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Enhanced ocean landscape and ecological value characterization for the Rhode Island Ocean Special Area Management Plan study area using Habitat Typology and Habitat Template approaches

by

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Executive Summary

In this study, we used two different approaches to characterize habitats across the entire Rhode Island Ocean SAMP (RIOSAMP) study area. The observational approach used only abiotic variables and the theoretical approach used both abiotic and biotic variables. Despite the different approaches and variables, both methods identified similar factors as important for structuring habitats in the RIOSAMP area. Our major findings were:

Two main environmental variables control marine landscapes, or habitats, within the RIOSAMP area: degree of "coastalness" and seafloor geomorphology.

Biodiversity in the RIOSAMP area peaks at a variety of geomorphological types, therefore factors other than geomorphology contribute to the biological value of a habitat (i.e., not all moraines are equally 'valuable').

Table of Contents

List of Figures

List of Tables

1 Introduction

For many of the benthic habitat studies in the Rhode Island Ocean SAMP (RIOSAMP) area, a fine-scale (order of 100s of meters) approach was used because this is the scale at which potential developers, regulators and managers interact and choose appropriate sites for various activities. For impact monitoring and assessment, this fine-scale approach is essential. However, in order to put developed and protected benthic habitats into a larger context, and to understand relationships with regional habitat patterns and migratory species, a broad-scale habitat analysis is necessary (order of kilometers); patterns developing at such a larger scale or, regional scale, are often referred to "marine landscapes" (Verfaillie et al., 2009). For this study, we asked "what are the 'marine landscapes' or 'habitats' across the entire RIOSAMP area and how do they compare by ecological value?" We defined "ecological value" as "the intrinsic value of marine biodiversity, without reference to anthropogenic use" (Derous et al., 2007).

First, to identify marine landscapes, an ecosystem typology method was used. Typologies have been approached previously in the RIOSAMP project to classify the study area into oceanographic and ecological zones, or sub-regions based on similar oceanographic and ecological characteristics (Grilli et al., 2011, 2012). Similar methods were used for other coastal spatial planning issues (Borja et al. 2000; Buddemeier et al., 2008; Jordan 2010) or for similar renewable energy planning and management related issues (Williams et al., 2012). The Belgium Management Unit of the North Sea Mathematical Model (MUMM), in particular, has developed a similar analysis to our approach for the North Sea, offshore of the Belgium coast (Verfaillie et al., 2009; Degraer, 2008).

In this analysis, we extend and refine the initial RIOSAMP typology to include specific geomorphological variables known to be particularly relevant to marine habitat or landscape characterization. This results in a marine landscape typology uniquely based on abiotic variables. The set of variables is quasi-identical to that used in Verfaillie (2009) and are defined in Section 2.

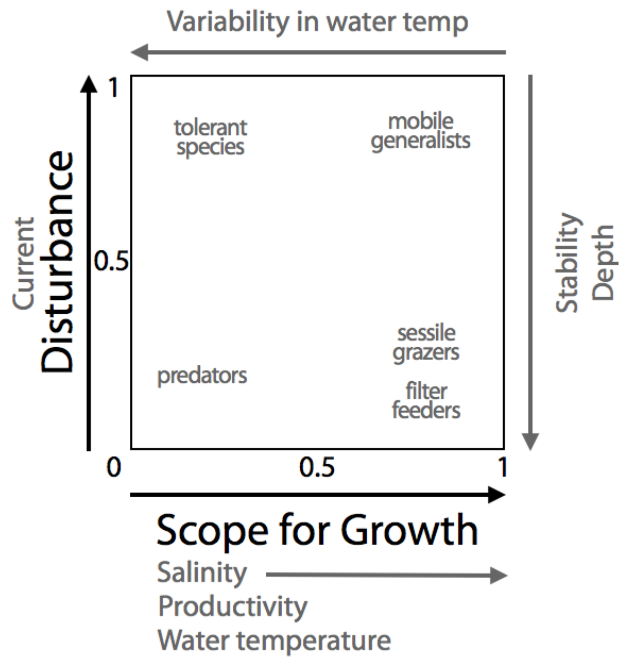

Figure 1. Modeling Natural Disturbance and Scope for Growth using a habitat template approach.

In order to assess the ecological value of the habitats, we modeled biodiversity using a habitat template approach (e.g., Kostylev and Hannah, 2007). The habitat template approach uses features of the environment to predict biodiversity. The major features of the marine environment that determine where species can live and how well they grow and reproduce include "Natural Disturbance" and "Scope for Growth". Natural Disturbance includes forces that physically disturb the seabed every day (e.g., bottom currents from tides) and during extreme short-term events (e.g., storms). Scope for Growth refers to the biological production of an area, or the energy available to organisms for growth and reproduction. Natural disturbance and Scope for Growth can be modeled using variables we measure in the environment. Natural Disturbance is modeled using tidal current velocity and extreme wave height; Scope for Growth is modeled using primary productivity, water column layering, and bottom temperature. By modeling Natural Disturbance and Scope for Growth, we can develop predictions about where certain types of organisms (and perhaps what species) might live in the RIOSAMP area (e.g., Southwood 1988; Figure 1). Ecological theory predicts that biodiversity will be highest in areas with an intermediate Natural Disturbance regime and with high Scope for Growth (Southwood 1988). Because we have a concept of how Natural Disturbance and Scope for Growth relate to biodiversity (Figure 2), we can create maps of predicted "ecological value"— biodiversity hotspots—for the entire RIOSAMP area. Figure 1 also illustrates the relationships between the habitat template and the environmental variables modeled using the ecosystem typology approach discussed above (grey text in Figure 1).

The goal of this study was to compare the spatial representation of the two models' outputs: (1) the typology using only abiotic variables; (2) the Habitat Template using abiotic and biotic variables. This exercise will better our understanding of the nature and distribution habitats across the entire RIOSAMP area. Because both methods result in maps, they each contribute scientific information to the marine spatial planning process. Maps of habitats can be overlaid with maps of human activities such as fishing, boat traffic, and disposal areas. Examining patterns in the natural environment along with human activities will allow us to discuss the potential impacts of human activities and perhaps better designate areas for renewable energy development, resource extraction and conservation.

