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**INTEGRATION OF BIOTIC AND ABIOTIC DATA
TO MAP BENTHIC HABITATS WITHIN
BLOCK ISLAND AND RHODE ISLAND SOUNDS**

BY

MONIQUE LAFRANCE

**A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF**

MASTER OF SCIENCE

IN

OCEANOGRAPHY

UNIVERSITY OF RHODE ISLAND

2011

ABSTRACT

The mapping of benthic habitats presents the distribution and extent of seafloor environments, including biotic and abiotic characteristics, in a geo-spatial context. This thesis aims to improve methodologies used in the field of benthic habitat mapping and works towards establishing a standard mapping protocol to facilitate more effective communication both among scientists and resource managers in effort to further the goal of science-based decision making. This study is in response to interest in wind turbine construction within Rhode Island waters. A thorough understanding of benthic habitats is essential for making scientifically valid management decisions to minimize ecological and economical development impacts.

Two major challenges facing benthic habitat mapping are: 1.) Appropriate methodology; and 2.) Producing maps that can easily and effectively convey information. APPROVED:

Thesis Committee:

Major Professor

DEAN OF THE GRADUATE SCHOOL

UNIVERSITY OF RHODE ISLAND
2011

ABSTRACT

The mapping of benthic habitats presents the distribution and extent of seafloor environments, including biotic and abiotic characteristics, in a geo-spatial context. This thesis aims to improve methodologies used in the field of benthic habitat mapping and works towards establishing a standard mapping protocol to facilitate more effective communication both among scientists and resource managers in effort to further the goal of science-based decision making. This study is in response to interest in wind turbine construction within Rhode Island waters. A thorough understanding of benthic habitats is essential for making scientifically valid management decisions to minimize ecological and economical development impacts.

Two major challenges facing benthic habitat mapping are: 1.) Appropriate methodology; and 2.) Producing maps that can easily and effectively convey information important to a broad range of users (e.g. scientists, management agencies, non-profit organizations, individual citizens). The first challenge is examined in Chapter 1, which investigates the effectiveness of two mapping approaches, top-down and bottom-up, for classifying and mapping offshore marine environments. Both methods incorporate acoustic data (side-scan sonar and bathymetry), along with sediment and benthic macrofauna samples. The traditional top-down mapping approach identifies biological community patterns based on geologically-defined habitat map units, whereas the bottom-up approach aims to establish units based on biological similarity and then use statistics to determine relationships with associated environmental parameters. Both methods showed statistically strong and significant abiotic-biotic relationships and produced habitat units with distinct macrofaunal

assemblages. Overall, the bottom-up approach was more effective at mapping benthic habitats, producing more clearly defined macrofaunal assemblages. However, the spatial heterogeneity prevented development of full-coverage maps with the currently available number of ground-truth samples. Therefore, for the mapping needs of RI, the top-down method is recommended because it can produce full-coverage maps.

Chapter 2 addresses the second challenge. Commonly, maps characterize habitats according to dominant species or general community type. While useful, such maps do not always offer practical information to managers and can inadequately represent important habitat characteristics and relationships. In response, benthic habitats were classified according to biological and environmental metrics considered important to the existence of healthy, productive benthic habitats. The weighted metrics were totaled to develop an overall index of benthic habitat value. The index also provides individual metric scores, allowing habitats to be evaluated based on metrics relevant to the user. Furthermore, indices can be used to discern biotic-abiotic relationships between and among habitats and index metrics. The indices identified habitats that scored considerably higher than the others. In general, though, the indices did not indicate specific biological or environmental characteristics that lend to high habitat value, signifying management efforts need to consider all habitat types. However, a correlation was found between tube-building species and species richness, indicating tube mat structures lead to increased biodiversity. The indices also show that habitats within each study area have different relationships with the index metrics, indicating macrofauna have their own associations with the environment within each study area.

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“top-down” and “bottom-up” in Chapter 1 describe benthic habitat mapping methodologies and are not to be confused with the same terms used in ecology to refer to food web interactions regarding population regulatory processes.

This thesis is prepared in manuscript format and consists of two manuscripts, with the unifying theme of improving the use and understanding of benthic habitat mapping. The first manuscript compares two mapping methodologies and is to be submitted to *Estuaries, Coasts and Shelf Science*. The second manuscript endeavors to produce maps that both scientists and managers can benefit from by developing an index of benthic habitat value. This manuscript will be submitted to *Biological Applications*.

PREFACE

For clarification of terminology, habitat is defined as “a spatially defined area where the physical, chemical, and biological environment is distinctly different from the surrounding environment,” as stated by Kostylev et al. (2001). Also, the terms “top-down” and “bottom-up” in Chapter 1 describe benthic habitat mapping methodologies and are not to be confused with the same terms used in ecology to refer to food web interactions regarding population regulatory processes.

This thesis is prepared in manuscript format and consists of two manuscripts, with the unifying theme of improving the use and understanding of benthic habitat mapping. The first manuscript compares two mapping methodologies and is to be submitted to *Estuarine, Coastal and Shelf Science*. The second manuscript endeavors to produce maps that both scientists and managers can benefit from by developing an index of benthic habitat value. This manuscript will be submitted to *Ecological Applications*.

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Two methods, top-down and bottom-up, were compared for their ability to classify benthic habitat types in Narragansett Bay, Rhode Island, an area being considered for wind turbine installation. The traditional top-down mapping approach identifies biological community patterns based on geologically-defined habitat types, under the assumption that geologic environments contain distinct biological communities. The bottom-up approach uses statistical analysis to establish habitat map units based on biological similarity and then use statistics to determine relationships between habitat types and environmental variables. This approach, however, is more resource- and time-intensive. *Will be submitted to the journal Estuarine, Coastal and Shelf Science*

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1.1. Abstract

Two methods, top-down and bottom-up, were compared for their ability to classify and map benthic habitats within Rhode Island's offshore waters at two study areas being considered for wind turbine installation. The traditional top-down mapping approach identifies biological community patterns based on geologically-defined habitat map units, under the assumption that geologic environments contain distinct biological assemblages. Alternatively, the bottom-up approach aims to establish habitat map units based on biological similarity and then use statistics to determine relationships with associated environmental parameters. This approach, however, is more resource- and time-intensive.

Both methods showed statistically strong and significant abiotic-biotic relationships and produced habitat units with distinct macrofaunal assemblages. Overall, the bottom-up approach was more effective at mapping benthic habitats because it produced more clearly defined macrofaunal assemblages and offered finer-scale habitat characterization. However, the spatial heterogeneity of the study areas prevented development of full-coverage maps with the currently available number of ground-truth (species assemblage and grain size) samples. Therefore, for mapping needs of this study, the top-down method is recommended in Rhode Island waters because it can produce full-coverage maps.

The methodologies applied here can be extended to other study locations and work towards establishing a standard mapping protocol to facilitate more effective communication both among scientists and managers.

1.2. Introduction

Benthic habitat is described as “a spatially defined area where the physical, chemical, and biological environment is distinctly different from the surrounding environment” (Kostylev et al., 2001). Therefore, distinct biological assemblages are thought to represent distinct environmental conditions (Kostylev et al., 2001). The mapping of benthic habitats presents the distribution and extent of biotic and abiotic characteristics of seafloor environments in a geospatial context (Auster et al., 2009). Typically, geologic and water depth parameters define the abiotic characteristics. Benthic habitat maps are valuable tools for numerous ecological and management reasons, including understanding benthic habitat and faunal species and/or community distribution patterns and processes (Valesini et al., 2010; Hewitt et al., 2004; Connor et al., 2004; Brown et al., 2002; Zajac et al., 2000); defining essential fish habitat (Rooper and Zimmermann, 2007; Greene et al., 1999); establishing environmental baselines (Hewitt et al., 2004); and implementing appropriate management strategies, such as marine spatial planning, resource regulation, restoration, conservation, monitoring, and impact assessment (Last et al., 2010; Auster et al., 2009; Valentine et al., 2005; Diaz et al., 2004; Kostylev et al., 2001; Zajac et al., 1999; Greene et al., 1999).

There are typically two components to benthic habitat mapping: seafloor imaging and ground-truth studies (Rooper and Zimmermann, 2007). Seafloor imaging is often performed with side-scan sonar and swath bathymetry. These data sets can offer continuous coverage, high-resolution data of large areas (Kenny et al., 2003) and can be acquired relatively rapidly and affordably (Collier and Brown, 2005). Bathymetry

maps indicate the depths and topography of the seafloor. Side-scan sonar backscatter intensity reflects the amount of sound returning to the sonar after hitting the seafloor and is indicative of the density, slope, and roughness of the seafloor (Goff et al., 2000). Backscatter intensity has also been linked to seafloor sediment characteristics (Brown and Collier, 2008; Collier and Brown, 2005). Therefore, side-scan has traditionally been used to map the spatial complexity and heterogeneity of seafloor sedimentary and geological features (Hewitt et al., 2004). Acoustic data are less able to capture biological characteristics of the seafloor (Zajac, 1999). However, side-scan may delineate biological features when the biota modifies the physical structure of the seafloor and produces unique acoustic return patterns, such as with coral reefs (e.g. Kendall et al., 2005; Collier and Humber, 2007; Roberts et al., 2005; Mumby et al., 2004), shellfish beds (e.g. van Overmeeren et al., 2009; Kostylev et al., 2003), and submerged aquatic vegetation (e.g. Lefebvre et al., 2009; Jones et al., 2007; Sabol et al., 2002).

Ground-truth studies refer to the acquisition of surficial seafloor grab samples, cores, trawl data, and/or underwater imagery (Brown and Collier, 2008; Kenny et al., 2003). These data offer point- or transect-coverage over small areas (Rooper and Zimmermann, 2007) and are usually collected at coarse spatial resolutions (Eastwood et al., 2006). Ground-truth studies are performed to obtain fine-scale information of seafloor characteristics (such as biota, sediment grain size, geological formations, wave/current processes) (Brown and Collier, 2008), often to assist with interpretation and classification of acoustic data. While ground-truth samples can offer detailed point data, the low sampling resolution usually prevents such data from being stand-

alone mapping tools, as they may be unable to detect habitat and/or biological structure changes, particularly over small spatial scales and in heterogeneous areas (Eastwood et al., 2006). In addition, interpolating between point samples can produce inaccurate results (Brown et al., 2002).

Commonly, benthic habitat mapping employs a top-down approach (Shumchenia and King, 2010; Hewitt et al., 2004). This methodology develops habitat map units based on geological similarity, following the assumption that geologic environments or features, such as sediment type, contain distinct biological assemblages. The approach involves acoustically mapping an area of seafloor and then interpreting the data into distinct regions according to backscatter patterns and/or depth (either visually or using automated classification software). The biological characteristics of each map unit type is identified from ground-truth data and integrated into the map unit description (Shumchenia and King, 2010; Eastwood et al., 2006; Hewitt et al., 2004; Solan et al., 2003; Brown et al., 2002; Ellingsen et al., 2002; Kostylev et al., 2001).

Using acoustic methods as the primary tools to delineate benthic habitats is attractive because it is less time- and cost-intensive, and requires minimal ground-truth data (Eastwood et al., 2006). However, since side-scan data primarily reflect physical characteristics of the seafloor, the top-down approach tends to produce geology-based habitats and inadequately represent biological communities (Valesini et al., 2010; Shumchenia and King, 2010; Valentine et al., 2005). In addition, the validity and cohesiveness of the biological assemblages defined among these habitats is often not statistically examined (Last et al., 2010; Shumchenia and King, 2010).

Often, studies employing the top-down approach find that benthic fauna tend to transcend acoustically-derived habitat boundaries – that is, biological communities are present in multiple habitats and a defined habitat exhibits a range of biological communities (Shumchenia and King, 2010; Eastwood et al., 2006; Hewitt et al., 2004; Freitas et al., 2003; Brown et al., 2002; Kostylev et al., 2001). However, this finding does not indicate organism-sediment relationships do not exist. Many studies have found links between sediment type and benthic fauna community structure (Verfaillie et al., 2009; Brown and Collier, 2008; Ellingsen, 2002; Zajac et al., 2000; Snelgrove and Butman, 1994; Gray, 1974; Rhoads, 1974). The discrepancy may be because sediment grain size is not the sole determinant of species distribution (Snelgrove and Butman, 1994) and some acoustically defined habitats have similar sediment characteristics. In addition, it is likely that a combination of environmental parameters define the range limits of biological assemblages, such as water depth, nutrient and food supply, hypoxia/anoxia, current patterns, disturbance events, competition and predator-prey interactions. For example, in Long Island Sound, community structure changes occur with bathymetric and meso-scale circulation patterns (Zajac et al., 2000).

The goal of the bottom-up approach is to produce ecologically relevant map units by integrating multiple types of data over various scales to establish statistically significant relationships between biological communities and environmental parameters. The habitat map units are based on biological similarity, such that biological assemblage samples within a unit are significantly similar to each other and distinct across units. The biological units are then given environmental context by

establishing significant relationships with abiotic parameters (acoustic, sediment, water column, spatial) using multivariate statistics. The resulting habitats are classified by their biotic and abiotic characteristics (Shumchenia and King, 2010; Hewitt et al., 2004; Kostylev et al., 2001). The spatial distribution of the habitat map units can be determined objectively through interpolation of the meaningful point-source parameters (Eastwood et al., 2006). This extrapolation allows the creation of full-coverage, benthic habitat maps (Shumchenia and King, 2010; McBreen et al., 2008; Hewitt et al., 2004).

The bottom-up approach has many advantages. It has the potential to preserve species-environment relationships preserved (Shumchenia and King, 2010; Rooper and Zimmermann, 2007), biological assemblages are more well-defined (Shumchenia and King, 2010; Hewitt et al., 2004; Eastwood et al., 2006), finer-scale habitat attributes can be discerned, and the multivariate analyses employed indicate how well biological assemblage variability is captured by abiotic parameters. This approach is especially useful in benthic environments characterized by gradual transition zones, low relief, and relatively homogenous sediment types, such as gravel and sand (Eastwood et al., 2006) and soft-sediment (Hewitt et al., 2004). In these environments where the ability of acoustic methods to distinguish benthic habitats is limited, the bottom-up method may be better able to detect habitats (Shumchenia and King, 2010; Eastwood et al., 2006).

The bottom-up method, however, requires a higher density of point-samples compared to the top-down method (Hewitt et al., 2004; Zajac, 1999), causing it to be more resource-intensive (Shumchenia and King, 2010; Eastwood et al., 2006).

Furthermore, ground-truth surveys must be extensive enough to sample all habitats within the study area; habitats not sampled will not be represented in the final benthic habitat classification map (Rooper and Zimmermann, 2007).

1.3 The primary purpose of this study was to investigate the effectiveness of two mapping approaches, top-down and bottom-up, in offshore marine environments. This comparison is important for advancing methodologies and working towards a standard protocol within the field of benthic habitat mapping that can be applied regardless of study location. Furthermore, to my knowledge, the application of the bottom-up approach in offshore waters, where data density tends to be lower, has not been done before. Secondly, this study aims to classify benthic habitats to assist in determining appropriate locations for wind turbine installation.

1.3. Methods

1.3.1. Study Area

Rhode Island Sound (RIS) and Block Island Sound (BIS) are transitional waters that separate the estuaries of Narragansett Bay and Long Island Sound from the outer continental shelf. RIS and BIS are environmentally, economically, and culturally valuable for renewable energy development, fishing, boating, ferry and shipping routes, and tourism (RI CRMC, 2010). The benthic habitats of two areas identified as primary potential wind farm locations through a Tier 1 screening process (Spaulding et al., 2010) were examined in detail (Figure 1.1). The BI study area is a 138.6 sq km

survey area located within state waters to the south of Block Island, and the FED study area is 178.7 sq km and is located in federal waters in eastern RIS.

1.3.2. Acoustic surveys

a. Acquisition

Side-scan and swath bathymetric data were simultaneously collected within the study areas using an interferometric sonar (C3D, Teledyne Benthos) (Figure 1.2). The 200 kHz system was pole-mounted to the starboard side of the vessel. Data were obtained over 33 survey days between September 2008 and September 2009. During the surveys, Triton Isis software (2008 BI data) or Ocean Imaging Consultants (OIC) GeoDas software (2009 BI and FED data) was used to continuously record the raw data. The 2008 data were collected in association with a DGPS (Trimble Pathfinder ProXT) to assure positional accuracy, a gyro-compass (TSS Meridian model) to correct for vessel heading, and a motion reference unit (TSS DMS-05) to correct for the vessel's motion (pitch, roll, and heave). For the 2009 data, a POS-MV V4 system (Applanix) was used for positional accuracy and to correct for vessel heading and motion.

Hypack navigation software was used to plan surveys and log in real-time. The acoustic surveys were composed of parallel track lines, with line spacing between 100 m and 150 m. In order to obtain 100% coverage, line spacing was such that each swath overlapped at least 25% with its neighboring swaths and resulted in every portion of the seafloor being imaged at least once.

b. Processing

The raw files were processed using OIC CleanSweep software. For the side-scan backscatter, 2 m resolution mosaics were created. Bottom tracking, angle-varying gains (AVG) and look-up tables (LUT) were applied to the data as necessary to correct for water column returns, arrival angle, and to increase the signal-to-noise ratio of the backscatter returns. These corrections helped create a uniform image to effectively display the features of the seafloor. The backscatter intensity mosaic is displayed on a false color scale as an inverse grey-scale image, ranging from zero (black) to 255 (white). Stronger backscatter is depicted by lighter pixels and represents highly reflective (usually harder or rougher) surfaces, whereas weaker backscatter (darker pixels) represents acoustically absorbent (usually softer or smoother) bottoms (Wille, 2005). The final side-scan backscatter mosaics were exported as geo-referenced tiff files and imported into ArcMap 9.3 (ESRI GIS software). The mosaics reveal the heterogeneity of the benthic environments within the study areas, especially in BI (Figure 1.3).

For the bathymetry, each swath was corrected for tide, vessel motion, and sonar mount angle. An angle filter was applied to remove potential outlier soundings. Partial overlap of adjacent swaths allowed the data to be filtered to 6-8X the water depth, ensuring the highest quality soundings were used to build the mosaics. The final bathymetry mosaics (10 m resolution) were exported as ArcGrid files and imported into ArcMap 9.3 (Figure 1.4).

c. Analysis

Although both side-scan and bathymetry datasets were collected at very high resolution (2 m and 10 m pixels, respectively), creating habitat maps at this level of

detail would be prohibitive (computation time, file sizes). Therefore, 100 m pixel size was chosen, a scale at which major geophysical changes and boundaries across both study areas were still visible in the mosaics. The mean, minimum, maximum and standard deviation of both the side-scan and bathymetry were calculated at 100 m resolution. These parameters were calculated using ArcMap 9.3 with the Block Statistics feature in the Spatial Analyst Toolbox. Slope was derived using the slope function in Neighborhood Statistics in the Spatial Analyst extension.

