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Effects of the Block Island Wind Farm on Benthic and Epifaunal Communities

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ABSTRACT

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This study reports on monitoring surveys conducted at three of the five commercially operating turbines in U.S. waters off Block Island, Rhode Island, U.S.A., with an emphasis on the final, fourth year of a Bureau of Ocean Energy Management sampling program. The monitoring focused on changes to sediments and infaunal and epifauna species abundance, richness, and diversity caused by the presence of the turbine structure. As anticipated, based on a comparison with other study results, far-field changes in benthic conditions were not evident. Clear changes to the seabed sediments and faunal composition manifested only in the immediate footprint of the turbine foundations. Aside from a localized and sustained shift in particle size, little evidence of a temporally or spatially progressive pattern (as a function of distance away from the turbines) of change in seabed physical and biological composition, or on the turbine structures themselves, was found. The lack of a systematic pattern of influence suggests that many of the intra- and interannual differences may be attributed to natural fluctuations, especially the epifauna on the turbine structures. Notably, the faunal dynamics suggest a community in constant flux and, as seen in other studies, lacking a trend toward the formation of a climax community, which is characterized by stable faunal composition. For these dynamic communities, future sampling may consider using a fixed station, repeated measures approach, as has been done in similarly dynamic, intertidal communities to manage these scales of habitat variability.

ADDITIONAL INDEX WORDS: *Monitoring, offshore, turbine, impacts, sampling design.*

INTRODUCTION

The influence of offshore wind-energy structures on marine communities has long been studied in Europe but has only just begun in waters off the United States (see reviews by Degraer *et al.* [2020], Farr *et al.* [2021], Hogan *et al.* [2023], and Vandendriessche, Derweduwen, and Hostens [2015]). This is primarily because only five commercially operating turbines can be found in the United States to date. Block Island Wind Farm (BIWF) was constructed in Rhode Island state waters (state waters extend to three nautical miles, whereas federal waters of the United States and its territories extend to 200 nautical miles, forming the exclusive economic zone); the BIWF was the nation's first offshore wind facility. Although the BIWF is only a small representation of the emergent offshore wind-energy industry in the United States, the lessons learned from much larger offshore wind farms (OSWFs) in Europe provide a basis for defining anticipated ecological changes arising from their placement.

To start understanding the applicability of these studies in the nascent U.S. offshore wind industry, the U.S. Department of the Interior, Bureau of Ocean Energy Management (BOEM) initiated a biotic monitoring campaign (Realtime Opportunity for Development Environmental Observations [RODEO]) spanning the BIWF turbines located SE of Block Island (BOEM, 2024). The overall goal of the multiyear monitoring study was to characterize the spatial and temporal scales of the anticipated alterations in benthic community characteristics caused by the BIWF and to understand development of communities on the turbine structures. Characteristics include sediment composition, faunal species abundance, richness, and diversity; assemblage structure; and any localized effects of structure-related macrofaunal communities on associated environments. This study describes the general outcomes of the RODEO campaign with an emphasis on the final, fourth (Year 4) monitoring of the campaign (further details can be found in Erickson *et al.* [2022]).

Alterations in benthic conditions may occur because of the presence of turbine structures, as they can modify local hydrodynamic conditions and localized sediment grain-size distribution. The underwater structures also provide a substrate with vertical relief for the growth of epifaunal marine organisms (biofouling). Benthic habitat and biota in the immediate vicinity of offshore turbines may be influenced by the epifaunal communities developing on the structures. Over time, these structure-related communities can provide continuous organic input to the surrounding seabed from biomass sloughing due to predator activity, storms, senescence, and feces (HDR, 2023; Lefaible *et al.*, 2023). Presumably, as it accumulates at the base of the foundation, this organic enrichment could influence sediment

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Table 1. *Summary of selected studies conducted on offshore wind farms with assessment objectives similar to that of the present study. Organized by year and author, starting with recent.*

Reference	Object (s)	Location of Study/Methodology	Relevant Findings
Boutin *et al*. (2023)	Macrobenthic community	English Channel (Irish Sea and North Sea) and literature search	Functional trait-based approach helped identify species' responses to environmental disturbances, ease comparisons of the hard-substrate habitat community structures, and could predict colonization of anthropogenic structures.
HDR (2023)	Macrobenthic community	Coastal Virginia Offshore Wind Project	The rate of initial colonization on biofouling plates is dependent on the season and water depth in which they are placed, with late summer and fall having the highest rates of colonization. Hydroids, amphipods, and stalked barnacles began the colonization within the first 3–6 months. Dominant *Mytilus* sp. communities formed after 1 year, with the greatest biofouling after 2 years. Patches of *Mytilus* sp. beds on rock scour suggest expansion from the foundations, and large quantities of dead mussel shells accumulate near the foundations. Reef effect is in place, with numerous fish observed near the structures.
Hogan *et al*. (2023)	Offshore wind ecosystem	Literature review and synthesis	Generally, the pattern of colonization of turbines is similar between projects; however, substantial differences may occur based on design, materials used, and location. For example, jacket foundations seem to host more mussels than monopiles, although they lack scour protection, or is minimal compared with monopiles. Caution should be taken when comparing U.S. wind farm impacts to those in European waters because varying prohibitions exist for fishing within windfarms, which varies benthic disturbances. Major data gaps still exist.
Lefaible *et al*. (2023)	Macrobenthic community	Belgium, North Sea	Impacts related to the artificial reef effect can influence the surrounding soft sediments; however, the nature and extent of these pressures were site dependent because different results were found between monopile and jacket foundation types.
Li *et al*. (2023)	Macrobenthic community	North Sea	Life cycle impact assessment for benthic communities concluded that no net adverse effects occur.
Guarinello and Carey (2022)	Bathymetric survey, underwater video, and still imagery	Block Island Wind Farm	Multimodal approach was used to assemble baseline data in meaningful ways, which allowed comparison for assessing recovery from anchoring in a moraine habitat.
Roach, Revill, and Johnson (2022)	European lobster (*Homarus gammarus*)	Westermost Rough Wind Farm, UK, North Sea	The short-term increase in size and catch rates observed during construction but not the operational phase may be due to interannual variability more than closure from fishing during construction.
Wilber *et al*. (2022)	Artificial reef effect	Block Island Wind Farm	A 7-year, BACI-designed monitoring study (monthly demersal trawl surveys) supported the artificial reef effect. CPUE of structure-oriented species, such as black sea bass (*Centropristis striata*) and Atlantic cod (*Gadus morhua*), increased following turbine installation.
Farr *et al*. (2021)	Changes to atmospheric and oceanic dynamics, electromagnetic fields, habitat alterations, noise, presence of structures, and water quality	Literature review and synthesis	A literature review (narrowed down to 89 articles) to assess potential effects and possible mitigation measures, focusing on changes to atmospheric and oceanic dynamics, electromagnetic fields, habitat alterations, noise, presence of structures, and water quality.
Ivanov *et al*. (2021)	Macrobenthic community	Belgian Coastal Zone, North Sea	Modeled biodeposition from *Mytilus edulis* on particle composition showed small fluctuations compared with tidal deposition and resuspension. The total organic carbon (TOC) increased up to 50% in sediments in a 5 km area around the monopiles and notably decreased up to 30 km from the monopiles.

Table 1. *(Continued)*.

Reference	Object (s)	Location of Study/Methodology	Relevant Findings
Wilber *et al*. (2021)	Flounder, gadids, and black sea bass foraging	Block Island Wind Farm	Stomach content analysis of flounder, gadids, and black sea bass included mussels and associated epifauna (mysids) following turbine installation, indicating that fish foraged at the colonized turbines. Substantial changes to fish diets were not evident.
Degraer *et al*. (2020)	Artificial reef effect	Literature review and synthesis	Summary paper about the ecosystem function of the turbines creating an artificial reef effect.
HDR (2020)	Macrobenthic community and epifauna	Block Island Wind Farm	A 3-year benthic habitat monitoring study (grab samples and underwater video) showed a transition to organically enriched sediment up to 30 m from the turbines, which supported dense mussel aggregations, with the greatest rate of change occurring at Turbine 1. An invasive tunicate *Didemnum vexillium* colonized the turbine structures, whereas the coral *Astrangia poculata* was noted near the foundations. The amount of growth on the turbine structures added up to 85% drag force.
Hutchison *et al*. (2020)	Macrobenthic community	Block Island Wind Farm	A summary of the 3 years of benthic monitoring showed the largest change within the turbine footprint. *Mytilus edulis* dominated the foundations with an increase of predators such as moon snails, sea stars, cancer crabs, and *Centropristis striata*. The presence of juvenile crabs may be an indicator of nursery habitat. Coordinated monitoring strategies of multiple offshore wind projects would allow for an effective, adaptive, monitoring effort.
Lu *et al*. (2020)	Macrobenthic community	Pinghai Bay, China	Most macrobenthos recovered quickly after construction, with an increased abundance (94.75%) of annelids, arthropods, and echinoderms compared with that before the construction. Mollusks may require more time to recover. There was a shift in species dominance, to Annelida (73.28%–77.78%) in the macrobenthic community.
Mavraki *et al*. (2020)	Macrobenthic community	C-Power Wind Farm, Thornton Bank, North Sea	Samples from one gravity-based foundation across water depths and its surroundings showed a considerable degree of trophic plasticity in both sessile and mobile fauna. Most invertebrate species showed zone-specific dietary shifts, except one species of anemone, which was a trophic specialist.
HDR (2018)	Bathymetric surveys and scour monitors	Block Island Wind Farm	Bathymetric surveys were conducted during the construction phase and 12 months postdisturbance to track the benthic recovery of the scars. Seafloor recovery rates correspond to seabed mobility with in-filling taking place between surveys. Scour monitors were also used to track the long-term changes in seabed elevations, which would support design of future wind farm projects.
Todd, Lavallin, and Macreadie (2018)	Macrobenthic community, including fish	Dogger Bank, North Sea	Standard decommissioning of offshore infrastructure could eliminate entire communities due to vertical zonation on the structures and use as a spawning site, which may also produce and not only attract fish.
Krone *et al*. (2017)	Cancer crabs (*Cancer* sp.)	German Bight, North Sea	Monopiles with scour protection were colonized by cancer crabs by more than twice the amount found at foundations without scour. The foundations serve as aggregation sites, as well as nursery grounds for cancer crabs.
Coates *et al*. (2015)	Macrobenthic community	Thornton Bank and Goote Bank, Belgium, North Sea	A higher abundance of opportunistic species was observed during the construction year, and rapid infill from surrounding soft bottom habitat lead to a fast recovery by the subsequent year.