2 Methods

2.1 Habitat Typology

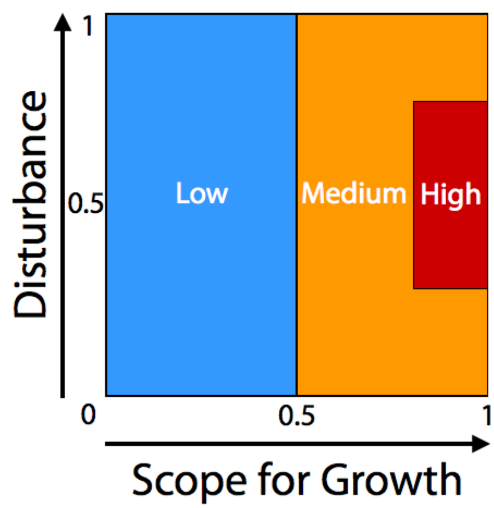

Figure 2. The relationship between diversity, Disturbance and Scope for Growth. Highest species diversity will occur in areas with an intermediate Disturbance regime and high Scope for Growth (red).

2.1.1 Principle

The RIOSAMP area (Figure 3) is spatially discretized into a finite number of grid cells; each of these cells is defined by a large number of variables (i.e., a multivariate data point), describing the local marine landscape, such as depth, distance to coast, mean sea surface temperature, etc…(Table 1). Each grid cell is therefore defined in a multivariate space by multiple variables.

The objective of the typology is to regroup similar cells to create homogeneous marine regions, characterized by similar marine landscapes.

The analysis follows two major steps:

- *Step 1*: A reduction of the multivariate space by applying a Principal Component Analysis (PCA) to facilitate the grouping (Step 2).
- *Step 2*: Grouping of similar cells using a cluster analysis (CA). The k-means clustering method is used in this analysis.

The present study is performed using MATLAB.

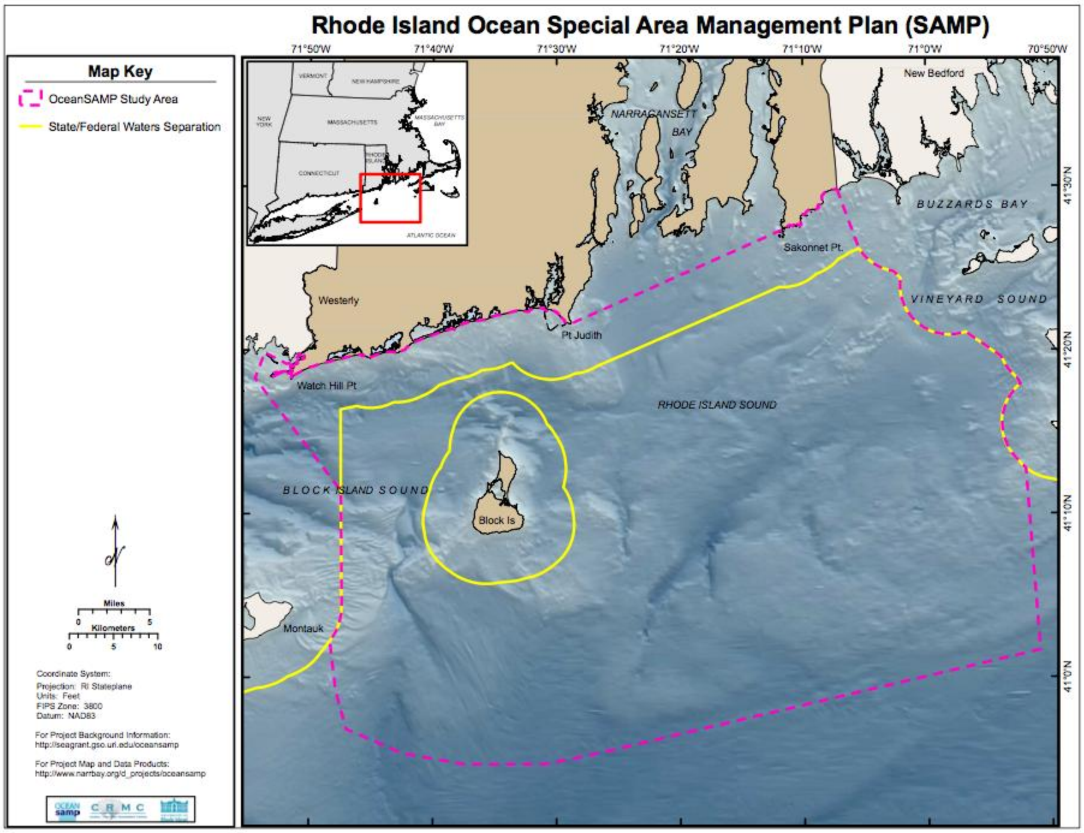

Figure 3. The spatial extent of the study area for both habitat models.

2.1.2 Data

The RIOSAMP area is discretized into grid cells of about 200 m by 200 m extending between -71.89 to -70.82 degrees W in Longitude and 40.88 to 41.5 degrees N in latitude. This discretization size has previously been shown to be relevant for benthic habitat analysis (Derous, 2007). Each grid cell is described by 17 abiotic variables (Table 1).

Table 1. Variables used in the analysis to describe the marine landscape and habitat. *indicates identical data layer was used for habitat template approach (see section 2.2).

Variable name	Description	Unit	Source
Tidal velocity*	Maximum tidal velocity	m/s	ROMS modeling Grilli S. et al. 2010; Harris et al., 2012.
Significant wave height*	95 % Significant wave Height in a 50 year storm event	m	STWAVE modeling Grilli A. et al 2008
Depth*	Water Depth	m	NGDC Coastal Relief Model
Distance to shore	Distance from each grid cell to closest point to shore	km	Grilli A. et al, 2010
Slope	Maximum slope between 2 grid cells (200 m apart)	Deg.	NGDC Coastal Relief Model ; SURFER toolbox
Roughness	Slope Standard deviation in 1000 m radius		LaFrance et al. 2010
Phi median	Sediment median diameter (on a phi scale ; $\Phi = -\log_2 D_{mm}$)	Φ	SEABED: Atlantic coast offshore surficial sediment data. US Geological Survey Reid et al. 2005
Clay	Fraction of clay in sediment	%	SEABED: Atlantic coast offshore surficial sediment data. US Geological Survey Reid et al. 2005
SST Spring	Mean Seasonal Sea surface Temperature (Spring)	Degree Celsius	Satellite data NASA Terra and Aqua (MODIS sensors)Codiga et Ullman, 2010