In addition, a set of 1.9 million National Ocean Service (NOS) soundings was also compiled. These soundings were used to create a data layer that is a broad-scale measure of surface roughness throughout RIS and BIS. Using the Neighborhood Statistics function, this surface roughness layer was derived by calculating the standard deviation of the slope (100 m resolution) within a search radius of 10 pixels (i.e. 1,000 m) using a moving widow algorithm (Damon, Pers. Comm.). Therefore, the resulting data layer has a 100 m pixel resolution and each pixel has a value that is the standard deviation of the slope of the surrounding 1,000 m.

1.3.3. Bottom samples

Surface samples were collected using a Smith-McIntyre grab sampler (0.05 m² area). A total of 48 bottom samples were gathered within BI (average of 1 grab/3 sq km; Figure 1.5) over four occasions between October 2008 and August 2009. For FED, 30 bottom samples were collected, concentrated within the western two-thirds (117.8 sq km) of the study area (average of 1 grab/6 sq km), over two days in December 2009 and June 2010. Sampling stations were positioned within distinct

geophysical bottom types such that most physical habitats contained at least one bottom sample. Bottom types were identified through visual interpretation of the side-scan backscatter and bathymetry imagery.

a. Sediment samples

A sub-sample was taken from the surface of each bottom sample and sediment properties characterized using a particle size analyzer (Malvern Mastersizer 2000E). The Mastersizer generated the weight percent of each Wentworth particle size fraction (very fine sand, fine sand, medium sand, etc.), along with the standard deviation of the particle size distribution for the entire sample.

b. Macrofauna samples

The remaining material from each bottom sample was sieved on 1 mm mesh and macrofauna were retained. All individuals were counted and identified to at least the genus level. In addition, a functional group designation (e.g. surface burrower, tube-builder, mobile) for each genus was made. The macrofauna abundances (# of individuals) from the BI and FED study areas were pooled and only the genera contributing to 97% of the total abundance between the two areas were included in further analyses. This eliminated genera with very low abundances ($< 0.09\%$ of the total abundance, equivalent to < 19 individuals) and resulted in the removal of 663 individuals from the study (of 21,862).

For statistical analyses, abundance is defined as the number of individuals per bottom sample. Using the statistical software package, PRIMER 6 (PRIMER-E, Ltd.), the macrofauna abundances for each of the 78 bottom samples were 4th root

transformed to reduce the influence of highly abundant genera and the Bray-Curtis similarity index was used to create a matrix of station-similarity.

Genus-level abundance data were used, with the exception of three genera: *Ampelisca*, *Lumbrineria*, and *Nucula*. The tube-building amphipod genus, *Ampelisca*, remained separated into the species *A. vadorum* and *A. agassizi* because *A. vadorum* is a dominant species within BI, but rare within FED, while the opposite is true for *A. agassizi*. The genus *Lumbrineria*, small surface-burrowing polychaetes, were examined on the species level (*L. hebes* and *L. fragilis*) because *L. hebes* is much more abundant. *Nucula annulata* and *Nucula delphinodonta*, deposit-feeding molluscs, were kept separate because *N. annulata* has a higher abundance within FED. Examining these three genera at the species-level allows for investigation into if the individual species have distinct relationships with their respective environments.

1.3.4. Top-down benthic habitat mapping approach

a. Habitat map units

Geologic depositional environment types define the extent of the habitat map units for the top-down approach (Figure 1.6). The environments were visually interpreted for both the BI and FED study areas from high-resolution side-scan and bathymetry mosaics, sub-bottom seismic reflection profiles, surficial sediment samples, and underwater video (Oakley et al., 2010, in LaFrance et al., 2010). The environments have two components, form and facies. Form represents large-scale Quaternary geologic features (e.g. glacial alluvial fan, moraine shelf, glacial lake floor), having map units > 10 sq km. The smaller scale facies component (typically <

2.6 sq km) describes surficial sediment characteristics and seafloor roughness (e.g. sand waves, boulder gravel concentration, coarse silt) and represent modern (Late Holocene) processes. Form and facies correspond to the Geoform and Subform levels, respectively, in the CMECS (Coastal and Marine Ecological Classification Standard) classification framework, (Madden et al., 2010).

b. Multivariate analyses

Analysis of similarity (ANOSIM) was performed on the Bray-Curtis similarity matrix to test the null hypothesis that there were no differences between macrofaunal assemblages among geologic depositional environment types. The test was permuted 999 times to generate a significance level ($p < 0.05$). The similarity percentages (SIMPER) routine was then used to compare the degree (percentage) to which each individual genus contributes to the within-environment similarity and among-environment dissimilarity (Clarke and Gorley, 2006). SIMPER also reports the percent average within-environment similarity and among-environment dissimilarity. All analyses were executed in PRIMER 6.

c. Classification

Habitat map units were classified according to the average most abundant genus (# of individuals) within the bottom samples retrieved there, following CMECS protocol. To show biotic-abiotic associations, map units were also labeled by geologic depositional environment type.

1.3.5. Bottom-up benthic habitat mapping approach

a. Multivariate analyses

A suite of abiotic variables was generated from the multiple data layers (i.e. side-scan backscatter, bathymetry, sediment samples, NOS soundings) at each of the 78 bottom sample stations (Table 1.1). The variables were normalized to correct for differences in units, and a resemblance matrix created based on the Euclidean distance metric. All analyses were performed in PRIMER 6 (refer to Clarke et al. (2008) or Clarke and Gorley (2006) for further details of statistical analyses).

The biotic Bray-Curtis similarity matrix and the abiotic Euclidean distance resemblance matrix were subject to the BIOENV procedure. BIOENV identifies a subset of abiotic variables that best “explain” the patterns in the macrofaunal composition. BIOENV searches for high rank correlations between the Bray-Curtis and Euclidean matrices and outputs the highest Spearman rank correlation, ρ , between combinations of abiotic variables and the macrofaunal assemblages. The maximum number of variables permitted in the output was capped at ten. The BIOENV routine was permuted 999 times to allow for the significance of the results to be assessed. Statistical significance was assigned when $p < 0.05$.

The BIOENV procedure was performed twice, once using all of the abiotic variables and once removing variables that were highly correlated, and therefore, redundant ($r > 0.85$), as assessed from a draftsman plot was created to assess correlations between the abiotic variables. The more sensible variable was chosen for analysis (for example, mean water depth was chosen over minimum water depth).

The variables identified as important by BIOENV were then entered into the LINKTREE procedure to classify the macrofauna samples according to patterns in these important abiotic variables. LINKTREE groups the macrofauna samples by successive binary division using the abiotic variables as drivers and maximizing the ANOSIM R value at each division. The ANOSIM R was constrained to be greater than 0.30 and the minimum group size was set at two so that each LINKTREE class has at least two samples. A suite of biological samples and quantitative thresholds of the abiotic variable(s) define each of the resulting classes. A similarity profile test (SIMPROF) within LINKTREE was used to determine if a group of samples should be split into further LINKTREE classes and to evaluate the significance of each class. The test was permuted 999 times to assess significance.

An ANOSIM was performed on the LINKTREE classes to test the null hypothesis that there were no significant differences in the macrofaunal assemblages among classes. SIMPER was used to determine both the overall and individual contributions of each genus to the within-group similarity and between-group dissimilarity of the resulting LINKTREE classes.

b. Habitat map units

To develop full coverage habitat map units, interpolation of the grain size point sample dataset is necessary. However, attempts to interpolate using traditional methods (Ordinary Kriging, Inverse Distance Weighting) in ArcMap 9.3 were unsuccessful due to semi-variograms that failed to show similarity (low semi-variance) at short lag distances. This results from point samples being spaced too far apart resulting in a lack of spatial autocorrelation. Using continuous coverage data

(water depth, side-scan backscatter, surface roughness) to predict sediment properties was also not successful. For example, the best linear model explaining variation in coarse grain size based on surface roughness and minimum depth had an r^2 of 0.59. This was considered too weak to develop a predictive map of grain size using surrogate data and a least-squares regression model approach. Because full-coverage map units could not be confidently developed, the bottom-up maps were constructed by classifying pixels for which all abiotic data were available and at the original extent (i.e. 78, 100 m pixels). This conservative approach was taken to preserve the accuracy of the maps. This concern for retaining accuracy is echoed by Brown and Collier (2008) who remarked that interpolation methods can often lead to erroneous assumptions in the resulting map, particularly if the degree of seafloor heterogeneity reflected by surficial geology and biota is high (as it is in this study).

c. Classification

The habitat classes follow the LINKTREE output. Each class is described by the average most abundant genus (# of individuals) across all samples within the class (following CMECS protocol) and its relevant abiotic variables to indicate biotic-abiotic relationships.

1.4. Results

1.4.1. Bottom samples

a. Sediment samples

Medium grained sand was the dominant sediment (29.7%) of the 78 sample stations between the BI and FED study areas, followed by coarse sand (24.3%) and fine sand (20.8%), which together accounted for 74.8% of the sediment sampled (Table 1.2). Overall, BI was comprised of coarser sediment, with medium, coarse, and very coarse sands accounting for 83.2% of the sediment samples. The FED sediment samples, however, were mostly finer sediments, with 75.2% of the samples made of very fine, fine, and medium grained sands. Similar to the acoustic data, BI seemed to exhibit more heterogeneous sediment size characteristics, having a larger range with regard to the standard deviation of grain size (90.6 μm to 459.8 μm range for BI versus 61.4 μm to 316.2 μm for FED).

b. Macrofauna samples

More than 21,000 individuals belonging to seven phyla and 87 genera were sampled across the 78 stations within BI and FED (Table 1.3). For both areas, the majority of the recovered macrofauna (97.1%) belonged to three groups – Crustacea (Arthropoda phylum) (53.4%), Polychaeta (Annelida phylum) (24.2%), and Mollusca (19.5%). In terms of spatial distribution, the most spatially extensive genus was *L. hebes*, a small surface burrowing polychaete recovered at 69.2% of the stations sampled (Table 1.4). The second and third spatially most extensive genera were the small surface burrowing amphipod crustacean, *Unciola* (56.4% of stations), and the bivalve clam, *Astarte* (52.6% of stations). The most abundant genera (# of individuals) were *A. vadorum* (comprised 18.6% of the total recovered individuals) and *B. serrata* (12.6%), both tube-building amphipods, followed by *N. annulata* (8.3%), a deposit feeding bivalve.

Of the 78 bottom samples, 30 genera/species were most abundant within one or more samples. The 48 samples within BI were dominated by 25 genera/species, whereas seven genera/species dominated the 30 samples within FED.

1.4.2. Top-down benthic habitat mapping approach

a. Multivariate analyses

There were strong and significant differences in macrofaunal assemblages among the geologic depositional environments (ANOSIM global $R = 0.60$, $p = 0.001$). SIMPER showed within-environment similarity ranged from 6.2% to 59.4%, with an average of 34.2% (Table 1.5). Samples in the map unit “*B. serrata*/*A. agasizzi* – Pt. Judith-Buzzards Bay (PJ-BB) Moraine with sand sheets, sand sheets with gravel, and sand waves” exhibited the most similarity (59.4%), followed by “*A. agasizzi* – Glacial Lake Floor with sand sheets” (58.3%) and “*N. annulata*/*A. agasizzi* – Glacial Lake Floor with fine or coarse sands” (56.1%). The contribution for the genera/species most responsible for the within-environment similarity ranged between 7.9% and 100%. The genus/species most responsible for the similarity of each unit varied (18 genera/species identified). Some units were labeled by multiple genera because they contribute equally or nearly equally. The percent dissimilarity between map units ranged from 40.7% to 97.3%, having an average of 77.3%. *B. serrata*, *A. vadorum*, *A. agasizzi*, and *N. annulata* were the most responsible for the dissimilarity.

b. Classification

The top-down benthic habitat mapping approach generated 18 map units, none of which were present within both study areas. There were 12 map units within BI and

six within FED (Figure 1.7). The areas of the map units ranged between 2.6 sq km and 60 sq km. Each map unit contained between two and 14 bottom samples, with the exception of “*B. serrata* – Hummocky Moraine, fine or coarse sand,” which was sampled once. In cases where the same genus/species was dominant, map units were distinguished with roman numerals, since the macrofaunal communities among the geologically derived map units were significantly distinct. Map units were identified by two dominant genera/species when their abundances were nearly identical or are very high compared to the remaining abundances within that environment. Geologic depositional environments within which no samples were collected were classified as undefined (7 sq km of the 138.6 sq km BI site and 22.8 sq km of the bottom sampled 117.8 sq km FED site).

Tube-building amphipods defined 11 and co-defined 2 of the 18 map units and spatially comprised the majority of the study areas. Within BI, tube-building amphipods defined eight of the 12 map units. *A. vadorum* and *B. serrata* were each responsible for three units, and *J. falcata*, and *Corophium* each represented one unit. The remaining map units were dominated by polychaete species, one of which, *P. medusa*, was also tube-building. For FED, the six map units were about equally defined by the bivalve, *N. annulata*, and tube-building amphipods (*A. agassizi* and *B. serrata*). One map unit was an exception, being defined by the surface-burrowing polychaete, *L. hebes*.

In total, 10 genera/species defined or co-defined the 18 habitat map units, with eight genera/species representing the units in BI and four representing the units in

FED. Five of the 10 genera/species were tube-building amphipods, three were burrowing polychaetes, and there was one tube-building polychaete and one bivalve.

Colored circles representing the dominant genus in each bottom sample were overlaid on the top-down classification maps (Figure 1.8), and used to indicate the unity and variability among samples within each map unit. For example, the majority of samples within units defined by *A. vadorum* were dominated by that species. However, the dominant genus/species varies for bottom samples collected within the *P. medusa/L. hebes* map units.

1.4.3. Bottom-up benthic habitat mapping approach

a. Multivariate analyses

The BIOENV procedure identified a subset of six abiotic variables as being the most correlated the macrofaunal composition ($\rho = 0.70$, $p = 0.001$). The variables responsible were percent medium sand, percent coarse sand, standard deviation of the grain size (μm), maximum backscatter intensity, mean depth (m), and surface roughness. Mean depth was the single variable having the highest correlation ($\rho = 0.52$) with the macrofaunal assemblage. These results persisted whether highly correlated variables were included or excluded in the analysis.

The LINKTREE identified 22 classes, each of which was defined by a series of abiotic quantitative thresholds of the six input variables (Figure 1.9, Table 1.6). Each of the class breaks was significant ($> 5\%$) and ANOSIM R values were between 0.36 and 0.81. Six of the thresholds were defined by percent medium sand, five by surface roughness, four by mean water depth, three by percent coarse sand, two by standard

deviation of the grain size, and one by maximum backscatter intensity. Some of these thresholds were defined over a narrow range. For example, split “J” divided to the left at surface roughness less than 0.120 and to the right at greater than 0.124, and split “M” was defined by mean water depth less than 19.0 m to the left and greater than 19.7 m to the right.

The macrofaunal assemblages among LINKTREE classes were significantly distinct (ANOSIM $R = 0.83$, $p = 0.001$). SIMPER showed within-LINKTREE class similarity ranged from 5.8% to 64.8% (Table 1.7) and had an average similarity of 36.3%. Samples in the class “*A. agasizzi*/*N. annulata*” were the most similar (64.8%), followed by “*B. serrata*/*N. annulata*” (60.6%) and “*Protohaustorius sp./Astarte/R. hudsoni*” (58.3%). The contribution for the genera/species most responsible for the within-class similarity ranged between 8.8% and 100%. The genus/species most responsible for the similarity of each class varied, with 19 genera/species identified. The average between class dissimilarity was 78.9%, ranging from 44.5% to 98.8%. The species most responsible for the dissimilarity were *B. serrata*, *A. vadorum*, *N. annulata*, and *J. falcata*.

b. Classification

The bottom-up benthic habitat mapping approach resulted in the classification of 78, 100 m pixels (Figure 1.10). The approach generated a total of 22 habitat classes, 18 of which were present in BI and 9 in FED. The two study areas had 5 classes in common. There were between 2 and 14 bottom samples within each class. In cases where the same genus/species was dominant, classes were distinguished with roman numerals, since the macrofaunal communities among the LINKTREE derived classes

were significantly distinct. Classes were identified by two dominant genera/species when their abundances were nearly identical or very high compared to the remaining abundances within that class.

Tube-building amphipods dominated the BI and FED habitats, defining or co-defining 12 of the 22 habitat classes and classifying 43 of the 78 pixels. Within BI, tube-building amphipods defined or co-defined 10 of the 18 classes and encompassed 18 of the 48 classified pixels. *B. serrata* and *A. vadorum* were each dominant or shared dominance for five classes and *J. falcata*, for one class. The remaining classes were defined or co-defined by burrowing polychaetes (4 classes, 10 pixels: *L. hebes*, *Syllis*, *H. extunata*, *Glycera*), tube-building polychaetes (2 classes, 16 pixels: *P. medusa* and *P. neglecta*), bivalves (2 classes, 4 pixels: *P. gouldii* and *Astarte*), amphipods (1 class, 2 pixels: *Protohaustorius sp.* and *R. Hudsoni*), and *Oligochaeta sp.* (1 class, 2 pixels). For FED, tube-building amphipods defined or co-defined seven of the nine classes and encompassed 25 of the 30 classified pixels. *B. serrata* and *A. vadorum* dominated or co-dominated four classes and three classes, respectively, and *A. agasizzi* shared dominance for one class. The bivalve, *N. annulata*, defined or co-defined three classes (21 pixels) and the burrowing polychaete, *N. nigripes*, defined one class (2 pixels).

Overall, 17 genera/species described or co-described the 22 habitat classes. Specifically, 14 genera/species represented the BI classes and five represented the FED classes. Five of the 17 genera/species were burrowing polychaetes, four were tube-building amphipods, two were tube-building polychaetes, three bivalves, two amphipods, and one species of *Oligochaeta*.

1.5. Discussion

Maps of the distribution of benthic habitats are valuable tools for numerous ecological and management purposes, including understanding ecosystem patterns and processes, determining environmental baselines, impact assessments, and conservation efforts. The goal of this study was to construct and compare the effectiveness of benthic habitat maps for two areas, using the traditional top-down method and the alternative bottom-up method, which has not before been applied to offshore environments.