Table 1. *(Continued).*

Reference	Object (s)	Location of Study/Methodology	Relevant Findings
Vandendriessche, Derweduwen, and Hostens (2015)	Macrobenthic community, including fish	Thornton Bank and Bligh Bank Wind Farms, Belgium, North Sea	Reef effects due to the addition of hard substrate extended into the soft substrates between the turbines. The observed effects were not consistent between wind farms, which stresses the necessity of monitoring activities across wind farms in different regions, topography, fishing pressures, foundation types, and developmental stages.
Coates *et al*. (2014)	Macrobenthic community	Zeeland Ridges, the Thornton Bank, Belgium, North Sea	Sediment grain size significantly reduced near the foundation while organic matter increased, which caused a shift (increase) in the macrobenthic community density.

characteristics, which may lead to changes in benthic macrofaunal community diversity and abundance.

A summary of selected studies on the effects of OSWF structures on living resources is provided in Table 1 (see also Farr *et al.* [2021] for similar summaries for floating wind systems). Table 1 shows that this study represents the seventh report or publication on the BIWF, making it perhaps one of the most-studied wind farms and all the more notable for its small extent. The scale (extent and resolution) over which these studies were conducted was also examined, but not shown), because comparing results across wide ranges of scale is a classic ecological challenge (Levin, 1992). Except for findings from Boutin *et al.* (2023), the studies in Table 1 have similar levels of sampling scale, ranging over only two orders of magnitude for sampling resolution and three orders of magnitude for sampling extent. Consequently, the findings among all these studies are capturing similar scales of community structure. Based on preliminary studies in Europe, changes in benthic composition attributable to wind-farm operation can be anticipated within 50 m of the foundation scour-protection systems (Coates, Vanaverbeke, and Vincx, 2012), with the possibility of a long-term shift in community composition, which in some settings may become spatially extended. Overall, however, these generally scale-comparable monitoring studies all point to limited spatial extent of benthic effects but with increased likelihood of persistent changes within that extent.

This study presents the generalized findings of the completed 4-year monitoring campaign. The results are discussed in relation to other OSWFs, but they also contribute to lessons learned on the approach to sampling and the ways in which future studies may be better aligned with the spatial and temporal dynamics of these living communities. Following Zupan *et al.* (2023), the notion of directional development and existence of climax communities (or lack thereof) in these benthic and epifaunal environments is considered. Moreover, understanding the basis of community development processes is fundamental to designing sampling approaches to measure disturbance and recovery from that disturbance (resiliency). To help understand the surrounding community and the way in which it responds to the turbine structure installation over time, three hypotheses were tested during the multiyear study period with respect to sediment composition, organic enrichment, and macrofaunal communities:

(1) $H_0$1: no differences between turbine areas;
(2) $H_0$2: no differences between control areas and turbine areas; or
(3) $H_0$3: no effects of distance from the wind-farm foundations.

Monitoring study results were used to evaluate spatial and temporal scales of changes in sediment composition and macrofaunal community characteristics on and around the turbines and to improve our understanding of ecosystem-level effects of the BIWF.

METHODS

The five, 30-megawatt BIWF turbines are located 4.5 km from Block Island in the Atlantic Ocean in a water depth of approximately 20 to 25 m (BOEM, 2019; Figure 1). Initial monitoring was conducted following the construction of the five turbines starting in December 2016 and continued through November 2019 (Monitoring 1–3; HDR, 2020; Hutchinson *et al.*, 2020). This study adds the final monitoring from fall 2021(Monitoring 4, Table 2), which concluded the RODEO monitoring campaign. Sampling of biota on the turbine structure and in the surrounding seafloor was conducted over this 4.9-year period.

Monitoring Design

Monitoring during RODEO was performed only on turbines 1, 3, and 5 (T1, T3, T5)—representing the middle and two ends of the row of turbine structures—and were numbered in order from NE to SW (wind turbine generator coordinates (latitude, longitude) in WGS84: WTG1 = 41.12572′, 71.5076′; WTG1 = 41.11993′, −71.51395′; WTG3 = 41.11477′, −71.52113′; WTG4 = 41.1102′, −71.52912′; WTG5 = 41.10638, −71.53765′). The average water depth was approximately 20 m for T3 and T5 and 25 m for T1. The focus was on detection of any continuously progressive, systematic changes in sediment composition and fauna with distance from the turbine structures.

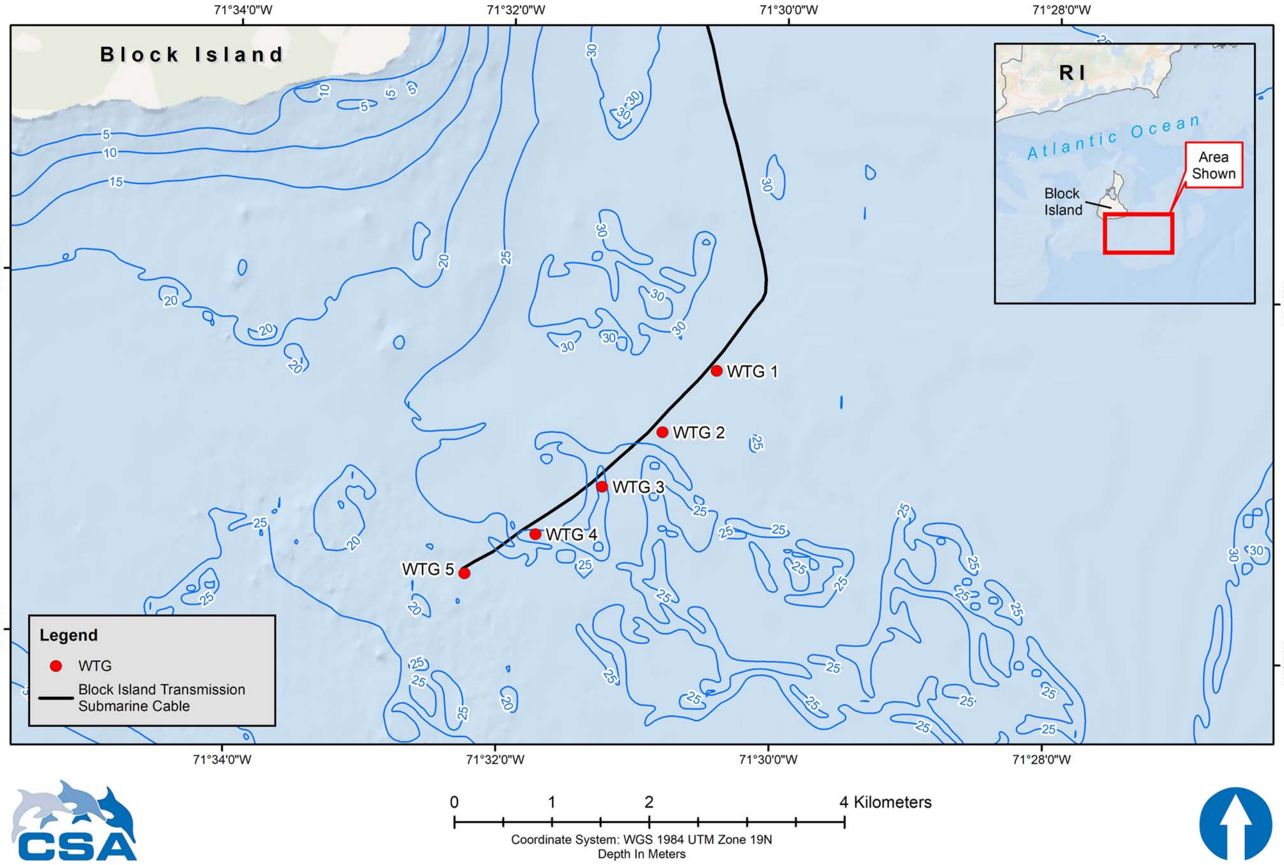

Figure 1. Location of five turbines at the Block Island Wind Farm offshore Rhode Island and local bathymetric contours (WTG = Wind Turbine Generator).

The field components of the benthic and epifaunal monitoring comprised the following tasks:

(1) Grab sampling (vessel- and diver-based) at designated sampling stations in and around T1, T3, and T5 and within three control areas;
(2) Capturing seabed video at grab locations using a camera affixed to the grab sampler;
(3) Collecting epifaunal scrape samples (diver-based) along the current and leeward sides of T1; and
(4) Collecting video imagery (diver-based) along the current and leeward sides of T1, T3, and T5.

Table 2. *Summary of the benthic sampling periods at Block Island Wind Farm conducted as part of the RODEO program (BOEM, 2024). Benthic sampling and sampling of the submerged portions of the turbine monopoles were conducted by both vessels and divers.*

Survey	Sample Basis	Sample Period and Dates					
		2016	2017	2018	2019	2020	2021
1	Vessel	Dec	Jan/Mar				
2	Vessel		Nov/Dec				
2	Diver			May/Jun			
3	Vessel				Feb		
3	Diver				Aug–Nov		
4	Vessel						Oct
4	Diver						Nov

Calibration studies demonstrated that results from diver-based collections (performed close to the turbines where vessel-based grab sampling was hazardous) in nearby Narragansett Bay, Rhode Island, were comparable to the results obtained from grab samples (HDR, 2020; Hutchinson *et al.*, 2020). Consequently, in this Year 4 monitoring survey, those samples were considered equivalent levels of replication.