Stratification Spring	Buoyancy frequency squared 0.25 to 2.5 km resolution	s^{-2}	FVCOM modeling. Codiga et Ullman, 2010 Chen et al (2006)
SST Fall	Mean Seasonal Sea Surface Temperature (Fall)	Degree Celsius	Satellite data NASA Terra and Aqua (MODIS sensors)Codiga et Ullman, 2010
Stratification Fall	Buoyancy frequency squared 0.25 to 2.5 km resolution	s^{-2}	FVCOM modeling Codiga et Ullman, 2010 Chen et al (2006)
Aspect Ratio	Slope directionality	Degree [0-360]	NGDC Coastal Relief Model ; Satellite data NASA Terra and Aqua (MODIS sensors) SURFER toolbox
BPI fine scale	Bathymetric position index fine scale [negative values indicate a canyon; positive values indicate a ridge; around 0, flat or constant slope]		NGDC Coastal Relief Model and GIS
BPI large Scale	Bathymetric position index large scale[negative values indicate a through; positive values indicate a ridge; around 0, flat or constant slope]		NGDC Coastal Relief Model and GIS
North-ness	North -South component in slope sin(Aspect Ratio) positive value indicates North-ness		NGDC Coastal Relief Model and GIS
East-ness	West-East component in slope Cos(Aspect Ratio) positive value indicates East-ness		NGDC Coastal Relief Model and GIS

The following analysis is performed in "deterministic" mode, meaning that we assume that the mean values are a representative value of the distribution at each grid point (e.g. Sea surface temperature at a specific grid point is assume to be represented by its mean value and this mean value is assumed to be exact). In other words, the statistical uncertainty associated to those data is not considered in this analysis. A stochastic approach was initiated but was out of the scope of this very short-term project.

Data were interpolated using a kriging algorithm on the study grid. While the uncertainty associated to the spatial interpolation was not quantitatively assessed, the quality of the interpolation was verified by comparing the statistical distribution of the variables before and after interpolation.

2.1.3 Principal Components and Cluster Analysis

PCA is used in the typology to simplify the grouping of cells occurring in a large multi-dimensional space. PCA reduces the multivariate-space dimensions, while keeping most of the information (or variance), using fewer variables: the Principal Components (PCs). Each PC is a linear combination of the original variables, which is orthogonal to the other components and therefore independent. The orthogonality between components eliminates any redundant information resulting from correlations between original variables. Principal components, consequently, explain most of the variance, with a reduced number of variables by comparison to the original number of variables (Zuur, 2009).

CA is then used to regroup similar cells in the principal component space. The k-mean clustering method is used in this study. The method calculates the distances between cells in the new reduced multivariate principal components space and regroups similar cells into clusters, based on their proximity in that multi-space, or, in other words, based on their similarity. This results in a set of clusters as compact and well-separated as possible. Each cluster reflects, in this application of the method, a specific or homogeneous "marine landscape".

2.2 Habitat Template

The methods used to construct the habitat template for the RI SAMP area are modified from those used by Kostylev and Hannah (2007). We used the same underlying data as for the habitat typology approach, when available, so that results might be quantitatively compared in follow-on studies.

Caution must be used when interpolating discrete point samples over large areas. To determine the minimum grid size allowable for the data available in this study, we used the inspection-density method of Hengl (2006). Knowing the minimum number of data points available (210 for stratification and temperature data) and the size of the RIOSAMP study area (1500 square miles), we calculated that a grid size of 215 meters was the finest allowable size. However, to be conservative, we chose to use 500 meter pixels for the final grid size.

2.2.1 Scope for Growth

Scope for Growth (SG) represents the energy available to organisms for growth and reproduction. Variables that contribute to high SG are high food availability, warm year-round bottom-temperatures and constant year-round bottom temperatures. In order to estimate food availability, we used data layers such as stratification, chlorophyll-a, and bathymetry. Stratification (water column layering), chlorophyll-a (primary productivity) and bathymetry (water depth) will help us estimate how much food is reaching the seafloor for benthic organisms. Deep water, low chlorophyll-a, and high degrees of stratification will be associated with low food availability. Bottom temperature values will help us estimate how much energy organisms are using in order to adapt and survive in their environment. Areas where bottom temperatures vary widely require more energy to survive. Areas with a relatively constant bottom temperature will allow for larger and more longer-lived organisms.

Stratification and temperature data were derived from Codiga and Ullman (2010), chlorophyll data from Hyde (2010) and bathymetry data from NOAA's coastal relief model. The Codiga and Ullman data are season means of temperature, salinity, and density at 10 depth intervals derived from a 27-year dataset (1980-2007) of 150-300 CTD casts distributed non-uniformly across the SAMP area.

<u>Stratification</u>

Codiga and Ullman (2010) provided sigma-t values at 10 depth intervals at 210 sites throughout the SAMP area. The surface value was subtracted from the bottom value to calculate stratification at every site for each season (spring, summer, fall, winter). The annual mean stratification was calculated for each site and these values were normalized on a scale of 0 to 1 to create a stratification index. These data were interpolated to a 500 meter grid using ordinary kriging.

<u>Chlorophyll a</u>

Monthly SeaWiFS data interpreted by Hyde (pers. comm.), for the years 1998-2007, were used to model chlorophyll a concentrations across the SAMP area. The October 10-year mean (1998-2007) value was chosen for this study because this appeared to best reflect the annual maximum chlorophyll a concentration for this dataset. This is in contrast with the data utilized by Kostylev and Hannah (2007), which was chosen to reflect spring blooms. Since no spring blooms were evident in the RI data, the October values were used. These data were normalized to a scale of 0 to 1 and interpolated to an 80 meter grid in order to match the resolution of the NOAA bathymetry dataset.

<u>Bottom Temperature</u>

Codiga and Ullman (2010) provided near-bottom temperature values at 210 sites throughout the SAMP area for each season. From these, we calculated the annual mean bottom temperature (TM), the annual range in bottom temperature (TA) and the interannual Root Mean Square (RMS) of bottom temperature (TI). Each of these was normalized on a scale of 0 to 1 and interpolated to a 500 meter grid using ordinary kriging.