1.5.1. Comparison of benthic habitat mapping approaches

The top-down classification was advantageous because it produced full-coverage habitat map units containing significantly distinct macrofaunal communities (ANOSIM global $R = 0.60$, $p = 0.001$) and described broad-scale biological and geological resources. Furthermore, because the habitats were based on geological similarity, data collection, processing, and analysis were relatively less time- and effort- intensive.

While successful, the top-down approach also had disadvantages. As is frequently found in other top-down studies, some benthic communities and fauna transcend the habitat boundaries as defined by depositional environment type. This is a concern for the top-down approach because it defies the assumption that distinct geological environments will contain distinct biological communities. The *A. vadorum* assemblage, for example, spans two surficial sediment types, silty sand and

pebble gravel coarse sand. Similarly, the *N. annulata* assemblage dominates environments categorized as coarse silt and fine or coarse sand. In addition, the degree of variability fluctuates among the defined habitats, as seen by examining the dominant species at each bottom sample within a given habitat. For instance, the majority of the bottom samples were dominated by the genus/species the unit is named for (e.g. the *A. vadorum* habitat), whereas within other units (e.g. the *P. medusa/L. hebes* habitat), the dominant genus/species varies among bottom samples. Furthermore, the “Glacial Lake Floor, fine or coarse sand” and “Pt. Judith-Buzzards Bay Moraine, boulder gravel concentration, cobble gravel pavement, coarse silt” map units combine a range of surficial sediment types, potentially grouping distinct biological assemblages together. In addition, the top-down method defines habitats on a broader scale ($2.6 \text{ sq km} < \text{habitat} < 60 \text{ sq km}$), and this “loss of resolution” is a potential drawback.

The bottom-up classification preserved macrofauna-environment relationships by creating habitats based on biological similarity. The approach was beneficial in that the macrofaunal assemblages among habitat types were more clearly defined (ANOSIM global $R = 0.83$, $p = 0.001$) and it provided fine-scale details of each habitat, identifying the abiotic parameters and their quantitative thresholds that are most influential to the macrofaunal composition patterns. In terms of methodology, the bottom-up approach was valuable because of its ability to incorporate all available data, regardless of resolution, to establish abiotic-biotic relationships. This ability is important from a practical and ecological perspective. The former refers to the collection of mapping data, which largely depends on methodology. Ecologically,

small-scale processes can play a role in the structuring of benthic communities, which, in turn, can influence broad-scale processes (e.g. seabed stability, hydrodynamics) (Hewitt et al., 2004). In addition, the bottom-up is a more objective approach, as it does not require habitat boundaries be defined, a difficult task if boundaries are not discrete due to gradual changes.

The major disadvantage of the bottom-up method is that full-coverage maps could not be created because bottom samples were spaced too far apart. The resulting lack of spatial auto-correlation between point sample datasets (i.e. grain size) prevented interpolation. This issue of creating full-coverage habitat map units is one of the challenges of the bottom-up approach and may be rectified given a higher spatial density of bottom samples.

The ANOSIM global R of the bottom-up habitat classes based on the LINKTREE output using the six variables identified by BIOENV (% medium sand, % coarse sand, standard deviation of grain size, surface roughness, mean water depth, maximum backscatter intensity) was greater than for the top-down map units defined by geologic depositional environments. This result indicates that the biological assemblages within the bottom-up approach are more distinct, and, therefore, the benthic habitats are better defined. However, both approaches had comparable within-group (i.e. depositional environment or LINKTREE class) similarity and among-group dissimilarity averages and ranges. This finding suggests that the grouping of the macrofauna samples is equally valid and produced cohesive assemblage for both mapping approaches. The high average dissimilarity between groups (77.3% and 78.9% for the top-down and bottom-up methods, respectively) suggests the

assemblages are distinct from one another, but the relatively low average within-group similarity argues for further splitting of the groups.

The top-down and bottom-up classifications were similar in that both found tube-building amphipods dominate the habitats within BI and co-dominate with *Nucula*, a genus of small bivalves, in FED, indicating these are the most abundant organisms within the two study areas. Tube-building amphipods form very dense, abundance-rich tube mats and a grab sample within one of these mats may contain over 1,000 individuals (as was found in stations BI 1 and 2). Because habitats are defined by the dominant genus/species, tube-building amphipods may be masking patterns and other influential genera within the study areas. Evidence of this overshadowing by amphipods can be seen in the top-down classification maps where map units are classified by a tube-building amphipod, but that same amphipod is not the most abundant in many of the individual bottom samples. However, that tube-building amphipods dominate in abundance in Block Island Sound and co-dominate with *Nucula* in Rhode Island Sound is consistent with historic descriptions (Batelle, 2003; Steimle, 1982; Pratt, 1973).

The top-down and bottom-up approaches differ primarily in three ways. First, the bottom-up method yielded four more habitat types than the top-down (18 versus 22). Second, BI and FED share 5 habitats in the bottom-up approach, whereas none are shared in the top-down approach. Third, the geospatial distribution is consistent for some habitats in the maps, but not for others. For example, the location of *A. vadorum* habitats is similar in both maps, whereas several different habitat types in the bottom-up map exist in the location of the habitat defined by *J. falcata* in the top-down map.

These three differences are likely due to the scale at which each classification approach was mapped, since the top-down map units expand over square miles and the bottom-up map strictly classifies 100 m pixels. It is interesting to note that because the bottom-up method defines habitat classes on a finer-scale, the distinct habitats identified may be sub-sets of the top-down habitats, particularly the larger units, encompassing several to 60 sq km.

Overall, the top-down and bottom-up habitat mapping approaches both yielded strong and statistically significant biotic-abiotic relationships and produced habitats containing distinct biological assemblages. Comparing the advantage/disadvantages and similarities/dissimilarities between the two mapping approaches, though, the top-down approach is recommended for mapping benthic environments within Rhode Island offshore waters. The top-down method is more effective here because the benthic habitat maps are needed to guide management decisions on where to place wind turbines, so full-coverage map units are required. However, for other locations, the appropriate method to use depends on the study objectives (i.e. biological, geological, environmental focus), the resolution needed (i.e. broad or fine scale, full coverage or partial), and available resources (expenses, time). While the environmental parameters examined and identified as important by BIOENV and the geologic depositional environments within an area will change with geographical location, this study provides two benthic habitat methodologies that can be easily adapted to other areas, including offshore environments.

The methodologies applied in this study, especially the bottom-up approach, were able to integrate various data sets of various resolutions, indicating they can be

extended to other study areas. This adaptability lends towards establishing a standard mapping protocol, which would facilitate more effective communication and comparable studies both among the scientific benthic habitat mapping community and management agencies.

1.5.2. Comparison of study areas

The benthic habitats of the two study areas, BI and FED, differ in their biotic and abiotic characteristics, suggesting macrofaunal assemblages primarily have their own associations with the environment. This difference can be seen in the results of the top-down approach, where BI and FED have none of the 18 map units in common, and in the bottom-up approach, where the two study areas share only 5 of the 22 classes.

If the goal of the mapping effort was to characterize the finest-scale abiotic-biotic relationships in both areas, then the observed degree of separation between BI and FED classes supports the case for conducting separate analyses and generating separate maps for each study area. From a management perspective, overly-site-specific analyses and maps may not be as useful as a geographically-broad analysis that allows habitat comparisons between areas. Our approach addresses the latter point, and the results indicate that BI and FED may differ fundamentally in terms of how species utilize the benthic environment.

It is hypothesized that the benthic habitats within BI and FED differ due to physical processes. For example, the depositional environment maps reveal that each study area has undergone different geologic processes. Furthermore, BI is located close to land (Block Island) and exhibits increasing water depth with increasing

distance from the coast. Because of its location, BI is a dynamic environment, as exemplified by its overall coarser sediment composition and the presence of mobile sand waves and sheet sands visible in the side-scan backscatter mosaic and depositional environment map. The benthic communities within BI may be more affected by storms and other disturbance events (adversely with regard to habitat damage and favorably in terms of nutrient cycling and mixing) and may exhibit more light availability. Alternatively, FED appears to be a more stable environment. The FED study area is located in the heart of Rhode Island Sound and has deeper water depths that change based on the presence/absence of glacial moraines. Benthic communities are likely influenced by factors such as stratification (possibly resulting in nutrient deficiencies) and light availability.

Both study sites exhibit a high degree of benthic environment heterogeneity (BI throughout and FED within moraines). This heterogeneity resulted in there being little to no spatial autocorrelation (i.e. samples closer in space are more similar than those further away) between the point-samples. Sediment samples were collected at a density of 1-1.5 samples per square mile, suggesting benthic environments change over spatial resolutions (i.e. scales) of less than one square mile. Evidence that this small-scale heterogeneity is not an artifact of sampling density is seen in the physical data (side-scan, depositional environment, bathymetry) and the LINKTREE results, where the thresholds used to define habitat classes occur over narrow ranges of the abiotic variables. The biological communities within the study areas likely vary over a similar spatial scale.

The BI study area exhibits a higher degree of benthic habitat heterogeneity than FED, as evidenced by the top-down and bottom-up approaches both producing twice as many habitats in BI. The side-scan and bathymetry mosaics, depositional environment maps, and grain size data also reflect the increased physical heterogeneity of BI compared to FED. With regard to biological characteristics, at least twice as many genera/species define the habitats in BI than in the larger FED site, and over 3x as many were found to be most abundant genera/species in one or more of the bottom samples.

1.5.3. Biotic-abiotic relationships

The scale at which the environmental parameters and acoustic patterns are examined is important in assessing abiotic-biotic relationships. This importance can be seen in the results of the bottom-up (via the BIOENV procedure) and top-down mapping approaches. For example, the results indicate macrofauna patterns within BI and FED are linked to geologic characteristics at both fine and broad spatial scales. The point-sample grain size, specifically percent medium and coarse sand, represents the fine scale link. Such sediment-macrofauna associations have been commonly observed in bottom-up mapping approaches (Todd and Kostylev, 2011; Shumchenia and King, 2010; Hewitt et al., 2004, Kostylev et al., 2001), as well as other studies (Verfaillie et al., 2009; Ellingsen, 2002; Zajac et al., 2000; Snelgrove and Butman, 1994; Chang et al., 1992; Gray, 1974; Rhoads, 1974). The relationship was also proposed for Block Island Sound by Steimle (1982), who suggested the biological communities are gradational, probably related to small- to large-scale differences in

sediment texture. The broad-scale geologic-biotic link is with depositional environment type, a relationship which other studies have had mixed results establishing (Todd and Kostylev, 2011; Shumchenia and King, 2010; Eastwood et al., 2006; Hewitt et al, 2004; Solan et al., 2003; Brown et al., 2002; Greene et al., 1999). Maximum side-scan backscatter intensity may be another broad-scale geologic connection. Studies have shown positive correlations between backscatter intensity and grain size (Goff et al., 2000, Hewitt et al., 2004, Collier and Brown, 2005). Therefore, the maximum backscatter intensity may reflect sediment characteristics.

The BIOENV analysis also revealed connections between macrofauna patterns and small and broad scale environmental heterogeneity, as reflected by the standard deviation of the sediment grain size and surface roughness datasets, respectively. That the macrofauna have such a close relationship to these two datasets is interesting because they are very different measures of environmental heterogeneity. The standard deviation of the sediment is a point sample data set that measures variation in the size of grains of sediment within a sample, perhaps representing habitat variety, following the rationale that a greater degree of sediment heterogeneity offers more potential niches (Rosenzweig, 1995). Surface roughness, in contrast, is a 100 m resolution dataset calculated as the standard deviation of the slope within a 1,000 m radius and is particularly intriguing since the biology is sampled over 0.05m² area and surface roughness integrates data from as far as 1,000 m away. The details behind this macrofauna-large-scale surface roughness relationship remain unresolved. It is possible this large-scale surface roughness is reflecting another environmental

parameter, though it is not correlated to any parameter used in this study (see Appendix).

On a broad scale, macrofaunal community composition was found to change with mean water depth. In fact, this broad-scale parameter exhibited the highest correlation with the biology in the BIOENV procedure ($\rho = 0.52$). Depth appears to be valuable parameters in bottom-up habitat mapping studies (Shumchenia and King, 2010; Hewitt et al., 2004, Kostylev et al., 2001). The details behind this depth-biology relationship, however, are difficult to sort out because water depth could be a proxy for one or more environmental parameters. Linear regression analysis between mean water depth and the remaining abiotic variables in this study indicate water depth may be reflecting sediment grain size variables to some degree (% coarse sand $r^2 = 0.488$, % very fine sand $r^2 = 0.477$, standard deviation of grain size $r^2 = 0.431$; see Appendix). Mean water depth may also be a proxy for unmeasured parameters, such as light availability, nutrient or chlorophyll concentration, temperature, or vertical mixing due to wave and wind energy, all of which relate to food supply. Therefore, water depth may relate to environmental productivity. Further studies examining depth-dependent physical and water column variables will help resolve this relationship.

While the BIOENV procedure was able to explain a high degree of the macrofaunal community composition pattern within BI and FED ($\rho = 0.73$), there remains some unexplained variability. This result suggests that additional environmental parameters not included in the study influence these benthic macrofauna. Other environmental parameters correlated to biological assemblages have been temperature variability, oxygen saturation, chlorophyll-a concentration,

stratification, and seafloor rugosity (Todd and Kostylev, 2011). Therefore, future studies aimed at resolving this variability should involve additional benthic and water column parameters. Furthermore, BIOENV does not demonstrate causality (Clarke et al., 2008). Possible explanations as to how each abiotic variable influences macrofaunal community patterns are discussed, but further investigation is needed to establish the causalities of the correlative links indicated for the BI and FED study areas.

1.6. Conclusion

Two benthic habitat classification approaches, top-down and bottom-up, were compared for their effectiveness in mapping two offshore environments within Rhode Island waters. Both approaches yielded statistically strong and significant biotic-abiotic relationships and generated habitat types containing distinct biological assemblages. Furthermore, in both approaches, tube-building amphipods define over half of the habitats. The traditional top-down method resulted in full-coverage habitat maps using geology-based map units. The alternative bottom-up method produced habitats based on biological similarity and added environmental context using multivariate statistics. With this approach, macrofaunal assemblages were more clearly defined and finer-scale habitat details were offered. However, full-coverage habitat maps could not be developed due to the high spatial heterogeneity of the study areas. Given additional bottom samples, this problem could be rectified. Overall, for mapping Rhode Island's offshore waters, at this time, the top-down approach is recommended because it is able to produce full-coverage habitat maps. However, for

other studies, the appropriate method depends on the goals of the study and resources available. The methodologies applied here can be extended to other locations and works towards establishing a standard mapping protocol to facilitate more effective communications both among the scientists and management agencies.

The macrofaunal communities were found to have strong correlations with a range of environmental parameters (sediment and acoustic) over a range of scales. Furthermore, biotic-abiotic relationships were statistically strong despite biologic and geologic differences in BI and FED, suggesting the macrofaunal assemblages primarily have their own associations with the environment.

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Figure 1.1. The BI and FED study areas within the RI Ocean SAMP study area, located within Rhode Island and Block Island Sounds.

Figure 1.2. Flow chart of the benthic habitat mapping process, including components of the top-down and bottom-up approaches. See methods text for further details.

Figure 1.2. Flow chart of the benthic habitat mapping process, including comparison of the top-down and bottom-up approaches. See methods text for further details.

Figure 1.3. Side-scan sonar backscatter mosaics of BI and FED. Mosaics are displayed on an inverse grey-scale. White (255) represents high backscatter intensity

and black (0) represents low intensity, indicative of reflective (usually harder) surfaces and absorbent (usually softer) surfaces, respectively. The pixel resolution of the backscatter mosaics is 2 m. For the statistical analyses, the pixels were aggregated to 100 m resolution (not shown; see text for more details).

Figure 1.4. Bathymetry of IM and PED. Water depth within the two study areas ranges from 9.4 m to 34.6 m. Note the scales for IM and PED are different, as is to

Figure 1.4. Bathymetry of BI and FED. Water depth within the two study areas ranges from 9.4 m to 54.6 m. Note the scales for BI and FED are different, so as to

visually enhance the features within each area. The pixel resolution of the mosaics is 10 m. For statistical analyses, the pixel resolution was aggregated to 100 m (not shown).

Figure 1.5. Locations of the bottom samples taken within the BI and FED study areas.

Figure 1.5. Locations of the bottom samples taken within the BI and FED study areas.

Figure 1.6. Benthic geologic depositional environments of the BI and FED study areas. The polygons are labeled by depositional environment Geoform (capital letters)

followed by Subform (lower case letters). For visual emphasis, each general color represents Geoform type and shades of the same color represents Subform type. The abbreviations are as follows: Form: DB = Depositional Basin; GAF = Glacial Alluvial Fan; GDP = Glacial Delta Plain; GLF = Glacial Lake floor; GLN = Glacial Lacustrine Fan; HM = Hummocky Moraine; ISM = Inner Shelf Moraine; MS = Moraine Shelf; PBM = PJ-BB Moraine; Facies: bgc = boulder gravel concentrations; cgp = cobble gravel pavement; csd = coarse sand with small dunes; cs = coarse sand; fs = fine sand; pgcs = pebble gravel coarse sand; si = silt; sic = coarse silt; sisa = silty sand; ss = sheet sand; ssg = sand sheet with gravel; sw = sand waves.