Throughout the campaign, a stratified random sampling design for benthic sampling was used in which five strata were positioned around the center points of T1, T3, and T5 at the BIWF. These turbines were selected for monitoring on previous campaigns because data indicated they had the broadest representation of biotope classifications present within the study area (HDR, 2020). Although slight changes were made to the benthic sampling design between the first three and the fourth and final (Year 4) monitoring surveys, during all monitoring, five distance strata in a bull's-eye pattern were randomly sampled around each of the three selected turbines. During the first three monitoring surveys, three control areas were located at various distances from the turbines in similar biotopes. The control areas were

Table 3. *Modified study area, strata, sampling method, and number of stations. Grab sampler methods were vessel based.*

Study Area	Strata	Sampling Method	Number of Stations
T1	Foundation footprint	Diver grab	8
	Very near field (<30 m)	Diver grab	8
	Near field (30–49 m)	Grab sampler	8
	Intermediate field (50–69 m)	Grab sampler	8
	Far field (70–90 m)	Grab sampler	8
		Total number of stations at T1	40
T3	Foundation footprint	Diver grab	8
	Very near field (<30 m)	Diver grab	8
	Near field (30–49 m)	Grab sampler	8
	Intermediate field (50–69 m)	Grab sampler	8
	Far field (70–90 m)	Grab sampler	8
		Total number of stations at T3	40
T5	Foundation footprint	Diver grab	8
	Very near field (<30 m)	Diver grab	8
	Near field (30–49 m)	Grab sampler	8
	Intermediate field (50–69 m)	Grab sampler	8
	Far field (70–90m)	Grab sampler	8
		Total number of stations at T5	40
Control: Turbine area 1 (>250 m)		Grab sampler	8
Control: Turbine area 3 (>250 m)		Grab sampler	8
Control: Turbine area 5 (>250 m)		Grab sampler	8
		Total number of control stations	24
		Total number of sampling stations	144

positioned at varying distances from each turbine, and each had a diameter of 180 m. The control areas were repositioned after each monitoring and were placed in similar habitat types (biotopes). All control areas were located within the biotope classified as "*Polycirrus* sp. and *Lumbrinereis* sp. in coarse sand with small dunes within glacial alluvial fan," which seems to be the predominant biotope at T1, T3, and T5 (LaFrance *et al*., 2014). Three stations were located within most distance strata, and the collection of triplicate "cluster" samples was attempted at each station (Table 3).

Because results from the first three monitoring surveys indicated a high fine-scale similarity among the triplicate samples and because of the need to increase the number of independent benthic samples, a slightly modified sampling design was implemented for the Year 4 monitoring survey. This modified design included the previously designated five sampling strata described previously, with the following modifications. Triplicate sampling at stations was eliminated; placement of sampling stations was separated by a minimum distance of 5 m within each stratum to reduce sample clustering and improve spatial generalization; and control stations were randomly reassigned around each turbine (200 m minimum among station distance) and located in a biotope similar to that of the turbine itself, classified as having coarse sand (LaFrance *et al*., 2014). The modified sampling design comprised eight randomly distributed stations within each of the five sampling strata for a total of 40 sampling stations per turbine, with one independent sample collected at each station (Figure 2, Table 3).

To explicitly define benthic control areas, the Year 4 monitoring survey was divided into five sections (*i.e.* one for each turbine, including the two not sampled). Eight control stations were randomly positioned based on the biotope classification mapping from previous monitoring (HDR, 2020; Hutchinson, *et al*., 2020) that contained similar substrate (coarse sand) to the sampled turbine sections (Table 3). Control stations were located more than 250 m from each turbine.

Sample Collection

Samples were collected using vessel-based grab sampling but were also collected by commercial divers for samples too close to the turbine structures for safe vessel maneuvering. Samples taken on the structures (epifauna) were collected by commercial divers.

Vessel and Diver-Based: Benthic Infauna and Sediments

Sampling for the Year 4 monitoring survey included eight sampling stations per stratum (as done throughout the campaign, five strata at each turbine: foundation footprint, very near field, near field, intermediate field, far field) and eight control sampling stations associated with each turbine for a total of 24 control stations and 144 stations overall (Figure 2, Table 3). Vessel and diver-based grab samples were successfully obtained from 135 of the 144 planned sampling benthic (macroinfauna/sediment) stations in Year 4 (nine of the attempted 96 vessel-based grab samples could not be collected because of rocky conditions at those stations preventing grab sampler closing, as evidenced by review of the grab sampler video or the sampler recovered with rock lodged in the grab).

Benthic sampling data for previous years can be found in HDR (2020) and Hutchinson *et al*., (2020). Vessel-based field sampling during Year 4 used a Smith-McIntyre sediment grab (0.1-m^2 sampling area, 16-cm depth penetration) and a grab-mounted camera system augmented by commercial diver

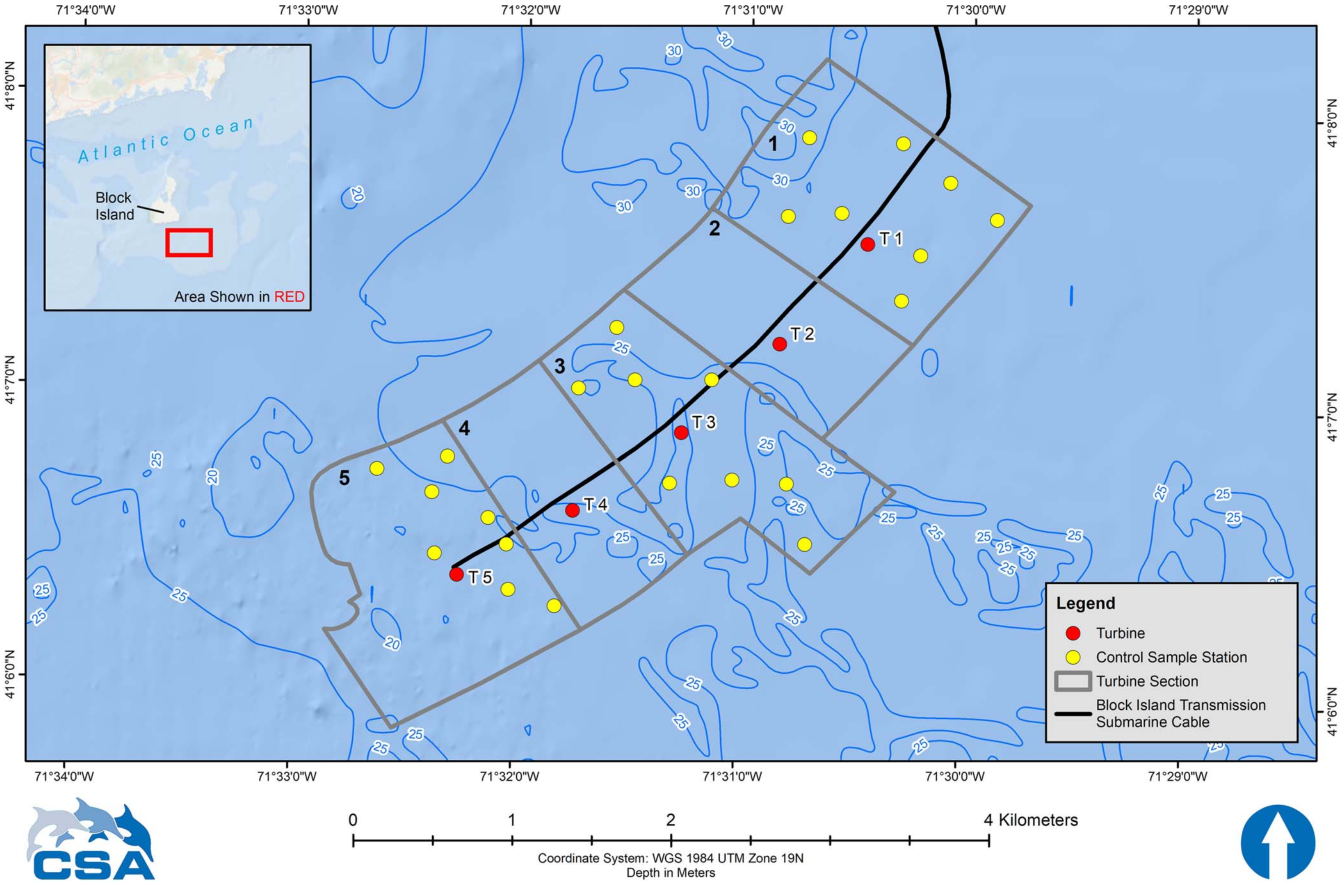

Figure 2. Modified sampling design with new (Year 4 Monitoring Survey) sampling-wide control designations and preliminary control station locations. Control stations were in biotopes like the turbines, which primarily consist of coarse sand. Station locations were re-randomized before each survey.

sampling. Vessel and diver-based sediment grab samples were collected between 1 October and 21 November 2021.

Benthic macroinfauna and sediment physicochemical samples collected from the vessel-based grab sampler were obtained from a single grab by using a metal insert to split the sediment content. One portion of the partitioned sediment was used for sediment physicochemical parameters and the other portion for macroinfauna analyses. The metal insert was positioned so that the portion for macrofauna analysis would have a surface area of 0.04 m^2 (BOEM, 2019).

For the vessel-based grab samples, macroinfauna samples were collected from the full depth of sediment from the designated side of each grab. The sediment from the top 4 to 5 cm was taken from the opposite side of the grab, homogenized, and appropriately allocated for grain size and total organic carbon/total organic material (TOC/TOM). Sediment samples were placed in precleaned and labeled sample containers (as appropriate for specified parameters).

Commercial divers were used to collect 48 grab samples within the footprint of the three turbine foundations and the very near-field strata, where sampling from the vessel was not possible. The diver grab stations within the three turbine foundations were sampled along a transect extending outward 30 m and diagonally from the corner of the turbine foundation. The diver-based grab samples were collected at equal spacing along the transect. Diver grab sampling was taken within a quadrat matching the footprint dimensions of the Smith-McIntyre grab sampler. After placing the sampling transect on the seabed, divers designated the sediment-sampling quadrats that were photographed underwater before sampling. The top 4 to 5 cm of sediment from one side of the quadrat were collected by the divers with a hand-held scoop, then transferred into prelabeled 1-L high-density polyethylene jars for analyses of physicochemical parameters. The top 7 to 10 cm of sediment from the other side of the quadrat, with surface area 0.04 m^2, were similarly collected and placed in 2-gallon bags for infauna analysis. After collection, the diver-based grab samples were brought to the vessel for processing. Onboard, the sediment samples were photographed, and observations were noted regarding sediment appearance, texture, odor, and presence/absence of fauna, flora, and anthropogenic debris. All sediment physicochemistry samples were analyzed following American Society for Testing and Materials (ASTM, 2009) standard methods for particle-size distribution, ASTM D6913, and standard methods for organic content (TOC/TOM), Method 9060A (USEPA Method, 2004) and ASTM D2974 (2003).