In order to estimate SG, the Food Availability (FA) index was calculated by taking the log of the ratio of chlorophyll a concentration to water depth and then subtracting the stratification index, as an estimate of food reaching the seafloor (Kostylev and Hannah 2007). The resulting index was scaled from 0 to 1. To calculate SG, the Food Availability, Mean Bottom Temperature, Annual Range in Bottom Temperature and Interannual RMS of Bottom Temperature indices were combined in a linear additive model where each variable received equal weight. The equation used was:

$$SG = (FA + TM – TA – TI)/4.$$

The final SG index was scaled from 0 to 1 and gridded at 500 meter pixels.

2.1.2 Natural Disturbance

To model natural disturbance (ND) in the RIOSAMP area, we used datasets that approximate the average and the extreme hydrodynamic conditions in the study area.

The maximum tidal velocity represented average hydrodynamic conditions and the average amount of hydrodynamic drag experienced by particles and organisms on the seafloor. Maximum tidal velocity was modeled by Dr. Jeff Harris (pers. comm.) of the URI Department of Ocean Engineering. Extreme hydrodynamic conditions were modeled using 50-year significant wave height simulations (Grilli A., et al, 2008). Areas with high tidal velocity (high drag) and high significant wave height will be more disturbed than areas with low tidal velocity and low significant wave height.

Tidal Current Power

Maximum tidal velocity was provided on a 300 meter grid. The power needed to overcome the drag created by tidal currents increases as the cube of the current velocity. Therefore we used the maximum tidal current velocity to create a current power "proxy" (CP) by cubing (V^3) the velocity at every grid node. CP is assume to be correlated with the probability that sediment grains are mobilized by tidal fluctuations and represents an index of mean hydrodynamic condition at the seabed. CP data were re-interpolated on a 500 m grid using the ArcGIS grid export utility and were normalized on a 0 to 1 scale. This dataset was log-transformed to create normally distributed data.

Extreme Wave Height

In order to create a proxy for wave power, (WP) the significant wave height for the 50-year extreme wave events were square-transformed and interpolated on the grid (original data were on a 700 meter grid). The two grids had a Pearson correlation coefficient of 0.94. The 500 meter wave height grid was then normalized on a 0 to 1 scale.

ND is a proxy for mean input power into the water column from waves and tides and is defined as the simple average of those two variables, CP and WP:

$$ND = (CP + WH)/2$$

The resulting ND index was gridded at 500 meters, transformed (using sqrt(1 - x)) to normalize the distribution (in Gaussian sense), and normalized on a 0 to 1 scale.

2.1.3 Habitat Template

The SG and ND indices were visualized together by using a color map corresponding to the four expected species types (see Figure 1). Biodiversity hotspots were mapped by shading areas on the map that correspond to expected high, medium and low diversity according to ecological theory (Southwood 1988) (see Figure 2).

2.3 Summary

The first method, the Habitat Typology, is a classical method designed to extract information or patterns from a large set of data, without a-priori inferring any pattern or relationship. It naturally regroups areas that "look alike". By choosing only abiotic variables, we decided to identify regions based on geomorphological and oceanographic characteristics: those define the oceanic landscape or habitat.

The ultimate objective of the analysis is to identify biotopes associated to those regions, or specific ecological assemblages associated to those habitats. We have previously used a similar method to identify "ecological regions" based on biodiversity and establishing the link between those and habitats (Grilli, 2011,2012). In the present study, we focus on relating the abiotic Habitat Typology with ecological zones defined using the Habitat Template method. While the typology is a deductive approach (Observations-> "pattern"), the Habitat Template method is an inductive method (Theory -> "pattern"). Kostylev and Hannah (2007) establish a theory first to express the Scope for Growth and the Natural Disturbance: they assume that the disturbance is linearly proportional to tide and waves indices (proportional to tide and wave power) and that the scope for growth is linearly proportional to the phytoplankton availability, tendency to upwelling and water temperature. This modeling results in two indices, that when combined, provide a theoretical biodiversity template. The purpose of the present analysis is to validate the theoretical Habitat Template model with the observed marine landscapes identified within the Habitat Typology.

3 Results

3.1 Habitat Typology

3.1.1 PC Analysis

Applying the PCA to the data set results in reducing the number of original variables to a smaller number of components to explain a large fraction of the total spatial variance. Here, we find that the first 6 PCs contain about 75 % of the information (total variance) of the 17 original variables defined in Section 2.

It is standard, however, for the clustering analysis to limit the number of PCs used to the number of PCs that explain 90 to 95 % of the variance. Here, the first 10 PCs explain 92 % of the variance and will therefore be considered as the new variables to represent the spatial information (Figure 4).

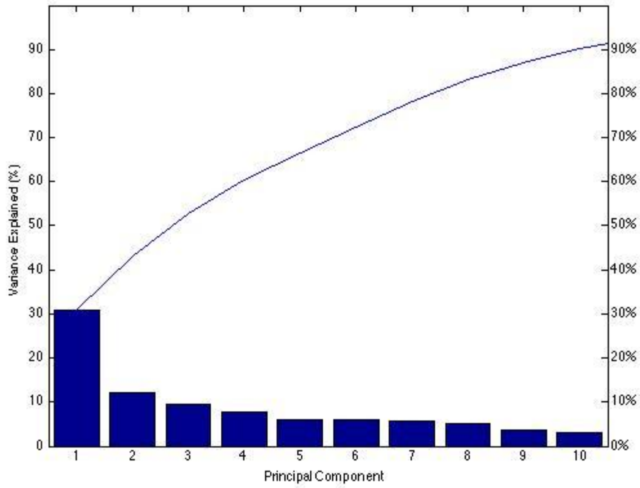

Figure 4. Principal components (PCs) listed by decreasing order of total variance explained by each component. Solid line indicates cumulative variance explained.

In a second stage, the PCs are rotated in the multi-space to maximize the correlation with the original variables so that they can be more easily interpreted. Indeed, this rotation results in PCs that are close in space to some original variables, which facilitates their physical interpretation. In this work, we are only interested in creating homogeneous regions by clustering and, hence, a physical interpretation of PCs is not of critical interest at this stage. However, it is enlightening to have a grasp on the physical interpretation of the PCs, as this provides a feeling for the physical processes driving the regionalization into different marine landscape and habitats. Let's note that the discussion of the physical meaning is restricted to the first 6 PCs (which are those which have a clear physical interpretation). Even if other variables do not have a clear physical interpretation, they still carry some potentially relevant information that will be included in the clustering process.

