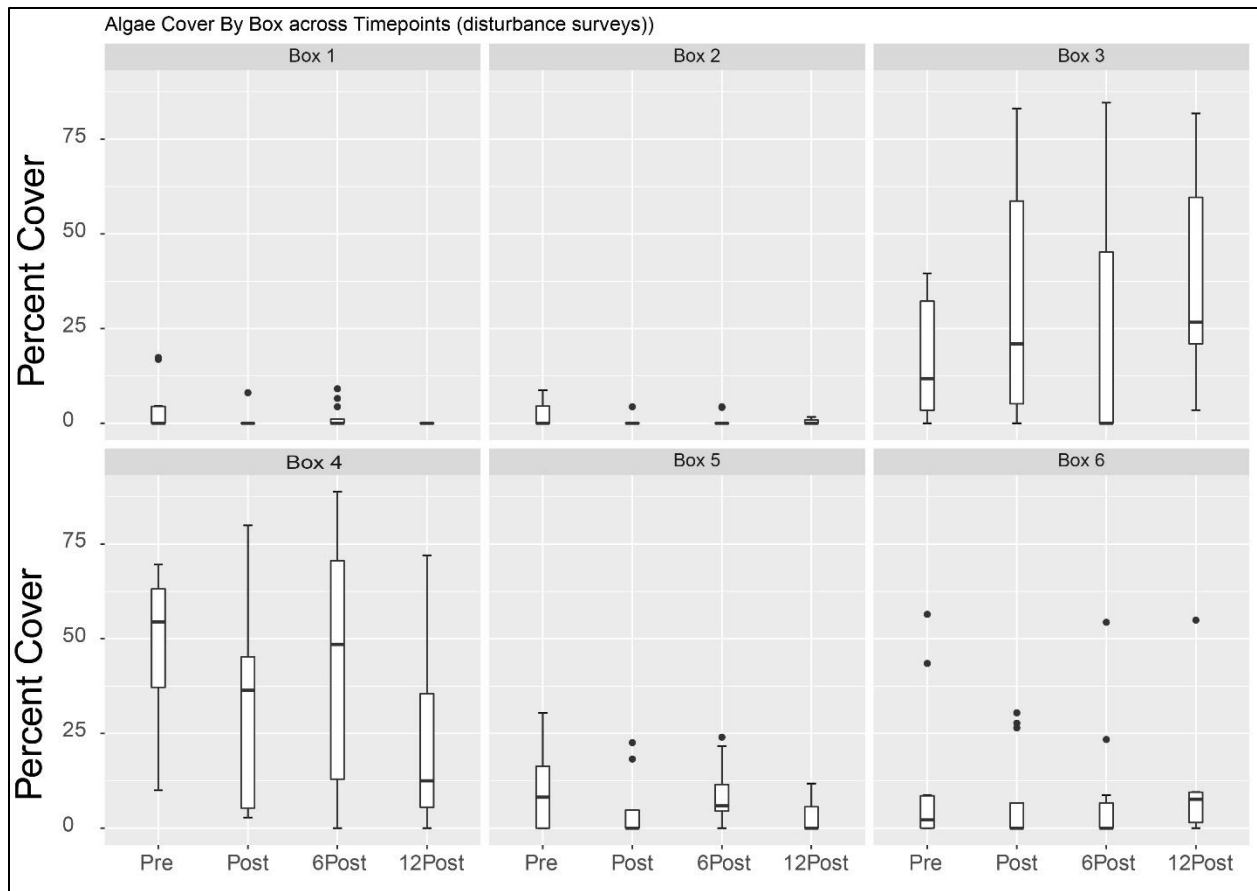


Figure 49. Algae cover from all drops in each box of the disturbance study across each time point from the Video assessment analysis.



Figure 50. Interpolation of percent cover of gravel at invertebrate stations at Herring Cove from video analysis.

4.10. Physical Recovery of the Seafloor

This section—while not specific to an instrument, data set, or technique, as are the above sections—is presented here to discuss results from the synthesis of the relevant information presented thus far. Recovery as defined here is the physical recovery of the substrate, or absence

of dredge tracks in places where they were present in the past. This was determined via inspection of sidescan imagery.

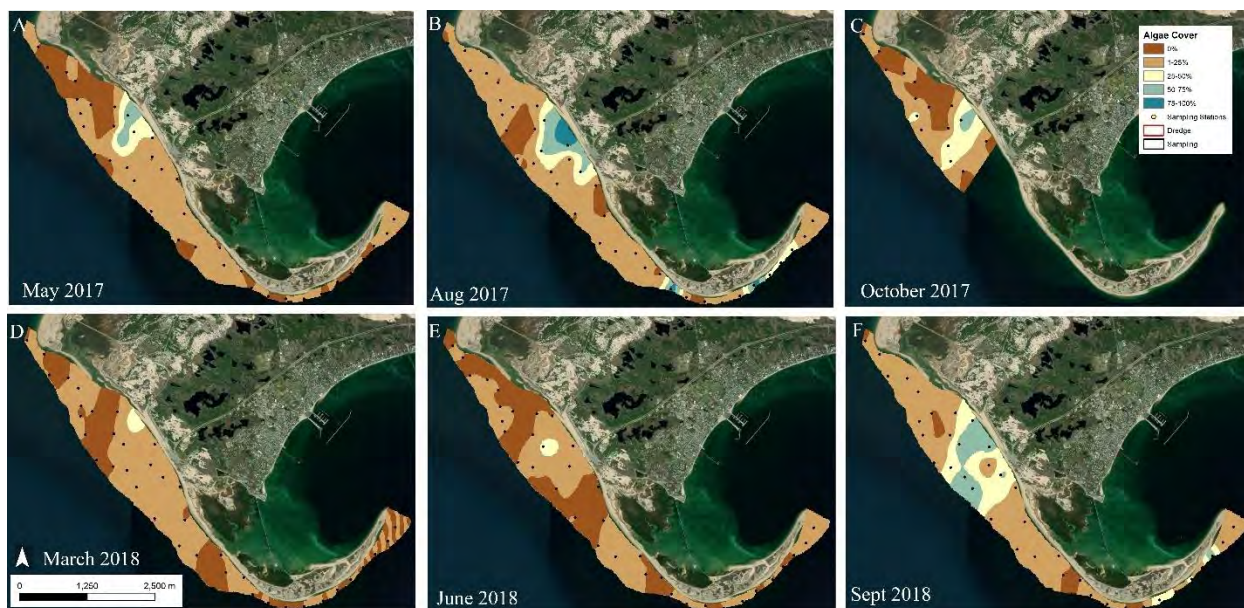


Figure 51. Interpolation of percent algae cover as determined by quarterly video analysis along transects from Race Point to Long Point.

To explain the factors that influence the physical recovery of the substrate, a series of quantitative, descriptive, and non-parametric analyses were undertaken. Models and statistics were developed in the statistical open-source software R and utilized the package “RandomForest”. Recursive partitioning methods (e.g. Random Forest), which break complicated analyses into simple analyses that are easier to understand. As such, they are a popular tool to classify data sets with large numbers of predictor variables with complex interactions, and they can be used to predict outcomes. Random Forest relies on both a training and testing datasets, to assess the accuracy of the model. Data are partitioned into the two datasets by randomly assigning two thirds of the data as a training set and the remaining one third as a testing set. Simple classification decision trees are then created by calculating cut points resulting binary outputs. In Random Forest, many of these decision trees (many trees form a forest) are created by either bootstrapping or subsampling the training data set across many permutations by randomly restricting each split in the decision tree. This combination of restrictive splits and bootstrapped/subsampling during multiple permutations creates an improved model, even from weak relationships.

The Random Forest models were developed to predict the physical recovery from disturbance dredging at different time points, including immediately after the disturbance occurred. The following analysis was used to examine both the 2014 – 2015 and 2017 data sets. The final model was chosen by a combination of low mean squared error (MSE), variance, and simplest number of variables (**Table 17**).

Table 17. Random Forest model results for different combinations of variables. Lowest MSE (Mean Square Error), % Variance of the response (%Var(y)) and Low number of variables were chosen used to select Model 1.

Model	Out of bag MSE	% Var (y)	Dredge intensity	V_Gravel (%)	Algae (%)	Depth (m)	QSBC	Grain size	Slope
Model 1	0.04596	8.23	x	x	x	x	x		
Model 2	0.04762	8.53	x	x	x	x	x	x	x
Model 3	0.04802	8.6	x	x	x		x	x	
Model 4	0.04957	8.88	x	x	x		x	x	
Model 5	0.12000	21.48	x			x	x	x	x
Model 6	0.07350	13.16	x	x		x	x		x
Model 7	0.08466	15.16	x	x		x	x		x
Model 8	0.10260	18.36	x	x		x	x		
Model 9	0.08033	14.38		x	x		x		
Model 10	0.04603	8.24		x	x	x	x	x	x
Model 11	0.07707	13.8	x	x	x	x			

The final model equation is as follows:

$$Recovery = Dredge\ Intensity + V_Gravel\ \% \ Cover + Algae\ \% \ Cover + Depth\ (m) + QSBC$$

Since we did not have an initial impact and extent of the 2014 – 2015 disturbance, we could not predict persistence based on many of the parameters available for the 2017 disturbance. Models were only useful within the time points and dredging intensities observed. For example, recovery for the controlled disturbance study was modeled for four time points (PRE, POST, 6POST, and 12POST) for all areas impacted between 1-11% dredge intensity. Recovery for the 2015 uncontrolled dredging did not have an initial impact component and was modeled at 5 time points (2015, PRE, POST, 6POST, and 12POST) at dredge intensities between 0-53%. The accuracy of the models was high as for the 2017 data as both training and testing data sets resulted in a high overall accuracy for the training data (95%) and testing data (92%) (Table 18). The accuracy of the models was high as for the 2015 data as well as both training and testing data sets resulted in a high overall accuracy for the training data (95%) and testing data (93%) (Table 19).

Decision trees for the 2015 and 2017 data sets identified important breaks in the data (Figure 53). In the 2014 – 2015 dredging event areas that had a dredge intensity of less than 22% were found to recover between the 2015 survey and the “PRE” time point (10/23/2017). Dredge tracks that survived from the 2015 survey to the final survey of this study (12 months; 12/9/2018) were those that had high compaction (QSBC > 65.5 kPa), and/or gravel cover greater than 20.5% (Figure 53).

Table 18. Confusion matrix for random forest model predictions for the 2017 data sets. Both training and testing data sets resulted in a high overall accuracy for the training data (95%) and testing data (92%).

Training Accuracy 2017				
Prediction	PRE	POST	6POST	12POST
Impact	5113	128	12	10
POST	120	2748	49	10
6POST	5	34	508	22
12POST	5	13	19	229
Overall	Accuracy	0.9527		
	95% CI	(0.9481,0.957)		
No information rate	0.5809			
P-Value	<2e-16			
Kappa	0.9142			

Testing Accuracy 2017				
Prediction	PRE	POST	6POST	12POST
Impact	1567	56	1	8
POST	77	880	29	5
6POST	2	18	152	8
12POST	6	4	8	75
Overall	Accuracy	0.9233		
	95% CI	(0.913,0.933)		
No information rate		0.5704		
P-Value		<2e-16		
Kappa		0.9632		

Table 19. Confusion matrix for random forest model predictions for the 2015 data sets. Both training and testing data sets resulted in a high overall accuracy for the training data (95%) and testing data (93%).

Training Accuracy 2015					
Prediction	2015	PRE	POST	6POST	12POST
2015	11537	25	134	53	27
PRE	12	79	17	1	1
POST	92	30	1250	88	49
6POST	29	4	71	1097	39
12POST	38	3	66	48	2826
Overall	Accuracy	0.9531			
	95% CI	(0.9498, 0.9561)			
No information rate		0.6646			
P-Value		2.20E-16			
Kappa		0.9088			

Testing Accuracy 2015					
Prediction	2015	PRE	POST	6POST	12POST
2015	3791	16	79	29	14
PRE	8	28	4	0	2
POST	51	9	337	26	21
6POST	20	0	26	344	12
12POST	16	1	41	27	918
Overall	Accuracy	0.9309			
	95% CI	(0.9241 ,0.9373)			
No information rate		0.6677			
P-Value		2.20E-16			
Kappa		0.8643			

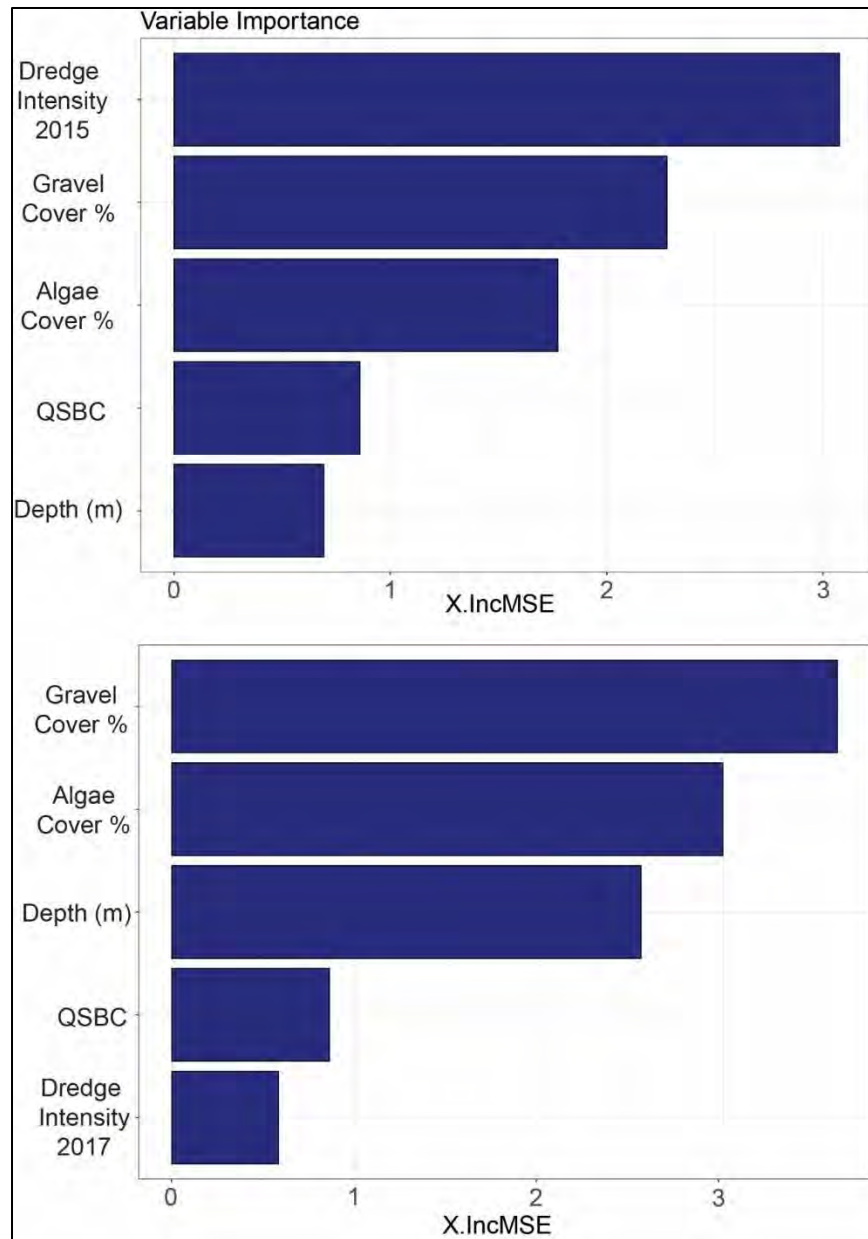


Figure 52. Variables of importance from the 2015 random Forrest model (top) and the 2017 random forest model (bottom) indicating which variable is most influential to the models outcome by measuring the increase of mean squared error (X.IncMSE).

This indicates the multi-year recovery of the dredge tracks were a combination of dredge intensity, and habitat constituents. The 2017 data set, dredge intensity which was all under 11% was the least important variable (Figure 52). The model identified habitats that recovered between disturbance and survey (PRE to POST; 24 days) that were primarily sand with less than 12.5% gravel (Figure 53). Long-term recovery occurred in habitats that in addition to high gravel included high algae cover (>28.5%) (Figure 53). This analysis emphasizes that the video analysis of bottom types is an important factor. This was particularly due to the greater understanding of the microhabitats

across the study sites provided by video than was available via bottom grab samples alone. In addition to the persistence of dredge tracks through time as dependent on habitat type, dredge track persistence was greater in the alongshore direction than the cross-shore direction (Figure 34, Figure 35).

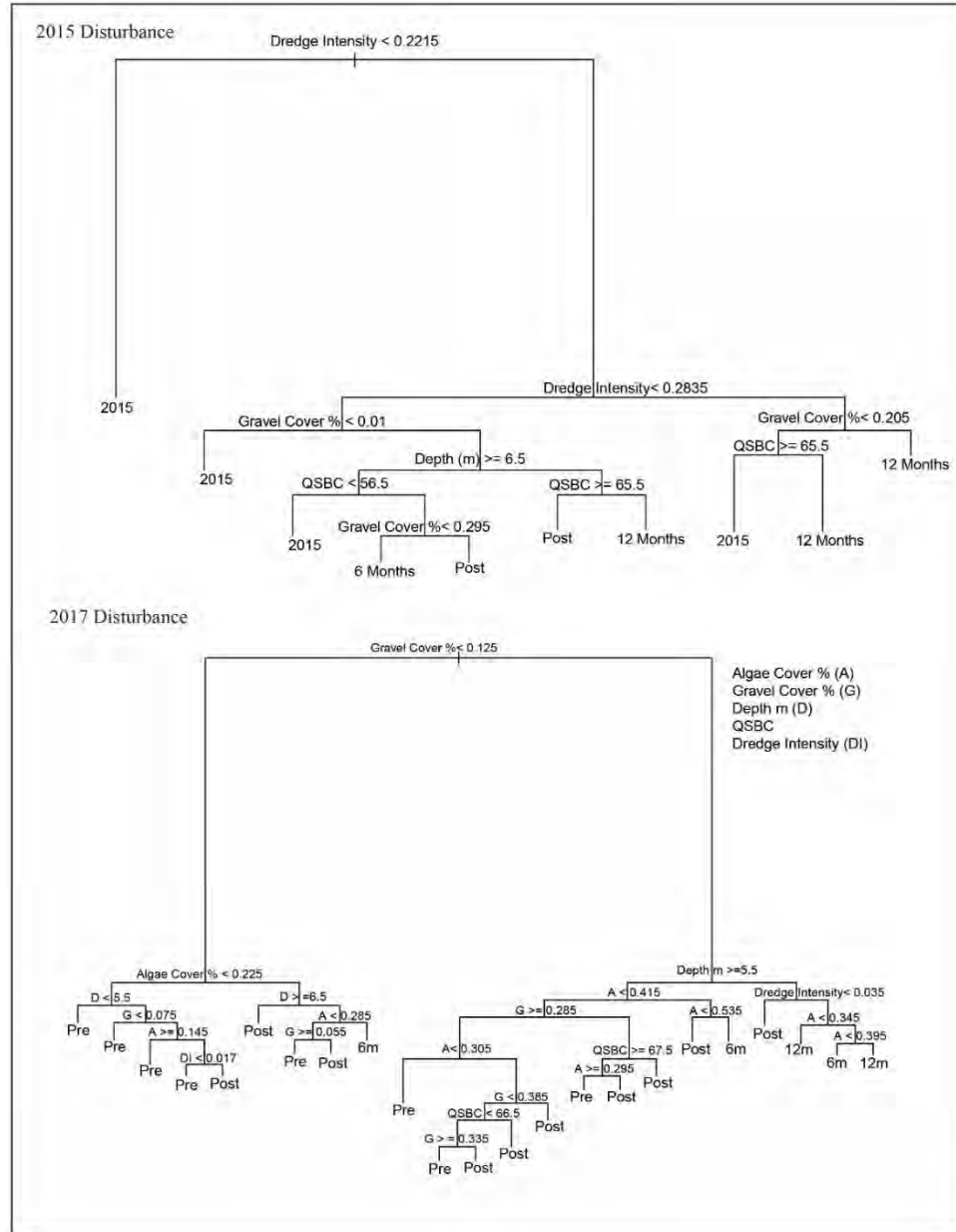


Figure 53 Decision tree from Random Forest model for both the 2015 data set (top) and 2017 data set (bottom).

5. CONCLUSIONS

This section uses the above results to support or refute the hypotheses developed for this study. If a hypothesis cannot be fully supported or refuted, further work is needed and the hypotheses tested must be refined in light of recent findings.

The six hypotheses developed for this report and the relevant data are as follows:

1. A seasonal pattern to tidal current velocities and wave climate in the vicinity of Herring Cove Beach can be documented by quarterly, spring-to-neap Acoustic Doppler Current Profiler (ADCP) surveys.
 - Finding: **We can support this hypothesis.**

Our ADCP data are in good agreement with NOAA buoys both in Cape Cod Bay and north of Provincetown, suggesting that the ADCP is collecting meaningful data that can be used to characterize the wave and current energy at the study site. Per the Bird (2008) classification thresholds, the mean annual significant wave height at our study site indicates a low wave energy coast.

There is a clear seasonal pattern to tidal currents and wave climate in the study area (Figure 14, Appendix D). The tidal current velocities are semi-diurnal (twice-daily) and bi-directional. Falling tides move water along shore from Long Point to Race Point; the opposite is true for rising tides, with currents moving along shore from Race Point to Long Point. The wave climate pattern follows the regional trends with northwest waves dominant in the winter months, or during storm-weather conditions, and southwest waves in the summer months, or fairweather conditions. Although an oversimplification, tidal current velocities increase when they are moving in the same direction as the predominant waves and decrease when they are moving in opposing directions.

The overall results were expected with regards to seasonality, but the rigorous measurement of these parameters, during six surveys from July 2017 through January 2019, are critical to accurately and quantitatively classify this coastal compartment. These most basic wave and current data had never been collected off Herring Cove Beach and will aid in addressing other hypotheses within this study, improve the management of this area, and greatly benefit future studies across a wide range of disciplines.

2. There is a direct relationship between the offshore tidal currents and wave climate and the onshore coastal morphology.
 - Finding: **We can support this hypothesis.**

The onshore and offshore environments demonstrate this relationship. For example, the Hatches Harbor barrier spit and Long Point (also a barrier spit) are elongating alongshore in the direction of net sediment transport roughly to the southeast and northeast respectively. Increased wave

energy during the winter months leads to a decrease in the onshore slope and a slight increase in the offshore slope as the system equilibrates to the seasonal wave climate. This is typical along natural beaches. In the summer, the beachface is steep as the beach is ‘high and wide’ as sediment is moved onshore by the fairweather wave conditions. The offshore beach profile becomes flatter as the material is moved from the offshore onto the beach. In the winter, when storm weather conditions prevail, material is eroded from the beach, which results in decreases in slope as the beach becomes ‘low and flat.’ That material is moved offshore with a commensurate slight increase in the offshore slope.

3. There exists a spatial variability of compaction of non-cohesive sediment from Race Point to Long Point for similar-sized sediment.

- Finding: **We can support this hypothesis.**

The quasi-static bearing capacity (QSBC), a proxy for sediment strength relative to compaction, based on the deployment of the free-fall penetrometer ($n = 796$) documents variability in study area. Based on the peer-reviewed literature, the variability seen in the data for this project is demonstrable and repeatable. We cannot say conclusively, however, what the drivers or processes are responsible for the documented variability. There is not a direct correlation between QSBC and water depths, though the range of water depths seen here ($\sim 4 - 8$ m) are not as great as other locations with documented relationships (Albatal et al. 2019). We also do not see a strong signal for seasonality, which suggests that wave energy and/or other seasonal parameters are not the main drivers in sediment compaction. It is very likely that the consistency of sediment characteristics (grain size, sorting, skewness) throughout the study area both temporally and spatially are linked to the low variability of sediment compaction in the area.