Sediment for infauna analyses was elutriated and wet-sieved on board over a 0.5-mm mesh sieve with gentle streams of high-volume, low-pressure seawater. Use of a 0.5-mm sieve aligns with BOEM guidelines (BOEM, 2019). Processed infauna samples were placed in 1-L plastic jars and labeled, taped, and properly stored on the vessel. Once preserved with 7% to 10% buffered formalin, infauna samples were stored at an ambient temperature and transferred to the analytical laboratory.

All benthic organisms—except juveniles, damaged individuals, or other forms lacking defining taxonomic characters—were identified to the lowest practical identification level (LPIL), typically species, and counted by a certified commercial laboratory. Relative proportions of each phylum by number of species and individuals were determined to evaluate the dominance of the most common phyla, mean and total number of individuals for each station, and density of organisms per station. All macroinfauna samples were normalized by sample surface area to estimate infauna density.

The primary infauna community metrics used in this study are Shannon-Wiener diversity index (H'), Margalef's diversity index (D), and Pielou's evenness (J'). Shannon-Wiener index (H') emphasizes species in the middle (not common or rare) of the species rank abundance sequence and accounts for both abundance and evenness of the species present. The H' values ranging from 2.5 to 3.0 is considered indicative of good biodiversity in the community. Margalef's diversity index (D) is a simple indicator of species diversity (Margalef, 1958). Here, species diversity values between 2.0 and 3.0 were considered moderate. Evenness is a measurement of the homogeneity of a community or sample. Pielou's evenness (J') compares the diversity value (*i.e*. Shannon-Wiener Index [H']) to the maximum possible H' value when all species are equally abundant. This calculation is constrained between 0 and 1, with higher values representing a more even community. The J' values heavily depend on sample size. Here, species evenness values between 0.70 and 0.85 were considered moderate.

Turbine Structure: Epifauna

Epifauna biomass scrape samples were collected on what was presumed to be the leeward and current sides of T1 by divers (the side presumed to be leeward had visibly higher epifaunal colonization based on coverage and biomass, suggesting that an apparent upstream-downstream influence on colonization patterns of the turbine leg structures occurs). For diver-based epifaunal collections on the turbine leg, divers used a 10-cm wide scraper to dislodge epifauna at each sample location. The scrape samples were collected—taking care to minimize damage to the individual epifauna—and placed in a cloth bag or plastic jar and returned to the vessel. Once at the surface, samples were stored in a 10% buffered formalin solution and dispatched to the lab for processing and analysis.

Divers used a GoPro Hero 4 camera to capture video of biofouling on the current-facing and leeward sides of the southern leg of the three turbine foundations (T1, T3, and T5). Divers collected video footage with identifiable scales between the base of the foundation and the intertidal water mark. This translated into six videos along vertical transects (two transects for each of the three turbine foundations). Video footage was collected with the camera positioned parallel to and approximately 0.2 m from the foundation and was reviewed in the laboratory. Any notable megafauna (*e.g.*, fishes, sea stars) were noted, and screenshots were taken. To estimate the percentage cover of epifauna on each video transect, screenshots were taken from the video files of non-overlapping segments of the turbine leg approximately every 20 seconds as the diver moved up or down the turbine leg. For images, the percentage cover of epibiota were estimated using the Coral Point Count with Excel extensions (CPCe V4.1) software analysis program (Kohler and Gill, 2006). CPCe uses the random point count method to accurately estimate the percentage cover of organisms from digital images. Twenty-five random points were projected on each screenshot, and the epibiota (or bare turbine leg) were identified to the LPIL. The number of images analyzed varied across transects because of the quality of diver videos and the inconsistent rate at which the divers ascended or descended the turbine leg. Identification to species for small epifaunal organisms (*e.g.*, solitary tunicates, bryozoans, hydroids, barnacles) was generally not possible. If an alga could not be identified to the phylum level, it was categorized as unidentified algae. Similarly, an unidentified biota category was used where the scientist conducting the taxonomic identifications was unable to confidently identify whether the random point fell on fauna or algae.

Statistical Analyses

Univariate analyses were used to assess patterns of individual taxa within each monitoring site and station. A two-way analysis of variance (ANOVA) was performed using SAS (2023, version 9.4) Proc Mixed for each diversity and sediment metric to determine overall significant differences, if any, for each factor or if there were any interactions between factors. Before analysis, SAS Proc Univariate (SAS Institute Inc., 2023) was run on each parameter to examine data structure for normalcy and the need for any transformations. Results of Shapiro-Wilk testing was examined for significance. If significance was found, the frequency distribution and probability plot was inspected to judge the severity of any departure from normalcy (SAS Proc Mixed and ANOVA, in general, are particularly robust to any non-normalcy). All the data were normally distributed, and, as such, no transformation of data was performed.

The following interactions and main effects were examined for this study: turbine areas; distance strata (strata defined by distance from turbine); and turbine × stratified distance from turbine.

If a significant (at the $p < 0.05$ level) difference was reported, then a post-hoc Tukey's multiple-means comparison test was performed to determine where those significant differences occurred. If an interaction among main effects was found, then only those interactions relevant to this study (*e.g.*, differences among strata at one turbine, differences in the same stratum across turbines) were described. A semivariogram was developed to test numerical abundance of infauna by distance to determine if controls were autocorrelated with habitats near the turbine foundation. Statistical analyses accompanied by data visualization were performed

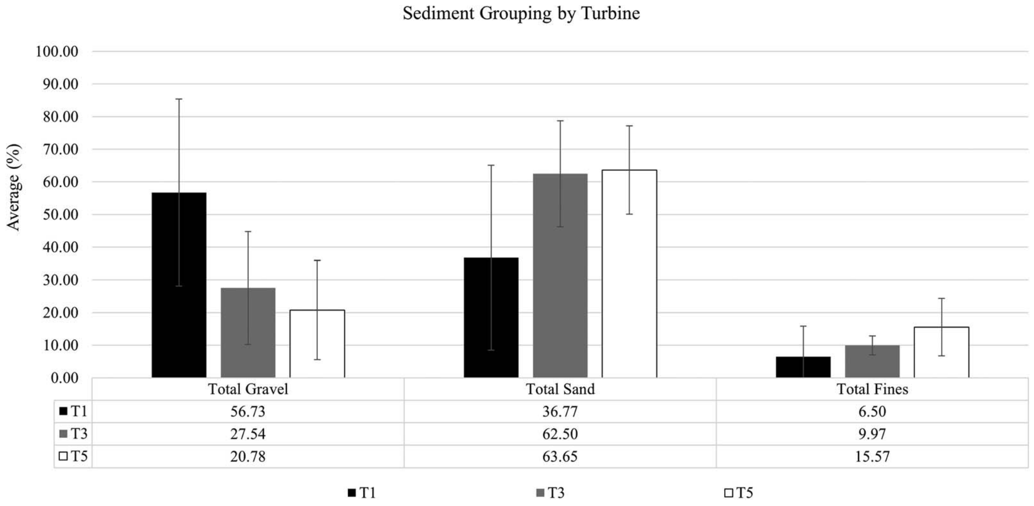

Figure 3. Mean higher-level sediment grouping (± standard deviation) by turbine (T) at the Block Island Wind Farm. Values are provided in a data table below the chart.

to compare epifaunal abundance and composition by water depth and on the current-facing and leeward side on each of the turbines and the turbines collectively.

ANALYSIS

Seafloor composition analysis included sediment particle size, TOM, and TOC. Benthic (in)faunal was analyzed to the LPIL and then organized into community metrics. Epifauna on the turbine structure was also identified to the LPIL and assessed for aspects of species prominence.

Sediment Composition: Particle Size

No boulder-sized sediment was observed in any of the Year 4 sediment sample attempts; therefore, the boulder category was not included in the following data representations. The largest grain size found in Year 4 sediment samples was cobble, which was present at nine (6.8%) stations, five of which were control stations, all from T3. Pebbles were encountered at all turbine stations and were present in 96.2% ($n = 128$) of samples.

Cobble material was present in 15.0% ($n = 9$) of the sediment samples. The sediment samples from T3 were mostly very coarse sand and coarse sand, averaging 23.2% and 22.0%, respectively. Medium sand closely followed, with an average of 16.2%. Like T3, coarse and very coarse sands were dominant at T5 stations, averaging 26.7% and 24.6%, respectively. Of the three turbines, silt and clay particle sizes were the most common at T5 stations, with a combined average of 15.6%. Notably, no cobble was present at T5 stations (turbine or control areas).

The distribution of high-level, particle-size components (total gravel, total sand, and total fines) is presented to make general comparisons between turbines. Total gravel comprised boulder (none in Year 4 samples), cobble, pebble, and granule components. Total sand was comprised very coarse sand, coarse sand, medium sand, fine sand, and very fine sand. Total fines comprise silt and clay and did not exceed 50% sediment composition at any station. A summary of the mean (± standard deviation [SD]) of the high-level sediment groupings by turbine is shown in **Figure 3**. Total gravel was most abundant at T1, whereas total sand was most abundant at T3 and T5.

A significant interaction occurred among strata and turbine in total sands ($F_{(17,115)} = 6.19$; $p = 0.0019$). A post-hoc Tukey multiple-means comparison test indicated the proportion of total sand in the foundation footprint ($t_{115\ =}$ 4.53; $P < 0.01$) of T1 was significantly lower than the total sand at the control stations. This interaction prevented further statistical examinations of turbines to control stations.