Accordingly, Table 2 lists correlation coefficients with the 17 original variables, for the first six (rotated) PCs. Each PC is ranked 1 to 6 based on the part of the variance that it explains. Large correlations with original variables highlight the driving factors. Each PC can therefore be associated to one, or a combination of physical processes, driving the marine landscape diversification, and ranking the controlling factors in the marine landscape diversification process.

Table 2. Correlation between the 16 original variables and the first 6 rotated Principal Components. Red numbers indicate high correlation between PC and variable.

	PC1	PC2	PC3	PC4	PC5	PC6
Bottom velocity	-0.32069	-0.11305	**-0.77121**	0.18186	0.13051	-0.065777
Significant wave height	**0.70849**	-0.078078	-0.10504	-0.11468	-0.21253	0.023365
Depth	**0.74975**	0.090743	0.019154	-0.29029	-0.25577	0.38232
Distance to shore	**0.88467**	0.019237	-0.28915	-0.11754	-0.20535	-0.03078
Slope	-0.26698	-0.11134	-0.030921	0.13633	0.38085	-0.019022
Roughness	-0.27386	0.098847	-0.099713	0.25152	**0.88977**	-0.13099
Phi median	-0.12696	**0.72991**	0.26466	0.041732	0.0068522	0.15258
Clay (%)	0.015152	**0.97422**	-0.080831	0.031853	0.0098546	-0.095706
SST (Spring)	-0.072142	0.061674	**0.82282**	-0.08333	-0.047488	0.086222
Stratification (Spring)	0.48124	0.041967	0.23937	-0.10638	-0.1431	**0.65474**
SST (Fall)	0.65504	-0.16876	0.096254	0.0090079	-0.069389	0.002001
Stratification (Fall)	**0.86155**	0.007841	0.16841	-0.063213	-0.17153	0.31478
Aspect Ratio	-0.0048927	-0.018657	0.010708	0.017365	-0.0055405	-0.0049363
BPI fine scale	-0.10485	0.10576	-0.082224	0.55616	0.39357	0.013593
BPI large Scale	-0.10282	-0.0015277	-0.10069	**0.96255**	0.13756	-0.12496
Southward sloping	-0.0087505	0.00037461	-0.0031748	0.0076542	0.0018941	0.0017756
Eastward sloping	-0.0013689	-0.00077779	-0.00090565	0.0016125	0.0020273	-0.0013082

The correlations provide the information to interpret the PCs in terms of physical processes. While it is generally easier to relate the first few PCs to physical processes, it is often impossible to find any physical meaning to the last PC. Therefore the correlations between PCs and physical variables are only shown in Table 2 for the first 6 PCs, which explain 75% of the total spatial variance. The examination of the correlations leads to the following physical interpretations for the first 6 PCs:

PC1: *Offshore-ness/coastal-ness*

Correlated with: water depth, distance to shore, water column stratification

PC2: *Sedimentology*

Correlated with: sediment grain size and type.

PC3: *Fresh Water input*

Correlated with: Sea Surface Temperature (SST) and bottom velocity.

PC4: *Large scale geomorphology*

Correlated with: Large scale BPI.

PC5: *Fine scale geomorphology*

Correlated with: Roughness.

PC6: *Upwelling*

Correlated with: Stratification.

3.1.2 Cluster Analysis

The regrouping of the grid cells is based on their similarity. The similarity is measured in terms of Euclidian distance in the reduced multivariate-space of the PCs. Cells close to each other are regrouped within the same cluster.

The analysis was performed using 10 PCs, and 9 clusters were identified in the analysis as statistically relevant to characterize the SAMP marine landscape and habitat.

Let us note that the grouping occurred in a 10-dimensional space, since we kept 10 PCs, which is impossible to visualize. We show in Figure 5, the resulting clusters projected in a reduced 3-D PC space, but we have to keep in mind that the multi-space is far more complex.

Similarly, each cluster can be interpreted in terms of the original variables, rather than in terms of PCs. In Table 4, each cluster is associated with its mean value in terms of original variables. For example in Cluster 1, individuals or grid cells have on average a depth of 29 m and a mean distance to shore of 21 km. In this analysis, we actually have the complete statistical distributions of each of these variables for each cluster, but for sake of clarity, here, we only present the mean values.

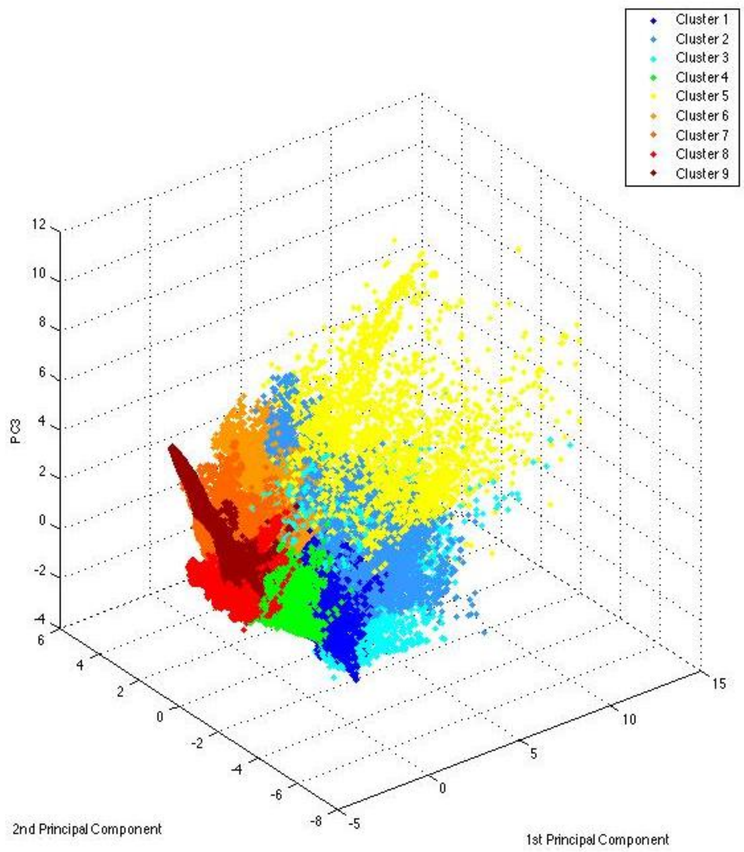

Figure 5. Projection of 9 clusters in the reduced 3-D space of the 3 first PC.