4. The compaction of similar-sized sediment is different in areas of documented bottom disturbance (e.g., hydraulic clamming) than in areas with no documented bottom disturbance.

- Finding: **We can partially support this hypothesis.**

A clear pattern can be seen at each impact box (1-6) of increasing QSBC values (a proxy for sediment compaction) over the course of the study (Figure 18), however, we do not see a strong signal in the QSBC data before and after the 2017 impact. Boxes 1, 2, and 6 show only a slight increase in QSBC between the pre- and post-impact periods. Boxes 3, 4, and 5 show smaller change in magnitudes relative to 1, 2 and 6. These changes have been documented, but do not support this hypothesis as standalone data points.

The six boxes were drawn to create a control and impact group for the 2017 clamming event, but also to incorporate in both groups different levels of disturbance from the 2015 event. The relationship between the pre- and post- changes in QSBC correlate well with the presence/absence

of gravel shown in the QSBC data collected along transects as well as the bottom video analysis. In areas where gravel is present we see smaller changes in PRE- vs post-impact QSBC values. This would be consistent with a thin sand layer over a gravel bottom that is typical in the higher energy wave climates between fall and early spring. While this is itself an hypothesis, it is supported by the data and serves to partially support the larger hypothesis.

5. Providing no further anthropogenic disturbance, the compaction in bottom disturbed areas will increase through time to pre-disturbance levels.

- **Response: We can partially support this hypothesis.**

Our analysis and a subsequent article in the peer-reviewed literature (Legare et al. 2020b) shows that as of October 2017, the pre-disturbance survey documented dredge tracks made between October 2014 – April 2015 had persisted in some instances more than 875 days and up to maximum of 1,350 days. By fall of 2017, ~3% of the 2015 dredge tracks mapped by the CCS within the present study area in July 2015 (Borrelli et al, 2019) remained - 1,290 to 1,765 days after the 2015 dredge event. The most important parameter related to persistence of these tracks was the density of dredge tracks on the seafloor – the denser the dredge tracks, the more persistent the impacts.

Despite being a relatively low-energy area, shear velocities at the site are large enough for initiation of sediment movement. During the more than 150 days of ADCP deployment, shear velocity at the site was above the threshold for sediment movement (based on average grain size across the study area) for 81% of deployment time periods. Current velocities at the site are sufficient for moving sediment most of the time and likely play a role in evolution of dredge tracks.

The 2017 dredge tracks largely recovered over the course of the year. Even as the impacts from the 2017 event were largely gone, less than 1% of dredge tracks remained, 3% of the 2014-2015 dredge tracks persisted through the end of the study. It should be noted that the mapping of the 2014-2015 clamming was mapped by CCS 3-6 months after impact ended in July 2015 and therefore did not map the entire impact. The physical recovery of the sea floor was in part related to the constituents of the habitat and the intensity of the harvest. Dredge track density ranged from 0-11% at initial impact for the 2017 event. When adding the 2014-2015 dredge tracks that were still present in 2017, the dredge track density ranged from 0-17% (Figure 23). The majority (75%) of dredge tracks were oriented alongshore with the remaining 25% being cross shore. As the dredge tracks evolved from initial disturbance, the cross-shore tracks disappeared faster than the alongshore tracks. This pattern was also evident in the evolution of the dredge tracks that were created in the 2014-2015 disturbance event.

The combination of video habitat assessment and vessel-based sonar surveys has provided insight into the physical recovery of the substrate. The 2014-2015 dredging event and the 2017 dredging event represent two different dredging intensities and impacts to the seafloor. The most important

variable to predict the recovery of the substrate was the high dredge intensity for the 2014-2015 event and gravel cover for the low intensity 2017 dredge event. As mentioned above, dredging intensity herein is a measure of bottom disturbance quantified during GIS-based spatial analysis of acoustic data. The 2014-2015 model indicates that areas that have high initial impact across complex habitat (such as off Herring Cove Beach) will recover slower than low impact areas of lower complexity such as the sand (between Race Point and Herring Cove or from Herring Cove to Wood End). Our analysis indicates that when dredging intensity exceeds 22.5% of the seafloor, recovery is a multiple year process. As the dredging intensity and equipment was lighter in 2017, this event allowed us to document recovery rates relative to habitat type. The 2017 model indicates that high gravel (exceeding 12.5%) and/or high algae (exceeding 28.5%) are more sensitive habitats and are slower to recover when exposed to dredging. It also indicates that areas with more sand and low complexity (low algae and gravel) can recover in a short period of time.

6. The benthic invertebrate communities are different in areas of documented bottom disturbance (e.g., hydraulic clamming) than in areas with no documented bottom disturbance. Providing no further anthropogenic bottom disturbance, the invertebrate communities in disturbed areas of the sea floor will recover through time to pre-disturbance levels.

- **Response: We can partially support this hypothesis.**

There was no significant difference in species richness at disturbed vs. not disturbed areas. At all four timepoints, the most important variables explaining species diversity were algae and water depth, explaining a total of 33.37%, 35.46%, 45.7% and 26.06% (tables 5-8).

Separating the data set into mobile and sessile species groups showed that mobile species appear to follow a typical seasonal pattern of higher diversity in spring/summer and lower diversity in fall/winter (Mellard et al. 2019; Tonkin et al. 2017), with 6POST (in spring) richness reaching 81% of pre-disturbance levels. Indicating that, while the mobile species assemblage changed in numbers, it continued following seasonal pattern and appeared to suffer little to no effects caused by the disturbance event. However, sessile species, after decreasing in diversity by 40% from PRE to POST sampling dates, did not follow expected seasonal patterns. Spring (6POST) diversity in mobile species reached 67% of pre-disturbance levels indicating that while some increase was observed, it did not reach the same level as in mobile species.

In a previous, unrelated study, CCS collected invertebrate samples within the study area in 2015 (Borrelli et al. 2019). Three of the previously sampled stations (PT4, PT9, and PT10) overlap with this current study. Data collected then showed 62 taxa of benthic infauna, 56 of which were also identified in the current study. Statistical analyses showed no significant differences between species community composition at those three stations in 2015 and this current study. This

previous, larger, study area, lacking substantial benthic fishing activity due to federal protection within Seashore boundaries and local town moratoriums, can act as a seed population, providing the individuals necessary to re-populate the impacted areas. Healthy populations surrounding impacted areas (both natural and anthropogenic) are essential in the recovery of the affected ecosystem (Barnes and Conlan 2006; Dittmann et al. 1999; Goode et al. 2020; McLusky et al. 1983). Mobile species, such as certain types of polychaetes (Neredidae, Polynoidae) are opportunists that can re-colonize a recently disturbed area following specific succession patterns (Hilbig and Blake 2000). Species with low mobility and/or high site fidelity (e.g. molluscs attached to substrate) generally follow colonizing species and can be expected to appear in lower numbers while the area is still recovering (as can be seen in Table 20) (Legare et al. 2020a; Medeiros-Bergen and Miles 1997.; Patricio and Dearborn 1989). Studying the effects of a previous dredging event in 2014-2015 in the same area, Legare et al. (2020a) mention that “low levels of disturbance led to a mixture of opportunistic species and site attached, low mobility organisms, consequently resulting in the highest species abundance and diversity that was found.” This fits directly with the intermediate disturbance hypothesis, in which varied levels of natural or anthropogenic disturbances result in higher biodiversity and species richness compared to newly formed habitats or mature habitats (Connell 1978; Lasiak and Field 1995).

Video assessment has become a major tool providing information on benthic habitats. Not only do still images aid in the determination of ground cover, which was of significant importance in determining drivers of benthic species communities in this study, the still images also allowed for a better understanding of the study area (e.g. why grabs were unsuccessful). The quarterly transects helped provide a look into the natural trends of the system showing the ephemeral nature of the algae growth and identified the area off Herring Cove as a complex hard bottom with a matrix of sand, gravel, shell, and algae that contributes to the diverse ecosystem. The video assessment allowed for augmentation of benthic habitat maps, development of models of recovery, and insight into how the benthic invertebrate community responds. It is a well-known fact that vegetation, indeed any kind of structure, on the seafloor results in increased species diversity as compared to non-vegetated areas (Beck 2000; Dealteris et al. 2004; Minello 1999; Orth et al. 1984). Vegetation such as *Codium* sp., *Chorda* sp., *Fucus* sp. *Ulva* sp. and other green, red, and brown filamentous algae as have been observed off Herring Cove provide shelter and food for many marine invertebrates (Heck et al. 1995; Mattila et al. 1999; Mittermayr et al. 2022), thus making a population more resilient to disturbances. More research could evaluate drivers of algal habitats and any relationships between disturbances and algal cover.

While the recovery of mobile species diversity was well underway by the last sampling event (12POST), sessile species diversity numbers had recovered to a lesser extent. The high prevalence of vegetation in the area and the adjacent protected areas provided a healthy population of mobile colonizing species that were able to supplement impacted areas.

After 12 month, pre-impact (12POST) levels of biodiversity have not been reached. However, given no further disturbances, the continuation of areas of abundant submerged aquatic vegetation and the continuation of the recovery rate that was observed in the first year, biodiversity for both mobile and sessile species, is very likely (IPCC 2022) to can reach pre disturbance levels (**Table 20**).

Table 20. Percent recovery of mobile and sessile taxa in the Herring Cove study area measured at 6 months post-disturbance (6POST) and predictions for years 2-6 post disturbance. 6POST (spring) was chosen as this timepoint is closest to peak biomass (summer)

Group	PRE	6POST	18POST	30POST	42POST	54POST	66POST
Mobile	100	81	93	100			
Sessile	100	67	74	81	88	95	100

It has been speculated in the past that eelgrass beds could not become established off Herring Cove Beach as well as surrounding areas due to high wave energy. In terms of seagrass bed habitat, Fonseca (Fonseca 1998) indicates that areas with currents > 30 cm/s are considered high current speed and therefore are less favorable for seagrass bed colonization and restoration. Depth-averaged cross-shore velocities were rarely greater than 25 cm/s in either the onshore or offshore direction, and maximum depth-averaged along-shore velocity was 50 cm/s in the northwest or southeast direction, but bottom velocities rarely exceeded 25 cm/s in either direction. This suggests that while some exceedingly fast currents (mostly attributed to storms) may discourage seagrass colonization, most of bottom current conditions at the study site are below a reasonable threshold for the maintenance of seagrass habitat. Therefore, current velocity at the site is not the main factor for seagrass habitat distribution. In fact, there is anecdotal evidence that the study area has extensive eelgrass beds up until the mid 20th century.

6. LITERATURE CITED

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7. APPENDIX A

Species List for PRE, POST, 6POST and 12POST

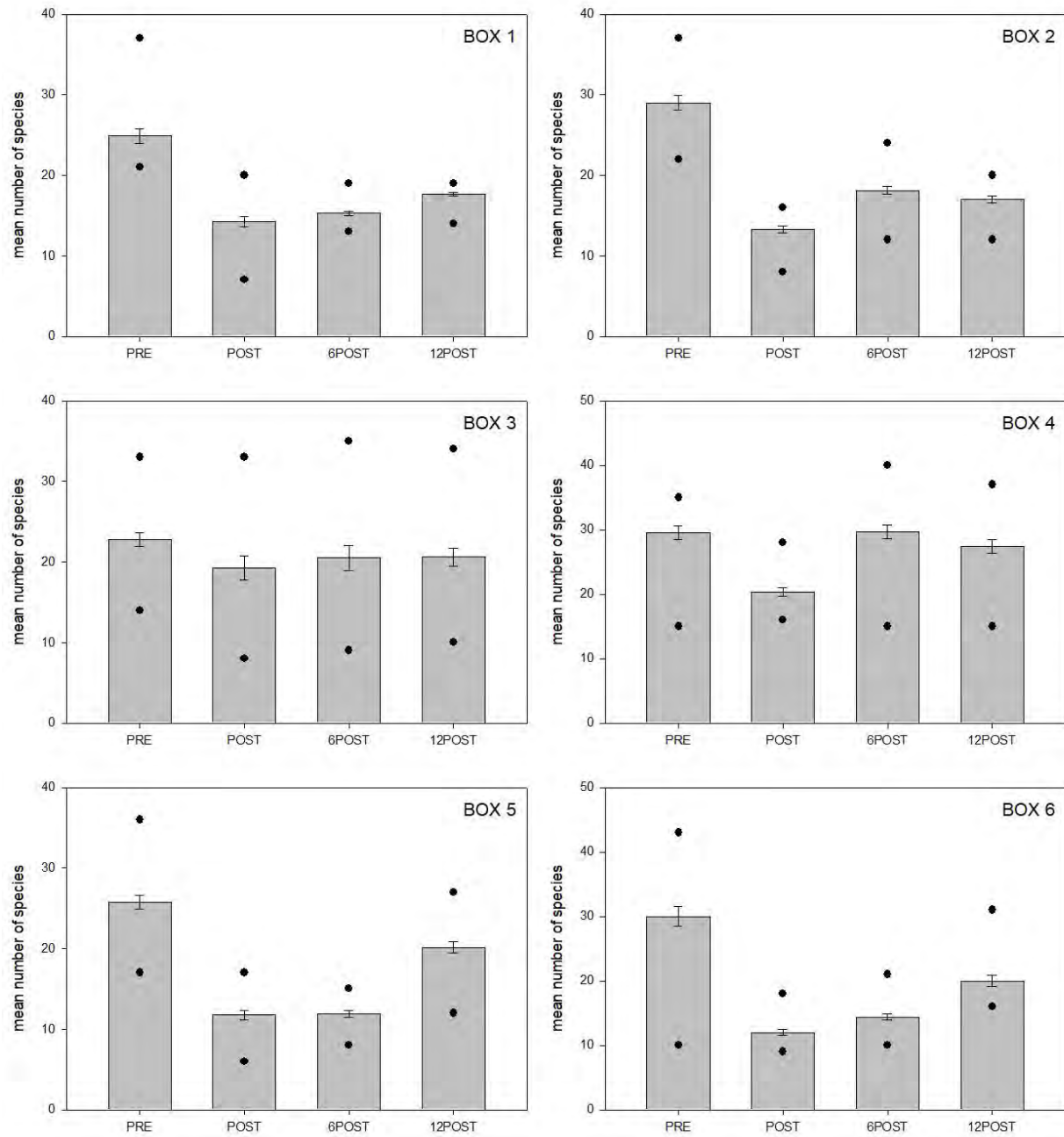


Figure A1: Mean species number ($\pm$ SE) for boxes and time points, including minimum and maximum number of species.

Table A1: Species list for PRE, POST, 6POST, 12POST

Phylum	Class	Order	Family	Genus	Taxon	AphiaID	PRE	POST	6 POST	12 POST
Mollusca	Gastropoda	Cephalaspidea	Tornatinidae	Acetocina	<i>Acetocina canaliculata</i>	160065	✓	✓	✓	✓
Cnidaria	Anthozoa	Actiniaria	Thalassianthidae	ActinERIA	<i>ActinERIA</i> spp.	267197	✓			
Annelida	Polychaeta	Phyllodocida	Nereididae	Alitta	<i>Alitta succinea</i>	234850	✓			
Annelida	Polychaeta	Phyllodocida	Nereididae	Alitta	<i>Alitta virens</i>	234851	✓	✓	✓	✓
Mollusca	Bivalvia	Cardiida	Tellinidae	Ameritella	<i>Ameritella agilis</i>	878476	✓	✓	✓	✓
Arthropoda	Malacostraca	Amphipoda	Ampeliscidae		Ampeliscidae sp	101364	✓			
Arthropoda	Hexanauplia	Sessilia	Balanidae	Amphibalanus	<i>Amphibalanus venustus</i>	421142		✓		
Echinodermata	Ophiuroidea	Amphilepidida	Amphiuridae	Amphipholis	<i>Amphipholis squamata</i>	125064		✓	✓	✓
Arthropoda	Malacostraca	Amphipoda	Ampithoidae	Ampithoe	<i>Ampithoe longimana</i>	158026		✓		✓
Arthropoda	Malacostraca	Amphipoda	Ampithoidae	Ampithoe	<i>Ampithoe</i> spp.	101459	✓			
Mollusca	Gastropoda	Neogastropoda	Columbellidae	Anachid	<i>Anachis</i> spp.	137802	✓			
Mollusca	Bivalvia	Arcida	Arcidae	Anadara	<i>Anadara transversa</i>	156734	✓	✓	✓	✓
Mollusca	Bivalvia	Pectinida	Anomiidae	Anomia	<i>Anomia simplex</i>	156737		✓	✓	✓
Mollusca	Bivalvia	Pectinida	Anomiidae	Anomia	<i>Anomia</i> spp.	137650	✓	✓		
Cnidaria	Anthozoa				<i>Anthozoa</i> spp.	1292				✓
Annelida	Polychaeta	Terebellida	Cirratulidae	Aphelochaeta	<i>Aphelochaeta</i> spp.	129240			✓	
Arthropoda	Malacostraca	Amphipoda	Corophiidae	Apocorophium	<i>Apocorophium acutum</i>	148604		✓	✓	✓
Annelida	Polychaeta	Eunicida	Oenonidae	Arabella	<i>Arabella iricolor</i>	129854	✓	✓	✓	
Echinodermata	Echinoidea	Arbacioida	Arbaciidae	Arbacia	<i>Arbacia punctulata</i>	158058			✓	
Mollusca	Bivalvia	Pectinida	Pectinidae	Argopecten	<i>Argopecten irradians</i>	156817				✓
Annelida	Polychaeta	Scolecida	Paraonidae	Aricidea	<i>Aricidea</i> spp.	129430	✓	✓	✓	✓
Chordata	Ascidiacea				<i>Ascidiacea</i> spp.	1839			✓	
Mollusca	Bivalvia	Carditida	Astartidae	Astarte	<i>Astarte castanea</i>	156744	✓	✓	✓	✓
Mollusca	Bivalvia	Carditida	Astartidae	Astarte	<i>Astarte undata</i>	156747	✓			
Echinodermata	Asteroidea				<i>Asteroidea</i> spp.	123080		✓		
Mollusca	Gastropoda	Neogastropoda	Columbellidae	Astyris	<i>Astyris lunata</i>	160102	✓	✓	✓	✓
Mollusca	Bivalvia	Galeommatida	Galeommatidae	Austrodevonia	<i>Austrodevonia percompressa</i>	876591			✓	✓
Arthropoda	Hexanauplia	Sessilia	Balanidae	Balanus	<i>Balanus crenatus</i>	106215			✓	✓
Mollusca	Gastropoda		Cerithiidae		<i>Bittiinae</i> spp.	411649	✓			

Phylum	Class	Order	Family	Genus	Taxon	AphiaID	PRE	POST	6POST	12POST
Mollusca	Gastropoda	Caenogastropoda	Cerithiidae	Bittium	<i>Bittium alternatum</i>	160172		✓	✓	✓
Mollusca					<i>Bivalvia</i> sp	105		✓	✓	✓
Mollusca	Gastropoda	Pylopulmonata	Pyramidellidae	Boonea	<i>Boonea seminuda</i>	420438		✓	✓	✓
Annelida	Polychaeta	Phyllodocida	Syllidae	Brania	<i>Brania</i> spp.	129648		✓		
Mollusca	Gastropoda	Littorinimorpha	Caecidae	Caecum	<i>Caecum cooperi</i>	160193			✓	
Arthropoda	Malacostraca	Amphipoda	Calliopidae	Calliopius	<i>Calliopius laeviusculus</i>	102178			✓	
Arthropoda	Malacostraca	Decapoda	Canceridae	Cancer	<i>Cancer borealis</i>	158056		✓	✓	✓
Arthropoda	Malacostraca	Decapoda	Canceridae	Cancer	<i>Cancer irroratus</i>	158057	✓	✓	✓	✓
Annelida	Polychaeta	Scolecida	Capitellidae		<i>Capitellidae</i> spp.	921			✓	✓
Arthropoda	Malacostraca	Amphipoda	Caprellidae	Caprella	<i>Caprella linearis</i>	101839		✓	✓	✓
Arthropoda	Malacostraca	Amphipoda	Caprellidae	Caprella	<i>Caprella penantis</i>	101846	✓	✓	✓	✓
Arthropoda	Malacostraca	Decapoda	Carcinidae	Carcinus	<i>Carcinus maenas</i>	107381	✓			
Nemertea	Palaeonemertea		Cephalotrichidae	Cephalotrichidae	<i>Cephalotrichidae</i> spp.	766122			✓	✓
Arthropoda	Malacostraca	Isopoda	Chaetiliidae	Chiridotea	<i>Chiridotea coeca</i>	157842	✓	✓	✓	✓
Annelida	Polychaeta	Terebellida	Cirratulidae		<i>Cirratulidae</i> spp.	919	✓		✓	✓
Annelida	Polychaeta	Terebellida	Cirratulidae	Cirratulu	<i>Cirratulus cirratus</i>	129959	✓			
Annelida	Polychaeta	Terebellida	Cirratulidae	Cirratulu	<i>Cirratulus parvus</i>	326787	✓			
Annelida	Polychaeta	Terebellida	Cirratulidae	Cirriformia	<i>Cirriformia grandis</i>	157297	✓	✓	✓	✓
Arthropoda	Malacostraca	Amphipoda	Corophiidae	Corophium	<i>Corophium</i> spp.	101489	✓			✓
Mollusca	Gastropoda	Neogastropoda	Columbellidae	Cotonopsis	<i>Cotonopsis lafresnayi</i>	511730	✓	✓	✓	✓
Arthropoda	Malacostraca	Decapoda	Crangonidae	Crangon	<i>Crangon septemspinosa</i>	158355	✓			
Arthropoda	Malacostraca	Amphipoda	Corophiidae	Crassiorophium	<i>Crassiorophium bonellii</i>	237004		✓	✓	✓
Mollusca	Bivalvia	Ostreida	Ostreidae	Crassostrea	<i>Crassostrea virginica</i>	140657	✓			
Mollusca	Gastropoda	Littorinimorpha	Calyptaeidae	Crepidula	<i>Crepidula fornicata</i>	138963	✓			
Mollusca	Gastropoda	Littorinimorpha	Calyptaeidae	Crepidula	<i>Crepidula</i> spp.	137722	✓	✓	✓	✓
Echinodermata	Holothuroidea	Dendrochiroidea	Cucumariidae	Cucumaria	<i>Cucumaria</i> spp.	123479	✓			
Arthropoda	Malacostraca	Cumacea			<i>Cumacea</i> spp.	1137	✓			
Arthropoda	Malacostraca	Amphipoda	Ampithoidae	Cymadusa	<i>Cymadusa compta</i>	158082	✓			
Arthropoda	Malacostraca	Amphipoda	Dexaminidae	Dexamine	<i>Dexamine thea</i>	102136	✓	✓	✓	✓
Mollusca	Gastropoda	Cephalaspidea	Cylichnidae	Diaphana	<i>Diaphana minuta</i>	139557			✓	