Higher-level groupings of sediment-particle sizes (totals of fines, sand, and gravel) were used to look for trends between the strata at each turbine. In general, the highest total gravel was found in the foundation footprint of T1 and decreased with distance from the turbine; the same pattern was seen for total fines. All strata of T1 were dominated by total gravel except the far field, which was sand dominant. A statistical difference was found in total sand between the foundation footprint ($F_{(17,115)} = 6.19$; $p < 0.00$) and the far field at T1. A post-hoc Tukey multiple-means comparison test indicated the proportion of total sand in the foundation footprint ($t_{115} = 4.12$; $P < 0.01$) was significantly lower than that in the far-field stratum. This interaction of sand content and strata prevented further statistical examinations of the effects of distance. A general comparison between strata at T3 and T5 showed that total sand exceeded 50% in all strata except the T3 foundation footprint (47.2%). The highest amount of sand was found within the near-field stratum where total gravel was low (T3 = 14.6%, T5 = 13.1%). Total fines increased with distance from the turbine foundation footprint. Total sand was most abundant in all strata, with the highest amount in the near-field stratum.

Table 4. *Mean (± standard deviation) of total organic matter and total organic carbon at each study area (turbine and control areas) at the Block Island Wind Farm.*

Sampling Period	Study Area	Average Total Organic Matter (%)	Average Total Organic Carbon (%)
Year 4	Turbine 1	0.27 ± 0.18	0.18 ± 0.17
	Turbine 3	0.29 ± 0.03	0.06 ± 0.18
	Turbine 5	0.30 ± 0.07	0.07 ± 0.12
	All Turbine Areas	0.29 ± 0.11	0.10 ± 0.16
	T1 Controls	0.38 ± 0.06	0.10 ± 0.22
	T3 Controls	0.34 ± 0.07	0.11 ± 0.12
	T5 Controls	0.37 ± 0.03	0.07 ± 0.25
	All Control Areas	0.36 ± 0.06	0.09 ± 0.2

Table 5. *Summary of phyla composition reported from benthic samples at turbines T1, T3, and T5 at the Block Island Wind Farm—Year 4 Monitoring Study.*

Phyla	Number of Individuals	Percentage Composition
Annelida	23,402	83.50%
Arthropoda	2236	7.98%
Chordata	1	0.004%
Cnidaria	30	0.11%
Echinodermata	36	0.13%
Mollusca	1964	7.01%
Nemertea	355	1.27%
Platyhelminthes	1	0.004%

Large changes occurred in the percentage of total fines from Year 1 to Year 4, increasing from 0.1% to an average across all samples of 15.0%. However, an unknown part of this difference may be explained by changing grain-size analytical methodologies. In Year 1, a Malvern Mastersizer 200E was used to analyze particle size by laser diffraction (HDR, 2017), whereas Year 4 results were determined via a less precise wet sieving technique for assessing the fine fraction.

Sediment Composition: TOM and TOC Content

The mean (±SD) TOM and TOC by study area are shown in Table 4. The control stations generally had higher TOM than the turbine stations. Average TOC was highest at T1 stations (0.18%). TOC at T5 was the same (0.07%) at turbine and control stations.

To answer $H_0$1—no differences occurring between turbine areas—an ANOVA test was administered to compare TOM and TOC concentrations between turbines. The TOM sediment concentration was not significantly different between any of the turbines. ANOVA results (at the $p < 0.05$ level) indicated no interactive effect occurring between turbines ($F_{(9,96)} = 0.97$; $P = 0.4665$). A significant interaction of TOC was found among strata and turbines ($F_{(16,103)} = 3.47$; $P < 0.001$). A post-hoc Tukey multiple means comparison test indicated the proportion of TOC in the T1 near-field stratum ($t_{103} = 4.14$; $P = 0.0076$) was significantly higher than that of the control stations. This TOC interaction prevented further statistical examinations of the turbines.

TOM at each turbine was not significantly different between turbine and control stations. ANOVA results ($p < 0.05$) indicated no interactive effect regarding TOM between turbines ($F_{(9,96)} = 0.97$; $P = 0.4665$). As mentioned previously, a significant difference between TOC at the T1 control stations and the T1 near-field stratum ($F_{(16,103)} = 3.47$; $P < 0.001$) was found, which contributed to the significant interaction. This interaction prevented further statistical comparisons.

Interactive effects of TOC among turbine and strata ($F_{(16,103)} = 3.47$; $P < 0.001$) were found. A post-hoc Tukey multiple-means comparison test determined a significantly higher TOC at the near-field stratum than the very near-field stratum ($t_{103} = 3.56$) and the far-field stratum ($t_{103} = 4.2$). The very near-field and far-field strata had the same average TOC (0.10%); the lowest was at T1. These were the only significant interaction terms for TOC.

ANOVA results (at the $p < 0.05$ level) indicated no interactive effect of TOM results between strata ($F_{(9,96)} = 0.97$; $P = 0.4665$). TOM between strata was not significantly different; therefore, the TOM results can be extrapolated to the study areas. At T3, the highest average TOM was in the far-field stratum (0.44%), and the highest average TOC was tied between the foundation footprint and the far-field stratum (0.08%).

Benthic Faunal Composition

Benthic faunal samples yielded a total of 28,025 individuals from 216 unique taxa. Annelida were the numerically dominant phyla, accounting for 84% ($n = 23{,}402$) of the total organisms counted. Arthropods (8%; $n = 2236$) and Mollusca (7%; $n = 1964$) were also observed in relatively large numbers (Table 5). The five most abundant taxa within the BIWF study area belonged to the Annelida; *Polygordius* (LPIL) was at 19%, with *Polycirrus eximius* next at 17%, *Pisione remota* at 7%, *Tharyx acutus* at 5%, and *Parapionosyllis uebelackerae* at 3%. Overall diversity metrics are given in Table 6. The number of taxa, individuals, diversity (H'), and evenness (J') are given in Figure 4A–D.

An isotropic semivariogram (there was no anisotropic model) was exceptionally noisy ($r^2 = 0.07$) with a Gaussian best fit (vs. linear, spherical, exponential) with a predicted range of approximately 42 m (range of scale dependency), indicating that the control stations, located beyond 250 m, were not autocorrelated with habitats near the turbines. An isotropic Moran's model was similarly noisy with moderate departures from the best-fit model occurring at the near and intermediate distances. A two-way ANOVA was conducted to determine any main (*i.e.* turbine and distance from turbine) or interactive (*i.e.* turbine × distance from turbine) effects on the number of taxa, number of individuals, species richness (Margalef D), species diversity (Shannon-Wiener H'), and species evenness (Pielou J') from samples collected during the Year 4 monitoring study.

No interactive effects among the number of taxa ($F_{10,117} = 1.51$; $P_{a<0.05} = 0.14$), number of individuals ($F_{10,117} = 0.82$; $P_{a<0.05} = 0.61$), species diversity ($F_{17,117} = 1.68$; $P_{a<0.05} = 0.055$), or species evenness ($F_{10,117} = 1.54$; $P_{a<0.05} = 0.13$) were found. Therefore, results for these parameters can be extrapolated to the greater study area. An interactive effect for species richness was found ($F_{10,117} = 2.41$; $P_{a<0.05} = 0.01$).

Table 6. *Overall diversity metrics (average ± standard deviation) for benthic infauna by turbine (T) at the Block Island Wind Farm—Year 4 Monitoring Study.*

Turbine	Number of Samples	Number Taxa	Number of Individuals	Density (# m^{-2})	Diversity (Shannon-Wiener H')	Evenness (Pielou J')
T1	44	30 ± 10	216 ± 151	5417 ± 3784	2.32 ± 0.51	0.70 ± 0.16
T3	46	28 ± 8	210 ± 121	5270 ± 3050	2.40 ± 0.31	0.73 ± 0.10
T5	45	22 ± 6	195 ± 131	4887 ± 3281	2.22 ± 0.35	0.73 ± 0.11

Therefore, results for this parameter can be described only in the context of sample distance from each turbine; results cannot be extrapolated to the greater study area.

All turbines were characterized as having moderate species diversity and species evenness. No significant differences among the three turbines for number of individuals ($F_{2,127} = 0.33$; $P_{a<0.05} = 0.71$), species diversity ($F_{2,127} = 2.27$; $P_{a<0.05} = 0.11$), or species evenness ($F_{2,127} = 1.00$; $P_{a<0.05} = 0.37$) were found; however, the number of taxa among the three turbines was statistically significant ($F_{2,127} = 14.27$; $P_{a<0.05} < 0.0001$). A post-hoc Tukey multiple-means comparison test indicated the number of taxa reported at T5 was significantly lower than the number of taxa reported at T1 ($t_{127} = 5.19$; $P_{a<0.05} < 0.0001$) and T3 ($t_{127} = 3.69$; $P_{a<0.05} = 0.0009$).

Because of the significant interaction between turbine and distance from turbine strata for species richness (Margalef D – diversity index), it was not possible to generalize regarding this parameter. Instead, each turbine stratum was compared relative to its corresponding stratum at each turbine (Figure 5). Species richness was significantly greater within the very near-field ($t_{117} = 3.75$; $P_{a<0.05} = 0.003$) and intermediate-field ($t_{117} = 5.61$; $P_{a<0.05} < 0.0001$) strata of T1 compared with T5. The control stratum within the T3 area had a significantly greater species richness than the control stratum within the T5 area ($t_{117} = 4.34$; $P_{a<0.05} = 0.004$). Significant differences were not observed for the footprint, near-field, or far-field strata. Other significant differences in species richness were observed between different strata among turbines (*i.e.* far-field stratum at T1 compared with very near-field stratum at T5), but these comparisons were not meaningful within the overall scope of the campaign.