Table 3. Mean values of the original 16 variables within each of 9 clusters. Red numbers indicate the most significant variables defining each cluster.

	C1	C2	C3	C4	C5	C6	C7	C8	C9
Bottom velocity(m/s)	**0.36**	**0.72**	0.26	0.18	**0.31**	0.16	0.13	0.15	0.16
Significant wave height(m)	7.2	7.4	5.6	**8.9**	6.4	7.1	7.8	**9.5**	**9.4**
Depth(m)	28.8	22.7	**18.1**	**37.1**	19.5	23.3	36.0	**48.9**	**50.1**
Distance to shore(km)	20.8	19.5	**6.1**	**40.5**	16.2	**11.3**	19.8	**43.8**	**60.5**
Slope	0.18	0.26	**0.70**	0.12	0.32	0.18	0.14	0.09	0.04
Roughness	0.25	**0.51**	**0.67**	0.12	**1.00**	0.34	0.16	0.09	0.07
Phi median	1.47	**2.29**	1.82	1.75	**2.45**	**2.91**	**2.97**	2.19	2.67
Clay (%)	0.68	**4.67**	1.35	0.30	**5.68**	**4.71**	**3.42**	1.72	**9.26**
SST Spring (deg. C)	9.30	9.02	9.66	9.49	9.40	9.85	9.90	9.71	9.25
Stratification Spring	5.706E-06	2.974E-06	2.806E-06	2.190E-05	2.342E-06	3.097E-06	**4.678E-05**	**5.372E-05**	2.824E-05
SST Fall (deg. C)	12.25	12.36	12.87	12.55	12.29	12.20	12.48	12.83	12.87
Stratification Fall	3.317E-06	1.122E-06	2.920E-06	7.125E-05	2.018E-06	1.632E-06	5.626E-05	**1.325E-04**	**1.095E-04**
Aspect Ratio	196.14	174.93	163.98	188.76	188.52	179.79	187.66	178.73	182.34
BPI fine scale	-1.64	**32.55**	17.66	-8.49	**330.89**	2.94	-7.23	-10.91	-14.05
BPI large Scale	-0.33	**79.63**	49.75	-0.62	**256.66**	11.08	-8.30	-9.42	-16.28
Southward sloping	0.004	0.006	0.003	0.002	0.038	-0.008	0.007	-0.014	-0.007
Eastward sloping	0.014	-0.014	0.007	-0.001	0.013	-0.005	-0.010	-0.004	0.001

Clusters are mapped on Figure 6.

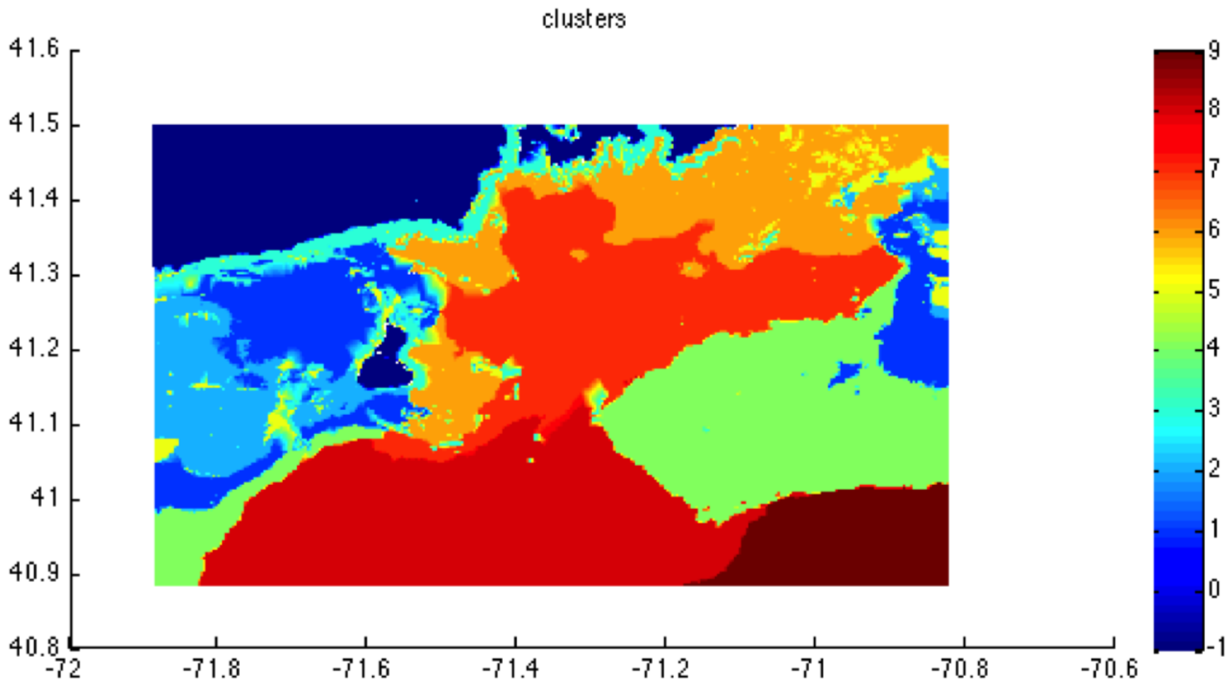

Figure 6. Typology of Marine Landscape and Habitat in SAMP area cluster (clusters 1-9 are color coded).

- ***Cluster 1 (C1):*** Intermediate depth and distance to shore; medium sand (phi 2-1); relatively cold water; relative high bottom velocity-> fresh water inflow on relative smooth geomorphology.
- ***Cluster 2 (C2):*** Intermediate depth and distance to shore; fine sand (phi 3-2) some clay; higher roughness and BPI index than C1; coldest water; highest bottom velocity-> fresh water inflow on relative rough geomorphology.
- ***Cluster 3(C3***): Shallow coastal water inside the stormy breaking wave area.
- ***Cluster 4 (C4):*** Offshore area in relatively shallower water; medium sand smooth geomorphology, no clay**.**
- ***Cluster 5 (C5***): Highest roughness and BPI index area of high bottom velocity and coldest temperature; fresh water inflow in shallow water and complex geomorphology (ridge), fine sand and clay.
- ***Cluster 6 (C6***): Close to shore; very fine sand and some clay; warmer than C1-C5.
- ***Cluster 7 (C7):*** Stratified warmer water in intermediate/deep water on similar fine sand as C6, but further away from shore.
- ***Cluster 8 (C8):*** Stratified warner water, in deeper offshore area on medium sand floor.
- ***Cluster 9 (C9)***: Similar Stratified offshore water in the deepest area, on fine sand and clay.