Phylum	Class	Order	Family	Genus	Taxon	AphiaID	PRE	POST	6POST	12POST
Annelida	Polychaeta	Eunicida	Onuphidae	Diopatra	<i>Diopatra cuprea</i>	157339	✓		✓	✓
Annelida	Polychaeta	Terebellida	Cirratulidae	Dodecaceria	<i>Dodecaceria spp.</i>	129246	✓			
Annelida	Polychaeta	Eunicida	Oenonidae	Drilonereis	<i>Drilonereis longa</i>	157357	✓	✓		
Arthropoda	Malacostraca	Decapoda	Panopeidae	Dyspanopeus	<i>Dyspanopeus sayi</i>	107412			✓	✓
Echinodermata	Echinoidea				<i>Echinoidea spp.</i>	123082		✓		✓
Cnidaria	Anthozoa	Actiniaria	Edwardsiidae	Edwardsia	<i>Edwardsia elegans</i>	158235		✓	✓	✓
Mollusca	Gastropoda	Littorinimorpha	Calypttracidae	Egrea	<i>Egrea walshi</i>	572294	✓			
Arthropoda	Malacostraca	Amphipoda	Maeridae	Elasmopus	<i>Elasmopus levis</i>	421508	✓	✓	✓	✓
Mollusca	Bivalvia	Adapedonta	Pharidae	Ensis	<i>Ensis leei</i>	876640	✓		✓	✓
Arthropoda	Malacostraca	Amphipoda	Phoxocephalidae	Eobrolgus	<i>Eobrolgus spinosus</i>	158087		✓		
Annelida	Polychaeta	Phyllodocida	Phyllodocidae	Eteone	<i>Eteone longa</i>	130616	✓			
Arthropoda	Malacostraca	Decapoda	Thoridae	Eualus	<i>Eualus pusiolus</i>	107507		✓		✓
Annelida	Polychaeta	Phyllodocida	Phyllodocidae	Eumida	<i>Eumida sanguinea</i>	130644	✓		✓	
Mollusca	Gastropoda	Littorinimorpha	Naticidae	Euspira	<i>Euspira heros</i>	160315	✓	✓	✓	✓
Mollusca	Gastropoda	Littorinimorpha	Naticidae	Euspira	<i>Euspira spp.</i>	138239		✓		
Mollusca	Gastropoda	Littorinimorpha	Naticidae	Euspira	<i>Euspira triseriata</i>	160323	✓	✓	✓	✓
Annelida	Polychaeta	Phyllodocida	Syllidae	Eusyllis	<i>Eusyllis blomstrandii</i>	131290	✓			
Arthropoda	Malacostraca	Amphipoda	Gammaridae	Gammarus	<i>Gammarus lawrencianus</i>	158093		✓		
Arthropoda	Malacostraca	Amphipoda	Gammaridae	Gammarus	<i>Gammarus spp.</i>	101537	✓		✓	✓
Mollusca	Bivalvia	Venerida	Veneridae	Gemma	<i>Gemma gemma</i>	156803				✓
Annelida	Polychaeta	Phyllodocida	Glyceridae	Glycera	<i>Glycera americana</i>	157388	✓	✓	✓	✓
Annelida	Polychaeta	Phyllodocida	Glyceridae	Glycera	<i>Glycera capitata</i>	130118	✓			
Annelida	Polychaeta	Phyllodocida	Goniadidae	Goniadella	<i>Goniadella gracilis</i>	130145		✓	✓	✓
Annelida	Polychaeta	Phyllodocida	Goniadidae		<i>Goniadidae spp.</i>	953	✓			
Annelida	Polychaeta	Phyllodocida	Polynoidae	Harmothoe	<i>Harmothoe extenuata</i>	130762		✓	✓	✓
Annelida	Polychaeta	Phyllodocida	Polynoidae	Harmothoe	<i>Harmothoe imbricata</i>	130769	✓	✓	✓	✓
Annelida	Polychaeta	Phyllodocida	Polynoidae	Harmothoe	<i>Harmothoe spp.</i>	129491	✓	✓	✓	✓
Annelida	Polychaeta	Phyllodocida	Nereididae	Hediste	<i>Hediste diversicolor</i>	152302	✓			
Annelida	Polychaeta	Phyllodocida	Hesionidae		<i>Hesionidae spp.</i>	946		✓		
Arthropoda	Malacostraca	Mysida	Mysidae	Heteromysis	<i>Heteromysis formosa</i>	148701		✓		

Phylum	Class	Order	Family	Genus	Taxon	AphiaID	PRE	POST	6POST	12POST
Mollusca	Bivalvia	Adapedonta	Hiatellidae	Hiatella	<i>Hiatella arctica</i>	140103			✓	
Mollusca	Bivalvia	Adapedonta	Hiatellidae	Hiatella	<i>Hiatella</i> spp.	138068	✓			
Annelida	Polychaeta	Terebellida	Ampharetidae	Hobsonia	<i>Hobsonia florida</i>	333624	✓			
Mollusca	Gastropoda	Littorinimorpha	Hydrobiidae	Hydrobia	<i>Hydrobia</i> spp	138081	✓			
Arthropoda	Malacostraca	Isopoda	Idoteidae	Idotea	<i>Idotea balthica</i>	119039	✓		✓	
Arthropoda	Malacostraca	Amphipoda	Ischyroceridae	Jassa	<i>Jassa marmorata</i>	102433			✓	
Mollusca	Bivalvia	Galeommatida	Lasaeidae	Kurtiella	<i>Kurtiella planulata</i>	876479	✓			
Mollusca	Gastropoda	Littorinimorpha	Littorinidae	Lacuna	<i>Lacuna vincta</i>	140170	✓		✓	
Mollusca	Bivalvia	Cardiida	Cardiidae	Laevicardium	<i>Laevicardium mortini</i>	156782		✓		
Arthropoda	Malacostraca	Amphipoda	Aoridae	Lembos	<i>Lembos websteri</i>	102033	✓			
Annelida	Polychaeta	Phyllodocida	Polynoidae	Lepidonotus	<i>Lepidonotus squamatus</i>	130801	✓	✓	✓	✓
Echinodermata	Holothuroidea	Apodida	Synaptidae	Leptosynapta	<i>Leptosynapta tenuis</i>	158485	✓	✓	✓	✓
Annelida	Polychaeta	Scolecida	Paraonidae	Levinsenia	<i>Levinsenia gracilis</i>	130578	✓			
Arthropoda	Malacostraca	Decapoda	Epialtidae	Libinia	<i>Libinia dubia</i>	107335	✓			
Arthropoda	Malacostraca	Decapoda	Epialtidae	Libinia	<i>Libinia emarginata</i>	158426			✓	✓
Mollusca	Bivalvia	Cardiida	Tellinidae	Limecola	<i>Limecola balthica</i>	880017	✓			
Mollusca	Gastropoda	Littorinimorpha	Velutinidae	Limneria	<i>Limneria undata</i>	159903	✓			
Nemertea	Pilidiophora	Heteronemertea	Lineidae	Lineidae	<i>Lineidae</i> spp.	122314		✓	✓	✓
Mollusca	Gastropoda	Littorinimorpha	Littorinidae	Littorina	<i>Littorina littorea</i>	140262	✓	✓	✓	✓
Annelida	Polychaeta	Eunicida	Lumbrineridae		<i>Lumbrineridae</i> spp.	967	✓			
Annelida	Polychaeta	Eunicida	Lumbrineridae	Lumbrinerides	<i>Lumbrinerides acuta</i>	130228	✓			
Mollusca	Bivalvia	Venerida	Mactridae	Lutraria	<i>Lutraria angustior</i>	140294	✓			
Mollusca	Bivalvia		Lyonsiidae	Lyonsia	<i>Lyonsia arenosa</i>	140290	✓			
Mollusca	Bivalvia	Anomalodesmata	Lyonsiidae	Lyonsia	<i>Lyonsia hyalina</i>	156793			✓	
Mollusca	Bivalvia	Anomalodesmata	Lyonsiidae	Lyonsia	<i>Lyonsia</i> spp.	138154	✓	✓		
Arthropoda	Malacostraca	Amphipoda	Lysianassidae	Lysianopsis	<i>Lysianopsis alba</i>	158036	✓			
Arthropoda	Malacostraca	Amphipoda	Maeridae	Maera	<i>Maera danae</i>	158037	✓			
Mollusca	Gastropoda	Trochida	Margaritidae		<i>Margarites helicinus</i>	141821	✓			
Arthropoda	Malacostraca	Amphipoda	Melitidae	Megamoera	<i>Megamoera dentata</i>	423508	✓			
Arthropoda	Malacostraca	Amphipoda	Melitidae	Melita	<i>Melita nitida</i>	146922	✓			

Phylum	Class	Order	Family	Genus	Taxon	AphiaID	PRE	POST	6POST	12POST
Mollusca	Bivalvia	Venerida	Veneridae	Mercenaria	<i>Mercenaria mercenaria</i>	141919	✓	✓	✓	✓
Arthropoda	Malacostraca	Amphipoda	Aoridae	Microdeutopus	<i>Microdeutopus anomalus</i>	102043		✓	✓	✓
Arthropoda	Malacostraca	Amphipoda	Aoridae	Microdeutopus	<i>Microdeutopus gryllotalpa</i>	102048	✓			
Mollusca	Bivalvia	Mytilida	Mytilidae	Modiolus	<i>Modiolus modiolus</i>	140467	✓	✓	✓	✓
Mollusca	Bivalvia	Myoida	Myidae	Mya	<i>Mya</i> spp.	138211	✓	✓	✓	✓
Mollusca	Bivalvia	Veneroida	Montacutidae	Mysella	<i>Mysella planulata</i>	156878		✓	✓	✓
Mollusca	Bivalvia	Mytilida	Mytilidae		<i>Mytilidae</i> spp.	211		✓	✓	
Mollusca	Bivalvia	Mytilida	Mytilidae	Mytilus	<i>Mytilus edulis</i>	140480	✓	✓	✓	
Annelida	Polychaeta	Phyllodocida	Nereididae	Neanthes	<i>Neanthes arenaceodentata</i>	334084		✓	✓	✓
Nemertea					<i>Nemertea</i>	152391	✓	✓		✓
Annelida	Polychaeta	Phyllodocida	Nephtyidae	Nephtys	<i>Nephtys bucera</i>	157499			✓	
Annelida	Polychaeta	Phyllodocida	Nephtyidae	Nephtys	<i>Nephtys</i> spp.	129370	✓			
Annelida	Polychaeta	Phyllodocida	Nereididae	Nereis	<i>Nereis grayi</i>	157503		✓		
Annelida	Polychaeta	Eunicida	Onuphidae		<i>Nothria conchylega</i>	130467	✓			
Annelida	Polychaeta	Phyllodocida	Syllidae	Odontosyllis	<i>Odontosyllis fulgurans</i>	131327	✓			
Annelida	Clitellata				<i>Oligochaeta</i> spp.	2036	✓	✓	✓	✓
Annelida	Polychaeta	Eunicida	Onuphidae		<i>Onuphidae</i> spp.	965	✓			
Annelida	Polychaeta		Opheliidae	Ophelia	<i>Ophelia verrilli</i>	157509		✓	✓	✓
Annelida	Polychaeta	Phyllodocida	Syllidae	Opisthodontia	<i>Opisthodontia longocirrata</i>	761606			✓	
Arthropoda	Malacostraca	Amphipoda	Tryphosidae		<i>Orchomenella minuta</i>	102690			✓	
Annelida	Polychaeta	Phyllodocida	Hesionidae	Oxydromus	<i>Oxydromus obscurus</i>	710702			✓	
Arthropoda	Malacostraca	Decapoda	Paguridae	Pagurus	<i>Pagurus acadianus</i>	158400		✓		✓
Arthropoda	Malacostraca	Decapoda	Paguridae	Pagurus	<i>Pagurus annulipes</i>	158401				✓
Arthropoda	Malacostraca	Decapoda	Paguridae	Pagurus	<i>Pagurus arcuatus</i>	158402	✓			
Arthropoda	Malacostraca	Decapoda	Paguridae	Pagurus	<i>Pagurus longicarpus</i>	158403			✓	✓
Mollusca	Bivalvia	Anomalodesmata	Pandoridae	Pandora	<i>Pandora gouldiana</i>	156932				
Mollusca	Bivalvia	Anomalodesmata	Pandoridae	Pandora	<i>Pandora</i> spp.	138310		✓		
Annelida	Polychaeta	Scolecida	Paraonidae	Paradoneis	<i>Paradoneis ilvana</i>	130584		✓	✓	✓
Annelida	Polychaeta		Paraonidae	Paradoneis	<i>Paradoneis lyra</i>	130585	✓			
Annelida	Polychaeta	Phyllodocida	Syllidae	Paraexogone	<i>Paraexogone hebes</i>	757970	✓	✓	✓	✓

Phylum	Class	Order	Family	Genus	Taxon	AphiaID	PRE	POST	6 POST	12 POST
Annelida	Polychaeta	Scolecida	Paraonidae		<i>Paraonidae</i> spp.	903	✓			
Annelida	Polychaeta	Scolecida	Paraonidae	Paraonis	<i>Paraonis fulgens</i>	146932	✓			
Annelida	Polychaeta	Scolecida	Paraonidae	Paraonis	<i>Paraonis pygoenigmatica</i>	157523		✓	✓	✓
Annelida	Polychaeta	Eunicida	Dorvilleidae	Parougia	<i>Parougia caeca</i>	130036	✓	✓	✓	✓
Mollusca	Bivalvia	Cardiida	Cardiidae	Parvicardium	<i>Parvicardium pinnulatum</i>	181343	✓			
Annelida	Polychaeta	Terebellida	Pectinariidae	Pectinaria	<i>Pectinaria gouldii</i>	334421		✓		
Mollusca	Bivalvia	Pectinida	Pectinidae		<i>Pectinidae</i> spp.	213	✓			
Mollusca	Bivalvia	Anomalodesmata	Periplomatidae	Periploma	<i>Periploma fragile</i>	156939		✓		
Mollusca	Bivalvia	Anomalodesmata	Periplomatidae	Periploma	<i>Periploma leanum</i>	156940			✓	✓
Mollusca	Bivalvia	Anomalodesmata	Periplomatidae	Periploma	<i>Periploma papyratum</i>	156958				✓
Mollusca	Bivalvia	Anomalodesmata	Periplomatidae	Periploma	<i>Periploma</i> spp.	156937		✓		✓
Mollusca	Bivalvia	Venerida	Veneridae	Petricolaria	<i>Petricolaria pholadiformis</i>	156961		✓	✓	✓
Sipuncula	Sipunculidea	Golfingiida	Sipunculidae	Phascolopsis	<i>Phascolopsis gouldii</i>	266603				
Annelida	Polychaeta	Phyllodocida	Pholoidae	Pholoe	<i>Pholoe minuta</i>	130603	✓			
Annelida	Polychaeta	Phyllodocida	Pholoidae	Pholoe	<i>Pholoe tecta</i>	130606		✓	✓	✓
Annelida	Polychaeta	Phyllodocida	Phyllodocidae	Phyllodoce	<i>Phyllodoce maculata</i>	130676		✓	✓	
Annelida	Polychaeta	Phyllodocida	Phyllodocidae	Phyllodoce	<i>Phyllodoce mucosa</i>	334512	✓			✓
Annelida	Polychaeta	Phyllodocida	Phyllodocidae	Phyllodoce	<i>Phyllodoce</i> spp.	931	✓	✓	✓	✓
Annelida	Polychaeta	Scolecida	Orbiniidae	Phylo	<i>Phylo ornata</i>	1548434	✓			
Platyhelminthes					<i>Platyhelminthes</i> spp.	793		✓	✓	✓
Annelida	Polychaeta	Phyllodocida	Nereididae	Platynereis	<i>Platynereis dumerilii</i>	130417				✓
Annelida	Polychaeta	Phyllodocida	Hesionidae	Podarkeopsis	<i>Podarkeopsis levifuscina</i>	330826			✓	
Annelida	Polychaeta	Terebellida	Terebellidae		<i>Polycirrus eximius</i>	157533	✓	✓	✓	✓
Annelida	Polychaeta	Spionida	Spionidae	Polydora	<i>Polydora aggregata</i>	157535			✓	
Annelida	Polychaeta		Polygordiidae	Polygordius	<i>Polygordius jouinae</i>	390168		✓	✓	✓
Annelida	Polychaeta		Polygordiidae	Polygordius	<i>Polygordius</i> spp.	129472	✓			
Annelida	Polychaeta	Phyllodocida	Polynoidae		<i>Polynoidae</i> spp.	939	✓		✓	
Arthropoda	Malacostraca	Amphipoda	Pontogeneiidae	Pontogeneia	<i>Pontogeneia inermis</i>	102223			✓	
Annelida	Polychaeta	Spionida	Spionidae	Prionospio	<i>Prionospio steenstrupi</i>	131164	✓			
Arthropoda	Malacostraca	Amphipoda	Stenothoidae	Proboloides	<i>Proboloides holmesi</i>	158134			✓	

Phylum	Class	Order	Family	Genus	Taxon	AphiaID	PRE	POST	6 POST	12 POST
Annelida	Polychaeta	Phyllodocida	Syllidae	Proceraea	<i>Proceraea cornuta</i>	131362	✓	✓		✓
Mollusca	Bivalvia	Nuculida	Nuculidae	Pronucula	<i>Pronucula tenuis</i>	607414	✓			
Annelida	Polychaeta	Eunicida	Dorvilleidae	Protodorvillea	<i>Protodorvillea kefersteini</i>	130041		✓	✓	✓
Annelida	Polychaeta	incertae sedis	Protodriloididae	Protodriloides	<i>Protodriloides chaetifer</i>	130837			✓	✓
Annelida	Polychaeta	Phyllodocida	Hesionidae	Psamathe	<i>Psamathe fusca</i>	152249			✓	
Mollusca	Gastropoda	Pylopulmonata	Pyramidellidae		<i>Pyramidellidae</i> spp.	160082	✓	✓		
Mollusca	Gastropoda	Littorinimorpha	Rissoidae		<i>Rissoidae</i> spp.	123	✓			
Annelida	Polychaeta		Saccocirridae		<i>Saccocirrus</i> spp.	995	✓			
Annelida	Polychaeta	Phyllodocida	Syllidae	Salvatoria	<i>Salvatoria clavata</i>	195986	✓			✓
Bryozoa	Gymnolaemata	Cheilostomatida	Schizoporellidae	Schizoporella	<i>Schizoporella unicornis</i>	111538	✓			
Mollusca	Bivalvia	Cardiida	Cardiidae	Serripes	<i>Serripes groenlandicus</i>	582749	✓			
Annelida	Polychaeta	Phyllodocida	Sigalionidae	Sigalion	<i>Sigalion arenicola</i>	157567		✓		
Annelida	Sipuncula				<i>Sipuncula</i> spp.	1268		✓		
Mollusca	Gastropoda	Littorinimorpha	Skeneopsidae	Skeneopsis	<i>Skeneopsis planorbis</i>	141539	✓			
Arthropoda	Malacostraca	Isopoda	Sphaeromatidae	Sphaeroma	<i>Sphaeroma quadridentatum</i>	157912				✓
Annelida	Polychaeta	Spionida	Spionidae	Spio	<i>Spio setosa</i>	157573	✓		✓	
Annelida	Polychaeta	Spionida	Spionidae	Spio	<i>Spio thulini</i>	157574			✓	
Mollusca	Bivalvia	Venerida	Mactridae	Spisula	<i>Spisula solidissima</i>	156996	✓	✓	✓	✓
Annelida	Polychaeta	Phyllodocida	Sigalionidae	Sthenelais	<i>Sthenelais limicola</i>	131077	✓			
Annelida	Polychaeta	Phyllodocida	Sigalionidae	Sthenelais	<i>Sthenelais</i> spp.	129595	✓			
Annelida	Polychaeta	Spionida	Spionidae	Streblospio	<i>Streblospio benedicti</i>	131191	✓			
Annelida	Polychaeta	Phyllodocida	Syllidae		<i>Syllidae</i> spp.	948	✓			✓
Arthropoda	Malacostraca	Tanaidacea			<i>Tanaidacea</i> spp.	1133				✓
Mollusca	Bivalvia	Myida	Teredinidae	Teredo	<i>Teredo navalis</i>	141607			✓	
Mollusca	Gastropoda	Patellogastropoda	Lottidae	Testudinalia	<i>Testudinalia testudinalis</i>	234208	✓	✓	✓	✓
Annelida	Polychaeta	Terebellida	Cirratulidae	Tharyx	<i>Tharyx</i> spp.	129249	✓			
Mollusca	Bivalvia	Anomalodesmata	Thraciidae		<i>Thraciidae</i> spp.	156937				✓
Mollusca	Gastropoda	Neogastropoda	Nassariidae	Tritia	<i>Tritia trivittata</i>	737284	✓	✓	✓	✓
Mollusca	Gastropoda	Pylopulmonata	Pyramidellidae	Turbonilla	<i>Turbonilla interrupta</i>	420446		✓	✓	✓
Mollusca	Gastropoda	Pylopulmonata	Pyramidellidae	Turbonilla	<i>Turbonilla nivea</i>	160084		✓	✓	✓

Phylum	Class	Order	Family	Genus	Taxon	AphiaID	PRE	POST	6 POST	12 POST
Mollusca	Gastropoda	Pylopulmonata	Pyramidellidae	Turbonilla	<i>Turbonilla</i> spp.	138421	✓			
Arthropoda	Malacostraca	Amphipoda	Unciolidae	Unciola	<i>Unciola inermis</i>	158155			✓	
Arthropoda	Malacostraca	Amphipoda	Unciolidae	Unciola	<i>Unciola irrorata</i>	158156			✓	

8. APPENDIX B

Abiotic factors measured at invertebrate sampling sites. (*) indicates factors excluded from statistical analyses