A two-way ANOVA was conducted to determine potential differences in abundance within the three most dominant phyla (*i.e.* Annelida, Arthropoda, Mollusca) around each turbine and within each stratum. No significant interactions in abundance occurred for Annelida ($F_{10,117} = 0.87$; $P_{a<0.05} = 0.57$) or

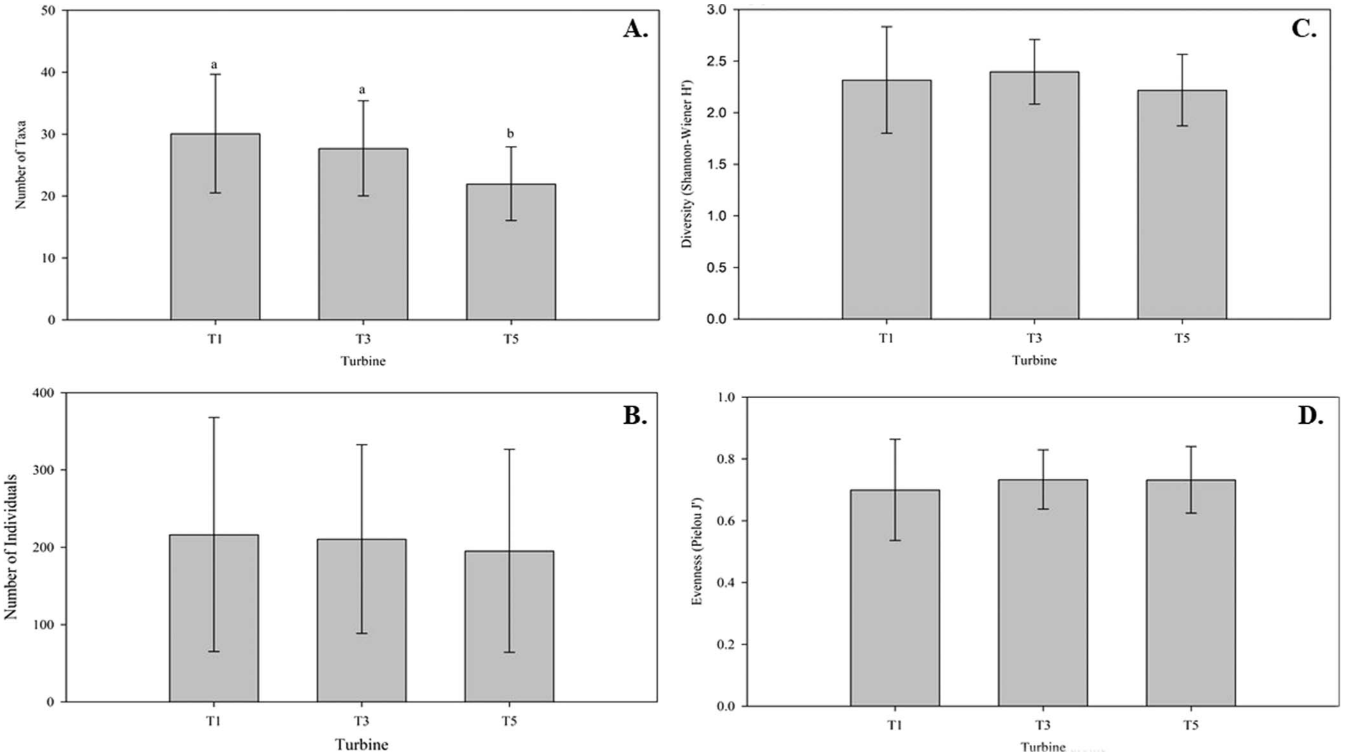

Figure 4. (A) Average (± standard deviation) number of taxa, (B) individuals, (C) diversity, and (D) evenness at each turbine (T) at the Block Island Wind Farm. Different letters indicate a significant difference at $P < 0.05$.

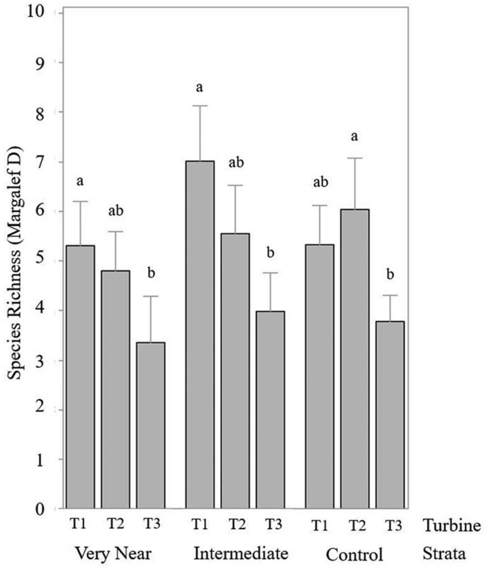

Figure 5. Average (± standard deviation) species richness (Margalef D) at each turbine (T) within the very near-field, intermediate-field, and control stratum at the Block Island Wind Farm. Different letters indicate a significant difference at $P < 0.05$.

Mollusca ($F_{10,117} = 1.50$; $P_{a<0.05} = 0.15$); therefore, it was possible to make a generalization regarding these phyla among turbines and among strata. A significant interaction in abundance was found for Arthropoda ($F_{10,117} = 2.43$; $P_{a<0.05} = 0.011$); therefore, it was not possible to generalize regarding Arthropoda. Instead, comparisons of turbine strata and comparisons of similar strata among turbines were conducted.

No overall difference in abundance occurred among turbines for Annelida ($F_{2,127} = 0.19$; $P_{a<0.05} = 0.83$) and Mollusca ($\mathrm{F}_{2,\,127} = 1.34$; $\mathrm{P}_{\mathrm{a}<0.05} = 0.27$) phyla. Significantly more Arthropoda were found within the foundation footprint stratum of T1 when compared against the foundation footprint stratum of T5 ($t_{117} = 3.59$; $P_{\mathrm{a}<0.05} = 0.046$). Also, significantly more Arthropoda were found within the very near stratum of T1 when compared against the very near stratum of T3 ($t_{117} = 4.52$; $P_{a<0.05} = 0.002$) and 5 ($t_{117} = 4.94$; $P_{a<0.05} = 0.0004$). No other significant differences were observed among corresponding strata between turbines.

During the Year 4 monitoring study, fewer taxa and individuals were observed within the footprint and very near-field stratum compared with the intermediate-field stratum, and fewer individuals were observed within the control stratum compared with the intermediate-field stratum. Species diversity and evenness were similar among all strata. Species richness was generally similar among strata at each turbine except the intermediate-field stratum at T1, which had greater species richness than the footprint stratum. Annelida were the most dominant phyla within all strata. The Annelida genus *Polygordius* was more abundant at strata farther from the turbines, and the Annelida species *P. remota* was more dominant at strata closer to the turbines. The following sections provide more detail on these findings.

All distances from turbine strata were characterized as having moderate species diversity and species evenness. No significant differences occurred among the six turbine strata for species diversity ($F_{5,127} = 0.59$; $P_{a<0.05} = 0.71$) or species evenness ($F_{5,127} = 0.80$; $P_{a<0.05} = 0.55$). An overall statistical significance for the number of taxa ($F_{5,127} = 4.26$; $P_{a<0.05} = 0.001$) and number of individuals ($F_{5,127} = 5.33$; $P_{a<0.05} = 0.0002$).

A post-hoc Tukey multiple-means comparison test indicated the number of taxa reported within the intermediate-field stratum was significantly greater than the footprint ($t_{127} = 4.11$; $P_{a<0.05} < 0.0001$) and very near field ($t_{127} = 3.45$; $P_{a<0.05} = 0.01$) strata (**Figure 6A**). No other significant differences were found in the number of taxa among turbine strata.

The post-hoc Tukey multiple-means comparison test indicated the number of individuals reported within the intermediate-field stratum was significantly greater than the footprint ($t_{127} = 4.38$; $P_{a<0.05} = 0.0003$), very near-field ($t_{127} = 3.09$; $P_{a<0.05} = 0.03$), and control ($t_{127} = 3.18$; $P_{a<0.05} = 0.02$) strata (**Figure 6B**). Additionally, the number of individuals reported within the near field stratum was significantly greater than the footprint stratum ($t_{127} = 3.62$; $P_{a<0.05} = 0.006$). No other significant differences occurred in the number of individuals among turbine strata. The greater number of individuals at the intermediate-field stratum was also seen to drive departures from the best-fit semivariogram model.

Because of the significant interaction between turbine and turbine strata (*i.e.* distance) for species richness, it was again not possible to generalize regarding this parameter. Instead, each stratum was compared with its corresponding turbine. The only relevant significant difference occurred at T1, where the intermediate-field stratum had a significantly greater species richness than the footprint stratum ($t_{117} = 3.81$; $P_{a<0.05} = 0.02$). No other significant differences were observed among strata at T1, T3, or T5, and no significant differences or interactions were found between turbine and turbine strata for either diversity (H') or evenness (J').

Epifaunal Composition

Videos from the diver-based epifauna transects along the turbine structure from the surface to the seabed were reviewed to identify motile megafauna or other organisms of interest. The only identifiable fish was the black sea bass (*Centropristis striata*). Numerous individuals of *C. striata* were present near the seabed at all three turbines. Unlike previous years, sea stars or other megafauna invertebrates were not observed in the videos on the turbine structure. **Figure 7** presents representative images from T1, T3, and T5 turbine structures in the approximate middle of the water column. The blue mussel (*Mytilus edulis*) was much sparser on T5 than on T1 and T3. This is a substantial difference from Years 2 and 3, where *M. edulis* percentage cover was highest on T5 and indicates substantial temporal and spatial variability in the epifaunal community.