Classification

- 1.1A. Depositional Basin (Type I) - Depositional Basin, silt, sand
- 2.1A. Depositional Basin (Type II) - Glacial Delta Plain, coarse gravel coarse sand
- 3.1A. Depositional Basin (Type III) - Glacial Delta Plain, sheet sand
- 4.1P. Depositional Basin (Type IV) - Glacial Alluvial Fan, boulder gravel concentrations
- 5.1B. Depositional Basin (Type V) - Glacial Alluvial Fan, coarse gravel coarse sand
- 6.1B. Depositional Basin (Type VI) - Glacial Alluvial Fan, sheet sand
- 7.1B. Depositional Basin (Type VII) - Glacial Alluvial Fan, sheet sand
- 8.1B. Depositional Basin (Type VIII) - Glacial Alluvial Fan, sheet sand
- 9.1B. Depositional Basin (Type IX) - Glacial Alluvial Fan, sheet sand
- 10.1B. Depositional Basin (Type X) - Glacial Alluvial Fan, sheet sand
- 11.1B. Depositional Basin (Type XI) - Glacial Alluvial Fan, sheet sand
- 12.1B. Depositional Basin (Type XII) - Glacial Alluvial Fan, sheet sand
- 13.1B. Depositional Basin (Type XIII) - Glacial Alluvial Fan, sheet sand
- 14.1B. Depositional Basin (Type XIV) - Glacial Alluvial Fan, sheet sand
- 15.1B. Depositional Basin (Type XV) - Glacial Alluvial Fan, sheet sand
- 16.1B. Depositional Basin (Type XVI) - Glacial Alluvial Fan, sheet sand
- 17.1B. Depositional Basin (Type XVII) - Glacial Alluvial Fan, sheet sand
- 18.1B. Depositional Basin (Type XVIII) - Glacial Alluvial Fan, sheet sand
- 19.1B. Depositional Basin (Type XIX) - Glacial Alluvial Fan, sheet sand
- 20.1B. Depositional Basin (Type XX) - Glacial Alluvial Fan, sheet sand
- 21.1B. Depositional Basin (Type XXI) - Glacial Alluvial Fan, sheet sand
- 22.1B. Depositional Basin (Type XXII) - Glacial Alluvial Fan, sheet sand
- 23.1B. Depositional Basin (Type XXIII) - Glacial Alluvial Fan, sheet sand
- 24.1B. Depositional Basin (Type XXIV) - Glacial Alluvial Fan, sheet sand
- 25.1B. Depositional Basin (Type XXV) - Glacial Alluvial Fan, sheet sand
- 26.1B. Depositional Basin (Type XXVI) - Glacial Alluvial Fan, sheet sand
- 27.1B. Depositional Basin (Type XXVII) - Glacial Alluvial Fan, sheet sand
- 28.1B. Depositional Basin (Type XXVIII) - Glacial Alluvial Fan, sheet sand
- 29.1B. Depositional Basin (Type XXIX) - Glacial Alluvial Fan, sheet sand
- 30.1B. Depositional Basin (Type XXX) - Glacial Alluvial Fan, sheet sand
- 31.1B. Depositional Basin (Type XXXI) - Glacial Alluvial Fan, sheet sand
- 32.1B. Depositional Basin (Type XXXII) - Glacial Alluvial Fan, sheet sand
- 33.1B. Depositional Basin (Type XXXIII) - Glacial Alluvial Fan, sheet sand
- 34.1B. Depositional Basin (Type XXXIV) - Glacial Alluvial Fan, sheet sand
- 35.1B. Depositional Basin (Type XXXV) - Glacial Alluvial Fan, sheet sand
- 36.1B. Depositional Basin (Type XXXVI) - Glacial Alluvial Fan, sheet sand
- 37.1B. Depositional Basin (Type XXXVII) - Glacial Alluvial Fan, sheet sand
- 38.1B. Depositional Basin (Type XXXVIII) - Glacial Alluvial Fan, sheet sand
- 39.1B. Depositional Basin (Type XXXIX) - Glacial Alluvial Fan, sheet sand
- 40.1B. Depositional Basin (Type XL) - Glacial Alluvial Fan, sheet sand
- 41.1B. Depositional Basin (Type XLI) - Glacial Alluvial Fan, sheet sand
- 42.1B. Depositional Basin (Type XLII) - Glacial Alluvial Fan, sheet sand
- 43.1B. Depositional Basin (Type XLIII) - Glacial Alluvial Fan, sheet sand
- 44.1B. Depositional Basin (Type XLIV) - Glacial Alluvial Fan, sheet sand
- 45.1B. Depositional Basin (Type XLV) - Glacial Alluvial Fan, sheet sand
- 46.1B. Depositional Basin (Type XLVI) - Glacial Alluvial Fan, sheet sand
- 47.1B. Depositional Basin (Type XLVII) - Glacial Alluvial Fan, sheet sand
- 48.1B. Depositional Basin (Type XLVIII) - Glacial Alluvial Fan, sheet sand
- 49.1B. Depositional Basin (Type XLIX) - Glacial Alluvial Fan, sheet sand
- 50.1B. Depositional Basin (Type L) - Glacial Alluvial Fan, sheet sand
- 51.1B. Depositional Basin (Type LI) - Glacial Alluvial Fan, sheet sand
- 52.1B. Depositional Basin (Type LII) - Glacial Alluvial Fan, sheet sand
- 53.1B. Depositional Basin (Type LIII) - Glacial Alluvial Fan, sheet sand
- 54.1B. Depositional Basin (Type LIV) - Glacial Alluvial Fan, sheet sand
- 55.1B. Depositional Basin (Type LV) - Glacial Alluvial Fan, sheet sand
- 56.1B. Depositional Basin (Type LVI) - Glacial Alluvial Fan, sheet sand
- 57.1B. Depositional Basin (Type LVII) - Glacial Alluvial Fan, sheet sand
- 58.1B. Depositional Basin (Type LVIII) - Glacial Alluvial Fan, sheet sand
- 59.1B. Depositional Basin (Type LIX) - Glacial Alluvial Fan, sheet sand
- 60.1B. Depositional Basin (Type LX) - Glacial Alluvial Fan, sheet sand
- 61.1B. Depositional Basin (Type LXI) - Glacial Alluvial Fan, sheet sand
- 62.1B. Depositional Basin (Type LXII) - Glacial Alluvial Fan, sheet sand
- 63.1B. Depositional Basin (Type LXIII) - Glacial Alluvial Fan, sheet sand
- 64.1B. Depositional Basin (Type LXIV) - Glacial Alluvial Fan, sheet sand
- 65.1B. Depositional Basin (Type LXV) - Glacial Alluvial Fan, sheet sand
- 66.1B. Depositional Basin (Type LXVI) - Glacial Alluvial Fan, sheet sand
- 67.1B. Depositional Basin (Type LXVII) - Glacial Alluvial Fan, sheet sand
- 68.1B. Depositional Basin (Type LXVIII) - Glacial Alluvial Fan, sheet sand
- 69.1B. Depositional Basin (Type LXIX) - Glacial Alluvial Fan, sheet sand
- 70.1B. Depositional Basin (Type LXX) - Glacial Alluvial Fan, sheet sand
- 71.1B. Depositional Basin (Type LXXI) - Glacial Alluvial Fan, sheet sand
- 72.1B. Depositional Basin (Type LXXII) - Glacial Alluvial Fan, sheet sand
- 73.1B. Depositional Basin (Type LXXIII) - Glacial Alluvial Fan, sheet sand
- 74.1B. Depositional Basin (Type LXXIV) - Glacial Alluvial Fan, sheet sand
- 75.1B. Depositional Basin (Type LXXV) - Glacial Alluvial Fan, sheet sand
- 76.1B. Depositional Basin (Type LXXVI) - Glacial Alluvial Fan, sheet sand
- 77.1B. Depositional Basin (Type LXXVII) - Glacial Alluvial Fan, sheet sand
- 78.1B. Depositional Basin (Type LXXVIII) - Glacial Alluvial Fan, sheet sand
- 79.1B. Depositional Basin (Type LXXIX) - Glacial Alluvial Fan, sheet sand
- 80.1B. Depositional Basin (Type LXXX) - Glacial Alluvial Fan, sheet sand
- 81.1B. Depositional Basin (Type LXXXI) - Glacial Alluvial Fan, sheet sand
- 82.1B. Depositional Basin (Type LXXXII) - Glacial Alluvial Fan, sheet sand
- 83.1B. Depositional Basin (Type LXXXIII) - Glacial Alluvial Fan, sheet sand
- 84.1B. Depositional Basin (Type LXXXIV) - Glacial Alluvial Fan, sheet sand
- 85.1B. Depositional Basin (Type LXXXV) - Glacial Alluvial Fan, sheet sand
- 86.1B. Depositional Basin (Type LXXXVI) - Glacial Alluvial Fan, sheet sand
- 87.1B. Depositional Basin (Type LXXXVII) - Glacial Alluvial Fan, sheet sand
- 88.1B. Depositional Basin (Type LXXXVIII) - Glacial Alluvial Fan, sheet sand
- 89.1B. Depositional Basin (Type LXXXIX) - Glacial Alluvial Fan, sheet sand
- 90.1B. Depositional Basin (Type LXXXX) - Glacial Alluvial Fan, sheet sand
- 91.1B. Depositional Basin (Type LXXXXI) - Glacial Alluvial Fan, sheet sand
- 92.1B. Depositional Basin (Type LXXXXII) - Glacial Alluvial Fan, sheet sand
- 93.1B. Depositional Basin (Type LXXXXIII) - Glacial Alluvial Fan, sheet sand
- 94.1B. Depositional Basin (Type LXXXXIV) - Glacial Alluvial Fan, sheet sand
- 95.1B. Depositional Basin (Type LXXXXV) - Glacial Alluvial Fan, sheet sand
- 96.1B. Depositional Basin (Type LXXXXVI) - Glacial Alluvial Fan, sheet sand
- 97.1B. Depositional Basin (Type LXXXXVII) - Glacial Alluvial Fan, sheet sand
- 98.1B. Depositional Basin (Type LXXXXVIII) - Glacial Alluvial Fan, sheet sand
- 99.1B. Depositional Basin (Type LXXXXIX) - Glacial Alluvial Fan, sheet sand
- 100.1B. Depositional Basin (Type LXXXXX) - Glacial Alluvial Fan, sheet sand

Classification

- 1.) *A. vadorum* (Type I) - Depositional Basin, silty sand
- 2.) *A. vadorum* (Type II) - Glacial Delta Plain, pebble gravel coarse sand
- 3.) *A. vadorum* (Type III) - Glacial Delta Plain, sheet sand
- 4.) *B. serrata* (Type I) - Glacial Alluvial Fan, boulder gravel concentration
- 5.) *B. serrata* (Type II) - Glacial Alluvial Fan, pebble gravel coarse sand
- 6.) *B. serrata* (Type III) - Glacial Alluvial Fan, sheet sand
- 7.) *J. falcata* - Moraine Shelf, boulder gravel concentration
- 8.) *Corophium* spp. - Moraine Shelf, pebble gravel coarse sand
- 9.) *P. remota* - Moraine Shelf, coarse sand with small dunes/sand waves
- 10.) *P. medusa* / *L. hebes* (Type I) - Glacial Alluvial Fan, coarse sand with small dunes
- 11.) *P. medusa* / *L. hebes* (Type II) - Inner Shelf Moraine, coarse sand sheets/waves/small dunes
- 12.) *Syllis* spp. / *P. medusa* - Glacial Alluvial Fan, sand waves
- Undefined

Classification

- 13.) A. agassizi - Glacial Lake Floor, sheet sand
- 14.) B. serrata (Type IV) - Hummocky Moraine, fine sand
- 15.) B. serrata / A. agassizi - PJ-BB Moraine, sheet sand, sheet sand with gravel, sand waves
- 16.) N. annulata - Glacial Lake Floor, coarse silt
- 17.) N. annulata / A. agassizi - Glacial Lake Floor, fine or coarse sand
- 18.) L. hebes - PJ-BB Moraine, boulder gravel concentration, cobble gravel pavement, coarse silt
- Undefined

Figure 1.7. Top-down habitat classification maps of the BI and FED study areas. Each map unit, as defined by depositional environment types, is classified according to the most abundant genus. ANOSIM revealed the macrofaunal assemblages are significantly different (global $R = 0.60$, $p = 0.001$). The two study areas have none of the 18 habitats in common. See Table 1.5 for further descriptions of habitats.

Dominant Genus

○ A. vadorum

○ B. serrata

● Caprella spp.

○ Corophium spp.

● Corophium spp. - Crenella spp.

● E. parma

○ Ericthonius spp.

● Glycera spp.

○ H. extunata

● J. falcata

● L. caeca - Protohaustorius sp.

● L. fragilis - Glycera spp.

○ L. hebes

● L. hebes - E. parma

○ L. hebes - P. remota

● L. hebes - P. medusa

○ M. edulis

● Oligochaeta sp. - P. gouldii

● Protohaustorius sp. - Astarte sp. - R. hudsoni

● P. remota

● P. remota - M. zonalis

● P. medusa

○ P. medusa - Syllis spp.

● Polygordius sp.

○ Polygordius sp. - P. remota

● P. neglecta

○ Protohaustorius sp.

○ Syllis spp.

Dominant Genus

○ A. agassizi	● L. pinguis - A. agassizi
● A. agassizi - N. annulata	● L. hebes
● B. serrata	● N. nigripes
● B. serrata - L. hebes	● N. annulata
○ B. serrata - N. annulata	● N. annulata - N. delphinodonta
	● N. delphinodonta

Figure 1.8. The dominant genus found at each bottom sample site overlaid on the top-down classification maps for BI and FED. This data layer was added so that the unity and variability among samples within each map unit could be assessed.

□ 100 m pixel size

Classification

- A. vadorum (Type I) - % coarse sand, % medium sand, mean depth
- A. vadorum (Type II) - % coarse sand, % medium sand, mean depth
- A. vadorum (Type III) - % coarse sand, % medium sand, mean depth, surface roughness
- A. vadorum (Type IV) - % coarse sand, std dev of grain size, mean depth, max backscatter intensity, surface roughness, % medium sand
- A. vadorum / B. serrata - % coarse sand, std dev of grain size, mean depth, max backscatter intensity, surface roughness
- B. serrata (Type I) - % coarse sand, % medium sand, mean depth, surface roughness
- B. serrata (Type II) - % coarse sand, std dev of grain size, mean depth
- B. serrata (Type III) - % coarse sand, % medium sand, mean depth
- B. serrata (Type IV) - % coarse sand, std dev of grain size, mean depth, max backscatter intensity
- J. falcata - % coarse sand, std dev of grain size, mean depth, % medium sand
- P. medusa - % coarse sand, std dev of grain size, mean depth, max backscatter intensity, surface roughness, % medium sand
- P. neglecta - % coarse sand, std dev of grain size, mean depth, max backscatter intensity, surface roughness, % medium sand
- Glycera spp. - % coarse sand, std dev of grain size, mean depth, max backscatter intensity, surface roughness, % medium sand
- H. extunata - % coarse sand, std dev of grain size, mean depth, % medium sand
- L. hebes - % coarse sand, % medium sand
- Syllis spp. - % coarse sand, std dev of grain size, mean depth, max backscatter intensity, surface roughness, % medium sand
- P. gouldii / Oligochaeta sp. - % coarse sand, std dev of grain size, mean depth, max backscatter intensity, surface roughness
- Protochaetorhynchus sp. / Astarte spp. / R. hudsoni - % coarse sand, std dev of grain size, mean depth

Figure 1.10. Bottom-up habitat classification maps of the BI and FED study areas. Classes follow the LINKTREE output and are labeled according to dominant species/genus and their relevant abiotic variables. Refer to Table 1.6 for the list of quantitative thresholds and Table 1.7 for further description of each class. Habitat classes contain distinct macrofaunal assemblages (ANOSIM global $R = 0.83$, $p = 0.001$). A total of 22 benthic habitat classes were identified from the analyses. BI and FED share five classes and there are 13 classes present only within BI and nine only within FED. Note classes are mapped at 100 m pixel resolution.

Table 1.1. List of abiotic variables used in the bottom-up mapping approach. The variables marked with * exhibit a high correlation ($r > 0.85$) with another variable, as revealed through a draftsman plot, and were removed for the second BIOENV procedure.

Source	Resolution	Variable
Backscatter	100 m, Continuous-coverage	Mean
		Maximum
		Minimum
		Standard Deviation
Bathymetry	100 m, Continuous-coverage	Mean (m)
		Maximum (m)*
		Minimum (m)*
		Standard Deviation
		Slope (degrees)
Grain Size	78 stations, Point-coverage	% Clay
		% Fine Silt*
		% Coarse Silt*
		% Very Fine Sand
		% Fine Sand*
		% Medium Sand
		% Coarse Sand
		% Very Coarse Sand
		Standard Deviation
NOS soundings	1.9 million soundings, Point to Continuous coverage	Surface Roughness (Std Dev of Slope within 1000 m Radius)

Table 1.2. Grain size percent composition and ranges from analysis of the bottom samples taken within BI and FED. BI is dominated by medium and coarse-grained sands, while fine and medium sands dominate FED. Note the bottom sample stations within BI and FED exhibit similar ranges for most of the sediment variables.

Sediment Variables	Percent Composition		
	BI	Fed	BI and Fed
% Clay	1.3	5.3	2.8
% Fine Silt	3.0	10.4	5.8
% Coarse Silt	0.8	3.3	1.8
% Very Fine Sand	1.5	14.3	6.4
% Fine Sand	10.2	37.8	20.8
% Medium Sand	33.7	23.1	29.7
% Coarse Sand	36.2	5.4	24.3
% Very Coarse Sand	13.3	0.4	8.3
Standard Deviation of Grain Size (um)	--	--	--
Sediment Variables	Range		
	BI	Fed	BI and Fed
% Clay	0 - 10.6	0 - 19.2	0 - 19.2
% Fine Silt	0 - 33.0	0 - 34.1	0 - 34.1
% Coarse Silt	0 - 7.4	0 - 15.0	0 - 15.0
% Very Fine Sand	0 - 9.9	0 - 34.3	0 - 34.3
% Fine Sand	0 - 57.8	0.5 - 63.1	0 - 63.1
% Medium Sand	0.7 - 76.3	0.4 - 67.8	0.4 - 76.3
% Coarse Sand	0.3 - 69.6	0 - 54.5	0 - 69.6
% Very Coarse Sand	0 - 62.7	0 - 12.8	0 - 62.7
Standard Deviation of Grain Size (um)	90.6 - 459.8	61.4 - 316.2	61.4 - 459.8

Table 1.3. List of species found within BI and FED study sites. The functional group is also given to provide a description of the ecological role of each species.