Station	Replicate	Organic Matter (%)	Median	Mode (1_μm)	Sorting	Skewness (ari_μm)	Sand (%)	Mud (%)	ph	Surface Temperature (°C)	Algae (%)	Shell (%)	V_Gravel (%)	Total impact 2015 (%)	L_Slope	Depth (m)	Total Initial impact 2017 (%)	Total 2017 Impact at Timepoint (%)	QSBC Max (kPa)*	V_Sand (%)*	Disturbance	Gravel (%)*	Mean (ari_μm) *	Kurtosis (ari_μm) *	4mm (%)*	Salinity*	Penetration at NqsbcmMax (cm)*	Velocity at NqsbcmMax (m/s)*	Deceleration at NqsbcmMax (g)*
1	PRE	0.47	1145	1090	0.544	2.514	90.79	0.02	7.88	14.4	12.86	2.78	7.37	0	0.07	5.25	0	NA	NA	75.97	1	9.19	1313.2	12.08	8.18	31.33	NA	NA	NA
2	PRE	0.45	1219.1	1090	0.623	2.388	84.39	0	8.08	14.4	1.52	0.53	4.81	0	0.235	5.42	4.2	NA	NA	93.15	1	15.61	1475.7	10.37	3.24	31.32	NA	NA	NA
3	PRE	0.41	1092.5	925	0.644	2.632	88.66	0	8.19	14.5	0	2.84	3.06	0	0.207	5.99	4.2	NA	NA	94.11	1	11.34	1322	12.14	4.97	31.31	NA	NA	NA
4	PRE	0.36	990.1	925	0.568	2.996	92.98	0.01	8.23	14.6	0	0	4.17	3.1	0.191	5.95	4.7	NA	NA	95.83	1	7.01	1177.8	14.26	5.36	31.34	NA	NA	NA
5	PRE	0.19	1256.9	1090	0.505	1.74	89.85	0	8.27	14.3	1.67	0.79	0	0	0.179	5.84	0	NA	NA	97.54	0	10.15	1380.8	8.60	0	31.41	NA	NA	NA
6	PRE	0.51	1146.9	1090	0.511	1.851	91.34	0	8.28	14.3	0.76	3.72	1.52	0	0.34	6.43	0	NA	NA	94.01	0	8.66	1286.7	8.59	0	31.41	NA	NA	NA
7	PRE	0.47	1290.1	1090	0.521	1.419	87.52	0	8.28	14.3	1.45	10.94	0	0	0.224	6.68	0	NA	NA	87.62	0	12.48	1420.8	6.45	0	31.41	NA	NA	NA
8	PRE	0.51	1272.6	1290	0.530	2.238	88.11	0	8.29	14.3	4.98	5.62	0	0	0.375	7.00	0	NA	NA	89.4	0	11.89	1409.8	13.06	0	31.42	NA	NA	NA
9	PRE	0.56	1740.9	1850	0.449	0.819	71.45	0	8.01	14.8	15.86	11.06	7.31	0	0.381	6.88	3.9	NA	NA	65.76	1	28.55	1773.1	5.01	0	31.15	NA	NA	NA
10	PRE	0.69	1152.5	1090	0.571	2.934	89.51	0.01	8.11	14.8	39.2	3.04	6.02	0.01	0.241	6.44	6.5	NA	NA	48.71	1	10.48	1402.2	12.66	26.55	31.2	NA	NA	NA
11	PRE	0.43	1214.3	1090	0.663	2.364	83.09	0.01	8.29	14.7	0	5.68	15.07	13.8	0.306	5.80	4.5	NA	NA	77.8	1	16.9	1516.6	9.73	15.93	31.29	NA	NA	NA
12	PRE	0.58	1041.6	925	0.591	2.779	90.96	0.02	8.24	14.7	12.48	6.21	12.34	0	0.485	6.48	2.7	NA	NA	68.97	1	9.02	1245.3	12.64	5.92	31.28	NA	NA	NA
13	PRE	0.94	1440.3	1850	0.603	1.377	77.72	0.02	8.28	14.2	49.41	15.48	10.89	5.9	0.261	8.16	0	NA	NA	24.21	0	22.26	1601.3	6.15	0	31.42	NA	NA	NA
14	PRE	0.97	1192.1	1090	0.545	2.759	89.2	0.02	8.27	14.1	59.67	2.17	27.51	0.6	0.189	8.12	0	NA	NA	10.65	0	10.78	1385.6	13.3	40.94	31.43	NA	NA	NA
15	PRE	0.73	1349.3	1290	0.550	2.472	83.6	0	8.28	14.1	22.35	4.02	27.65	0	0.137	8.31	0	NA	NA	45.23	0	16.4	1558.4	11.09	44.37	31.45	NA	NA	NA
16	PRE	0.72	1225	1090	0.641	2.8	85.91	0.01	8.24	14.2	66.5	1	32	0	0.032	8.37	0	NA	NA	0.5	0	14.08	1505.3	12.54	17.83	31.43	NA	NA	NA
17	PRE	0.37	1243.7	1090	0.617	2.409	85.03	0	8.27	14.7	2.67	0	10.67	0	0.167	6.53	0	NA	19.047	86.67	0	14.97	1512.2	9.76	12.25	31.28	7.933	1.526	11.146
18	PRE	0.44	1332.8	1290	0.590	2.32	83.05	0	8.3	14.8	28.36	3.04	22.29	0	0.227	5.86	0	NA	39.776	46.31	0	16.95	1600.2	8.89	0	31.29	5.15	1.725	13.438
19	PRE	0.92	1191.1	1090	0.516	3.482	90.05	0	8.3	14.8	4.35	0	1.52	0	-0.006	5.77	0	NA	29.672	94.14	0	9.95	1399.6	18.57	10.14	31.28	5.05	2.019	9.52
20	PRE	0.38	1178.4	1090	0.484	4.472	91.99	0	8.3	14.8	8.28	0	3.42	0	0.128	5.63	0	NA	34.562	88.31	0	8.01	1393.4	26.56	0	31.28	5.133	1.8	11.029
21	PRE	0.52	1065.7	1090	0.473	4.536	94.65	0	8.31	14.6	0	0	2.17	0.5	-0.114	7.75	3.4	NA	22.567	97.83	1	5.35	1209.7	32.89	0	31.35	6.6	1.685	11.839
22	PRE	0.76	1021.1	925	0.588	3.521	92.06	0	8.31	14.3	2.9	1.39	25.54	0	0.089	7.57	4.0	NA	23.126	70.17	1	7.94	1233.6	18.91	17.21	31.43	6.033	1.251	11.11
23	PRE	0.68	1228.6	1090	0.506	2.699	90.59	0.01	8.31	14.5	49.96	2.11	23.97	0	-0.001	7.58	5.5	NA	NA	23.97	1	9.4	1373.8	14.93	4.83	31.34	NA	NA	NA
24	PRE	1.11	1103.5	925	0.711	2.157	85.68	0	8.31	14.4	4.12	2.78	25.28	0	-0.19	7.33	5.7	NA	NA	67.83	1	14.32	1394.2	7.727	13.53	31.43	NA	NA	NA

Station	Replicate	Organic Matter (%)	Median	Mode (1_μm)	Sorting	Skewness (ari_μm)	Sand (%)	Mud (%)	ph	Surface Temperature (°C)	Algae (%)	Shell (%)	V_Gravel (%)	Total impact 2015 (%)	L_Slope	Depth (m)	Total Initial impact 2017 (%)	Total 2017 Impact at Timepoint (%)	QSBC Max (kPa)*	V_Sand (%)*	Disturbance	Gravel (%)*	Mean (ari_μm) *	Kurtosis (ari_μm) *	4mm (%)*	Salinity*	Penetration at NqsbcmMax (cm)*	Velocity at NqsbcmMax (m/s)*	Deceleration at NqsbcmMax (g)*
1	POST	0.14	1268.7	1090	0.662	2.047	81.3	0	8.15	10.6	0	1.52	4	0	0.176	4.79	4.8	0	22.296	94.48	1	18.7	1554.5	7.77	7.38	32.18	6	1.878	9.618
2	POST	0.5	1072.7	925	0.462	2.367	95.63	0	8.25	10.5	0	3.63	5.59	0	0.27	4.89	4.1	0	23.994	90.78	1	4.37	1175.5	14.67	0	32.22	5.8	1.978	9.894
3	POST	0.32	1064.7	925	0.491	3.287	94.62	0	8.25	10.4	0	1.52	6.28	0	0.27	5.38	4.7	0	20.99	92.21	1	5.38	1191	21.72	3.64	32.26	7.9	1.352	10.075
4	POST	0.41	1062.7	925	0.690	2.776	88.42	0	8.26	10.4	2.68	0.58	11.46	1.8	0.208	5.42	4.7	0	25.961	85.27	1	11.58	1398.7	10.56	25.51	32.19	8	1.204	12.085
5	POST	0.53	1256.7	1090	0.619	2.175	82.8	0	8.25	10.5	0	1.59	5.4	0	0.211	5.28	0	0	23.196	93.01	0	17.2	1500	9.315	5.02	32.26	6.767	1.617	10.14
6	POST	0.78	1210.7	1090	0.526	2.206	89.53	0	8.26	10.5	2.17	0	0	0	0.244	5.90	0	0	17.781	97.83	0	10.47	1365.8	10.86	3.81	32.26	7.633	1.729	8.908
7	POST	0.48	1289.9	1090	0.573	1.612	84.77	0.01	8.26	10.5	0	6.2	0	0	0.137	5.92	0	0	30.093	93.8	0	15.22	1451.7	7.24	0	32.75	5.5	1.928	11.76
8	POST	0.47	1198.2	1090	0.519	2.028	90.5	0	8.26	10.5	0	0	0	0	0.275	6.16	0	0	24.692	100	0	9.5	1342.6	9.79	0	32.23	7.8	1.841	9.869
9	POST	0.52	1431.6	1290	0.483	1.658	84.65	0	8.26	10.4	23.72	4.49	2.9	1.1	0.221	6.00	4.0	0	17.868	68.89	1	15.35	1548.3	7.98	2.18	32.21	7.467	1.233	9.437
10	POST	0.86	1030.3	925	0.444	4.271	96	0.01	8.26	10.4	27.15	1.59	4.76	2.4	0.349	5.23	6.1	1.4	32.739	66.5	1	3.99	1156.9	27.34	15.79	32.17	5.55	1.676	12.617
11	POST	1.24	1112.3	925	0.649	2.421	89.35	0.04	8.27	8.4	71.51	2.08	23.92	12.9	0.575	6.19	6.3	4.0	19.663	2.49	1	10.61	1309.8	10.97	18.36	32.02	6.767	1.47	9.599
12	POST	0.51	1075.7	925	0.631	2.47	88.5	0	8.29	8.4	1.59	3.25	11.27	0	0.377	6.36	3.4	1.2	26.953	83.89	1	11.5	1313.9	10.27	6.64	32.03	6	1.78	12.328
13	POST	0.61	1421.6	1850	0.576	1.727	79.9	0.01	8.23	8.5	4.11	11.05	4.16	0.6	0.054	7.67	0	0	34.678	80.69	0	20.09	1578.3	8.3	5.47	32.23	5.15	1.746	11.631
14	POST	0.65	1320.8	1090	0.790	1.888	75.35	0.02	8.25	8.5	43.58	4.91	51.51	2.9	0.133	7.44	0	0	49.665	0	0	24.63	1763.6	6.31	51.98	32.22	5.9	1.139	19.028
15	POST	0.64	1282.1	1090	0.719	1.928	78.69	0.01	8.26	8.7	7.22	6.24	39.87	0	0.153	7.72	0	0	26.33	46.67	0	21.3	1628.9	6.82	31.06	32.24	6.133	1.529	10.512
16	POST	0.67	1362.5	1290	0.637	2.473	81.67	0.01	8.25	8.7	56.8	2.79	39.4	0	0.183	7.79	0	0	34.382	1.01	0	18.32	1634.5	10.3	21.21	32.26	6.167	1.545	15.338
17	POST	0.49	1285.2	1090	0.549	2.652	86.31	0	8.29	10.4	9.11	2.08	23.26	0	0.404	6.04	0	0	21.039	65.55	0	13.69	1473.5	13.54	4.72	32.06	7.5	1.419	10.781
18	POST	0.67	1442.1	1290	0.706	1.995	75.06	0	8.3	10.2	7.67	0.72	17.06	0	0.372	5.25	0	0	14.828	74.55	0	24.94	1841.4	6.95	12.72	32.08	5.7	1.615	5.522
19	POST	0.5	1242.1	1090	0.533	4.226	88.9	0	8.3	10.3	1.45	0	5.68	0	0.063	5.29	0	0	19.676	92.87	0	11.1	1503.8	24.34	5.43	32.05	6.7	2.547	8.609
20	POST	0.38	1273.4	1090	0.513	3.705	87.57	0	8.29	10.3	0	0	4.75	0	0.122	5.08	0	0	23.295	95.25	0	12.43	1461.4	24.51	0	32.06	6.267	1.717	8.876
21	POST	0.48	1054.5	925	0.446	4.218	96.19	0	8.24	10.3	0	3.25	10.82	1.6	-0.282	7.28	3.8	0.2	25.534	85.92	1	3.81	1166.9	31.15	3.28	32.25	6.767	1.686	9.482
22	POST	0.42	1045.9	925	0.662	2.682	89.09	0	8.25	10.5	0	1.96	14.37	2.3	-0.253	6.60	5.3	0	32.102	83.67	1	10.91	1303.6	11.18	27.82	32.21	5.933	1.214	11.505
23	POST	0.68	1065.5	1090	0.499	3.827	93.21	0.01	8.25	10.3	28.19	3.91	30.54	1.6	0.033	6.91	5.8	1.7	37.639	37.36	1	6.78	1260	20.11	57.96	32.24	5.867	1.749	15.337
24	POST	0.39	1146.5	1090	0.609	2.619	88.45	0	8.25	10.5	0	0	24.87	0.1	-0.1	6.86	7.6	1.8	13.97	75.13	1	11.55	1385.6	11.13	8.22	32.19	9.15	0.948	8.799

Station	Replicate	Organic Matter (%)	Median	Mode (1_μm)	Sorting	Skewness (ari_μm)	Sand (%)	Mud (%)	ph	Surface Temperature (°C)	Algae (%)	Shell (%)	V_Gravel (%)	Total impact 2015 (%)	L_Slope	Depth (m)	Total Initial impact 2017 (%)	Total 2017 Impact at Timepoint (%)	QSBC Max (kPa)*	V_Sand (%)*	Disturbance	Gravel (%)*	Mean (ari_μm) *	Kurtosis (ari_μm) *	4mm (%)*	Salinity*	Penetration at NqsbcmMax (cm)*	Velocity at NqsbcmMax (m/s)*	Deceleration at NqsbcmMax (g)*
1	6POST	0.5	1377.7	1090	0.695	1.837	76.05	0	8.15	8.5	6.66	0.72	5.12	0	0.322	4.78	4.0	0	17.116	87.12	1	23.95	1693.7	6.71	7.75	32.18	7.3	1.067	8.534
2	6POST	0.3	1373.5	1090	0.685	1.96	76.53	0	8.25	7.73	0	0	20.22	0	0.186	4.76	4.0	0	22.798	79.78	1	23.47	1680.8	7.52	6.25	32.22	7.6	1.496	11.881
3	6POST	0.55	1061.3	925	0.507	2.675	93.82	0.01	8.25	7.52	0	0	0	0	0.182	5.39	4.1	0	21.306	79.42	1	6.17	1200.6	13.18	0	32.26	8.267	1.353	10.067
4	6POST	0.17	1049.2	925	0.543	2.688	92.25	0	8.26	7.75	0	0	0	1.1	0.212	5.39	4.2	0	15.323	87.58	1	7.75	1220.2	12.39	0	32.19	13.433	0.895	9.624
5	6POST	0.36	1340	1290	0.582	2.079	82.54	0	8.25	7.49	0	0	0	0	0.207	5.20	0	0	14.914	100	0	17.46	1555.9	8.73	2.7	32.26	10.7	0.945	9.377
6	6POST	0.62	1242	1290	0.486	1.693	91.46	0	8.26	7.5	0	0	4.96	0	0.375	5.8	0	0	22.69	95.04	0	8.54	1352.3	8.49	5.71	32.26	7.333	1.282	11.075
7	6POST	0.55	1283.7	1090	0.545	1.773	86.4	0	8.26	8.56	0	0	2.9	0	0.238	6.09	0	0	16.029	97.1	0	13.6	1441.8	7.81	0	32.75	10.367	1.455	10.019
8	6POST	0.4	1212.4	1090	0.574	2.029	86.05	0	8.26	7.5	2.84	1.67	0	0	0.32	6.26	0	0	24.692	94.05	0	13.95	1418.5	8.44	0	32.23	7.8	1.841	9.869
9	6POST	0.3	1072.4	925	0.419	2.122	96.54	0	8.26	7.69	0	0	0	0	0.255	5.87	4.0	0	21.393	79.8	1	3.46	1164.6	11.25	0	32.21	7.533	1.064	10.701
10	6POST	0.67	1203.9	1090	0.532	2.066	89.4	0	8.26	7.96	65.64	3.33	0	2.7	0.429	5.46	6.3	1.3	24.477	31.03	1	10.6	1359.7	9.66	7.45	32.17	6.4	1.002	12.289
11	6POST	0.6	1153.5	1090	0.477	3.512	93.27	0	8.27	8.53	42.85	2.55	27.24	4.8	0.546	5.86	2.6	1.6	29.084	27.37	1	6.73	1304.4	21.15	7.29	32.02	7.467	1.207	17.205
12	6POST	0.55	1262.7	1090	0.616	2.397	85.31	0	8.29	8.66	0	0	8.46	0	0.314	6.65	3.2	0	17.956	84.47	1	14.69	1541.3	9.09	5.25	32.03	10.55	0.709	10.822
13	6POST	0.69	1612.2	1850	0.698	1.439	67.53	0.03	8.23	7.92	0.83	13.92	10.79	2.5	0.34	7.42	0	0	18.558	74.45	0	32.44	1804.1	6.05	7.01	32.23	9.1	0.695	11.055
14	6POST	1.11	1333.5	1090	0.907	1.734	74.99	0.06	8.25	8.11	84.63	2.38	12.99	0	0.392	7.33	0	0	24.801	0	0	24.95	1721.4	6.22	36.75	32.22	5.933	1.505	10.298
15	6POST	0.51	986.9	925	0.466	3.525	97.01	0.02	8.26	7.83	57.17	1.62	9.67	0	0.111	7.46	0	0	22.206	31.55	0	2.97	1068.8	31.23	14.24	32.24	7.167	1.395	10.652
16	6POST	0.54	1412.7	1290	0.625	2.478	79.59	0	8.25	7.72	51	15.93	28.52	0	0.2	7.58	0	0	21.812	4.55	0	20.41	1717.9	10.24	34.3	32.26	5.833	1.9	9.703
17	6POST	1.01	1391.9	1290	0.511	2.278	84.55	0	8.29	8.97	16.74	0	7.72	0	0.354	5.9	0	0	44.71	74.2	0	15.45	1540.7	12.46	0	32.06	6.167	0.82	16.614
18	6POST	1.05	1353	1290	0.604	2.085	80.62	0	8.3	9	10.77	0.76	1.52	0	0.292	5.19	0	0	31.221	86.96	0	19.38	1601.9	8.53	3.84	32.08	6.6	1.643	12.019
19	6POST	0.47	1245.4	1290	0.464	2.019	92.49	0	8.3	8.78	3.25	0	0.79	0	0.098	5.19	0	0	25.091	95.95	0	7.51	1348.8	10.54	3.36	32.05	6.1	1.707	11.537
20	6POST	0.64	1155.4	925	0.650	2.035	83.76	0	8.29	8.64	4.78	0	0	0	0.062	5.68	0	0	28.164	95.22	0	16.24	1428.6	8.09	5.79	32.06	6.3	1.062	12.426
21	6POST	0.56	1156.7	1090	0.639	2.743	86.38	0	8.24	7.83	2.9	3.04	24.71	0.2	-0.139	7.20	3.7	0	38.498	69.36	1	13.62	1482.2	10.97	25.05	32.25	5.1	1.353	11.873
22	6POST	0.39	1129.1	1090	0.458	3.749	93.66	0	8.25	8.18	1.52	0	11.92	0	-0.197	6.43	4.1	0	26.962	86.56	1	6.34	1281.8	22.44	4.21	32.21	7.167	1.576	10.819
23	6POST	0.35	1219.4	925	0.828	1.915	77.82	0.01	8.25	7.92	38.87	0.88	22.36	0	-0.088	6.9	6.0	0	28.193	37.89	1	22.17	1671.6	6.25	37.2	32.24	5.733	1.619	11.712
24	6POST	0.75	1152	1090	0.735	2.349	82.98	0	8.25	8.26	0.46	0	40.74	0	-0.237	6.65	6.5	0	25.471	58.8	1	17.02	1546.7	8.48	13.55	32.19	8.2	1.006	11.146

Station	Replicate	Organic Matter (%)	Median	Mode (1_μm)	Sorting	Skewness (ari_μm)	Sand (%)	Mud (%)	ph	Surface Temperature (°C)	Algae (%)	Shell (%)	Gravel (%)	Total impact 2015(%)	L_Slope	Depth (m)	Total Initial impact 2017 (%)	Total 2017 Impact at Timepoint (%)	QSBC Max (kPa)*	V_Sand (%)*	Disturbance	Gravel (%)*	Mean (ari_μm) *	Kurtosis (ari_μm) *	4mm (%)*	Salinity*	Penetration at NqsbcmMax (cm)*	Velocity at NqsbcmMax (m/s)*	Deceleration at NqsbcmMax (g)*
1	12POST	0.45	1291.7	1090	0.573	2.154	84.31	0.01	8.3	9.5	0	0	6	0	0	4.77	4.1	0	23.945	94	1	15.68	1478.4	10.57	5.43	31.79	6	1.872	10.348
2	12POST	0.43	1160	1090	0.592	2.473	87.74	0	9.32	9.4	0	0	5.48	0	0.255	4.85	4.1	0	19.04	92.96	1	12.26	1383.7	10.95	6.05	31.78	7.733	1.577	10.003
3	12POST	0.38	1228.2	1090	0.605	2.429	85.22	0	8.32	10.1	0	1.19	0	0	0.225	5.47	4.2	0	22.582	98.81	1	14.78	1457.2	10.89	0	31.81	7.4	1.457	11.15
4	12POST	0.4	1056.4	925	0.633	2.786	89.75	0	8.3	8.9	0	6.78	0	1.0	0.099	5.26	4.7	0	28.495	93.22	1	10.25	1303.4	11.87	6.74	31.78	7	1.688	10.969
5	12POST	0.45	1212.1	1090	0.588	2.196	86.17	0	8.28	10.2	0	1.67	5.67	0	0.254	5.38	0	0	18.92	92.67	0	13.83	1425.9	9.49	4.81	31.78	8.233	1.529	10.018
6	12POST	0.55	1164	1090	0.569	2.268	87.4	0	8.31	10.3	0	1.47	3.95	0	0.324	6.01	0	0	21.914	94.58	0	12.6	1363.5	11.34	0	31.8	8.367	1.553	10.272
7	12POST	0.44	1210.4	1090	0.567	1.654	88.15	0	8.33	10.5	1.67	0	3.17	0	0.189	6.03	0	0	13.187	95.16	0	11.85	1365.7	6.95	0	31.77	12.633	0.961	8.246
8	12POST	0.47	1248.5	1090	0.525	2.016	89.2	0	8.33	10.5	0	24.21	0	0	0.556	6.49	0	0	26.745	75.79	0	10.8	1377.8	11.99	0	31.76	6.3	1.728	11.177
9	12POST	0.4	1313.6	1290	0.511	2.548	88.27	0	8.34	10.1	3.46	4.58	1.05	0	0.219	5.95	4.0	0	23.353	90.91	1	11.73	1448.2	15.07	3.57	31.81	7.667	1.563	8.194
10	12POST	0.51	1150.2	1090	0.647	2.597	86.7	0	8.33	9.8	26.13	1.43	27.37	0	0	5.32	5.0	0	29.43	45.06	1	13.3	1418.5	11.14	4.4	31.8	5.767	1.454	11.702
11	12POST	0.53	1186.9	1090	0.618	2.494	86.15	0	8.3	8.87	66.07	12.5	21.43	6.2	0.239	5.59	4.2	0	30.742	0	1	13.85	1433.9	10.92	0	31.81	7.633	1.187	13.03
12	12POST	0.61	1363.9	1090	0.695	1.677	76.6	0.01	8.3	9.03	41.42	7.01	3.74	0	0.449	6.57	4.8	0	27.639	47.8	1	23.39	1610.8	6.57	0	31.79	5.667	1.877	11.103
13	12POST	0.62	1684.6	1850	0.673	1.5	66.53	0	8.3	8.96	23.97	11	0	4.7	0	7.78	0	0	27.025	65	0	33.47	1877.2	5.61	18.09	31.82	7.4	0.673	14.427
14	12POST	0.47	1294.8	1090	0.670	2.099	80.62	0	8.3	9.02	18.34	0	16.64	0.6	0.045	7.61	0	0	34.894	65	0	19.38	1594.8	7.91	22.11	31.69	5.533	1.806	13.668
15	12POST	0.92	1397.5	1290	0.771	1.772	74.55	0.01	8.3	9.05	65.88	1.75	27.1	0	0.033	7.62	0	0	21.179	5.3	0	25.44	1789.2	5.94	24.97	31.81	5.05	2.108	6.724
16	12POST	0.36	1326.3	1290	0.578	2.095	84.54	0	8.3	9.16	1.59	0	1.8	0	0.053	7.68	0	0	25.088	96.6	0	15.46	1485.3	10.71	4.23	31.76	7.9	1.517	9.154
17	12POST	0.31	1192.8	1090	0.705	2.169	82.37	0	8.3	8.9	1.67	0	10.44	0	0.106	5.96	0	0	18.064	87.9	0	17.63	1558.9	7.59	9.4	31.78	7.3	1.641	10.483
18	12POST	0.58	1244.7	1290	0.549	3.059	88.66	0	8.3	8.68	5.59	1.96	7.35	0	0.181	5.46	0	0	25.343	85.1	0	11.34	1461.6	14.49	7.99	31.9	7.033	1.436	12.375
19	12POST	0.36	1297.7	1290	0.516	2.704	86.71	0	8.3	8.75	5.88	0	5.88	0	0.108	5.36	0	0	32.083	88.2	0	13.29	1482.9	13.85	0	31.81	5.767	1.306	12.142
20	12POST	0.35	1177.7	1090	0.430	1.807	94.98	0	8.3	8.73	1.19	0	1.96	0	0.147	5.06	1.3	0	33.26	96.8	0	5.02	1272.3	9.47	0	31.4	5.233	1.706	11.361
21	12POST	0.43	1153.1	1090	0.668	2.554	85.98	0	8.3	8.97	5.14	0	0	0	-0.117	7.02	2.7	0	22.031	94.9	1	14.02	1510.1	9.67	7.13	31.51	6	1.464	9.43
22	12POST	0.44	1086	925	0.492	2.52	94.26	0	8.32	10.5	0	2	14.33	0	-0.049	7.01	5.4	0	26.156	83.67	1	5.74	1210.2	12.99	26.15	31.76	6.667	1.619	11.614
23	12POST	0.37	1040.6	925	0.761	2.451	86.52	0	8.34	10.5	54.91	1.79	18.08	0	0.063	6.89	3.4	0	36.903	25.2	1	13.48	1408.3	8.77	44.79	31.77	5	1.144	10.477
24	12POST	0.28	1096.9	925	0.691	2.558	87.25	0	8.3	8.98	4.69	0	4.5	0	-0.244	6.78	6.2	0	32.889	90.8	1	12.75	1392.3	9.98	14.84	31.89	5	1.936	10.654

9. APPENDIX C

Summary of quarterly video analysis collected during sediment drops across each transect (in %).
Summary of habitat video analysis collected during invertebrate sampling across each invertebrate station. Boxes 1, 3 and 6 were impacted by dredging in 2017.