3.2 Habitat Template

The SG Index (Figure 7) and ND Index (Figure 8) highlight areas within the RIOSAMP study area where energy available to organisms might be highest (red areas on Figure 7) and where bottom disturbance due to natural causes might be highest (red areas on Figure 8). It is important to note that the results are scaled within the RIOSAMP area. Therefore, the red areas on the map represent the highest values for each index with respect to the RIOSAMP area; not with respect to neighboring Narragansett Bay or further offshore.

We categorized the values of SG and ND in order to visualize them in the context of the expected species types including filter feeders, predators, mobile generalists and tolerant species (Figure 9). Using the thresholds for biodiversity predicted by ecological theory (Southwood 1988; see Figure 2), we were able to visualize the areas of highest biodiversity in the RIOSAMP study area (Figure 10). We also visualized the areas of highest diversity in the context of geomorphology (Figure 11). The comparison between geomorphology and modeled diversity is particularly interesting because there are currently no geomorphic or sediment variables incorporated in the Habitat Template modeled for this study.

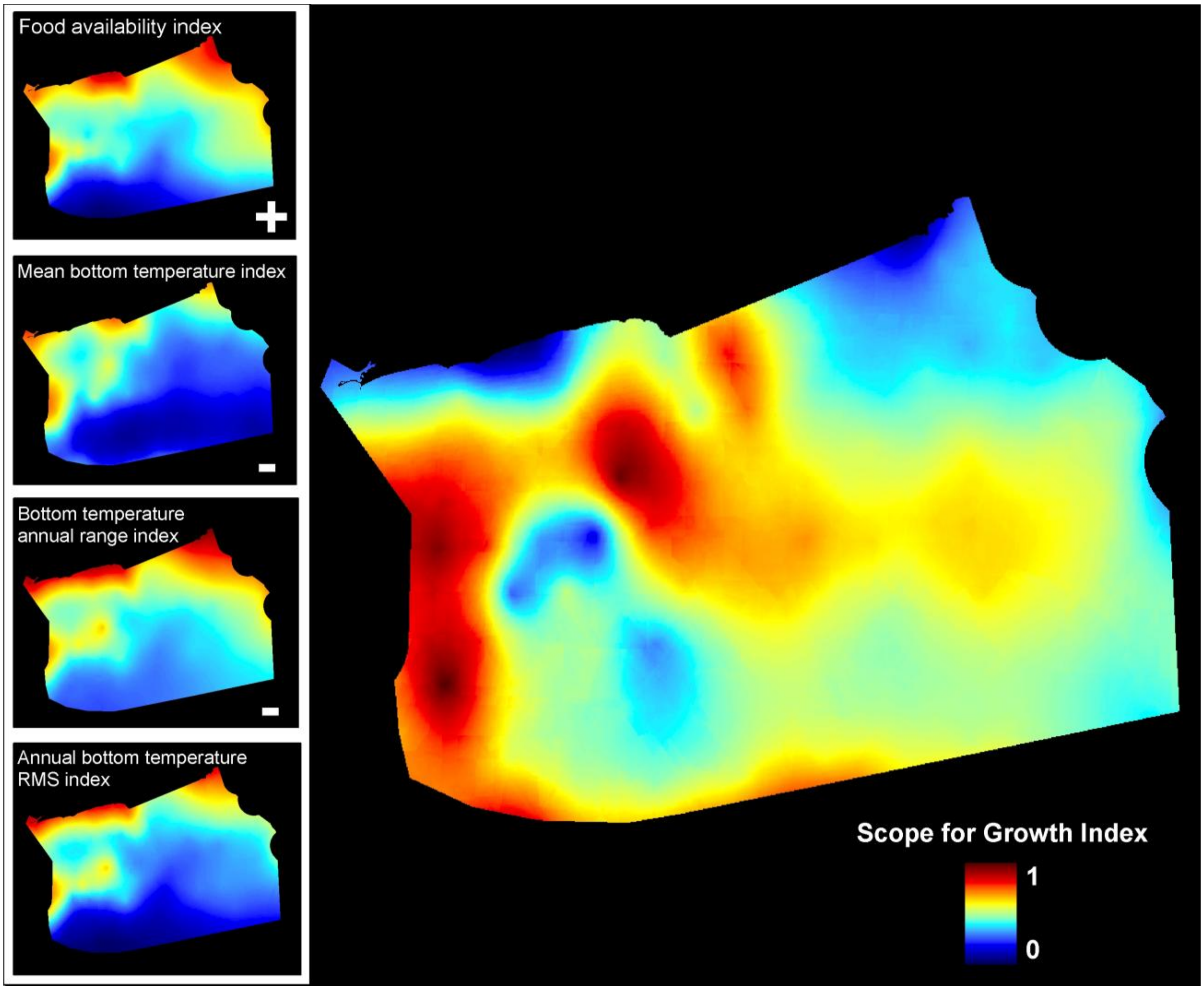

Figure 7. Modeled Scope for Growth Index for the RIOSAMP area (large right pane) and the data used to assemble the linear additive model (left stacked panes).