Phylum	Common Group	Species/Genus	Functional Group
Annelida	Polychaete	<i>Ampharete</i> spp.	Tube extends from sediment; selective surface feeder
Annelida	Polychaete	<i>Aricidea catherinae</i>	Tube coils within sediment; deposit feeder
Annelida	Polychaete	<i>Brania</i> sp.	Small on sponges, hydroids, etc.; carnivorous
Annelida	Polychaete	<i>Capitella capitata</i>	Near-surface burrowing; non-selective deposit feeder
Annelida	Polychaete (bamboo worm)	<i>Clymenella</i> spp.	Tube-building; head-down deposit feeder
Annelida	Polychaete	<i>Driloneries (longa, magna)</i>	Free burrowing; predaceous
Annelida	Polychaete	<i>Eumidea</i> sp.	Motile on sediment, shells, colonial tunicates, etc.; carnivorous
Annelida	Polychaete	<i>Exogone hebes</i>	Small, on sponges, hydroids, etc.; carnivorous
Annelida	Polychaete (bloodworm)	<i>Glycera (capitata, dibranchiata)</i>	Free burrowing; scavenger/ predaceous
Annelida	Polychaete	<i>Goniada maculata</i>	Free burrowing; predaceous
Annelida	Polychaete	<i>Goniadella gracilis</i>	Free burrowing; predaceous
Annelida	Polychaete (scale worm)	<i>Harmothoe extunata</i>	Motile on rocks, algae holdfasts, mussels, etc.
Annelida	Polychaete	<i>Leitoscoloplos (fragilis, robustus)</i>	Burrowing; head-down deposit feeder
Annelida	Polychaete	<i>Lumbrineria fragilis</i>	Burrowing; primarily carnivorous
Annelida	Polychaete	<i>Lumbrineria hebes</i>	Burrowing; primarily carnivorous

Annelida	Polychaete (bamboo worm)	<i>Macroclymene zonalis</i>	Tube-building; head-down deposit feeder
Annelida	Polychaete	<i>Marphysa bellii</i>	Tubes within stones, holdfasts, etc.; predaceous
Annelida	Polychaete	<i>Neanthes arenocedonta</i>	Weak tubes in sand, on rocks; carnivorous and herbivorous
Annelida	Polychaete	<i>Nephtys incisa</i>	Surface burrowing; selective deposit feeder?
Annelida	Polychaete	<i>Ninoe nigripes</i>	Burrowing; primarily carnivorous
Annelida	Oligochaete	<i>Oligochaeta sp.</i>	Small, burrowing; selective deposit feeder
Annelida	Polychaete	<i>Owenia (fusiformis, oculata)</i>	Tube extends from sediment; selective surface deposit feeder
Annelida	Polychaete (cage worm)	<i>Pherusa affinis</i>	Surface burrowing; selective deposit feeder
Annelida	Polychaete	<i>Pisone remota</i>	Small burrowing; selective deposit feeder?
Annelida	Polychaete	<i>Polycirrus medusa</i>	Soft tube; selective deposit feeder
Annelida	Polychaete	<i>Polygordius jouinae</i>	Surface burrowing; selective deposit feeder
Annelida	Polychaete (feather duster)	<i>Potamilla neglecta</i>	Tube-building; filter feeder
Annelida	Polychaete	<i>Sabellaria sp</i>	Tube-building; filter feeder
Annelida	Polychaete	<i>Scalibregma inflatum</i>	Burrowing; deposit feeder
Annelida	Polychaete	<i>Schistomeringos sp</i>	Small, motile/burrow/temporary tubes; carnivorous
Annelida	Polychaete (scale worm)	<i>Sthenelais</i>	Surface burrowing; predaceous?
Annelida	Polychaete	<i>Syllis spp</i>	Mobile; carnivorous
Annelida	Polychaete	<i>Terebellides stroemi</i>	Soft tube; selective deposit feeder

Annelida	Polychaete	<i>Tharyx (acutus, annulosus, maraoni)</i>	Surface burrowing; selective deposit feeder
Arthropoda (Crustacea)	Amphipod	<i>Ampelisca agassizi</i>	Tube-building
Arthropoda (Crustacea)	Amphipod	<i>Ampelisca vadorum</i>	Tube-building
Arthropoda (Crustacea)	Amphipod	<i>Byblis serrata</i>	Tube-building
Arthropoda (Crustacea)	Amphipod (skeleton shrimp)	<i>Caprella (equilibra, penantis)</i>	Mobile
Arthropoda (Crustacea)	Isopod	<i>Cirolana polita</i>	Mobile
Arthropoda (Crustacea)	Amphipod	<i>Corophium spp</i>	Tube-building
Arthropoda (Crustacea)	Cumacea (hooded shrimp)	<i>Diastylis (quadrspinosa, sculpta)</i>	Mobile
Arthropoda (Crustacea)	Isopod	<i>Edotea triloba</i>	Mobile
Arthropoda (Crustacea)	Isopod	<i>Erichsonella filiformis</i>	Mobile
Arthropoda (Crustacea)	Amphipod	<i>Erichthonius (difformis, rubricornis)</i>	Tube-building
Arthropoda (Crustacea)	Cumacea (hooded shrimp)	<i>Eudorella truncatula</i>	Mobile
Arthropoda (Crustacea)	Isopod	<i>Ianiropsis</i>	Mobile
Arthropoda (Crustacea)	Isopod	<i>Idotea (baltica, phosphorea)</i>	Mobile
Arthropoda (Crustacea)	Amphipod	<i>Jassa falcata</i>	Tube-building
Arthropoda (Crustacea)	Amphipod	<i>Leptocheirus pinguis</i>	Tube-building
Arthropoda (Crustacea)	Amphipod	<i>Lysianopsis alba</i>	Mobile
Arthropoda (Crustacea)	Amphipod	<i>Melita dentata</i>	Mobile
Arthropoda (Crustacea)	Amphipod	<i>Microdeutopus spp.</i>	Tube-building
Arthropoda (Crustacea)	Amphipod	<i>Orchomenella pinguis</i>	Mobile
Arthropoda (Crustacea)	Crustacean (hermit crab)	<i>Pagurus (acadianus, longicarpus)</i>	Mobile

Arthropoda (Crustacea)	Amphipod	<i>Phoxocephalus holbolli</i>	Burrowing
Arthropoda (Crustacea)	Amphipod	<i>Pleusymtes glaber</i>	Mobile
Arthropoda (Crustacea)	Amphipod	<i>Protohaustorius sp</i>	Surface burrowing
Arthropoda (Crustacea)	Amphipod	<i>Rhepoxynius hudsoni</i>	Burrowing
Arthropoda (Crustacea)	Amphipod	<i>Unciola irrorata</i>	Tube-building
Chordata	Tunicate	<i>Bostrichobranchus pilularis</i>	Sessile
Chordata	Tunicate	<i>Tunicata</i>	Sessile
Cnidaria	Cnidarian	<i>Astrangia danae</i>	Coral garden
Echinoderm ata	Echinoderm (common sand dollar)	<i>Echinarachnius parma</i>	Surface
Echinoderm ata	Echinoderm (brittle star)	<i>Ophiuroidea sp.</i>	Surface
Mollusca	Gastropod	<i>Alvania (onoba, pelagica)</i>	Mobile
Mollusca	Gastropod	<i>Anachis lafresnyi</i>	Clam bed
Mollusca	Bivalve (ocean quahog)	<i>Arctica islandica</i>	Clam bed
Mollusca	Bivalve	<i>Astarte (castanea, crenata, undata)</i>	Clam bed
Mollusca	Bivalve (cockle)	<i>Cerastoderma pinnulatum</i>	Clam bed
Mollusca	Mollusc	<i>Crassenella lunatea</i>	Clam bed
Mollusca	Bivalve	<i>Crenella (decussata, glandula)</i>	Mussel bed
Mollusca	Gastropod (slipper snail)	<i>Crepidula sp.</i>	Sessile
Mollusca	Bivalve	<i>Cyclocardia borealis</i>	Clam bed
Mollusca	Gastropod	<i>gastropod spp</i>	Mobile
Mollusca	Gastropod (nudibranch)	<i>Leptognatha caeca</i>	Mobile

Mollusca	Gastropod	<i>Metrella</i> (<i>lunatia, rosacea</i>)	Clam bed
Mollusca	Bivalve (blue mussel)	<i>Mytilus edulis</i>	Mussel bed
Mollusca	Bivalve	<i>Nucula annulata</i>	Clam bed; deposit feeder
Mollusca	Bivalve	<i>Nucula</i> <i>delphinodonta</i>	Clam bed; deposit feeder
Mollusca	Bivalve	<i>Pandora gouldii</i>	Clam bed
Mollusca	Bivalve	<i>Periploma</i> <i>papyratium</i>	Clam bed
Mollusca	Bivalve	<i>Pitar morrhuana</i>	Clam bed
Mollusca	Bivalve	<i>Yoldia sapotilla</i>	Clam bed
Nemertea	Nemertea (ribbon worm)	<i>Cerebratulus lacteus</i>	Surface
Nemertea	Nemertea (ribbon worm)	<i>nemertean spp</i>	Surface
Phoronida	Phoronida	<i>Phoronis mulleri</i>	Tube-building

Annellida	<i>Polygordius</i> sp	Small surface-burrowing polychaete	41.0
Annellida	<i>S. inflatum</i>	Small surface-burrowing polychaete	41.0

Phylum	Species/Genus	Description	% Contribution
Annellida	<i>L. helos</i>	Small surface-burrowing polychaete	66.7
Nemertea	<i>Nemertean spp</i>	Small surface-burrowing nemertean	62.5
Annellida	<i>Clyceta</i> spp.	Large deep-burrowing polychaete	60.4
Annellida	<i>Polygordius</i> sp	Small surface-burrowing polychaete	58.3
Annellida	<i>A. californica</i>	Small surface-burrowing polychaete	52.1
Mollusca	<i>A. edulis</i> spp	Clam bed	50.0
Annellida	<i>P. mulleri</i>	Small surface-burrowing polychaete	50.0
Annellida	<i>Y. edulis</i>	Small surface-burrowing polychaete	50.0
Mollusca	<i>Granella</i> spp	Mussel bed	45.3

Table 1.4. a.) The top ten most spatially extensive genera, as defined by the percentage of the bottom sample stations the genus is found within. b.) The top ten most abundant genera (counts of individuals), determined by the percent to which the genus contributes to the total number of individuals over all samples.

a. 10 Most Spatially Abundant Genera (% of stations found within)

BI and FED Combined			
Phylum	Species/Genus	Description	% Contribution
Annelida	<i>L. hebes</i>	Small surface-burrowing polychaete	69.2
Arthropoda	<i>U. irrorata</i>	Small surface-burrowing crustacean	56.4
Mollusca	<i>Astarte spp.</i>	Clam bed	52.6
Annelida	<i>Glycera spp.</i>	Large deep-burrowing polychaete	50.0
Mollusca	<i>Crenella spp.</i>	Mussel bed	48.7
Arthropoda	<i>B. serrata</i>	Tube-building amphipod crustacean	42.3
Mollusca	<i>N. annulata</i>	Deposit feeding	42.3
Arthropoda	<i>L. pinguis</i>	Tube-building amphipod crustacean	41.0
Annelida	<i>Polygordius sp</i>	Small surface-burrowing polychaete	41.0
Annelida	<i>S. inflatum</i>	Small surface-burrowing polychaete	41.0

BI			
Phylum	Species/Genus	Description	% Contribution
Annelida	<i>L. hebes</i>	Small surface-burrowing polychaete	66.7
Nemertea	<i>Nemertean spp.</i>	Small surface-burrowing nemertean	62.5
Annelida	<i>Glycera spp.</i>	Large deep-burrowing polychaete	60.4
Annelida	<i>Polygordius sp.</i>	Small surface-burrowing polychaete	58.3
Annelida	<i>A. catherinae</i>	Small surface-burrowing polychaete	52.1
Mollusca	<i>Astarte spp.</i>	Clam bed	50.0
Annelida	<i>P. remota</i>	Small surface-burrowing polychaete	50.0
Arthropoda	<i>U. irrorata</i>	Small surface-burrowing crustacean	50.0
Mollusca	<i>Crenella spp.</i>	Mussel bed	45.8

Echinodermata	<i>E. parma</i>	Sand dollar	45.8
Annelida	<i>Syllis</i>	Mobile polychaete	45.8

FED			
Phylum	Species/Genus	Description	% Contribution
Mollusca	<i>N. delphinodonta</i>	Deposit feeding	93.3
Arthropoda	<i>A. agassizi</i>	Tube-building amphipod crustacean	86.7
Arthropoda	<i>E. truncatula</i>	Mobile crustacean	86.7
Annelida	<i>N. nigripes</i>	Small surface-burrowing polychaete	86.7
Mollusca	<i>N. annulata</i>	Deposit feeding	86.7
Arthropoda	<i>Diastylis spp.</i>	Mobile crustacean	80.0
Arthropoda	<i>L. pinguis</i>	Tube-building amphipod crustacean	73.3
Annelida	<i>L. hebes</i>	Small surface-burrowing polychaete	73.3
Mollusca	<i>P. papyratium</i>	Clam bed	73.3
Mollusca	<i>A. islandica</i>	Clam bed	66.7
Annelida	<i>S. inflatum</i>	Small surface-burrowing polychaete	66.7
Arthropoda	<i>U. irrorata</i>	Small surface-burrowing crustacean	66.7

b. 10 Most Abundant Genera (% of total individuals)

BI and FED Combined			
Phylum	Species/Genus	Description	% Contribution
Arthropoda	<i>A. vadorum</i>	Tube-building amphipod crustacean	18.6
Arthropoda	<i>B. serrata</i>	Tube-building amphipod crustacean	12.6
Mollusca	<i>N. annulata</i>	Deposit feeding	8.3
Arthropoda	<i>A. agassizi</i>	Tube-building amphipod crustacean	7.0
Arthropoda	<i>L. pinguis</i>	Tube-building amphipod crustacean	3.4
Annelida	<i>L. hebes</i>	Small surface-burrowing polychaete	3.0
Annelida	<i>P. medusa</i>	Small surface-burrowing polychaete	2.6

Mollusca	<i>N. delphinodonta</i>	Deposit feeding	2.6
Arthropoda	<i>J. falcata</i>	Tube-building amphipod crustacean	2.0
Annelida	<i>N. nigripes</i>	Small surface-burrowing polychaete	1.8

BI			
Phylum	Species/Genus	Description	% Contribution
Arthropoda	<i>A. vadorum</i>	Tube-building amphipod crustacean	30.0
Arthropoda	<i>B. serrata</i>	Tube-building amphipod crustacean	14.8
Annelida	<i>P. medusa</i>	Small surface-burrowing polychaete	4.0
Arthropoda	<i>J. falcata</i>	Tube-building amphipod crustacean	3.2
Annelida	<i>L. hebes</i>	Small surface-burrowing polychaete	3.2
Arthropoda	<i>L. pinguis</i>	Tube-building amphipod crustacean	3.0
Arthropoda	<i>Corophium spp.</i>	Tube-building amphipod crustacean	2.3
Annelida	<i>Syllis spp.</i>	Mobile polychaete	2.2
Mollusca	<i>Metrella spp.</i>	Clam bed	2.1
Annelida	<i>P. remota</i>	Small surface-burrowing polychaete	2.1

FED			
Phylum	Species/Genus	Description	% Contribution
Mollusca	<i>N. annulata</i>	Deposit feeding	18.6
Arthropoda	<i>A. agassizi</i>	Tube-building amphipod crustacean	12.6
Arthropoda	<i>B. serrata</i>	Tube-building amphipod crustacean	8.3
Mollusca	<i>N. delphinodonta</i>	Deposit feeding	7.0
Annelida	<i>N. nigripes</i>	Small surface-burrowing polychaete	3.4
Arthropoda	<i>L. pinguis</i>	Tube-building amphipod crustacean	3.0
Mollusca	<i>P. papyratium</i>	Clam bed	2.6
Annelida	<i>L. hebes</i>	Small surface-burrowing polychaete	2.6
Arthropoda	<i>E. truncatula</i>	Mobile crustacean	2.0
Mollusca	<i>Alvania spp.</i>	Mobile gastropod	1.8

Table 1.5. Description of geologic depositional environments, which serve as the map units for the top-down classification. The location, size, and the number of bottom samples taken within each environment is given, along with the most abundant genus. The average within-environment similarity and the genus most responsible for the within-group similarity, both identified by the SIMPER procedure, are also provided. It is interesting to note that for some environments, the same genus is the most abundant and is the most responsible for the within-group similarity.

Habitat	Geoform-Subform	Avg. Dominant Genus/Species	Avg. Similarity (%)	Genus/Species Contributing Most to Similarity	Study Site	Area (sq km)	# Bottom Samples
1	DB sisa	<i>A. vadorum</i>	46.46	<i>A. vadorum</i> (23.25%)	BI	7.3	4
2	GDP pgcs	<i>A. vadorum</i>	34.31	<i>L. hebes</i> (14.80%); <i>Astarte spp.</i> (14.19%)	BI	6.9	4
3	GDP ss	<i>A. vadorum</i>	39.05	<i>Glycera spp.</i> (16.12%)	BI	4.2	2
4	GAF bgc	<i>B. serrata</i>	6.16	<i>Nemertean spp.</i> (100%)	BI	5.0	2
5	GAF pgcs	<i>B. serrata</i>	31.78	<i>B. serrata</i> (27.39%)	BI	13.2	5
6	GAF ss	<i>B. serrata</i>	23.33	<i>L. fragilis</i> (23.91%)	BI	10.3	2
7	MS bgc	<i>J. falcata</i>	24.56	<i>Polygordius sp.</i> (15.25%)	BI	30.0	5
8	MS pgcs	<i>Corophium sps</i>	12.02	<i>P. remota</i> (47.74%)	BI	7.7	2
9	MS csd, sw	<i>P. remota</i>	20.36	<i>L. hebes</i> , <i>Syllis spp.</i> , <i>Polygordis sp.</i> , <i>E. parma</i> (25% each)	BI	6.0	2
10	GAF csd	<i>P. medusa</i> – <i>L. hebes</i>	37.45	<i>L. hebes</i> (14.48%)	BI	29.4	14
11	ISM csd, ss, sw	<i>L. hebes</i> – <i>P. medusa</i>	33.47	<i>Protohaustorius sp.</i> (29.30%)	BI	7.3	4

12	GAF sw	<i>Syllis – P. medusa</i>	12.85	<i>Glycera spp.</i> , <i>A. catherinae</i> , <i>Crassenella</i> sp. (33.33% each)	BI	4.5	2
13	GLF ss	<i>A. agassizi</i>	58.25	<i>N. delphino-</i> <i>donta</i> (7.93%), <i>N. annulata</i> (6.97%)	FED	9.1	4
14	HM fs	<i>B. serrata</i>	na	na	FED	3.3	1
15	PBM ss, ssg, sw	<i>B. serrata – A. agassizi</i>	59.44	<i>N. nigripes</i> (8.51%), <i>N. delphino-</i> <i>donta</i> (8.25%), <i>N. annulata</i> (7.76%)	FED	2.8	4
16	GLF sic	<i>N. annulata</i>	53.47	<i>N. annulata</i> (16.83%)	FED	60.5	7
17	GLF fs cs	<i>N. annulata</i> – <i>A. agassizi</i>	56.11	<i>A. agassizi</i> (8.55%), <i>N. delphino-</i> <i>donta</i> (7.81%)	FED	41.6	10
18	PBM bgc, cgp, sic	<i>L. hebes</i>	31.84	<i>Astarte spp.</i> (17.07%)	FED	12.3	4

Table 1.6. LINKTREE thresholds. Reported here is the final threshold of each split; refer to Figure 1.9 to follow the series of thresholds responsible for each split. The branch to the left side of the LINKTREE is listed first and the branch to the right is listed second in brackets. For example, for split A, bottom samples on the left side of the split have a threshold of < 24.7 % coarse sand and bottom samples on the right side of the split have a threshold of > 26.9 % coarse sand. Note that many of the thresholds are defined by narrow ranges of the abiotic variables.