Transect		5/8/2017					8/12/2017				
		V Sand	V Gravel	Algae	Shell	Eelgrass	V Sand	V Gravel	Algae	Shell	Eelgrass
1146	1	97	1	1	1	0	100	0	0	0	0
1152	1	100	0	0	0	0	59	36	3	2	0
1158	1	39	6	0	0	0	74	21	0	5	0
1164	1	5	0	0	5	0	86	5	5	5	0
1170	1	19	1	0	0	0	100	0	0	0	0
1176	1	14	0	0	0	0	91	0	9	0	0
1182	1	34	2	0	1	0	87	9	4	0	0
1182	2	14	0	19	0	0	56	39	6	0	0
1188	1	64	19	4	3	0	64	27	9	0	0
1188	2	40	20	17	5	0	16	84	0	0	0
1194	1	21	15	65	0	0	23	24	52	1	0
1194	2	21	0	0	0	0	86	0	0	14	0
1200	1	4	24	53	10	0	18	27	49	6	0
1200	2	86	5	0	0	0	41	54	3	3	0
1206	1	75	0	25	0	0	1	16	80	3	0
1206	2	16	0	0	0	0	26	68	5	0	0
1212	1	1.0	0	0	0	0	83	0	13	4	0
1212	2	79	11	5	5	0	36	41	23	0	0
1218	1	78	11	11	0	0	45	5	50	0	0
1218	2	88	6	6	0	0	89	0	5	5	0
1224	1	100	0	0	0	0	100	0	0	0	0
1230	1	100	0	0	0	0	91	9	0	0	0
1236	1	98	0	3	0	0	100	0	0	0	0
1242	1	24	0	0	0	0	45	35	15	5	0
1248	1	10	0	0	0	0	71	0	24	5	0
1254	1	93	7	0	0	0	78	0	22	0	0
1260	1	11	4	2	0	0	73	11	11	6	0
1266	1	38	0	0	0	0	100	0	0	0	0
1272	1	18	9	0	0	0	12	0	82	6	0
1278	1	57	0	0	0	0	87	9	4	0	0
1284	1	100	0	0	0	0	100	0	0	0	0
1290	1	36	14	5	9	0	50	32	18	0	0
1296	1	24	0	0	0	0	75	15	10	0	0
1302	1	95	5	0	0	0	0	24	76	0	0
1308	1	79	21	0	0	0	16	47	37	0	0
1314	1	56	44	0	0	0	34	41	25	0	0
1320	1	80	19	0	1	0	0	56	44	0	0
1326	1	59	24	18	0	0	32	53	11	5	0
1332	1	39	22	6	11	0	39	52	9	0	0

Transect		10/26/2017					3/27/2018				
		V Sand	V Gravel	Algae	Shell	Eelgrass	V Sand	V Gravel	Algae	Shell	Eelgrass
1146	1	100	0	0	0	0	100	0	0	0	0
1152	1	98	2	0	0	0	100	0	0	0	0
1158	1	95	5	0	0	0	100	0	0	0	0
1164	1	100	0	0	0	0	96	0	0	4	0
1170	1	95	0	0	5	0	95	0	5	0	0
1176	1	94	3	0	3	0	100	0	0	0	0
1182	1	100	0	0	0	0	100	0	0	0	0
1182	2	48	19	29	5	0					
1188	1	83	13	2	2	0	76	24	0	0	0
1188	2	30	52	4	13	0	95	5	0	0	0
1194	1	25	19	53	2	0	5	53	42	0	0
1194	2	100	0	0	0	0	100	0	0	0	0
1200	1	27	28	38	7	0	43	0	10	48	0
1200	2	48	48	0	4	0	100	0	0	0	0
1206	1	61	6	33	0	0	63	32	5	0	0
1206	2	72	28	0	0	0	91	9	0	0	0
1212	1						89	0.11	0	0	0
1212	2	95	5	0	0	0	74	24	3	0	0
1218	1						65	22	4	0	0
1218	2						95	0	5	0	0
1224	1						100	0	0	0	0
1230	1						100	0	0	0	0
1236	1						100	0	0	0	0
1242	1						86	9	5	0	0
1248	1						100	0	0	0	0
1254	1						85	0.15	0	0	0
1260	1						100	0	0	0	0
1266	1						90	10	0	0	0
1272	1						96	0	0	0	0
1278	1						95	0	0	0	0
1284	1						100	0	0	0	0
1290	1						100	0	0	0	0
1296	1						100	0	0	0	0
1302	1						100	0	0	0	0
1308	1						100	0	0	0	0
1314	1						100	0	0	0	0
1320	1						71	27	0	2	0
1326	1						86	14	0	0	0
1332	1						85	15	0	0	0

Transect		6/14/2018					9/3/2018				
		V Sand	V Gravel	Algae	Shell	Eelgrass	V Sand	V Gravel	Algae	Shell	Eelgrass
1146	1	100	0	0	0	0	93	2	0	4	0
1152	1	66	34	0	0	0	24	39	18	20	0
1158	1						59	32	5	5	0
1164	1	95	5	0	0	0	90	0	5	5	0
1170	1	90	5	0	0	0	70	17	4	9	0
1176	1	100	0	0	0	0	82	5	9	5	0
1182	1	86	14	0	0	0	52	36	0	12	0
1182	2	94	0	6	0	0	63	21	11	5	0
1188	1	88	7	0	6	0	61	17	22	0	0
1188	2	94	0	0	6	0	45	41	9	5	0
1194	1	100	0	0	0	0	0	50	50	0	0
1194	2						79	14	7	0	0
1200	1	0	46	31	23	0	0	41	58	2	0
1200	2	100	0	0	0	0	85	5	0	10	0
1206	1	85	0	15	0	0	18	14	68	0	0
1206	2	0.18	76	3	3	0	53	6	41	0	0
1212	1	0.47	0	13	40	0	96	4	0	0	0
1212	2	0.33	67	0	0	0	45	0	55	0	0
1218	1	80	13	0	7	0	43	6	51	0	0
1218	2	100	0	0	0	0	28	0	72	0	0
1224	1	100	0	0	0	0	92	0	8	0	0
1230	1						79	0	11	11	0
1236	1	100	0	0	0	0	83	0	17	0	0
1242	1	84	16	0	0	0					
1248	1	0.47	24	24	6	0	41	23	18	18	0
1254	1	100	0	0	0	0	91	0	4	4	0
1260	1	94	0	0	6	0	79	7	0	14	0
1266	1	100	0	0	0	0	89	5	0	5	0
1272	1	100	0	0	0	0	88	6	6	0	0
1278	1	94	6	0	0	0	89	0	11	0	0
1284	1	100	0	0	0	0	95	5	0	0	0
1290	1	100	0	0	0	0	87	0	0	13	0
1296	1	0	95	5	0	0	23	34	41	2	0
1302	1	50	50	0	0	0	42	37	21	0	0
1308	1	94	6	0	0	0	35	35	26	4	0
1314	1	84	16	0	0	0	65	20	15	0	0
1320	1	38	62	0	0	0	20	15	65	0	0
1326	1	0	86	14	0	0	67	21	88	4	0
1332	1	17	66	18	0	0	15	30	10	10	35

Box	Station	PRE				POST				6POST				12POST			
		V_Sand	V_Gravel	Algae	Shell	V_Sand	V_Gravel	Algae	Shell	V_Sand	V_Gravel	Algae	Shell	V_Sand	V_Gravel	Algae	Shell
1	1	74	7	16	2	95	4	0	1	87	6	6	1	94	6	0	0
	2	93	5	1	1	91	6	0	4	80	20	0	0	93	5	0	0
	3	94	3	0	3	92	6	0	2	79	0	0	0	99	0	0	1
	4	81	9	9	1	70	18	11	1	88	0	0	0	74	5	19	3
2	1	98	0	1	1	93	0.05	0	2	100	0	0	0	93	0	0	7
	2	93	4	1	4	99	0	1	0	95	5	0	0	95	4	0	1
	3	88	0	1	11	94	0	0	6	97	3	0	0	95	3	2	0
	4	92	0	4	4	100	0	0	0	94	0	3	2	76	0	0	24
3	1	66	7	16	11	69	3	0.24	4	78	0	1	1	91	1	3	5
	2	47	6	39	4	66	5	0.27	1	37	0	60	2	45	27	26	1
	3	18	36	42	3	2	0.26	70	1	32	23	43	1	3	20	77	0
	4	69	12	12	6	84	0.11	2	3	84	8	0	0	58	4	32	5
4	1	33	17	40	11	82	4	3	10	73	15	1	10	58	3	24	15
	2	10	31	56	3	0	47	50	3	0	13	83	5	45	23	27	5
	3	43	27	25	4	51	33	9	7	30	14	51	3	5	27	66	2
	4	1	30	68	1	1	39	57	3	5	29	51	16	96	3	1	0
5	1	87	11	3	0	65	19	12	3	80	5	14	0	88	10	2	0
	2	46	22	28	3	72	16	10	1	82	4	12	2	87	6	4	3
	3	94	2	4	0	93	6	1	0	95	1	4	0	88	6	6	0
	4	88	3	8	1	95	5	0	0	96	0	4	0	97	1	2	0
6	1	65	7	27	1	86	11	0	3	71	24	2	0.02	95	0	5	0
	2	19	34	47	0	84	14	0	2	88	11	1	0				
	3	23	21	53	3	40	29	28	4	43	20	36	0.01	25	29	44	1
	4	68	25	4	3	73	27	0	0	68	31	1	0	88	6	6	0

10. APPENDIX D

Wave data and current velocities derived from ADCP deployment in July and October 2017 and February, May, August, and December 2018

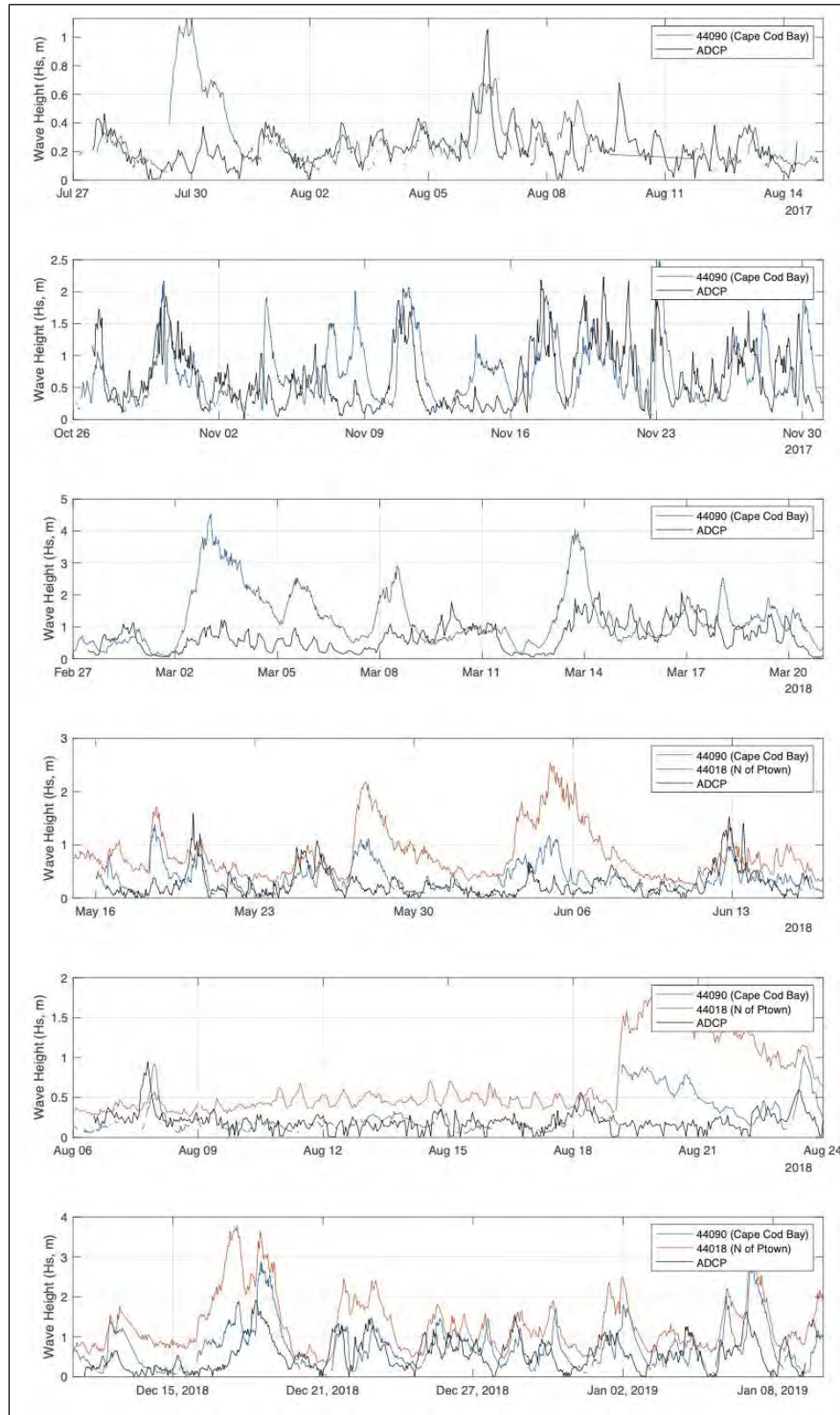


Figure D1. Comparison of ADCP wave height data to NOAA wave buoys in Cape Cod Bay (44090) and north of Provincetown (44018). Note strong event correlation though lower magnitude given ADCP was in much shallower water.

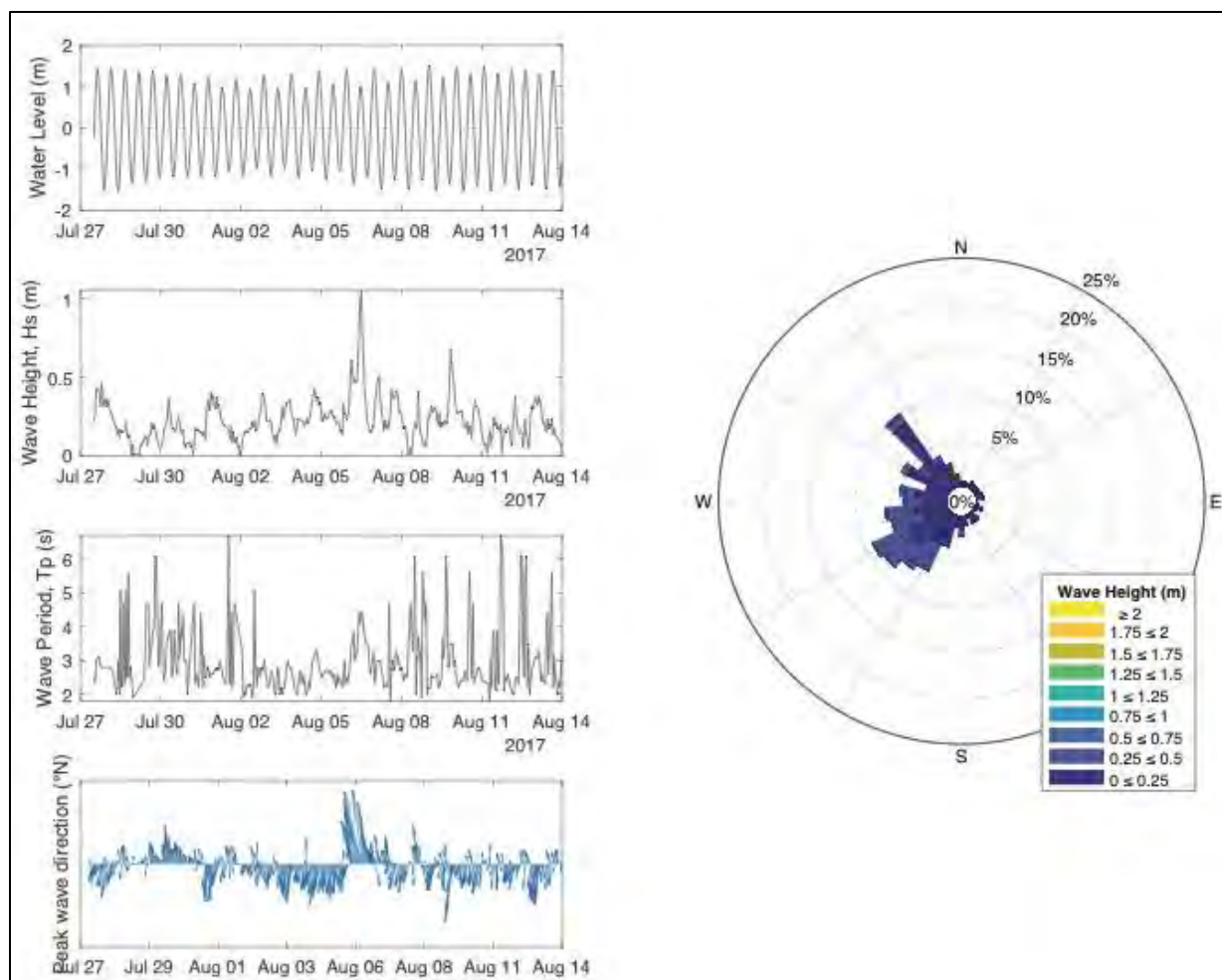


Figure D2. Wave data for ADCP deployment beginning July 27, 2017.

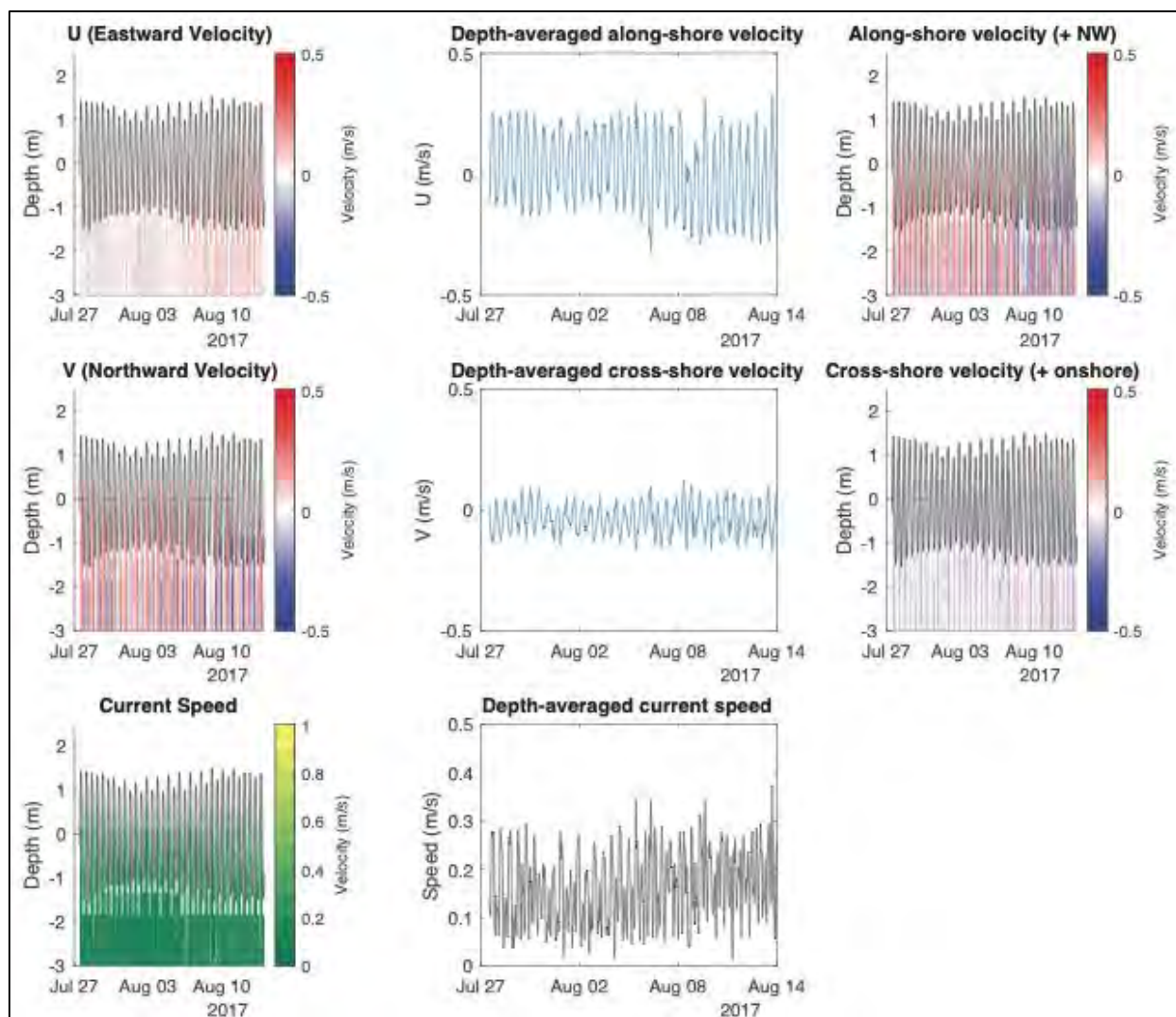


Figure D3. Current velocities for ADCP deployment beginning July 27, 2017.