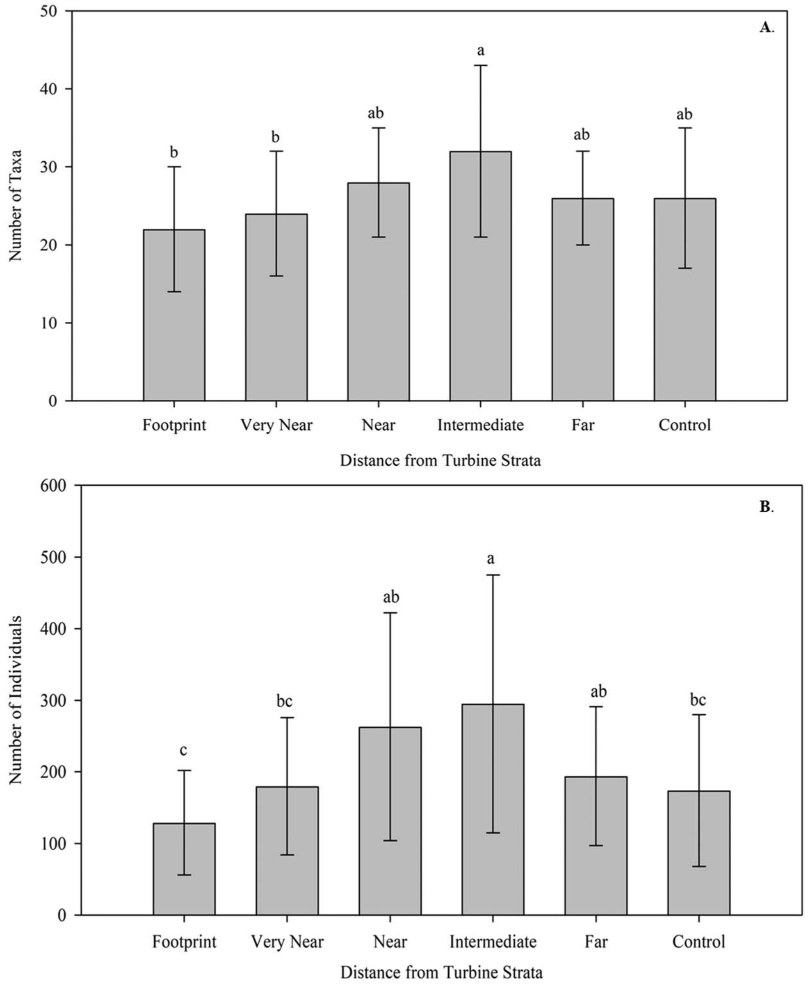

Figure 6. (A)Average (± standard deviation) number of taxa (top) and (B) individuals collected from each distance from turbine stratum (bottom) at the Block Island Wind Farm. Different letters indicate a significant difference at $P < 0.05$.

During the Year 4 monitoring study, a total of 56, 0.1-m^2 scrape samples for faunal composition and biomass were collected from the leeward and current-facing sides of the southern leg on T1. Scrape samples were collected every 1 m along both sides of the turbine leg, but sample materials were analyzed only every 2 m. No scrape samples were collected from the leeward side of the leg at 26 m depth and the current-facing side of the leg at 28 m.

The epifauna biomass from the diver-based scrape samples on the leeward and current-facing sides of the T1 southern leg yielded 51,101 individual organisms from 59 taxa. The most common taxon was the amphipod *Jassa falcata* ($n = 20{,}768$), which composed 40.6% of all identified individuals. Other common taxa were the amphipod *Stenothoe valida* ($n = 10{,}669$), amphipods from the family Caprellidae ($n = 6952$), and isopods from the genus *Uromunna* ($n = 3724$).

Scrape samples in Year 4 were collected on 21 October 2021, and, similar to previous monitoring, the *M. edulis* community and associated epibionts dominated the epifauna community on the T1 leg. *Mytilus edulis* individuals were found in 53 of the 56 scrape samples, with an average abundance of 48.6 ± 59.8 individuals per scrape sample and a total abundance across all scrape samples of 2719 individuals. *Mytilus edulis* density increased with depth and was far more common on the current-facing side of the T1 leg, with a total abundance of 2200 individuals compared with just 519 individuals on the leeward side of the leg. *Mytilus edulis* was absent on the T1 leg at the waterline. Table 7 presents the most abundant and frequently occurring epifauna taxa from the diver-based scrape samples during the Year 4 monitoring study.

The epifauna biomass from the diver-based scrape samples on the leeward and current-facing sides of the T1 southern leg (collected every 1 m but analyzed every 2 m) showed a somewhat consistently higher abundance on the current side of the leg. The biomass of leeward and current side samples during the Year 4 monitoring study were significantly

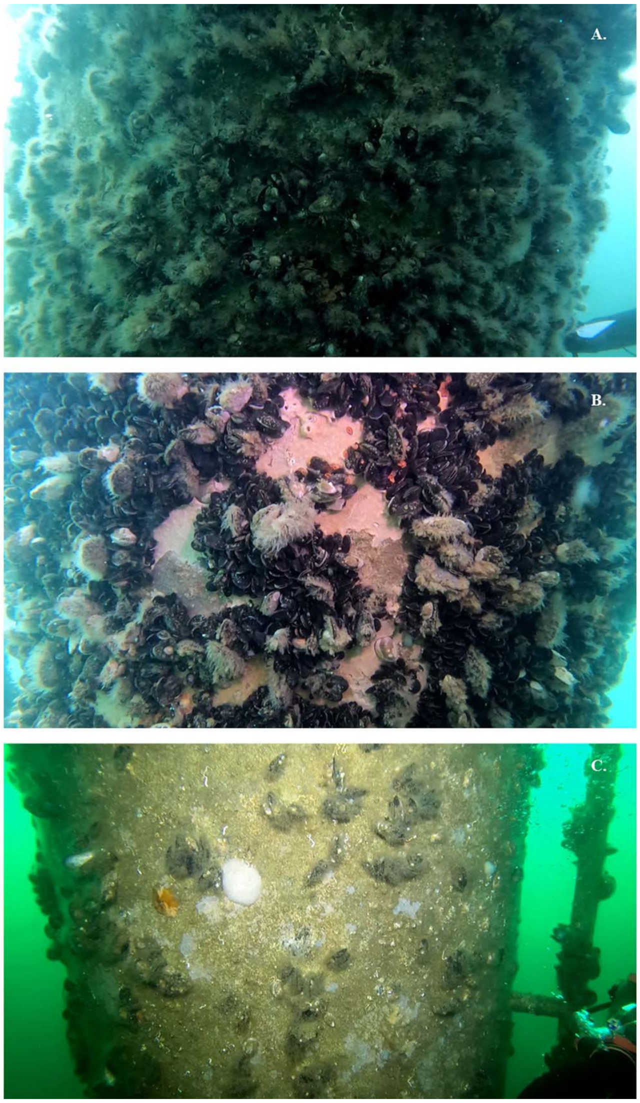

Figure 7. Representative images from video transects for Turbines 1 (top), 3 (middle), and 5 (bottom) all at midwater depth, showing simultaneous varying epifauna growth among turbine structures.

different ($t = 4.42$, $p < 0.0001$), with biomass significantly higher on the current-facing side of the turbine leg.

DISCUSSION

The overall goal of the multiyear monitoring campaign was to better understand the nature and potential spatial and temporal scales of the anticipated alterations in seabed sediments and changes to infaunal and epifauna (on the turbine structure) species abundance, richness, and diversity caused by the BIWF. As anticipated based on comparisons with other, relevant literature (Table 1), large-scale changes in benthic conditions do not appear to have manifested from the presence of the three BIWF turbines monitored, but alterations to seabed characteristics near the foundations have occurred.

Particle-Size Distribution and Sediment Organic Content Summary

On a finer scale of examination, the proportion of mean total fines within the turbine areas has increased from 0% in Year 1 to 16% in Year 4, whereas the amount of total sand has gradually declined from 20% to 17%. Part of this difference may be explained by changing methodologies (laser diffraction vs. the less sensitive wet sieving).

Although an increase in fine sediments occurred near or at the turbine foundations, no visually apparent patterns of TOM and TOC that support the idea of a gradually increasing organic content in the sediment closest to the turbine foundations arising from biomass sloughing were found. Because of differences in sampling (among years and due to mussel bed interference), however, a conclusive trend in temporal shifts was not evident.

Benthic Community Summary

In Years 2–3, the benthic community comprised *M. edulis* individuals and *M. edulis* patches below the turbines, which clearly differed from that found at >30 m distances. HDR (2020) concluded that associated organic enrichment could pose a moderate to high risk of potential adverse effects on composition and abundance of sessile fauna. Additionally, *M. edulis* aggregations within the turbine-foundation footprints and *M. edulis* patches within the 30 to 90 m area from the turbine center were developing and were not reported within control sites. However, this pattern of *M. edulis* abundance and data for infauna in general did not represent an obviously systematic progression of effect relative to the location of the turbines, and sustained changes in benthic sediment and faunal composition were limited primarily to the turbine foundation footprints. Future studies may benefit from added stratification to capture potential effects of prominent current flow.

Overall, the analysis of the video from the Year 4 grab-mounted camera suggested the seabed in the turbine distance strata and control areas was generally similar except in the immediate vicinity of the turbines where again, dense beds of *M. edulis* occurred. Farther from the turbines and in the control areas, the seabed was dominated by coarse sand, gravel, and cobbles of varying size. Based on Year 4 observations and given what is assumed to be a vigorous hydrodynamic regime in the study area, the seabed is presumably dynamic and likely changes naturally over time because of tidal current forces, as well as storm events (HDR, 2018).

The numbers of unique infauna taxa have numerically increased over time (Years 1–4) for all turbine areas, particularly at T1, which is in slightly deeper water than the others. Reference values at control areas remained relatively stable for Years 1–3, even though the control area positions differed substantially among years. In general, the number of taxa among turbine areas and control areas combined steadily increased over time, with roughly a 28% increase in the overall number of unique taxa present between Years 1 and 4.