Split	Threshold	Range	R value
A	% coarse sand	< 24.7 (> 26.9)	0.54
B	% medium sand	> 65.6 (< 57.6)	0.79
C	mean depth (m)	> 39.8 (< 32.8)	0.71
D	% medium sand	< 47.1 (> 49.5)	0.67
E	% coarse sand	> 10.8 (< 7.7)	0.81
F	surface roughness	> 0.329 (< 0.269)	0.52
G	% medium sand	< 24.7 (> 28.0)	0.59
H	standard deviation of sediment (um)	< 176.6 (> 194.6)	0.70
I	surface roughness	< 0.171 (> 0.201)	0.67
J	surface roughness	< 0.120 (> 0.124)	0.60
K	standard deviation of sediment (um)	< 196.0 (> 207.6)	0.70
L	mean depth (m)	> 26.8 (< 23.8)	0.50
M	mean depth (m)	< 19.0 (> 19.7)	0.50
N	% medium sand	< 14.8 (> 27.1)	0.50
O	max backscatter intensity	> 254.8 (< 247.9)	0.40
P	surface roughness	< 0.580 (> 0.846)	0.40
Q	mean depth (m)	> 37.4 (< 34.8)	0.42
R	% medium sand	< 46.5 (> 48.4)	0.47
S	surface roughness	< 0.496 (> 0.509)	0.36
T	% coarse sand	> 41.7 (< 39.9)	0.49
U	% medium sand	> 15.8 (< 13.7)	0.56

Table 1.7. Description of LINKTREE classes, which serve as the habitat classes for the bottom-up mapping approach. For each class, the stations comprising the class and the most abundant genus are listed. The overall within-class similarity and the genus, both identified by the SIMPER procedure, are also provided. Note some classes exhibit the same genus as being the most abundant and the most responsible for the within-class similarity.

LINK-TREE Class	Study Area	# Bottom Samples	Average Dominant Species/ Genus	Average Similarity	Genus/Species Contributing Most to Similarity
1	BI	3	<i>L.hebes</i>	21.11%	<i>Nemertean</i> (38.15%)
2	BI	3	<i>A. vadorum</i>	41.72%	<i>A. vadorum</i> (25.95%)
3	BI	3	<i>B. serrata</i>	51.70%	<i>B. serrata</i> (45.75%)
4	BI, FED	3	<i>A. vadorum</i>	30.54%	<i>L. hebes</i> (25.86%)
5	BI, FED	3	<i>A. vadorum</i>	36.44%	<i>N. annulata</i> (18.61%)
6	FED	2	<i>N. nigripes</i>	24.69%	<i>E. truncatula</i> (25.25%)
7	FED	3	<i>N. annulata</i>	52.45%	<i>N. annulata</i> (16.25%)
8	FED	13	<i>A. agassizi</i> – <i>N. annulata</i>	64.76%	<i>N. annulata</i> (9.73%) – <i>A. agassizi</i> (8.82%)
9	FED	5	<i>B. serrata</i> – <i>N. annulata</i>	60.58%	<i>B. serrata</i> (13.25%)
10	BI, FED	2	<i>B. serrata</i>	31.33%	<i>B. serrata</i> (24.20%)
11	BI, FED	2	<i>B. serrata</i>	5.80%	<i>L. fragilis</i> (100%)
12	BI	2	<i>Protohaustorius</i> sp. – <i>Astarte</i> spp. – <i>R. hudsoni</i>	58.25%	<i>Protohaustorius</i> sp. (30.49%)
13	BI	2	<i>H. extunata</i>	24.66%	<i>Polygordius</i> sp. (18.95%)
14	BI	2	<i>J. falcata</i>	45.41%	<i>J. falcata</i> (18.31%) – <i>Metrella</i> spp. (17.82%)
15	BI	2	<i>B. serrata</i>	32.32%	<i>Glycera</i> spp. – <i>L. pinguis</i> (29.21% each)
16	BI	2	<i>P. gouldii</i> – <i>Oligochaeta</i> sp.	22.37%	<i>L. hebes</i> – <i>Syllis</i> spp. – <i>Polygordius</i> sp. – <i>E. parma</i> (25.00% each)

17	BI, FED	2	<i>A. vadorum</i> – <i>B. serrata</i>	47.04%	<i>U. irrorata</i> (12.42%)
18	BI	2	<i>Glycera</i> spp.	6.44%	<i>Nemertean</i> spp. (100%)
19	BI	3	<i>A. vadorum</i>	29.72%	<i>M. bellii</i> (16.56%) – <i>L. hebes</i> (16.29%)
20	BI	2	<i>P. neglecta</i>	34.26%	<i>L. hebes</i> (15.74%)
21	BI	14	<i>P. medusa</i>	48.86%	<i>L. hebes</i> (11.22%) – <i>P. remota</i> (10.30%)
22	BI	3	<i>Syllis</i> spp.	28.28%	<i>Polygordius</i> sp. (30.04%)

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Development of an index of benthic habitat value to assist in siting for offshore wind farms

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2.1. Abstract

Presenting benthic habitat maps that effectively convey information relevant to a broad range of users (scientists, managers, public) can be challenging. Commonly, maps characterize habitats according dominant species or general community type, which does not always offer practical information to managers and can inadequately represent important biological and environmental habitat characteristics and relationships. To address this challenge, benthic habitats were classified according to biological and environmental metrics (abundance, biodiversity, value as a food source, presence of habitat-forming fauna, and habitat stability) considered important to the existence of healthy, productive benthic habitats. The metrics were then weighted and totaled to develop an index of benthic habitat value. The index is designed to indicate valuable benthic habitats, or “hot spots,” and scores of the individual metrics, allowing habitats to be evaluated based on metrics relevant to the user. Furthermore, indices can be used to discern biotic-abiotic relationships between and among habitats and index metrics.

Two offshore locations within Rhode Island waters, selected as potential wind farm locations, serve as the basis for developing this methodology. The indices were able to identify habitats that scored considerably higher than the others. In general, though, the indices did not indicate specific biological or environmental characteristics that lend to high habitat value, which suggests management efforts need to consider all habitat types within the study areas, and cannot focus on certain habitat attributes. However, a correlation was found between tube-building species and species richness, suggesting tube mat structures lead to increased biodiversity. The indices also show

that habitats within the two study areas have different relationships with the index criteria, indicating macrofauna have their own associations to the environment within each study area. The proposed relationships between the index metrics and habitats will be evaluated within the two study areas in the near future.

The methodologies applied in this study can be extended to other locations and tailored to meet project objectives. The development of indices that signify habitat value will help bridge the communication gap between scientists and resource managers, and further the goal of science-based decision-making.

2.2. Introduction

Recent interest in development of offshore wind farms within Rhode Island waters has initiated a state-supported, collaborative study of marine resources known as the Rhode Island Ocean Special Area Management Plan (Ocean SAMP). The Ocean SAMP is a spatial planning tool to assist in making scientifically valid management decisions, including identifying appropriate locations for wind turbine installation (RI CRMC (a), 2010). A primary task of the Ocean SAMP was to map the distribution of benthic habitats and identify biological-environmental relationships. A thorough understanding of these habitats is essential to minimize the ecological and economical impacts of wind farm development. The mapping of benthic habitats presents characteristics of seafloor environments in a geospatial context (Auster et al., 2009).

A major challenge facing the benthic habitat mapping community is presenting data and maps in a way that can effectively convey relevant information to a broad

range of users (e.g. scientists, managers, non-profit organizations, general public). The information habitat maps should portray depends on the goal of the mapping project (Auster et al., 2009; Van Lancker and Foster-Smith, 2007), which itself can also be difficult to define. Establishing a clear mapping purpose is important, since the type and resolution of data collected will determine the maps that can be produced (Van Lancker and Foster-Smith, 2007). In addition, the lack of a standard benthic habitat classification approach has led to the development of numerous frameworks (e.g. Last et al., 2010; Guarinello et al., 2010; Auster et al., 2009; Madden et al., 2009; Valentine et al., 2005; Snelder et al., 2005; Connor et al., 2004; Greene et al., 1999). These schemes vary in their level of organization, detail, and geographic focus (Auster et al., 2009).

Despite variations in methodology, maps classifying benthic habitats commonly characterize map units according to a dominant or conspicuous species or general community type, occasionally accompanied by one or a few environmental attributes (e.g. sediment type, water depth) (Madden et al., 2009). Such maps do not always offer practical information to managers, as they do not necessarily identify which habitats are important (e.g. ecologically, commercially) or should be focused on (e.g. monitored, conserved, restored, exploited). Aside from offering limited information, these benthic habitat classification maps define habitat value based on dominant species, which can be misleading. For instance, the average dominant species may not adequately represent all sample sites within the map unit, particularly if one species has very high abundance at one or a few sample sites. This is the case for tube-building amphipods for study areas within Block Island and Rhode Island Sounds

(LaFrance, 2011). Furthermore, benthic habitat classifications are often based on geologically or acoustically derived map units, and because benthic fauna tend to span such boundaries – that is, biological communities are present in multiple habitats and a defined habitat exhibits a range of biological communities (Shumchenia and King, 2010; Eastwood et al., 2006; Hewitt et al., 2004; Freitas et al., 2003; Brown et al., 2002; Kostylev et al., 2001), more information than dominant species is often needed to evaluate and understand benthic habitat distribution and patterns.

The purpose of this study is to develop an alternative to the “dominant species” approach to benthic habitat mapping. Biological and environmental metrics viewed as important to a wide range of users were identified and calculated for each habitat, including abundance, species richness and other biodiversity metrics, habitat stability, habitat-forming species, and habitat value as a food resource for demersal fish. From these criteria, an index of benthic habitat value was produced to identify habitat “hot spots.” Methodology to construct an index, including weighting the metrics and summarizing the scores, was also developed. The final index presents the overall benthic habitat value and offers the scores of each metric for each habitat, allowing habitats to be evaluated according to individual metrics relevant to user needs.

Furthermore, indices can be used to discern biotic-abiotic relationships among habitats, have the potential to identify characteristics of benthic habitats that lend to high index scores, and can be further developed as additional data becomes available.

Two locations within the RI Ocean SAMP were selected to serve as the basis for developing this methodology. Previous studies (LaFrance et al., 2010) suggest that these areas differ in biotic and abiotic characteristics, providing a complex

environment to classify and compare. The results of this study will be a valuable contribution for making ecosystem-based management decisions for Rhode Island waters, and serve as a pre-development baseline.

Beyond specific interests in our study areas, this study presents a method for describing benthic habitats that can be applied to any study location and can be tailored to any project objective. In addition, presenting benthic habitats through an index will help bridge the communication gap between scientists and resource managers, and further the goal of science-based decision making.

2.3. Study area

The Rhode Island Ocean SAMP study area is 3,800 sq km, primarily encompassing Rhode Island Sound (RIS) and Block Island Sound (BIS). RIS and BIS are transitional waters connected to and influenced by the Atlantic Ocean and three estuaries (Narragansett Bay, Buzzards Bay, and Long Island Sound) (RI CRMC, 2010a). These waters are environmentally, economically, and culturally valuable human-use areas, including renewable energy development, fishing, boating, shipping routes, and tourism (RI CRMC, 2010a). As it was not possible to survey the entire Ocean SAMP area in detail, this study focuses on two sites chosen as the primary potential locations from turbine installation (Figure 2.1). Specifically, “BI” is a 138.5 sq km area located within Rhode Island state waters of BIS to the south of Block Island, and “FED” is a 176 sq km area within eastern RIS in waters under federal jurisdiction.

24 The benthic habitats of BI and FED differ in their abiotic and biotic characteristics (LaFrance et al., 2010). The BI study area exhibits a higher degree of physical heterogeneity than FED, having a wider range of environments, which tend to change over smaller spatial scales (> 2 sq km) (Figures 2.2 and 2.3). In addition, BIS is a more energetic area, subject to intense mixing due to storms, tidal circulation (Codiga and Ullman, 2010), and powerful current velocities (RI CRMC, 2010b), as evidenced by transitory geologic features such as large-scale sand waves, sheet sands, sand dunes, small-scale sand ripples, and the overall coarse sediment composition seen within the BI study area. Alternatively, FED, located in the heart of RIS, appears to be a more stable environment, exhibiting milder current velocities (RI CRMC, 2010b), an overall finer sediment composition, and fewer transitory geologic features. In addition, RIS exhibits thermal stratification during warmer months (Nixon et al., 2010).

These differences in physical environment likely influence benthic community structure and patterns within the two study areas. For example, the more stable environments of FED probably promote long-standing communities, whereas the environments that are transitory within BI are more challenging for organisms to withstand. Similarly, the summer-stratified waters of FED may adversely influence benthic communities in terms of food and nutrient supply, whereas the energetic environment of BI may offer favorable conditions. Benthic communities within BI may also be affected by nutrient input from coastal community activity (Block Island), which may lead to an increase in local production.

2.4. Previous benthic habitat classification maps

Benthic habitat classification maps have been developed for the BI and FED study areas using map units of depositional environment type (see section 2.5.1. for description) (Figure 2.3; LaFrance, 2011). While the habitats were found to contain significantly distinct macrofaunal assemblages (ANOSIM global $R = 0.60$; $p = 0.001$) and can be used to discern some biotic-abiotic relationships, they are limited in that the only habitat characteristics provided are dominant species and geologic depositional environment.

In general, the classification maps indicate there are a variety of physical environments with the two study sites, including areas of flat seabed dominated by dense tube-mats constructed from fine sediments, flat beds of sand or cobble and gravel, small-scale ripples composed of fine sands, large-scale mobile sand waves and sand sheets composed of coarse material, small dunes of coarse sand, and clearly defined glacial moraines, characterized by boulder fields within cobble – gravel beds (LaFrance et al., 2010). Water depths range from 10 m to 55 m in BI and 22 m to 49 m in FED (Figure 2.4), being shallowest over glacial moraines and near the coast (BI).

Biologically, tube-building amphipods dominated 11 and co-dominated 2 of the 18 habitat types and classify the majority of the BI and FED study areas. The remaining habitats within BI are dominated by polychaetes, one of which is tube-building (*Polycirrus medusa*). Within FED, tube-building amphipods and the surface-feeding bivalve, *Nucula annulata* about equally define the habitats, with the exception of one habitat, defined by the surface-burrowing polychaete, *L. hebes*.

2.5. The average similarity of the macrofaunal assemblage within each habitat ranges from 6.2% to 59.4%, with a mean of 34.2% (Table 2.1; LaFrance, 2011). Samples in habitat “*B. serrata*/*A. agassizi* – PJ-BB Moraine, sheet sand, sheet sand with gravel, sand waves” exhibited the most similarity (59.4%), followed by the “*A. agassizi* – Glacial Lake Floor, sand sheets” habitat (58.3%). A variety of species were the most responsible or shared responsibility for the within-map unit similarity and contributed between 7.9% and 100% to the similarity.

2.5. Methods

Benthic habitats were classified according to eight biological and environmental metrics. These metrics were then weighted and used to develop indices of benthic habitat value for the BI and FED study areas. The metrics incorporated are average abundance, four measures of biodiversity (species richness, Shannon-Weiner index, Pielou’s evenness, taxonomic diversity), value as fish food resource, presence of habitat-forming fauna, and habitat stability.

The methods section is structured around constructing the indices. As such, the first sub-section describes the habitat map units and how they were derived. The second sub-section focuses on the abundance and the biodiversity metrics – starting with the datasets needed, how the metrics are defined, and, lastly, how they were calculated. The next three sub-sections follow a similar format to describe the other three metrics. The last sub-section explains how the metrics were weighted and the indices developed.

2.5.1. Habitat map units

Geologic depositional environments were chosen as the map units for the index maps of BI and FED because full-coverage maps can be created and so the indices can be used in association with the benthic habitat maps developed previously.

Furthermore, the map units identify important biotic-abiotic relationships, as there are significantly distinct macrofaunal assemblages among depositional environments (ANOSIM global $R = 0.60$, $p = 0.001$; LaFrance, 2011).

Depositional environments were visually interpreted from high-resolution side-scan and bathymetry mosaics, sub-bottom seismic reflection profiles, surficial sediment samples, and underwater video (Oakley et al., 2010, in LaFrance et al., 2010). The environments have two components, form and facies. Form represents large-scale Quaternary geologic features (e.g. glacial alluvial fan, moraine shelf, glacial lake floor), having map units > 10 sq km. The smaller scale facies component (typically < 2.6 sq km) describes surficial sediment characteristics and seafloor roughness (e.g. sand waves, boulder gravel concentration, coarse silt) and represents modern (Late Holocene) processes.

2.5.2. Abundance and biodiversity

a. Macrofaunal survey

The macrofaunal survey (Figure 2.5) was designed to sample distinct geophysical bottom types, as identified through visual interpretation of the side-scan backscatter and bathymetry mosaics. A Smith-McIntyre grab sampler (0.05 m^2 area) was used to collect 48 samples within BI (average of 1 grab/3 sq km) over four occasions between

October 2008 and August 2009. An additional 30 samples were collected within FED, concentrated within the western two-thirds (117.8 sq km) of the study area (average of 1 grab/6 sq km), over two days in December 2009 and June 2010. Each depositional environment contains between two and 14 samples.

The remaining material from each bottom sample was sieved on 1 mm mesh and macrofauna were retained. All individuals were counted, identified to at least the genus level, and described according to functional group (e.g. surface burrower, tube-builder, mobile). The macrofauna abundances from BI and FED were pooled and only the genera contributing to 97% of the total abundance were included in further analyses. This eliminated genera with very low abundances ($< 0.09\%$ of the total abundance, equivalent to < 19 individuals) and resulted in the removal of 663 individuals from the study (of 21,862). PRIMER 6 was used to 4th root transform all abundances to reduce the influence of highly abundant genera and the Bray-Curtis similarity index was used to assess between station similarity.

b. Abundance metric

Abundance, defined as the number of individuals per bottom sample (0.05 m² area), was calculated as an average across all samples belonging to each map unit.

c. Biodiversity metrics

Biodiversity metrics are commonly considered to be indicators of ecosystem health (Morin, 1999) and stability (Mann, 2000). Thus, though the relationships between biodiversity and benthic ecosystems have not been evaluated for the BI and FED areas, it is anticipated increased biodiversity is associated with higher quality

habitats. Biodiversity as an accepted measure of habitat value is the justification for its inclusion in the index.