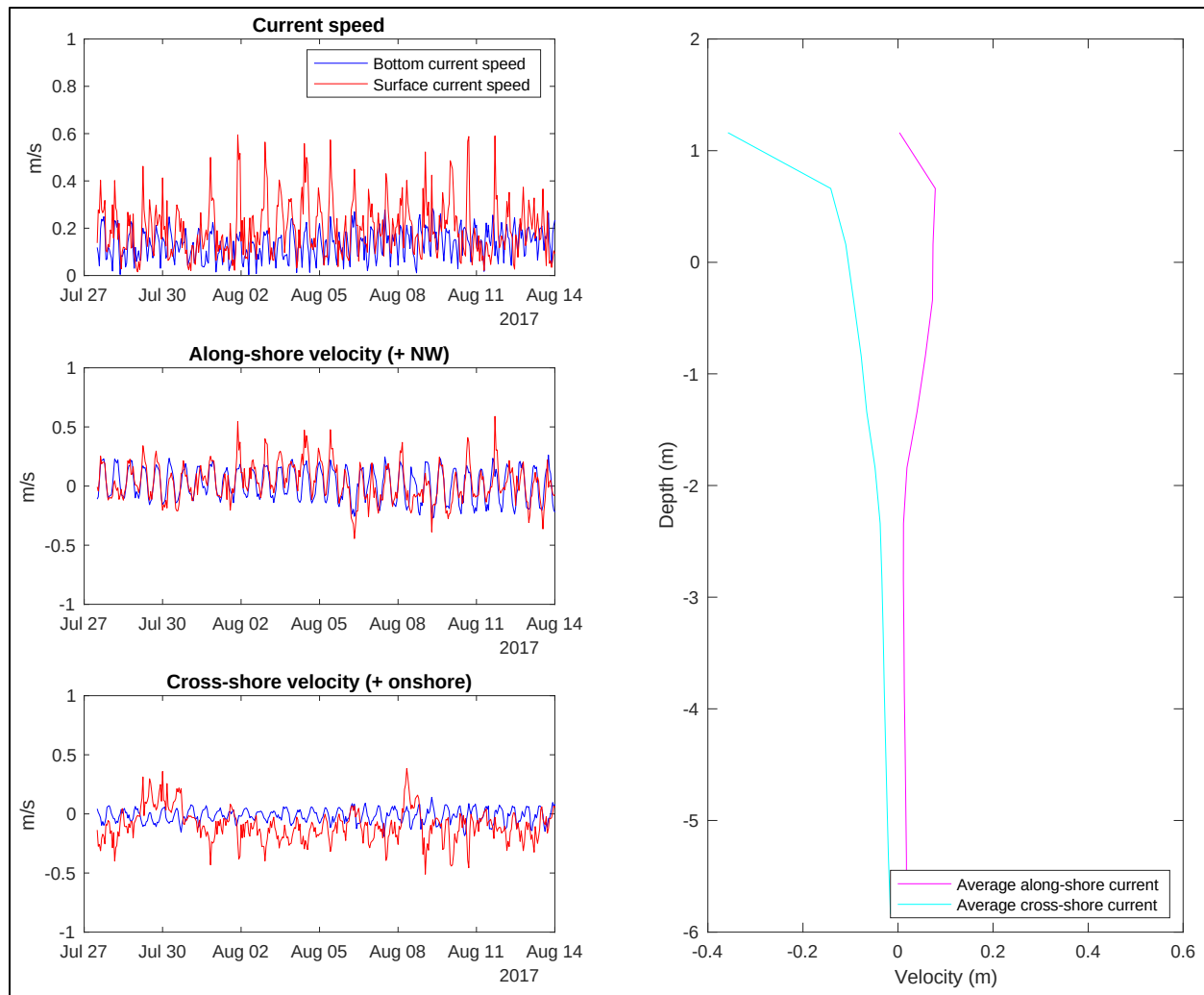


Figure D4. Surface and bottom current velocities for ADCP deployment beginning July 27, 2017.

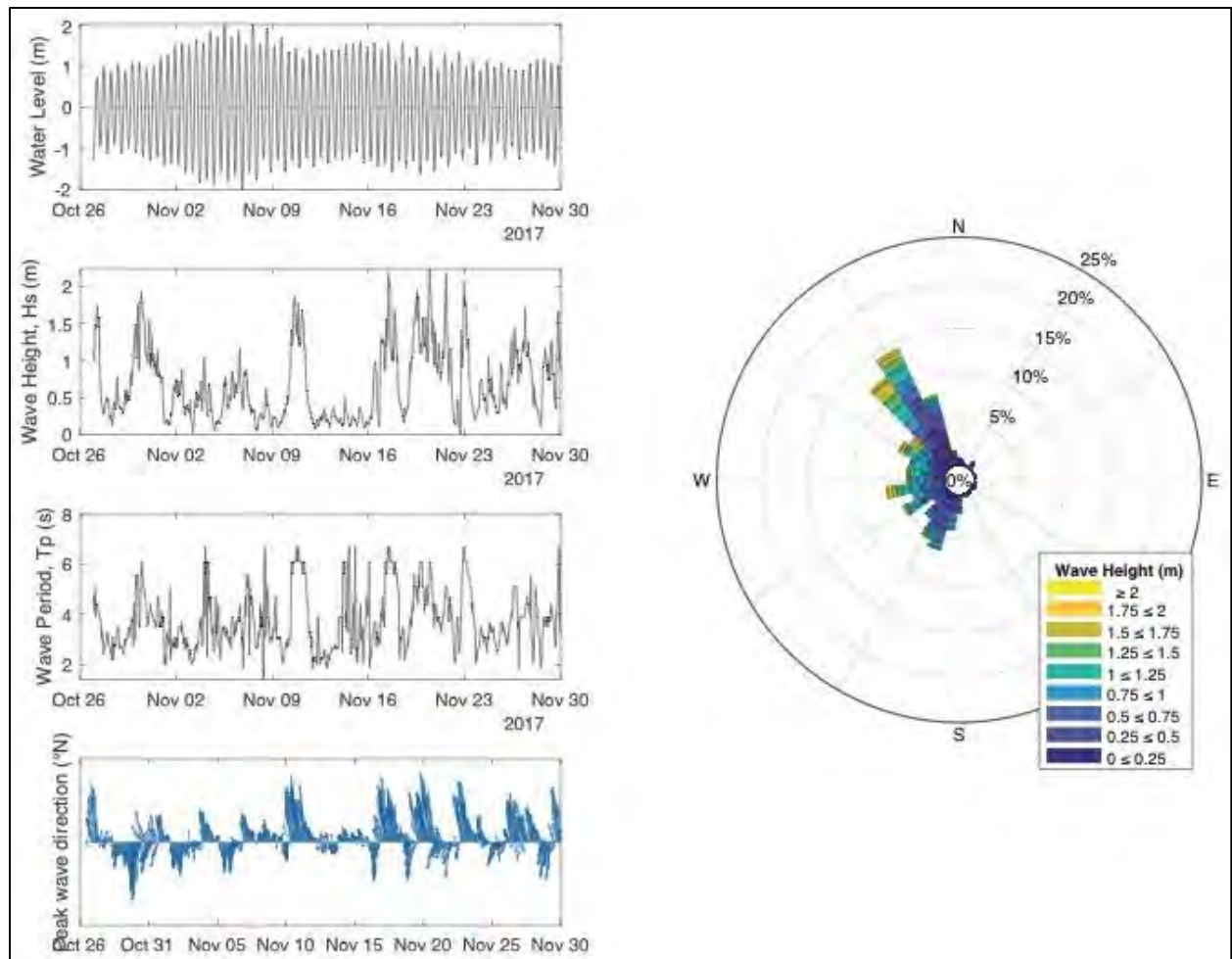


Figure D5. Wave data for ADCP deployment beginning October 26, 2017.

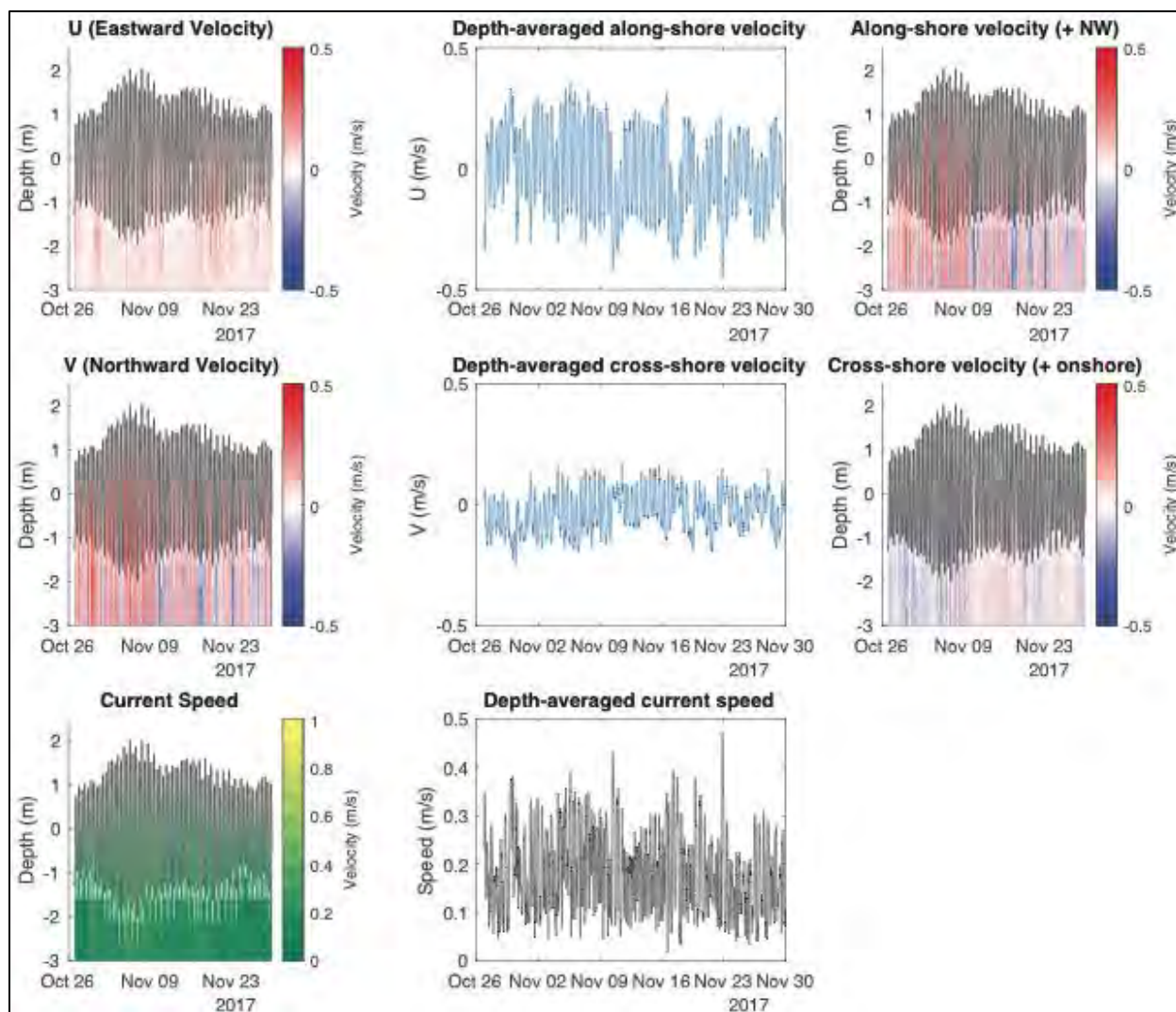


Figure D6. Current velocities for ADCP deployment beginning October 26, 2017.

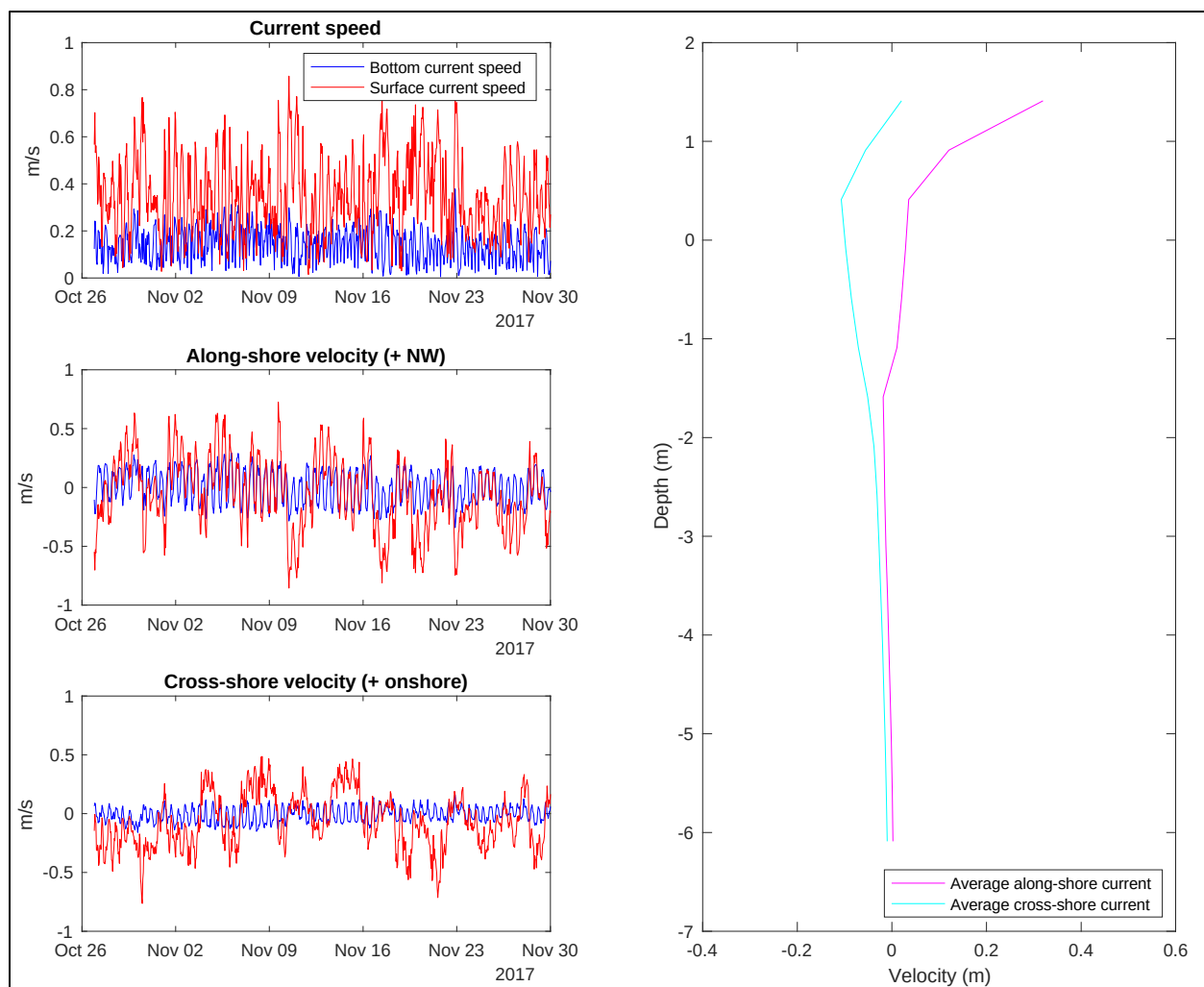


Figure D7. Surface and bottom current velocities for ADCP deployment beginning October 26, 2017.

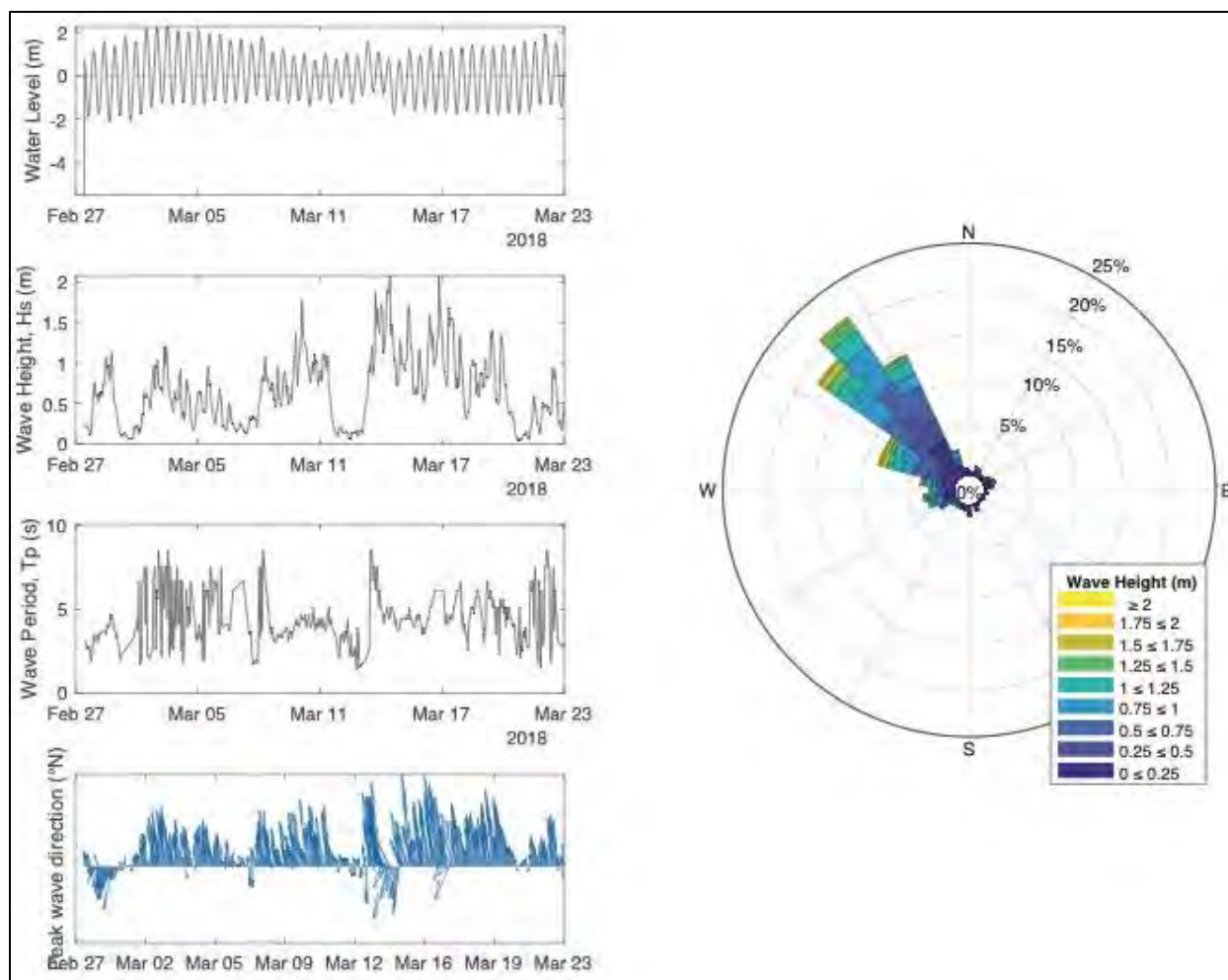


Figure D8. Wave data for ADCP deployment beginning February 27, 2018.

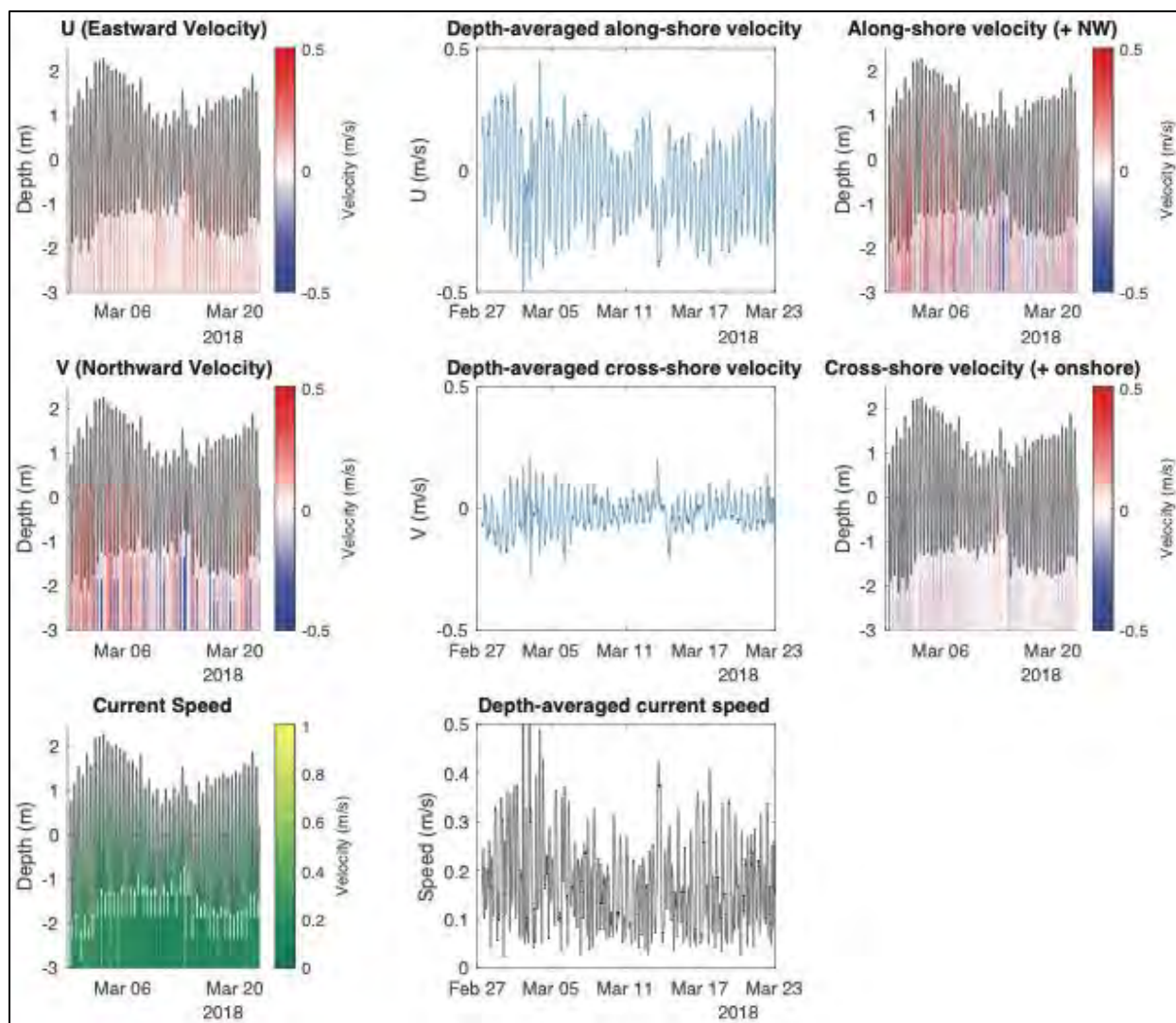


Figure D9. Current velocities for ADCP deployment beginning February 27, 2018.