Using data from Years 1–3, a two-way ANOVA analysis showed that infauna species number and abundance were

Table 7. *Most abundant and most frequently occurring taxa from diver-based epifauna scrape samples from the leeward and current side of the southern leg of Turbine 1.*

Taxon	Phylum	Total Abundance	Occurrence ($n = 56$)
Most abundant (>100 individuals)			
Jassa falcata	Arthropoda	20,768	55
Stenothoe minuta	Arthropoda	10,669	53
Caprellidae	Arthropoda	6952	56
Uromunna spp.	Arthropoda	3724	55
Mytilus edulis	Bivalvia	2719	53
Caprella mutica	Arthropoda	1978	54
Stenetriidae	Arthropoda	1647	51
Actinaria	Cnidaria	681	33
Crepidula fornicata	Mollusca	530	45
Dipolydora socialis	Annelida	323	29
Apocorophium spp.	Arthropoda	249	28
Anomia simplex	Bivalvia	159	32
Bemlos spp.	Arthropoda	104	13
Most frequent (>50 samples)			
Jassa falcata	Arthropoda	20,768	55
Stenothoe minuta	Arthropoda	10,669	53
Caprellidae	Arthropoda	6952	56
Uromunna spp.	Arthropoda	3724	55
Mytilus edulis	Bivalvia	2719	53
Caprella mutica	Arthropoda	1978	54
Stenetriidae	Arthropoda	1647	51

not significantly different between distance strata or between distance strata with turbine and year interactions. Similarly, for Year 4, no significant differences in infauna species diversity or evenness as a function of distance from the turbine were found. Significant differences in the number of infauna taxa and the number of individuals with distance were found, but the intermediate-field stratum was the outlier (higher), meaning no systematic progression of numbers of taxa or individuals with distance from the turbines occurred. Overall results suggest an absence of a continually progressive effect radius around the turbines.

Temporal tests of distance strata at each turbine were statistically significant for comparisons of macrofauna between Years 1 and 2 and Years 2 and 3. Although not continually visually apparent, a progressive trend of macrofaunal change was detected as a function of distance from the turbine. The increase in taxa and number of individuals at the 30- to 90-m area during Years 1–3 consistently stood apart from other strata; however, these are differences in the intermediate-field strata that do not conform to a pattern of a continually progressive, systematic change in the benthic community with distance from the turbines. By Year 4, a comparison of the percentage composition of the three most dominant phyla (Annelida, Arthropoda, and Mollusca) by distance—irrespective of turbine—revealed no visually apparent, ecologically relevant differences and no consistent, systematic progression of changing values as a function of distance from the turbines.

Epifauna Communities Summary

Year 4 was dominated by *M. edulis*, as observed from diver-based videos transects of the foundation leg;. however, substantial differences with previous years were noted. Percentage cover determinations of *M. edulis* on T1 and T3 were similar to previous years, although a decreasing trend was evident for both turbines. The most notable difference between years was noted on T5, where *M. edulis* cover in Year 3 was more than 80.0% but decreased to 20.1% in Year 4. This is a substantial difference in Year 4 coverage from Years 2 and 3, when *M. edulis* percentage cover was highest on T5. This drastic decrease is not unique, as interannual fluctuations in *M. edulis* populations have been previously documented (e.g., Commito and Dankers, 2001; McGrorty and Goss-Custard, 1991; see also the classic coverage fluctuations described in the long-term intertidal study at Mearn's Rock (NOAA, 2023).

$H_0$1: No Differences between Turbine Areas

Sediments. No boulder-sized sediment was found in any of the Year 4 samples; however, contrary to the null hypothesis, the particle-size distribution varied between turbines. Although T3 and T5 were sand dominant, T1 had the greatest amount of total gravel. One theory about this difference involves T1 being in slightly deeper water. An overall trend of decreasing sand fraction, with increasing total fines, was observed throughout the study, although this may in part be an artifact of the different methods used for sediment analysis in Years 1–3 vs. Year 4.

Infauna. A numerical increase occurred in the number of unique infauna taxa over time (Years 1–4) for all turbine areas, particularly at T1, which is in slightly deeper water than the others. Statistically significant differences were observed among individual turbines (recalling that only T1, T3, and T5 were sampled) for only one infaunal community metric in Year 4 (number of taxa, Figure 4) but not numbers of individuals, species diversity, or evenness. The T5 (22 taxa) was significantly lower than T1 and T3 (30 and 28 taxa, respectively). A taxonomic difference occurred among turbines for the phyla Arthropoda (the second most abundant phyla), where their abundances were significantly greater within the footprint and very near stratum of T1 when compared against Arthropoda abundances within T3 and T5. Infauna numbers were generally consistent among years; however, from an ecological perspective, these do not represent a dramatic functional difference.

Epifauna. Focusing on scrape samples and *M. edulis*, which was the most abundant epifauna on the turbine legs, as in past years, consistent differences were found in the numerically abundant *M. edulis* among the current-facing and leeward side of the turbine legs in Year 4. The current-facing side had a higher coverage than the leeward side among the three turbines by 23.2%. The T5 had lower overall *M. edulis* abundances at 17.5% cover vs. 57.9% and 50.0% cover for T1 and T3, respectively. Overall, in Year 4, uncolonized space on the turbine legs was higher at T5 (30.5%) than at T1 or T3 (7.5 and 2.5%, respectively). Abundances fluctuated noticeably over the years, but T5 may represent a consistently different level (fluctuating and currently low level) of epifaunal abundance. These observations were generally supported by video transect monitoring. Epifauna was documented to be a very spatially and temporally dynamic community.

$H_0$2: No Differences between Control Areas and Turbine Areas

Too much emphasis can be made of a direct comparison of differences between control areas and turbine areas. Evidence of a progression of some effects occurs, particularly in seabed sand vs. gravel with distance from turbines; however, a signal of stabilization of sediment composition with distance occurred, and so the capture of effects exceeds the extent of any turbine-induced scale dependence (*sensu* Schneider, 2001). The value of comparisons to a small sample size of controls in heterogenous landscapes—as is the case here—is to also use the controls to detect whether landscape-scale changes are occurring that may influence the entire sampling framework. Such changes may best be evaluated over time rather than among distance stations per sampling time and may benefit from a different statistical model (*i.e.* Methratta, 2020; Underwood, 1994) but also careful consideration of sampling grain and extent because these have been shown to affect landscape metrics (Wu, 2004).

Sediments. Differences were observed between turbines and controls regarding the spatial pattern of particle-size distribution with respect to distance from an effect producing source. Although the controls were independent (beyond the range of scale dependency), they were located far enough from the turbine foundations (>250 m) that could have been in a fundamentally different portion of the seabed mosaic of CMECS classes (*sensu* HDR, 2020). The controls may therefore be differently affected by other ambient factors (*e.g.*, water depth, currents, temperature) within the patchy benthic landscape. This theory is supported by the inconsistency of the particle-size distribution pattern by distance from turbine foundation. For example, the total gravel at T5 decreased as the distance from the turbine increased, reaching the minimum of 11.4%; however, the associated control for T5 had a gravel content of 22.5%. The unpredictable drop or jump of the numerical values of the controls shows the differences between controls and turbines with respect to particle-size distribution.

Infauna. Reference values at control areas remained relatively stable for Years 1–3, even though the control area positions differed substantially among years. In general, the number of taxa among turbine areas and control areas combined steadily increased over time, with a 28% increase in the overall number of unique taxa present between Year 1 and Year 4. Significant interaction terms limited effect radius comparisons, but the presence of these interactions indicates a good deal of variability. Although other significant differences in various metrics were observed between different strata among turbines, these comparisons did not present a systematic pattern of change and were interpreted to not be meaningful within the overall scope of the campaign.

Epifauna. No control areas for epifauna on turbine legs.

$H_0$3: No Effects of Distance from the Wind-Farm Foundations

Sediments. There was an effect of particle-size distribution with respect to distance from the wind turbine foundation. Overall, the percentage total gravel average decreased with distance, whereas the total sand average increased. This visually apparent pattern was observed at all three turbines, but with different degrees of variation. A statistical interaction occurred at T1 in the increase of total sand furthest from the turbine foundation, with 16.7% in the footprint vs. 56.4% in the far field; however, as stated previously, this pattern is not carried farther to the turbine controls. Again, this stabilization of sand vs. gravel content with distance indicates that the sampling design has fully captured the spatial extent of turbine-induced effects on seabed sediments (*i.e.* become scale independent).

Infauna. For all years monitoring thus far, statistical analyses for most infaunal metrics showed little difference between distance strata, irrespective of distance from turbine or year. In Year 4, significant differences were found with distance in the number of infauna taxa and the number of individuals. A significant difference also occurred in the overall abundance of Annelida phyla, with a change in distance from the wind turbine foundation irrespective of specific wind turbines. Annelida were the most abundant phyla collected around the turbines. Annelida abundances were significantly greater within the intermediate stratum when compared with abundances within the footprint, very near, and control strata and were generally elevated within the near- and far-field strata. It should be noted, however, that Annelid abundances between the closest turbine structure strata and the control stratum were similar to one another, with an increase in Annelida abundances observed only within the middle-distance strata. No difference was found for the other most dominant phyla (*i.e.* Arthropoda, Mollusca) by distance, irrespective of turbine. Overall, the results suggest that beyond the immediate vicinity of the turbine structures, a spatial effect on infauna is lacking.

Epifauna. No comparative samples were found for epifauna scrapes with distance because those samples occur only on turbine legs.

CONCLUSIONS

Year 4, with its more continuous and comparative statistical design, saw continuation for many of the trends found in Years 1–3. The spatial extent of sampling relative to the turbine structures was adequate to detect stabilization of environmental changes with distance when they were present. Taken altogether, a scenario emerges of substantial changes to the seabed sediments and faunal composition only in the immediate footprint of the turbine foundations. But aside from a shift in particle size, there is little evidence of a spatially or temporally consistent and progressive (as a function of distance away from the turbines to control locations) pattern of change in seabed physical and biological composition in the surrounding environment (*i.e.* greater than approximately 10 m from the foundation footprint). Lack of a systematic pattern suggests that much of the intra- and interannual differences may be attributed to natural fluctuations, especially in epifauna including that on the turbine structures. Consideration of changes in seabed structure and faunal abundance and composition may be informed by consideration of extreme storm events, but this is speculative. Notably, the faunal dynamics suggest a community in constant flux and absent a tendency toward formation of any climax community, as seen by Zupan *et al*. (2023) but in contrast to an attainment of climax structure suggested by Hutchinson *et al*. (2020). Rather, it appears that naturally occurring fluctuations in the abundance and distribution of the benthic and epibenthic fauna—all taxa with comparatively short life spans and diffuse dispersal recruitment strategies—are prevalent. This suggests that different sampling strategies in future studies (including a fixed station, repeated measures approach), as has been performed in similarly dynamic, intertidal communities (Engle *et al*., 2022), should be used to manage these scales of habitat variability.

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