Three of the biodiversity metrics describe biological assemblage structure (species richness, Shannon-Wiener diversity index, Pielou's evenness). Species richness refers to the total number of species and is a commonly used first-order measure of biodiversity. However, richness does not express how the diversity is distributed (Morin, 1999). Therefore, the Shannon-Wiener diversity index is often calculated as well because it takes species richness and relative abundance into consideration (Morin, 1999). Pielou's evenness measures how equal the abundances of different species are (Clarke and Warwick 2001; Pielou, 1969).

The fourth biodiversity metric, taxonomic diversity, is used to complement assemblage structure metrics. Instead of focusing on the number of species, taxonomic diversity considers how related species are on a taxonomic level. Thus, samples with species belonging to the same taxa (genus, family, etc.) are considered to be less diverse than samples with species that belong to wider variety of taxa (Gascón et al., 2009; Clarke and Warwick, 2001). This metric was calculated from species to genus between every pair of individuals (Clarke and Gorely, 2006; Clarke and Warwick, 2001).

All of the biodiversity metrics were calculated using PRIMER 6 (for explanations of equations refer to Clarke and Gorley, 2006 and Clarke and Warwick, 2001). High values suggest high biodiversity and evenness, and thus, those habitats are considered to be the most valuable.

2.5.3. Value as fish food resource

a. Fish stomach content analysis

Stomach content analysis was conducted on a subset of demersal fish collected from 14 bottom trawl stations equally distributed between RIS and BIS in the Fall of 2009 (Figure 2.6; see Malik et al., 2010 for trawl details). The subset included the stomachs of five individuals per species per size class. In total, the contents of 651 stomachs from 21 species were examined. The prey found in the stomachs were identified to the lowest taxonomic level and abundance was recorded as percent composition of total content for each individual stomach. The data were aggregated by location; the BI (FED) dataset indicated the total percent composition of each prey group among all stomachs found within the BIS (RIS) stations.

b. Value as fish food resource metric

The value of each habitat as a demersal fish food resource was included in the index because benthic organisms, particularly amphipods, can be an important trophic link, as they are a valuable food source for demersal fish (Chapman, 2007; Mann, 2000), including within RIS and BIS (Malek et al., 2010; RI CRMC, 2010b). Food resource value was evaluated by comparing the prey identified in the stomach analysis to the species found within each habitat. The habitats with the highest percent composition of prey available to demersal fish are viewed as most valuable.

2.5.4. Habitat-forming fauna

Habitat-forming species refer to organisms that create biogenic reefs. Habitat-formers are ecologically important, as they can stabilize sediment, provide complex

structures for other species to utilize as habitat or refuge, and be an important food source for benthic predators (Callaway et al., 2010; Holt et al., 1998). Functional descriptions of the recovered macrofauna species were used to determine the presence of habitat-forming species within BI and FED. Of the 87 species identified within the study areas, 18 are considered to be habitat-forming. These species include blue mussels, which create structure from calcareous aggregations (Mann, 2000), and tube-building amphipods and polychaetes that form dense mats of sediment tubes (Dubois et al., 2002) extending 5-10 cms above the surface (Mann, 2000). The more of these species present within a habitat, the more valuable the habitat, due to its reef-building potential.

2.5.5. Habitat stability

a. Underwater video survey

Video transects were taken at 42 of the macrofaunal sample locations within BI using an Applied Microvideo underwater video camera and two LED lights mounted to a PVC sled. At each station, the sled was towed behind the drifting vessel for five minutes, resulting in transects that averaged 130 m in length and ranged from 30 m to 230 m.

b. Habitat stability metric

The habitat stability metric was included in the index to infer temporal variability of physical habitat structures and biological communities. Physical stability was assessed based on characteristics of each habitat, as indicated from geologic depositional environment (see section 4.1) and underwater video data, and was

classified according to three categories. The first category, “stable benthos and water column,” was assigned to environments dominated by fine sediments (i.e. silt to fine sand). The existence of such substrate indicates there is weak water movement (i.e. currents and/or tides) in the area; otherwise the fine material would be carried away (Mann, 2000). The second category is “stable benthos, active water column” and was used to denote environments dominated by gravel, cobble, and boulders. The benthos here is considered to be stable because the relatively large, heavy substrate is non-mobile, since water movement will not carry it away. However, there is sufficient water movement to prevent the settlement of finer-grained sediments (i.e. silt to very coarse sand). The third category is “active benthos and water column,” which includes transitory environments, such as sand waves and ripples, sand dunes, and sheet sands. Such environments are mobile due to intense, high velocity currents, tidal action, or storm activity.

2.5.6. Index development

To develop an index of benthic habitat value for each study area, the seven objectively-derived metrics were weighted. Physical habitat stability was not weighted because it is a subjectively determined categorical metric, and the classifications do not imply negative or positive implications. A scale of zero to three was chosen for the weights to emphasize top-ranking habitats and for practical purposes; ranking the 18 habitats from one to 18 for seven metrics would be unmanageable.

A weight of three was assigned to the map unit considered most valuable for each metric (i.e. the map unit with the highest abundance, the unit with the highest species richness, the unit with the most prey available to demersal fish, etc.). Similarly, a weight of two was given to map units that rank second (e.g. second highest abundance) and a weight of one given to units that rank third. All other units were assigned a value of zero. The scores for each habitat were then totaled. The highest possible score any habitat can achieve is 21 and the lowest is zero.

The resulting index maps were color coded to emphasize the range of values. And physical habitat stability was indicated with hatch and stippling patterns. Additionally, a table describing the scores of each metric for each habitat was created to allow detailed interpretation of the indices.

2.6. Results

2.6.1. Abundance

More than 21,000 individuals belonging to seven phyla and 87 genera were sampled across the 78 stations within BI and FED. For both areas, the majority (97.1%) of the recovered macrofauna belonged to three groups: Crustacea (53.4%), Polychaeta (24.2%), and Mollusca (19.5%). With regard to counts of individuals, the most abundant species were *Ampelisca vadorum* (comprised 18.6 % of the total individuals) and *Byblis serrata* (12.6%), both tube-building amphipods, followed by *Nucula annulata* (8.3%), a deposit-feeding mollusk. Within BI, habitat 1 had the highest average abundance (841 individuals per sample station), followed by habitat 3

(811 individuals) and habitat 8 (536 individuals). For the FED study area, habitat 17 exhibited the highest average abundance (322 individuals per sample station), habitat 13 ranked second (274 individuals), and habitats 15 and 16 tied for third (256 and 255 individuals, respectively).

2.6.2. Fish stomach contents

Benthic macrofauna comprised approximately half of the diet of the demersal fish sampled within RIS (42.21%) and BIS (53.85%). Of the identified macrofauna, amphipods were the most common, followed by polychaetes and decapods. For RIS, the remaining stomach contents consisted of species of fish or shrimp (24.30%) and unidentifiable animal remains due to advance decomposition (33.49%). For BIS, the remaining stomach contents were comprised of fish and shrimp (19.97%), plants (3.37%), and unidentified animal remains (22.81%).

Within BI, Habitat 4 was considered to offer the most prey for demersal fish, being comprised of amphipods (95.4%), bivalves and polychaetes (each 1.8%). Habitat 3 ranked second (85.3% amphipods and 12.9% polychaetes) and habitat 5 ranked third (85.9% amphipods and 11.1% polychaetes). For FED, habitats 14, 15, and 13 were considered the most valuable as food for demersal fish. Habitat 14 was primarily comprised of amphipods (81.7%) and polychaetes (12.8%), while in habitats 15 and 13, amphipods and polychaetes made up about 65% of the macrofaunal composition and bivalves about 25%.

2.6.3. Index of benthic habitat value

The habitats are numbered 1-18 in each figure and table for referencing purposes. Habitats 1-12 are found within BI and 13-18 within FED. As described in the methods, the habitat map units are defined by depositional environments and contain significantly distinct macrofaunal assemblages.

a. BI study area

The resulting index for BI contained 12 habitats with scores ranging from zero to 12 (Figure 2.7, Table 2.2). The index reveals that there are no specific dominant species, depositional environment type, or habitat stability category that yields high index scores. Instead, the habitats with the highest index scores exhibit a wide range of abiotic and biotic characteristics, ranging from coarse sand with small dunes to pebble gravel coarse sand to silty sand and from tube-building amphipods to tube-building and surface-burrowing polychaetes. The habitats scoring the lowest values also possess a range of characteristics. In fact, the high and low scoring habitats are defined by some of the same features. Furthermore, there are no clear patterns among the index variables. Scores of one, two, and three were distributed across most of the habitats, with the exception of species richness and number of habitat forming species, which scored high in the same three environments.

The highest index value of 12 belongs to habitat 10 and is mainly due to the biodiversity metrics. The habitat is dominated by *Polycirrus medusa* and *Lumbrineria hebes*, tube-building and surface burrowing polychaetes, respectively. In addition to co-dominating the abundance, *L. hebes* also contributes most to the similarity (14.48%) among all of the macrofaunal samples within that habitat (refer to Table 2.1). Physically, the depositional environment of the habitat is glacial alluvial

fan – coarse sand with small dunes and an active benthos and water column characterizes the stability of the area.

Habitat 1 exhibits the second highest index value (seven) resulting from its high abundance, species richness, and number of habitat-forming species. The habitat is defined by the tube-building amphipod, *A. vadorum*, which is also most responsible for the habitat similarity (23.25%). The habitat is a depositional basin comprised of silty sand and is categorized as an area with a stable benthos and water column.

Two very different habitats, 5 and 11, exhibit the third highest index value (five). Habitat 5 has the highest number of habitat forming species, is valuable as a food resource for demersal fish, and has high species richness. The habitat is dominated by the tube-building amphipod, *B. serrata*, which also contributes most to the habitat similarity (27.39%). The depositional environment is glacial alluvial fan – pebble gravel coarse sand. Habitat stability is characterized as stable benthos, but active water column. Alternatively, habitat 11 has high species evenness and taxonomic diversity. It is defined by *P. medusa* and *L. hebes*, with the surface-burrowing amphipod genus *Protohaustorius* contributing most to the habitat similarity (29.30%). Geologically, the habitat is part of the inner shelf moraine and exhibits transitory features - coarse sand with small dunes, sheet sands, and sand waves. As such, the area is considered to have an active benthos and water column.

The remaining habitats had an index values four or less. Three habitats (2, 6, and 12) scored a value of zero. There were no commonalities between these three habitats. Dominant species ranged from the tube-builder *A. vadorum*, *B. serrata* and *P. medusa* to the mobile polychaete genus, *Syllis*. Depositional environments included glacial

delta plain – pebble gravel coarse sand, glacial alluvial fan – sheet sand, and glacial alluvial fan – sand waves. Accordingly, the habitats were categorized as having active water columns and stable or active benthos.

b. FED study area

The index scores for the six habitats within FED ranged from 15 to two (Figure 2.7, Table 2.2). Similar to the BI index, the highest scoring habitats possess a wide range of abiotic and biotic characteristics, some of which are shared with the lowest scoring habitats. Unlike the BI index, many of the FED index variables showed clear patterns. For example, the Shannon-Wiener diversity index, evenness, and taxonomic diversity were ranked third, second, and first at the same habitats. Average abundance, species richness, and number of habitat forming species also co-occurred.

Habitat 17 exhibits the highest index value, scoring a two or three in all of the criteria, with the exception of value as a food resource for demersal fish. The deposit-feeding bivalve, *Nucula annulata*, and the tube-building amphipod, *Ampelisca agassizi* dominate the habitat. *A. agassizi* and *Nucula delphinodonta* are most responsible for the within-in habitat similarity (8.55% and 7.81%, respectively) (refer to Table 2.1). Geologically, the habitat is glacial lake floor and defined by fine or coarse sand. The habitat is considered to have a stable benthos and water column.

The second highest index value of ten is exhibited by habitat 18. This habitat scored highest in the Shannon-Wiener diversity index, evenness, and taxonomic diversity metrics and scored a weight of one in the number of habitat forming species. *L. hebes* dominated habitat 18, but bivalve genus, *Astarte*, contributes most to the within-habitat similarity (17.07%). The habitat is on a moraine comprised of areas of

cobble gravel pavement and areas of coarse silt. Overall, the habitat is categorized as having a stable benthos and active water column.

The third highest index value, seven, belongs to habitat 13, exhibiting high average abundance, species richness, number of habitat-forming species, and acting as a valuable food source for demersal fish. The habitat is dominated by *A. agassizi*, but *N. delphinodonta* and *N. annulata* are most responsible for the within-habitat similarity (7.93% and 6.97%, respectively). Glacial lake floor with sheet sands define the habitat, and it is characterized as having an active benthos and water column.

The remaining habitats scored between two and six. Like with BI habitats, these lowest scoring habitats possess different abiotic and biotic characteristics. They are defined or co-defined by *B. serrata*, *A. agassizi*, or *N. annulata* and the depositional environments are hummocky moraine – fine sand, moraine – sheet sand/sheet sand with gravel/sand waves, and glacial lake floor – coarse silt. Habitat stability is defined as either stable benthos and water column or active benthos and water column. Though, the two lowest scoring habitats share two commonalities, being defined by fine sediments (fine sand or coarse silt) and considered to have a stable benthos and water column.

2.7. Discussion

The goal of this study was to develop indices of benthic habitat value for two offshore study areas (BI and FED) targeted as primary sites for potential wind farm development. These indices are designed to indicate valuable benthic habitat locations, or “hot spots,” by summarizing habitat characteristics viewed as important

to the existence of a healthy, productive benthic habitat. The highest scoring habitats are considered most valuable. For managers, indices are practical tools because decisions, such as where to construct wind turbines, must take into account broader-scale overall benthic habitat value. In addition, the table of scores allows for habitat value to be assessed based on individual criterion, as the user deems relevant. For scientists, the index maps are valuable in understanding the distribution of benthic habitats and relationships between abiotic and biotic characteristics. In addition, the table of scores can be examined to discern relationships between and among index criteria and habitats.

Additionally, indices of benthic habitat values complement benthic habitat classification maps. Classification maps, like the ones previously created for the BI and FED study areas, are commonly defined by the dominant species or community type present within the map unit, occasionally accompanied by one or few abiotic attributes. Such maps do not always offer practical information to managers, as they tend to not indicate habitats that are of value (e.g. ecologically, commercially) or that should be focused on (e.g. monitored, conserved, restored, exploited). Indices, though, have the ability to identify valuable habitats and offer additional information to help further discern biotic-abiotic relationships among habitats.

As the indices present summarized data, habitats scoring low index values are not invaluable. Instead, low values indicate these habitats rank below the top three in all or most of the index criteria. Also, habitats were scored according to a specific suite of criteria; examination of other factors may change how the habitats rank in the index.

2.7.1. Identifying benthic habitat “hot spots”

Benthic habitat “hot spots” were clearly identified by the BI and FED indices (habitat 1 and 10, respectively). These “hot spots” were relative to each index; the habitat with the highest index value scored five points more than the second highest scoring habitat.

Though “hot spots” were recognized, the BI and FED indices did not indicate specific abiotic or biotic characteristics that lend to high habitat value. Instead, in both areas, the habitats scoring highest exhibit a wide range of characteristics (from silt to boulder fields; a stable benthos and water column to active; and tube-building fauna to surface burrowers). That there was no correlation between habitat characteristics and index values suggests that the habitats within BI and FED are valuable in their own ways. Within BI, further evidence that a variety of habitat types are important is shown by the fact that not one environment dominated all of the index criteria. Within FED, one habitat (17), having the highest index value (15), scored in every criterion, except one, but did not overshadow the other habitats. In general, the results indicate management efforts need to consider all habitat types, and cannot focus on certain habitat attributes.

2.7.2. Comparison of BI and FED indices

As the top-scoring habitats suggest, the BI and FED indices were quite different. The relationships between abiotic and biotic characteristics that appear to exist within BI do not within FED, and vice-versa. For example, examination of the BI habitats

suggest the highest evenness occurs in environments defined by coarse sand with small dunes and are categorized as having an active benthos and water column. However, within FED, this relationship does not hold true. In fact, none of the top three ranking evenness habitats within FED are defined by coarse sand with small dunes and habitat stability varies. Rather than disproving potential relationships, however, the differences between BI and FED speak towards the macrofauna having their own associations to the environment within each study area, supporting previous findings of the BI and FED study areas (LaFrance, 2011).

2.7.3. Biodiversity and tube-building fauna

Habitat-formers, such as tube-building fauna, are ecologically important, as they can provide complex structures for other species to utilize as habitat or refuge, stabilize sediment, and be an important food source for benthic predators (Callaway et al., 2010; Holt et al., 1998). Consequently, habitat-formers tend to create areas of increased biodiversity relative to the surrounding environment (Callaway et al., 2010). Previous studies (e.g. Gray, 1974; Ellingsen, 2002) have reported positive relationships between habitat variety and species diversity, following the rationale that a greater degree of sediment heterogeneity offers more potential niches, and therefore, allows for higher diversity (Rosenzweig, 1995). For example, Pratt (1973) reported that suspension feeders (such as tube-building amphipods) physically dominate hard surfaces, but, despite this, a diverse range of fauna (deposit feeders, predators, browsers) reach high densities in mature epifaunal assemblages.

That habitat forming-species and species richness were correlated and that high biodiversity tended to occur in habitats defined at least in part by tube-building species, indicates tube-builders and/or their dense mats positively influence benthic ecosystems. Studies have suggested polychaete tube-mat structures increase sediment heterogeneity (i.e. habitat complexity), leading to increased biodiversity (Dubois, 2006; Ellingsen, 2002; Dubois, 2002). In addition, tube-builders specialize in resource uptake by building tubes that extend 5-10 cm above the seafloor. This strategy allows tube-builders to avoid competition for resources on the seafloor and allows them to obtain the more nutritious food that tends to concentrate a few centimeters above the seafloor in the water column (Mann, 2000). It is also possible that tube-builders positively interact with other species (predator-prey, competition, mutualism).