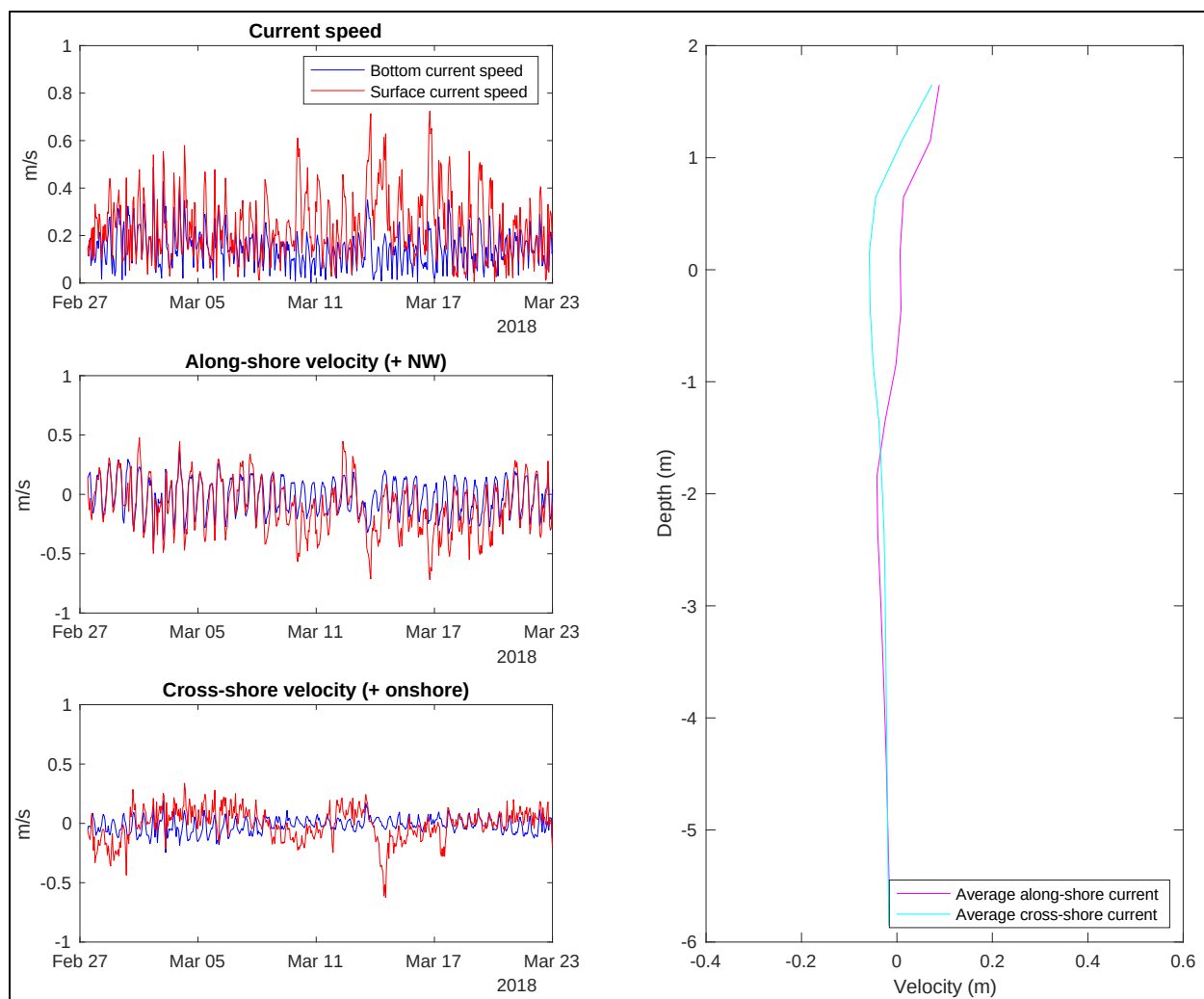


Figure D10. Surface and bottom current velocities for ADCP deployment beginning February 27, 2018.

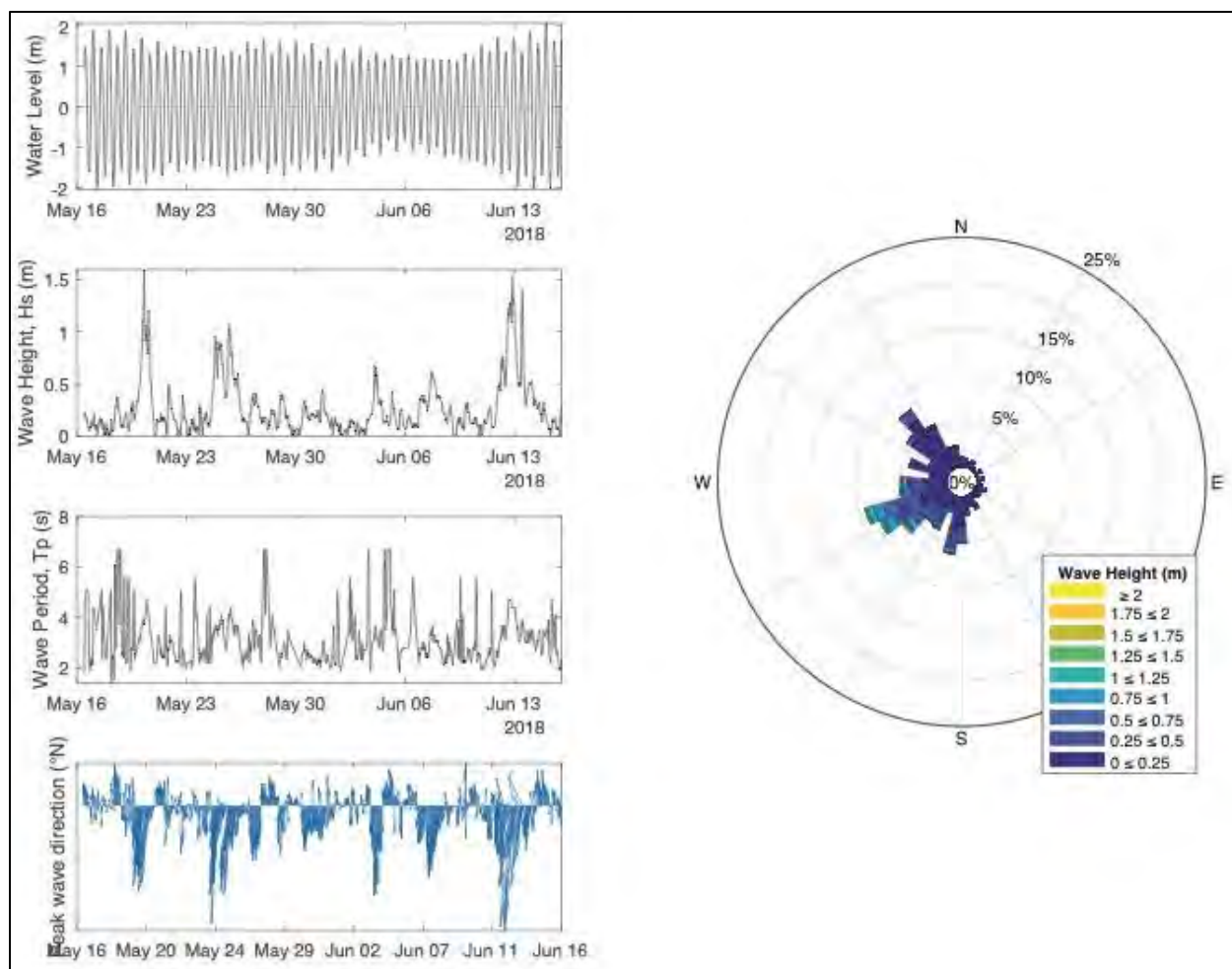


Figure D11. Wave data for ADCP deployment beginning May 16, 2018.

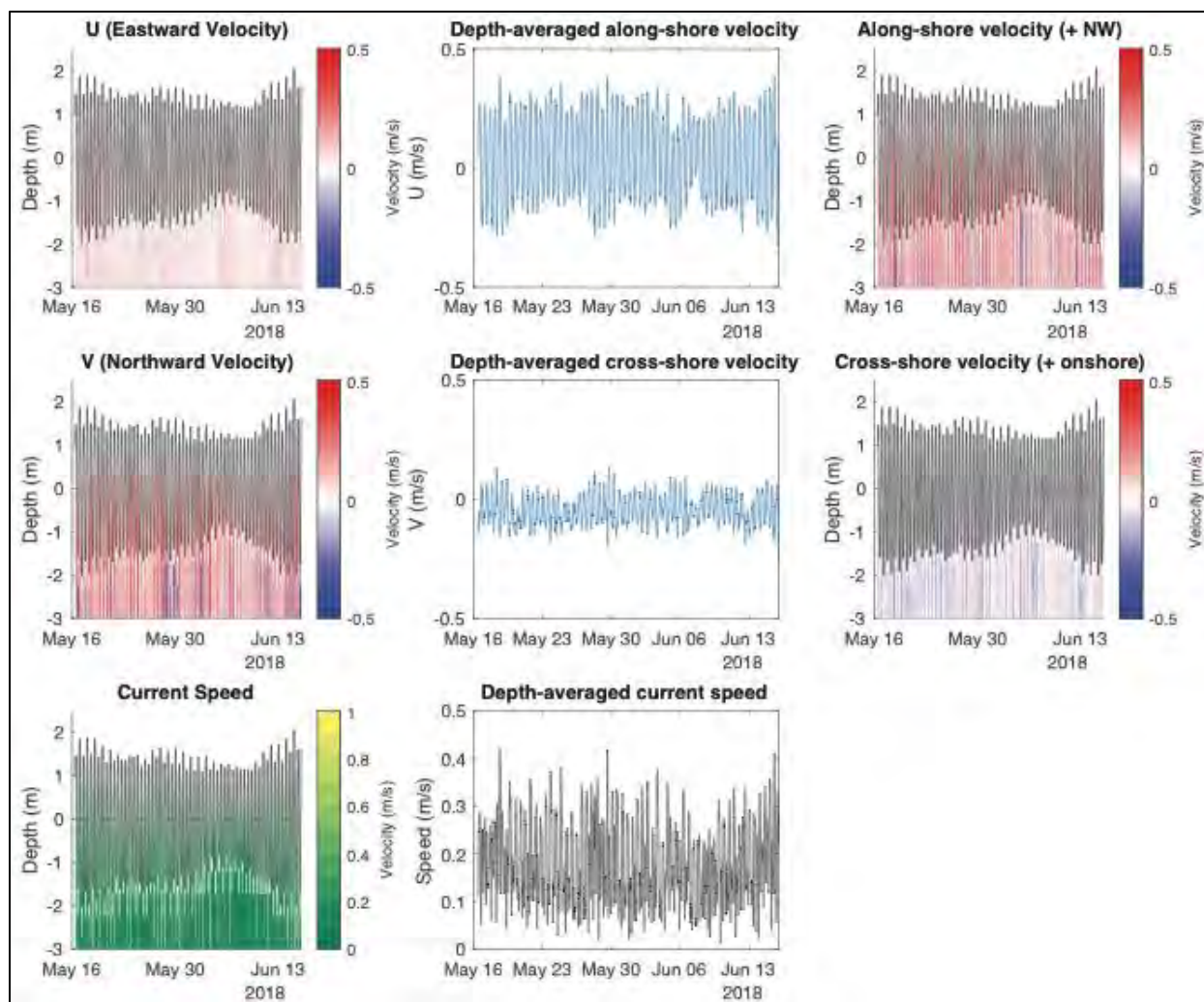


Figure D12. Current velocities for ADCP deployment beginning May 16, 2018.

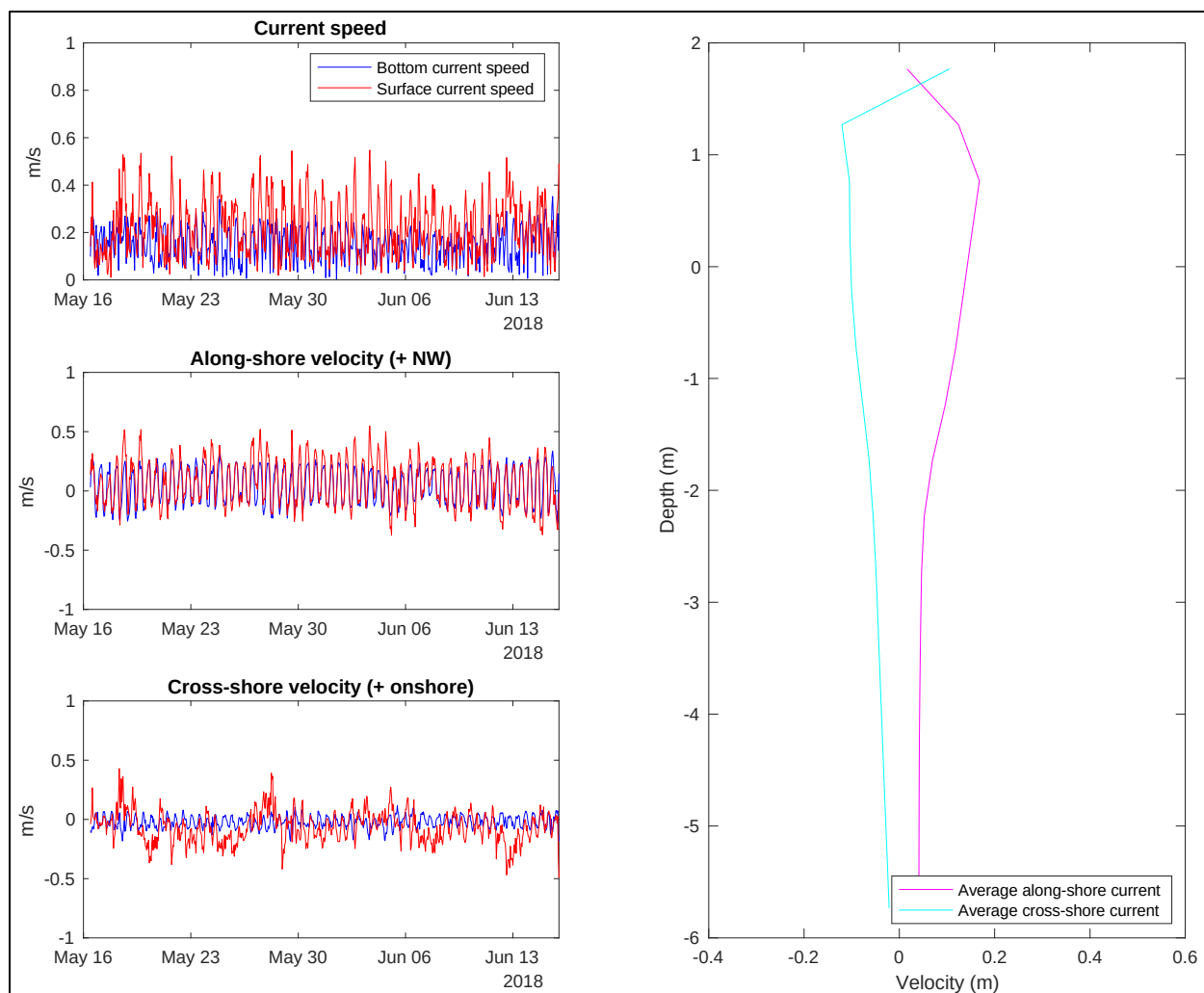


Figure D13. Surface and bottom current velocities for ADCP deployment May 16, 2018.

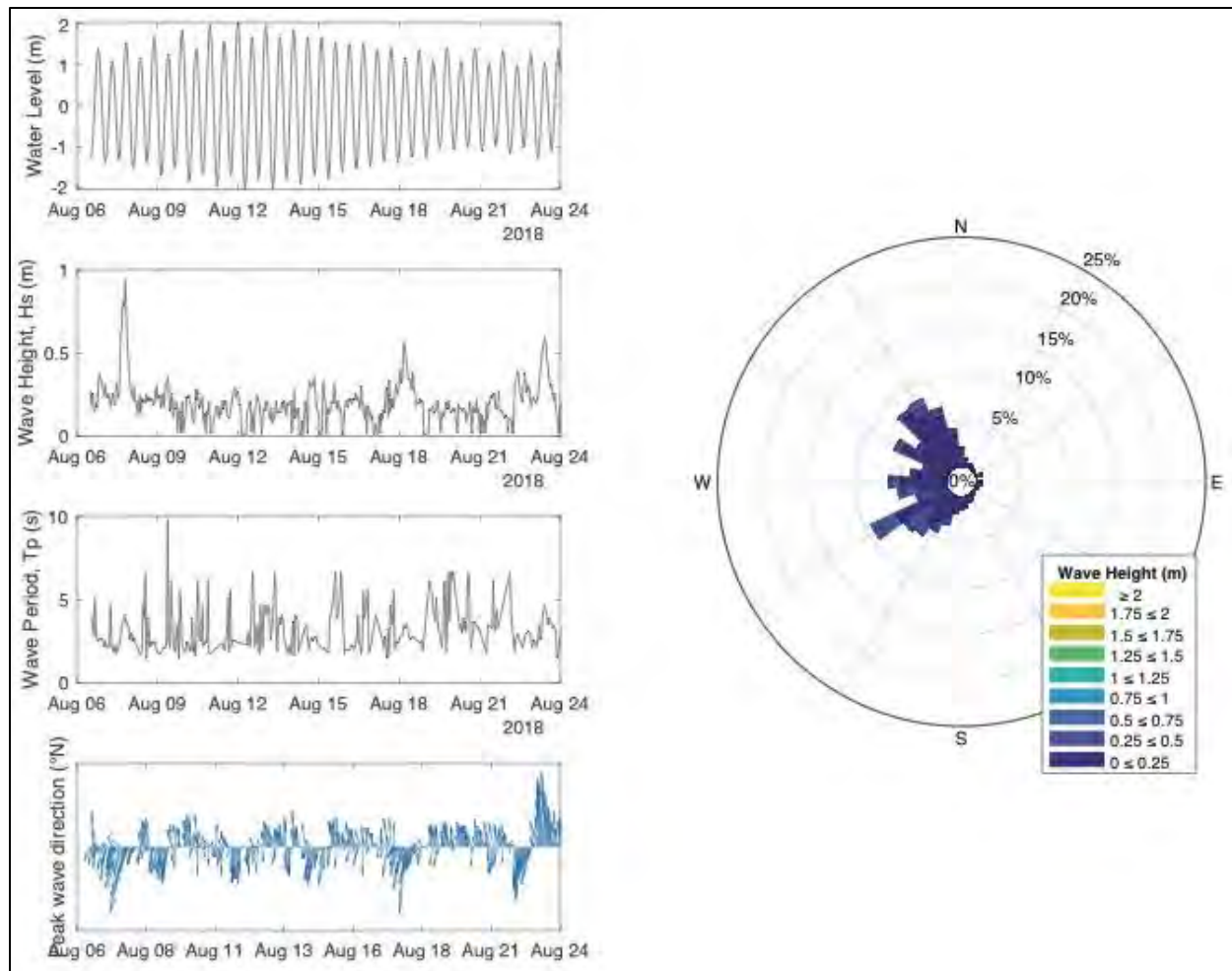


Figure D14. Wave data for ADCP deployment beginning August 6, 2018.

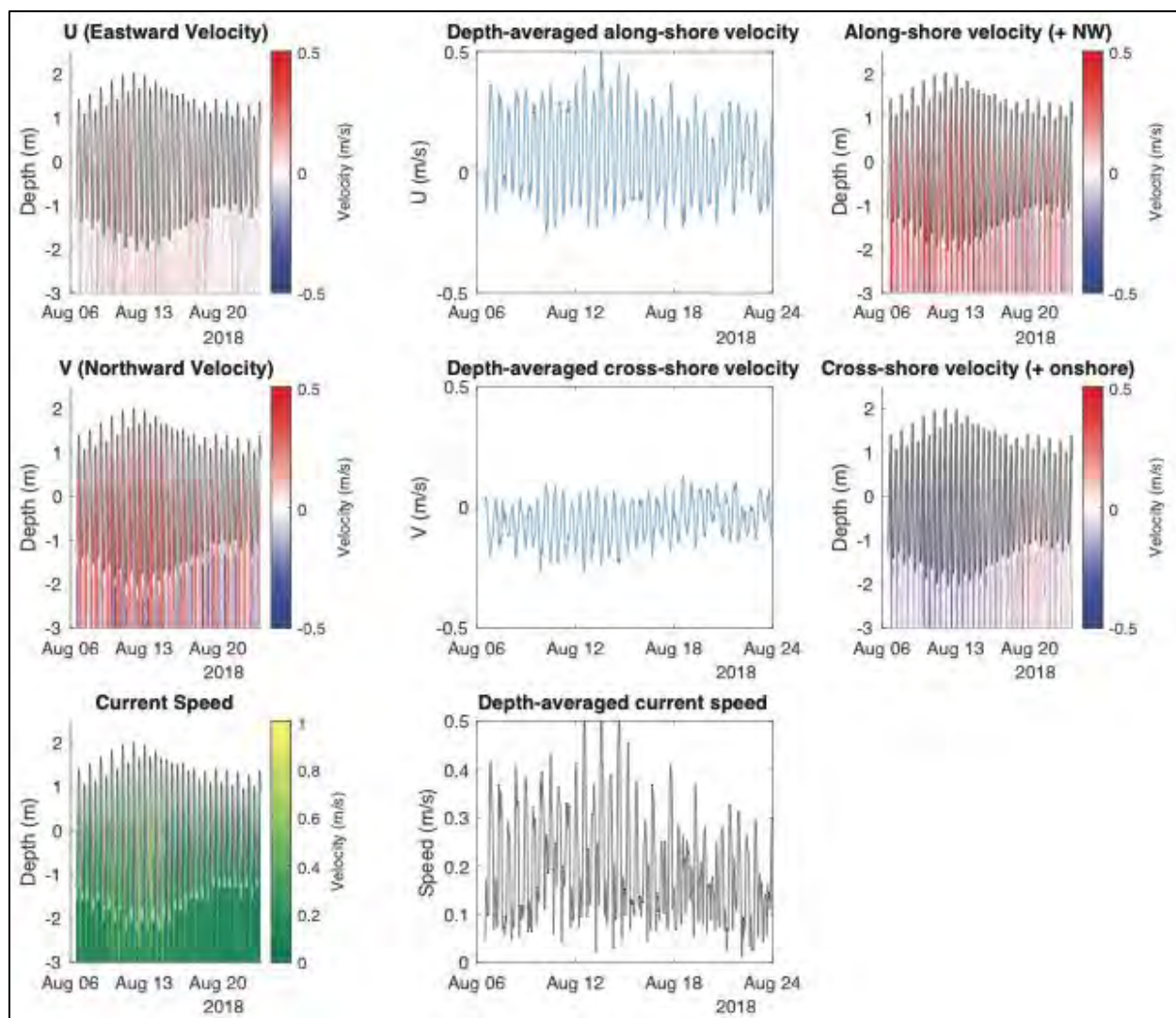


Figure D15. Current velocities for ADCP deployment beginning August 6, 2018.

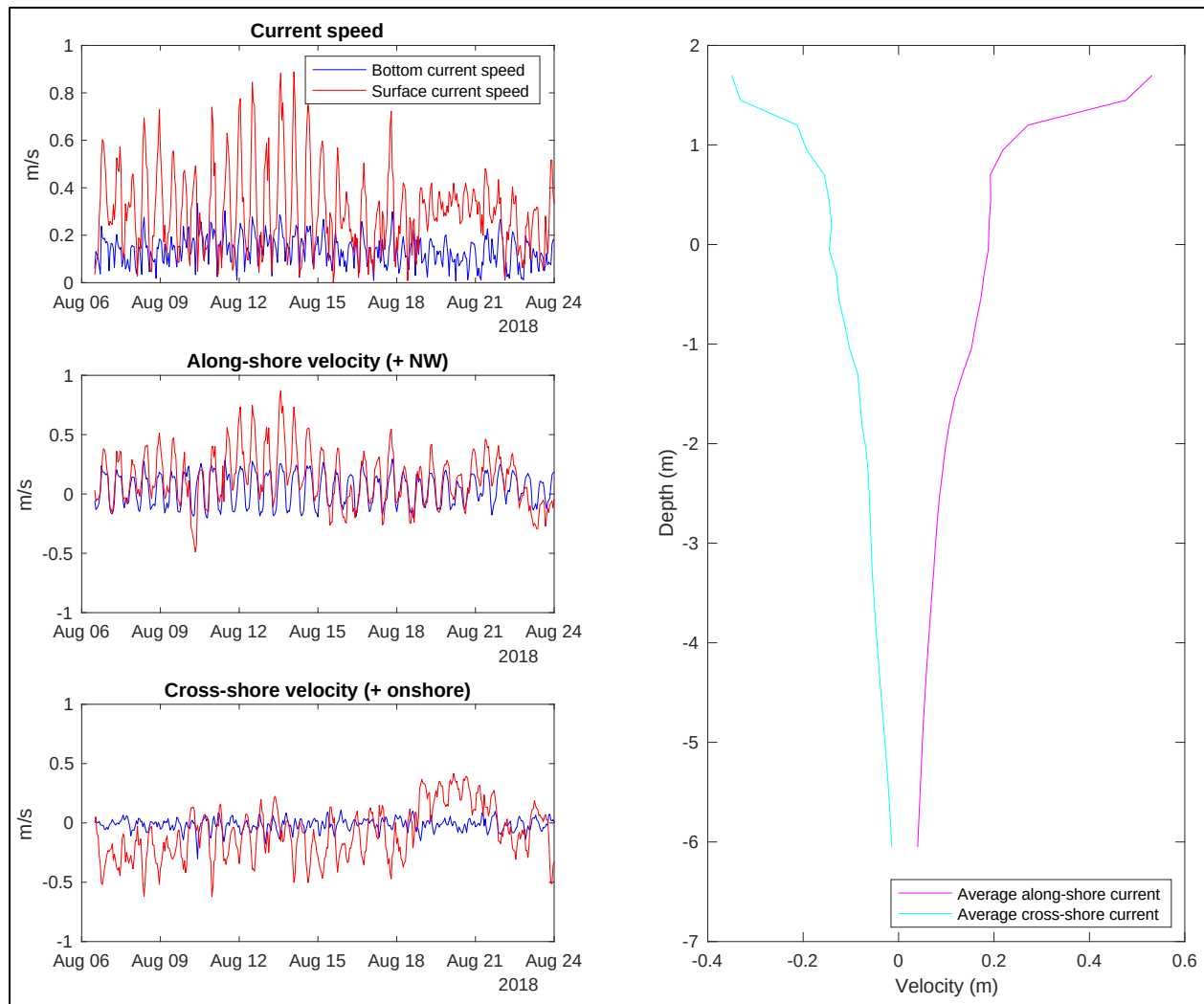


Figure D16. Surface and bottom current velocities for ADCP deployment August 6, 2018.

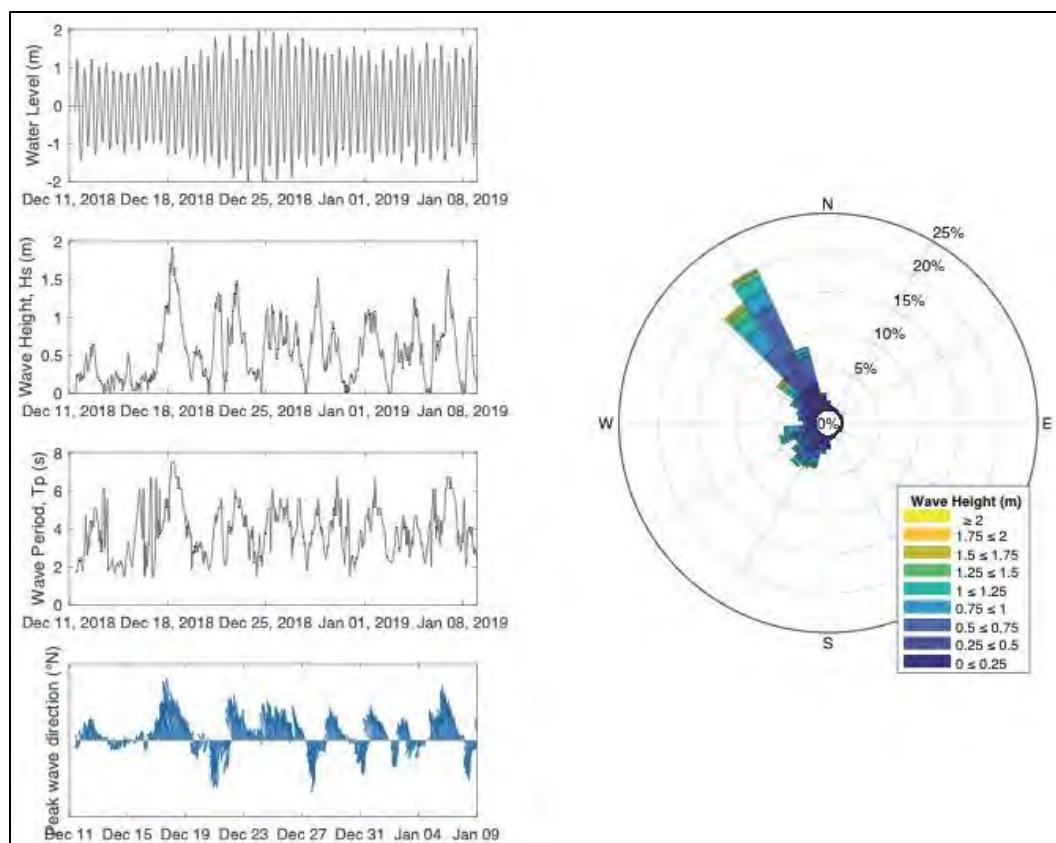


Figure D17. Wave data for ADCP deployment beginning December 11, 2018.

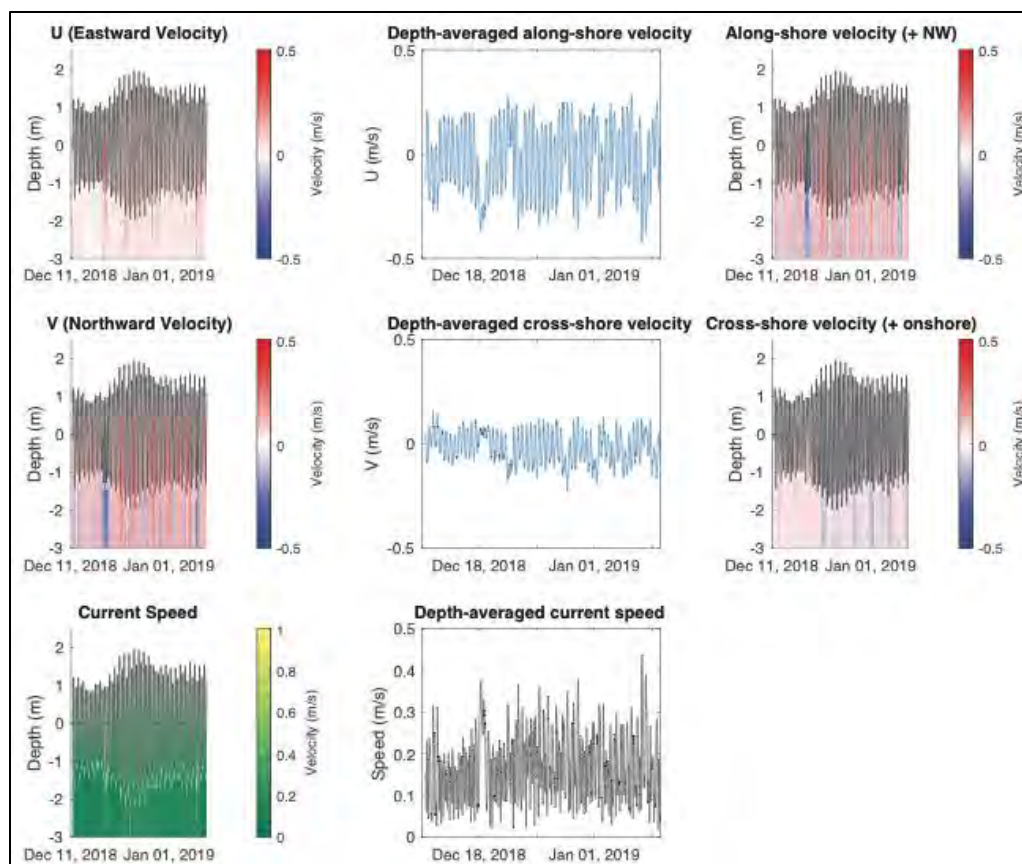


Figure D18. Current velocities for ADCP deployment beginning December 11, 2018.

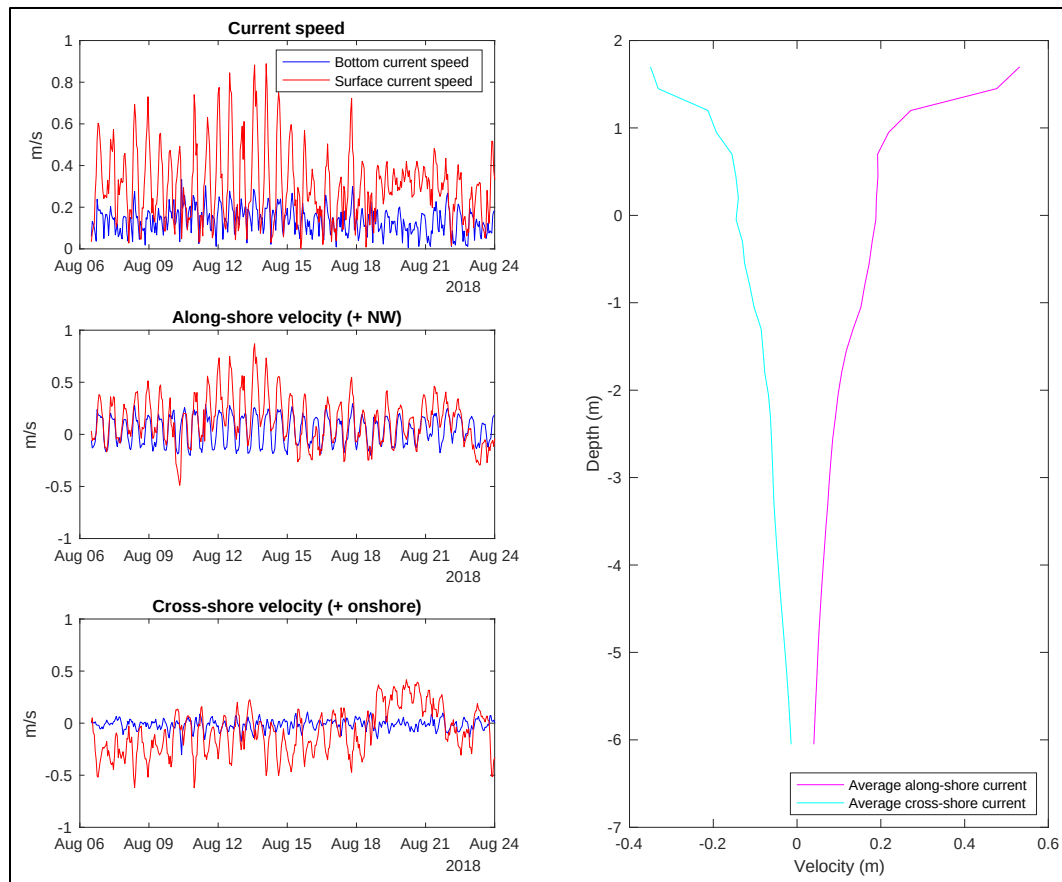


Figure D19. Surface and bottom current velocities for ADCP deployment December 11, 2018.

11. APPENDIX E

Penetrometer data for transects and invertebrate stations

Table E1. Data from all freefall penetrometer surveys.

Dataset	Date	# of drops	QSBC Average (kPa)	SD
Transect	10/5/2017	38	58.59	17.57
	14/08/2017	39	61.82	24.05
	28/10/2017	14	82.79	26.91
	3/11/2017	3	66.93	21.55
	29/03/2018	35	66.10	28.05
	16/06/2018	37	58.66	25.32
	5/9/2018	35	55.43	15.33
Total		201	61.80	23.52

FreeFall	1/11/2017	120	62.57	24.43
	30/11/2017	120	63.59	22.05
	9/5/2018	117	66.33	24.75
	18/11/2018	120	72.58	30.91
Total		477	66.27	25.97

Invert	22/10/2017	31	76.07	26.76
	15/11/2017	12	57.80	16.06
	18/11/2017	39	67.96	27.63
	28/11/2017	17	89.00	42.14
	30/04/2018	37	63.19	26.34
	1/5/2018	45	80.26	37.33
	15/11/2018	47	68.14	28.00
	18/11/2018	46	77.95	26.67
Total		274	72.82	30.42

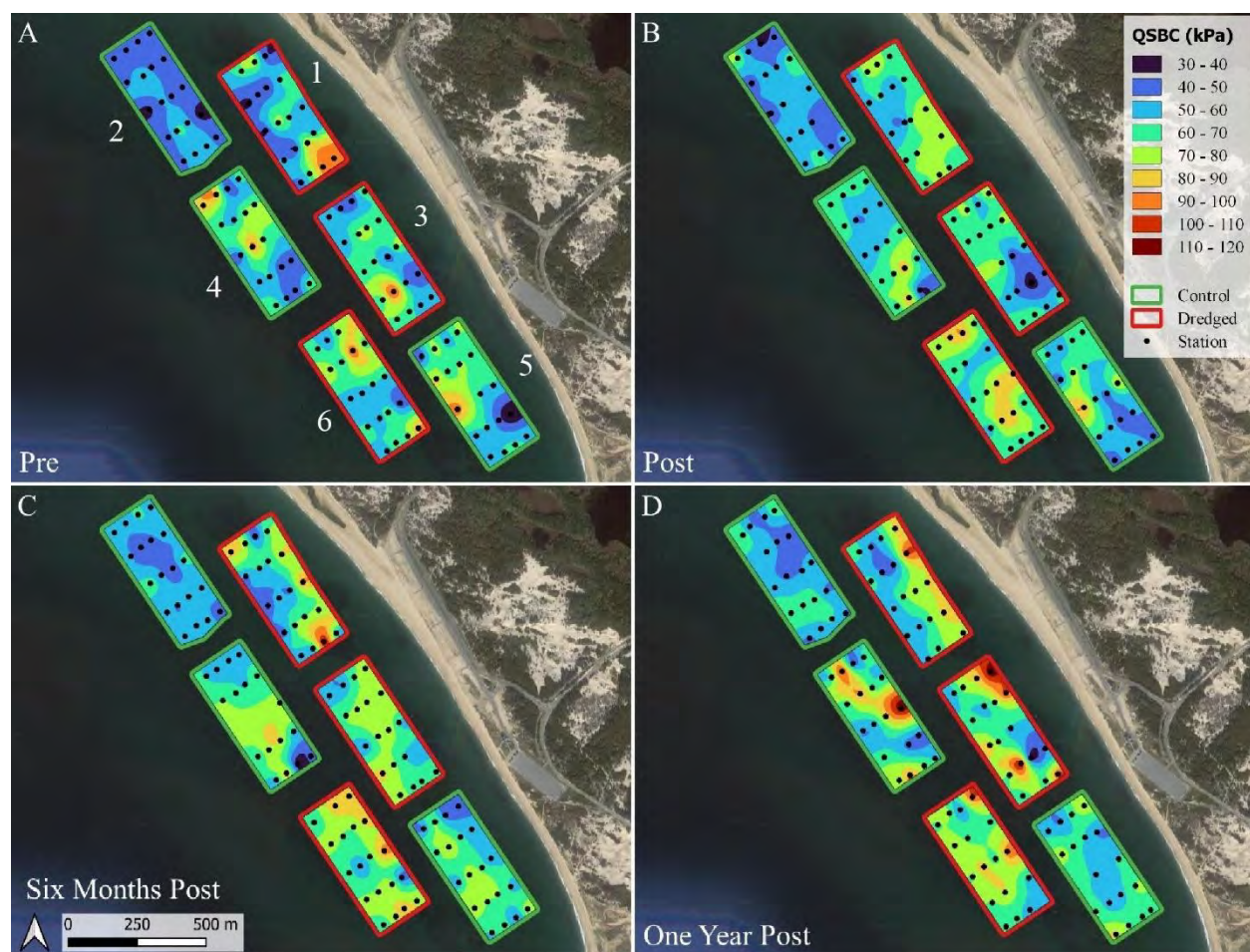


Figure E1. Interpolation of compaction data (QSBC kPa) sampling within each impact box across each monitoring period.

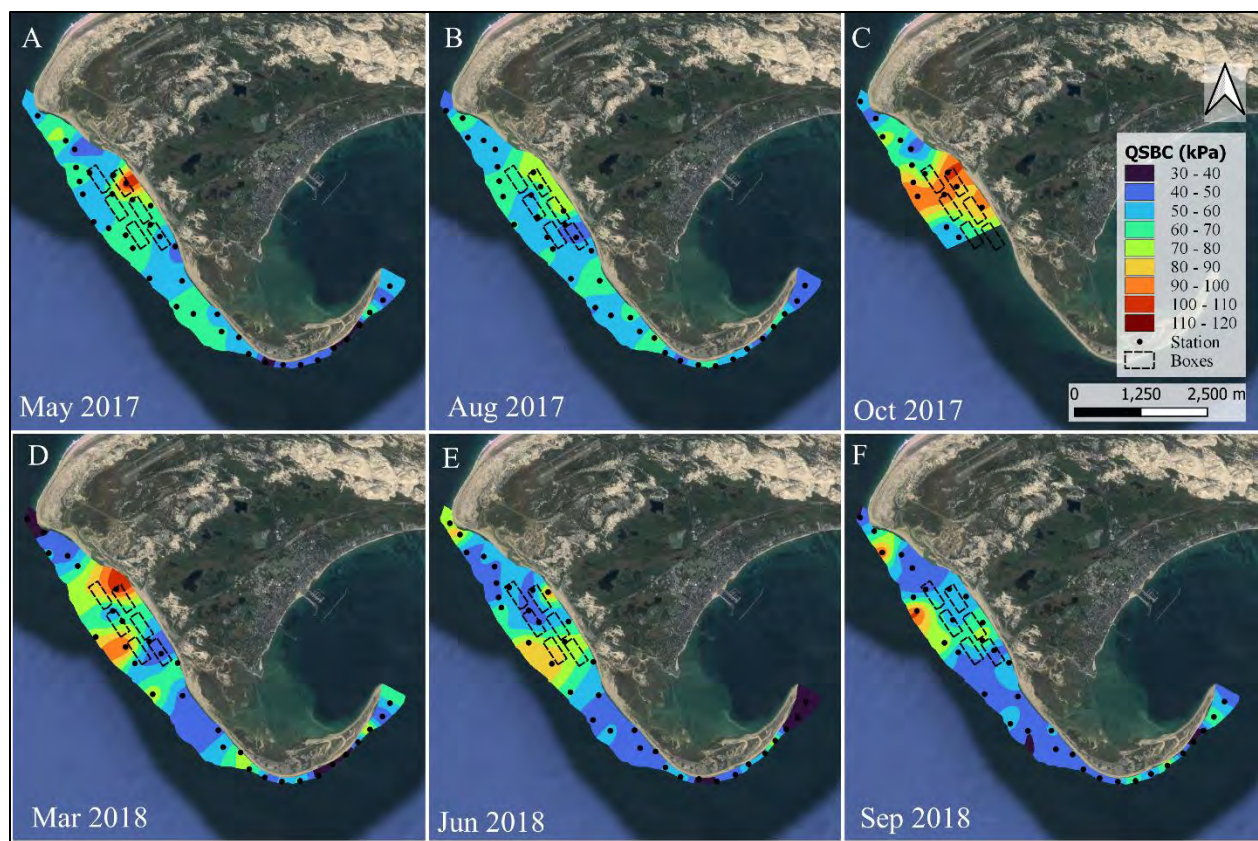


Figure. E2. Quarterly freefall penetrometer surveys with data collected along the 33 shore-perpendicular transects. Quasi-Static Bearing Capacity (QSBC) is a proxy for sediment compaction. The six impact boxes are shown for reference.

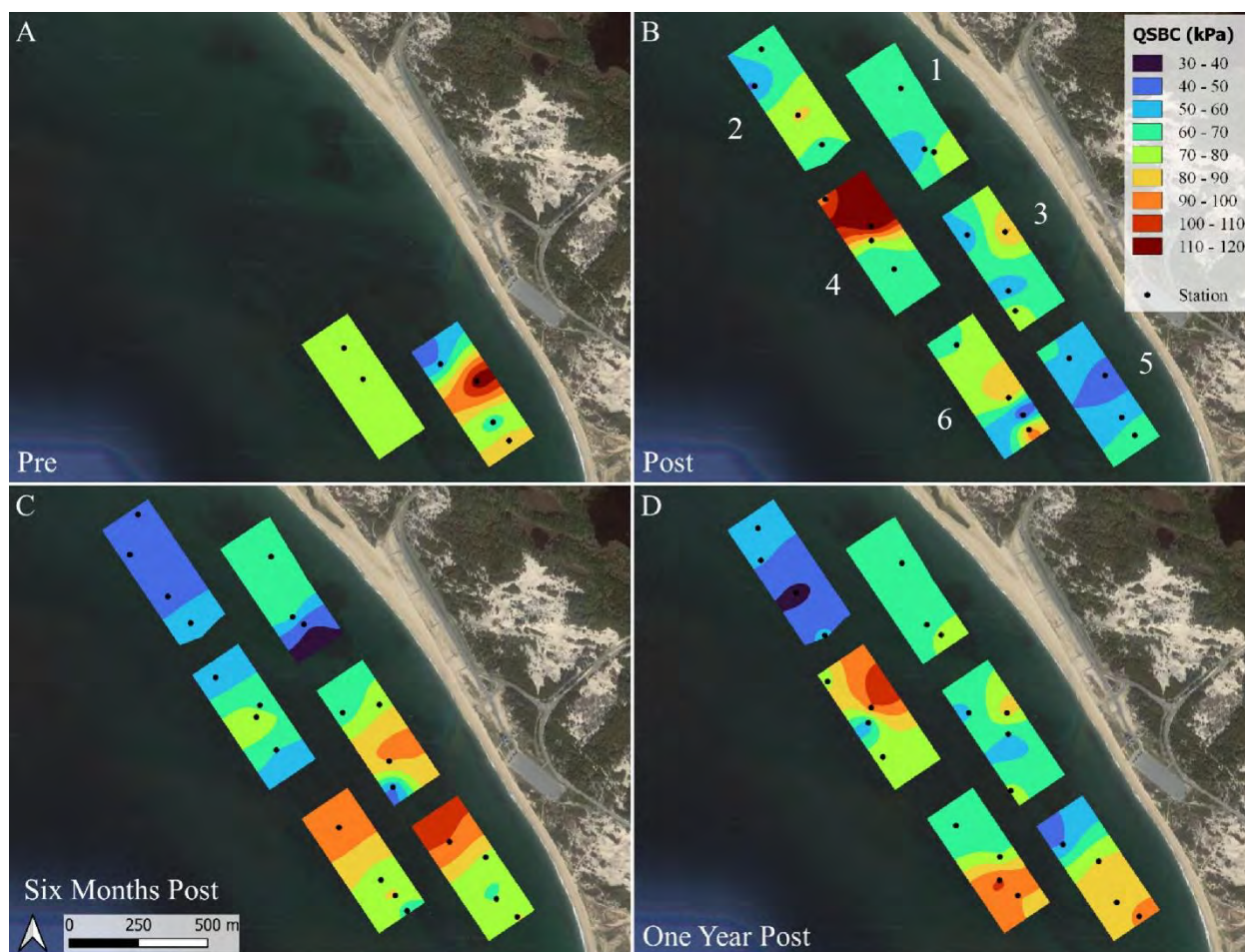


Figure E3. Van Veen-mounted Penetrometer data were collected alongside invertebrate samples in order to better characterize the seafloor adjacent to the individual sample sites. Note: the instrument failed to collect usable data during the pre-survey so the partial data set is shown here.

12. APPENDIX F

from Legare, et. al. 2020. Total area (km^2) of dredge tracks by density in 2015 (●) and total remaining area with dredge tracks in 2017 (○). Solid line indicates the percent recovered in each percent disturbance interval.