2.7.4. Biodiversity and habitat stability

While tube-building fauna are positively related to biodiversity, the indices suggest that the highest biodiversity is achieved when tube-builders co-dominate a habitat. Possibly tube-building fauna are able to out-compete other species for resources, as they do tend to occur in very high densities. In these study sites, three samples contained over 1,000 individuals of *A. vadorum* and 11 samples contained 200-700 individuals of *A. vadorum*, *B. serrata*, or *A. agassizi*. However, under disturbance populations may be reduced and allow other species to exist. Of the four habitats with the highest biodiversity scores, three (habitats 10, 11, and 18) are likely to experience intermediate levels of disturbance due to physical processes, as these habitats are defined by active water columns, evidenced by their transitory features

(coarse sand with small dunes, sand sheets, and sand waves) or concentrations of boulders, cobble, and gravel. Conversely, the remaining habitat (17) is stable (composed of fine and coarse sand). Perhaps in this habitat, disturbance is coming from biological factors, such as predation or competition.

This relationship between biodiversity and habitat stability reflects disturbance theory. Disturbance theory follows the rationale that highest diversity occurs when an intermediate amount of disturbance is present within a community (Mann, 2000). Disturbances can be physical (e.g. storms, currents, tides) or biological (e.g. predation). If a habitat is very stable, diversity is reduced due to the competitive exclusion – species that are optimally adapted for that environment will out-compete others. Conversely, if the intensity and frequency of environmental disturbance is too high, it may present conditions too stressful for many species, also resulting in reduced diversity. Pratt (1973) for example, noted that within RIS and BIS organisms living in active environments must be adapted for movement in sand and be able to recover from periodic burial. At intermediate disturbance levels diversity is highest because there is less competitive exclusion, which frees up resources for other species to utilize, and conditions are tolerable to a wider range of species (Clarke and Warwick, 2001; Mann, 2000).

2.7.5. Biodiversity metrics

Biodiversity metrics played an important role in developing the indices (four metrics are included) because they are considered to be indicators of ecosystem health (Morin, 1999) and stability (Mann, 2000), and because they indicate how biological

communities respond to their environment (Gascón et al., 2009). For example, evidence suggests that as species richness increases there is increased primary production, as well as increased resistance to natural disturbances and invasion within a community (Morin, 1999). Furthermore, biodiversity has been the focus of some conservation efforts (e.g. Last et al., 2010).

While using four measures of biodiversity may seem repetitive, especially in FED (where three of the metrics were correlated), each measure may be responding to different environmental parameters, and therefore, be valuable independent metrics (Gascón et al., 2009). Gascón et al., (2009) reported even significantly related biodiversity metrics revealed significantly distinct relationships with different environmental variables, and therefore could not be considered redundant. In this study, the relationships between biodiversity and habitat-forming fauna suggest the biodiversity metrics may represent habitat heterogeneity.

2.7.6. Temporal variability

Temporal variability can present a challenge to benthic habitat mapping, both in data collection and in creating final products. Because maps are created using abiotic and biotic datasets representing single sampling/survey events in time, they often do not reflect the temporal dynamics of transitory features. However, qualitative descriptors of temporal variability may be inferred, as was the purpose of including the habitat stability parameter in the indices. For example, within unstable physical environments (mobile sheet sands, sand waves, sand ripples), characteristics (abiotic and biotic) of the benthic habitats are more likely to change. With regard to biotic

data, temporal variability may be indicated by the presence of opportunistic species that reflect recent habitat disturbance, or the presence of large, long-lived individuals that indicate a more stable environment and potentially lower temporal variability in macrofauna composition (Pearson 1978).

It is possible seasonal differences in macrofaunal community composition are reflected in these results and that the indices may become outdated. However, Steimle (1982) reported there were no clearly defined seasonal changes between biological communities examined in February and in September within BIS. Steimle (1982) also presented evidence to suggest these habitats are relatively stable on a time-scale of decades.

2.7.7. Applicability

The methodology presented here can be applied to a broad range of environments, as evidenced by the success of the indices in identifying benthic habitat “hot spots” at two study areas differing in their abiotic and biotic characteristics. Moreover, the criteria incorporated into the indices can be tailored to meet individual project needs, and indices can be further developed as additional data becomes available. A table of relevant habitat attributes identified as important by a range of user groups is nicely presented in Auster et al. (2009). Following this table, other criteria that may be relevant in developing benthic habitat indices include finer-scale sediment data or water column processes, organic carbon content, chlorophyll-a concentration, importance of habitat for larval recruitment, and degree of anthropogenic impact/human-induced attributes (such as from construction, dredging, fishing).

Biologically, the presence of species of interest (e.g. key species, indicator species, endangered, commercially important) and biodiversity metrics of species rarity or taxonomic distinctness may be informative criteria. Along with dominant species and species contributing most to the habitat similarity, it may also be useful to label habitats according to dominant species groups.

2.7.8. Future work

This study represents an initial attempt to construct indices of benthic habitat value. The index results and proposed relationships will be verified through collection and analysis of additional data in the near future. For instance, the relationship between the diet of demersal fish and biodiversity will be evaluated throughout RIS and BIS. The analysis will involve examining demersal fish stomach contents to determine if their diet diversifies in areas where more types of prey are available. In other words, “Do fish take advantage of diverse habitats or just focus on eating amphipods within any given habitat?” If the correlation is positive, it supports that increased biodiversity is beneficial to benthic ecosystems within BI and FED. If there is no relationship, it would indicate certain food types (i.e. amphipods) are preferred, and, thus, the degree of biodiversity is unimportant to demersal fish.

With regard to biodiversity, future studies will assess the appropriateness of including four biodiversity metrics into the index by examining what the metrics represent and if they are repetitive. In addition, though high biodiversity is anticipated to be positively associated with benthic habitat value, future studies will evaluate such relationships within BI and FED.

2.8. Conclusion

Resource managers are increasingly faced with dwindling budgets and a lack of easily applicable, science-based methods with which to make far-reaching management decisions, such as locations for wind turbine installation. This paper addresses this issue with the development of an index to identify benthic habitat “hot spots” that can be applied to any study location and be adapted to meet any project objectives. Indices were constructed for two study areas within Rhode Island waters by classifying habitats according a suite of biological and environmental metrics considered relevant to a broad range of user groups. Previous research has shown the habitats contain significantly distinct macrofaunal assemblages. The indices present overall benthic habitat value and offers scores of each metric, allowing habitats to be evaluated based on user need. Each index identified a habitat that scored considerably higher than the other habitats. In general, though, the indices did not indicate specific abiotic or biotic characteristics that lend to high habitat value, which indicates management efforts need to consider all habitat types within the study areas, and cannot focus on certain habitat attributes. However, a correlation was found between tube-building species and species richness, suggesting tube mat structures lead to increased biodiversity. The indices also show that habitats within the two study areas have different relationships with the index criteria, indicating macrofauna have their own associations to the environment within each study area. Biodiversity metrics play a large role in development of the indices, as they are considered to be indicators of ecosystem health and stability. This expectation and the proposed relationships

among the index metrics and habitats will be evaluated within the two study areas in the near future.

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Figure 2.1. The BI and FED study areas within the RI Ocean SAMP study area, located within Rhode Island and Block Island Sounds.

Figure 2.2. Side-scan sonar backscatter mosaics of BI and FED. Mosaics are displayed on an inverse grey-scale. White (255) represents high backscatter intensity

and absorbent (usually softer) surfaces, respectively. The pixel resolution of the backscatter mosaics shown here is 2 m.

Classification

- 1.) A. vadorum (Type I) - Depositional Basin, silty sand
- 2.) A. vadorum (Type II) - Glacial Delta Plain, pebble gravel coarse sand
- 3.) A. vadorum (Type III) - Glacial Delta Plain, sheet sand
- 4.) B. serrata (Type I) - Glacial Alluvial Fan, boulder gravel concentration
- 5.) B. serrata (Type II) - Glacial Alluvial Fan, pebble gravel coarse sand
- 6.) B. serrata (Type III) - Glacial Alluvial Fan, sheet sand
- 7.) J. falcata - Moraine Shelf, boulder gravel concentration
- 8.) Corophium spp. - Moraine Shelf, pebble gravel coarse sand
- 9.) P. remota - Moraine Shelf, coarse sand with small dunes/sand waves
- 10.) P. medusa / L. hebes (Type I) - Glacial Alluvial Fan, coarse sand with small dunes
- 11.) P. medusa / L. hebes (Type II) - Inner Shelf Moraine, coarse sand sheets/waves/small dunes
- 12.) Syllis spp. / P. medusa - Glacial Alluvial Fan, sand waves
- Undefined

Classification

- 13.) A. agassizi - Glacial Lake Floor, sheet sand
- 14.) B. serrata (Type IV) - Hummocky Moraine, fine sand
- 15.) B. serrata / A. agassizi - PJ-BB Moraine, sheet sand, sheet sand with gravel, sand waves
- 16.) N. annulata - Glacial Lake Floor, coarse silt
- 17.) N. annulata / A. agassizi - Glacial Lake Floor, fine or coarse sand
- 18.) L. hebes - PJ-BB Moraine, boulder gravel concentration, cobble gravel pavement, coarse silt
- Undefined

Figure 2.3. Top-down habitat classification maps of the BI and FED study areas. Each map unit, as defined by the depositional environment, is classified according the most abundant genus. ANOSIM revealed the macrofaunal assemblages within form type are significantly different (global $R = 0.60$, $p = 0.001$; LaFrance, 2011). See Table 2.1 for further descriptions of habitats.

Figure 2.4. Bathymetry of BI and FED. Water depth within the two study areas ranges from 9.4 m to 54.6 m. Note the scales for BI and FED are different, so as to visually enhance the features within each area. Mosaic pixel resolution is 10 m.

Figure 2.5. Locations of the bottom samples taken within the BI and FED study areas.

Figure 2.6. Locations of demersal fish trawls within RIS and BIS.

Figure 3.7. Index of benthic habitat value for the BI and FID study areas. Habitats were classified and weighted according to 7 metric (see text for methods). Scores range from 12 - 0 in BI and 15 - 2 in FID. Habitat stability was not weighted.

Table 2.2. Description of habitats derived from BI and FED benthic habitat

Figure 2.7. Index of benthic habitat value for the BI and FED study areas. Habitats were classified and weighted according to 7 metrics (see text for methods). Scores range from 12 - 0 in BI and 15 - 2 in FED. Habitat stability was not weighted.

6	<i>Syllis</i> sp.	<i>Lyndwormia</i> <i>fragilis</i> (21.71%)	23.33%	Glacial Alluvial fine sheet sand	BI	3.96
7	<i>Anas</i> <i>fragilis</i>	<i>Polygordis</i> sp. (15.22%)	24.56%	Moraine Shell/ boulder gravel concentration	BI	11.57
8	<i>Corophium</i> sp.	<i>Pisana remota</i> (47.14%)	12.62%	Moraine Shell/ pebble gravel coarse sand	BI	2.96
9	<i>Pisana</i> <i>remota</i>	<i>Lyndwormia</i> <i>hebes</i> , <i>Syllis</i> sp., <i>Polygordis</i> sp., <i>Exhystero-</i> <i>chelis</i> <i>parva</i> (33% each)	20.36%	Moraine Shell/ coarse sand w/ small dunes, sand waves	BI	2.32

Table 2.1. Description of habitats derived from BI and FED benthic habitat classification maps. The average dominant species and geological features within each habitat are given, along with location and area. The average within-environment similarity and the species most responsible, as identified by the SIMPER procedure, are also provided. Data from LaFrance, 2011.

Habitat	Average Dominant Species/ Genus	Genus/ Species Contributing Most to Similarity	Average Similarity	Form and Facies	Study Area	Area (mi ²)
1	<i>Ampelisca vadorum</i>	<i>Ampelisca vadorum</i> (23.25%)	46.46%	Depositional Basin; silty sand	BI	2.81
2	<i>Ampelisca vadorum</i>	<i>Lumbrineria hebes</i> (14.80%); <i>Astarte</i> spp. (14.19%)	34.31%	Glacial Delta Plain; pebble gravel coarse sand	BI	2.67
3	<i>Ampelisca vadorum</i>	<i>Glycera</i> spp. (16.12%)	39.05%	Glacial Delta Plain; sheet sand	BI	1.64
4	<i>Byblis serrata</i>	<i>Nemertean</i> spp. (100%)	6.16%	Glacial Alluvial Fan; boulder gravel concentration	BI	1.93
5	<i>Byblis serrata</i>	<i>Byblis serrata</i> (27.39%)	31.78%	Glacial Alluvial Fan; pebble gravel coarse sand	BI	5.08
6	<i>Byblis serrata</i>	<i>Lumbrineria fragilis</i> (23.91%)	23.33%	Glacial Alluvial Fan; sheet sand	BI	3.96
7	<i>Jassa falcata</i>	<i>Polygordius</i> sp. (15.25%)	24.56%	Moraine Shelf; boulder gravel concentration	BI	11.57
8	<i>Corophium</i> sps	<i>Pisone remota</i> (47.74%)	12.02%	Moraine Shelf; pebble gravel coarse sand	BI	2.98
9	<i>Pisone remota</i>	<i>Lumbrineria hebes</i> , <i>Syllis</i> spp., <i>Polygordius</i> sp., <i>Echinarachnius parma</i> (25% each)	20.36%	Moraine Shelf; coarse sand w/ small dunes, sand waves	BI	2.32

10	<i>Polycirrus medusa - Lumbrinerie s hebes</i>	<i>Lumbrinerie hebes</i> (14.48%)	37.45%	Glacial Alluvial Fan; coarse sand w/ small dunes	BI	11.35
11	<i>Polycirrus medusa - Lumbrinerie s hebes</i>	<i>Protohaus-torius</i> sp. (29.30%)	33.47%	Inner Shelf Moraine; coarse sand w/ small dunes, sheet sand, sand waves	BI	2.81
12	<i>Syllis spp. - Polycirrus medusa</i>	<i>Glycera</i> spp., <i>Aricidea catherinae</i> , <i>Crassenella</i> sp. (33.33% each)	12.85%	Glacial Alluvial Fan; sand waves	BI	1.73
13	<i>Ampelisca agassizi</i>	<i>Nucula delphinodonta</i> (7.93%), <i>Nucula annulata</i> (6.97%)	58.25%	Glacial Lake Floor; sheet sand	FED	3.50
14	<i>Byblis serrata</i>	na	na	Hummocky Moraine; fine sand	FED	1.26
15	<i>Byblis serrata - Ampelisca agassizi</i>	<i>Ninoe nigripes</i> (8.51%), <i>Nucula delphinodonta</i> (8.25%), <i>Nucula annulata</i> (7.76%)	59.44%	PJ-BB Moraine; sheet sand, sheet sand w/ gravel, sand waves	FED	1.08
16	<i>Nucula annulata</i>	<i>Nucula annulata</i> (16.83%)	53.47%	Glacial Lake Floor; coarse silt	FED	23.37
17	<i>Nucula annulata - Ampelisca agassizi</i>	<i>Ampelisca agassizi</i> (8.55%), <i>Nucula dolphinodonta</i> (7.81%)	56.11%	Glacial Lake Floor; fine or coarse sand	FED	16.05
18	<i>Lumbrinerie s hebes</i>	<i>Astarte</i> spp. (17.07%)	31.84%	PJ-BB Moraine; cobble gravel pavement, coarse silt	FED	4.75

Table 2.2. Index of benthic habitat values for BI and FED study area. The table indicates the total index value, as well as the values of each criteria for each of the 18 habitats. Refer to Table 2.1 and Figure 2.3 for further description, including dominant species and geologic features of each habitat. Habitat stability code: stbl ben & wc = stable benthos and water column; stbl ben, act wc = stable benthos, active water column; act ben & wc = active benthos and water column.

Habitat	Avg. abundance	Species richness	Shannon-Wiener diversity index	Pielou's evenness	Taxonomic diversity	Value as fish food resource	# of habitat-forming species	Habitat stability	Total index value
1	3	2	0	0	0	0	2	stbl ben & wc	7
2	0	0	0	0	0	0	0	stbl ben, act wc	0
3	2	0	0	0	0	2	0	act ben & wc	4
4	0	0	0	0	0	3	0	stbl ben, act wc	3
5	0	1	0	0	0	1	3	stbl ben, act wc	5
6	0	0	0	0	0	0	0	act ben & wc	0
7	0	0	2	0	0	0	0	stbl ben, act wc	2
8	1	0	1	0	1	0	0	stbl ben, act wc	3

9	0	0	0	1	0	0	0	act ben & wc	1
10	0	3	3	2	3	0	1	act ben & wc	12
11	0	0	0	3	2	0	0	act ben & wc	5
12	0	0	0	0	0	0	0	act ben & wc	0
13	2	2	0	0	0	1	2	act ben & wc	7
14	0	0	0	0	0	3	0	stbl ben & wc	3
15	1	0	1	1	1	2	0	act ben & wc	6
16	1	1	0	0	0	0	0	stbl ben & wc	2
17	3	3	2	2	2	0	3	stbl ben & wc	15
18	0	0	3	3	3	0	1	stbl ben, act wc	10

APPENDIX. Squared correlation coefficient, r^2 , between abiotic variables.

r^2										
	% clay	% fine silt	% coarse silt	% very fine sand	% fine sand	% medium sand	% coarse sand	% very coarse sand	std dev (um)	mean water depth
mean bkstr 100m	0.004	0.003	0.013	0.095	0.072	0.005	0.084	0.132	0.202	0.041
max bkstr 100m	0.083	0.067	0.083	0.345	0.168	0.051	0.210	0.130	0.270	0.213
min bkstr 100m	0.040	0.041	0.017	0.018	0.010	0.071	0.018	0.010	0.003	0.041
std dev bkstr 100m	0.099	0.085	0.071	0.228	0.171	0.054	0.220	0.079	0.195	0.223
mean depth 100 m	0.314	0.309	0.239	0.477	0.338	0.114	0.488	0.270	0.431	1.000
max depth 100 m	0.144	0.150	0.121	0.237	0.143	0.058	0.237	0.098	0.246	0.732
min depth 100 m	0.323	0.307	0.241	0.498	0.368	0.120	0.519	0.271	0.465	0.954
std dev depth 100 m	0.094	0.071	0.063	0.187	0.176	0.013	0.198	0.201	0.246	0.163
slope 100m	0.073	0.044	0.039	0.116	0.096	0.002	0.140	0.123	0.117	0.062
surface roughness	0.084	0.060	0.049	0.191	0.236	0.002	0.324	0.167	0.190	0.231

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