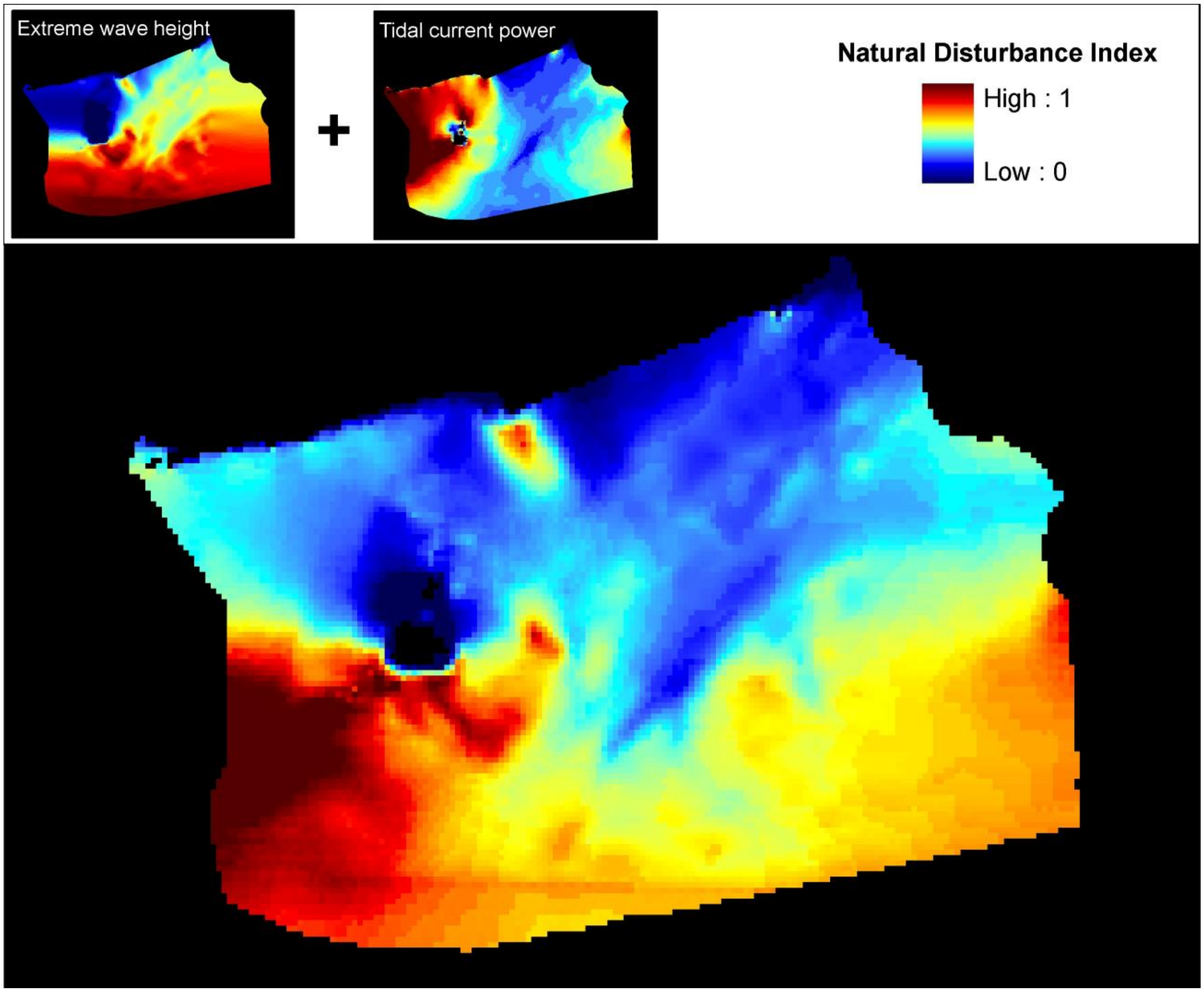

Figure 8. Modeled Natural Disturbance index for the RIOSAMP area (large bottom pane) and the data used to assemble the linear additive model (top left panes).

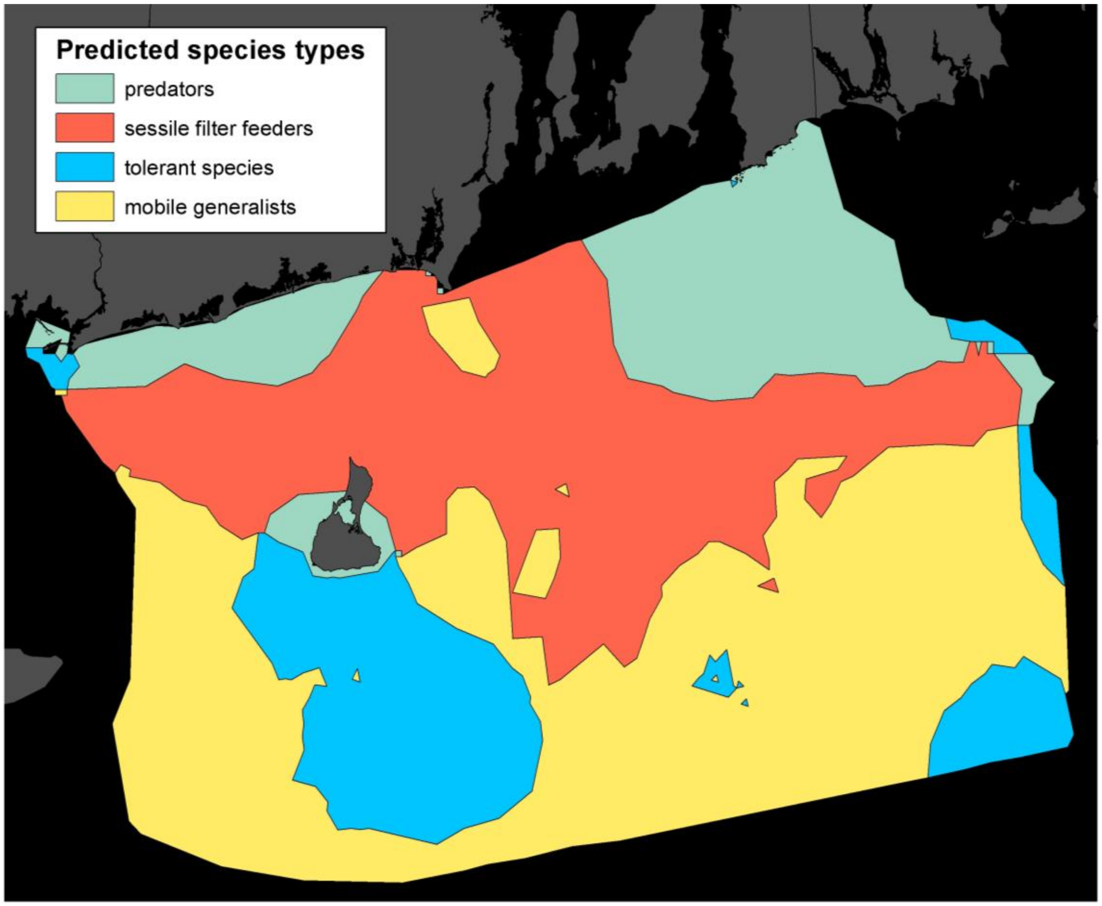

Figure 9. Predicted species types according to SG and ND index values (see Figure 1). Blue and yellow areas have the highest Disturbance; yellow and red areas have the highest Scope for Growth.

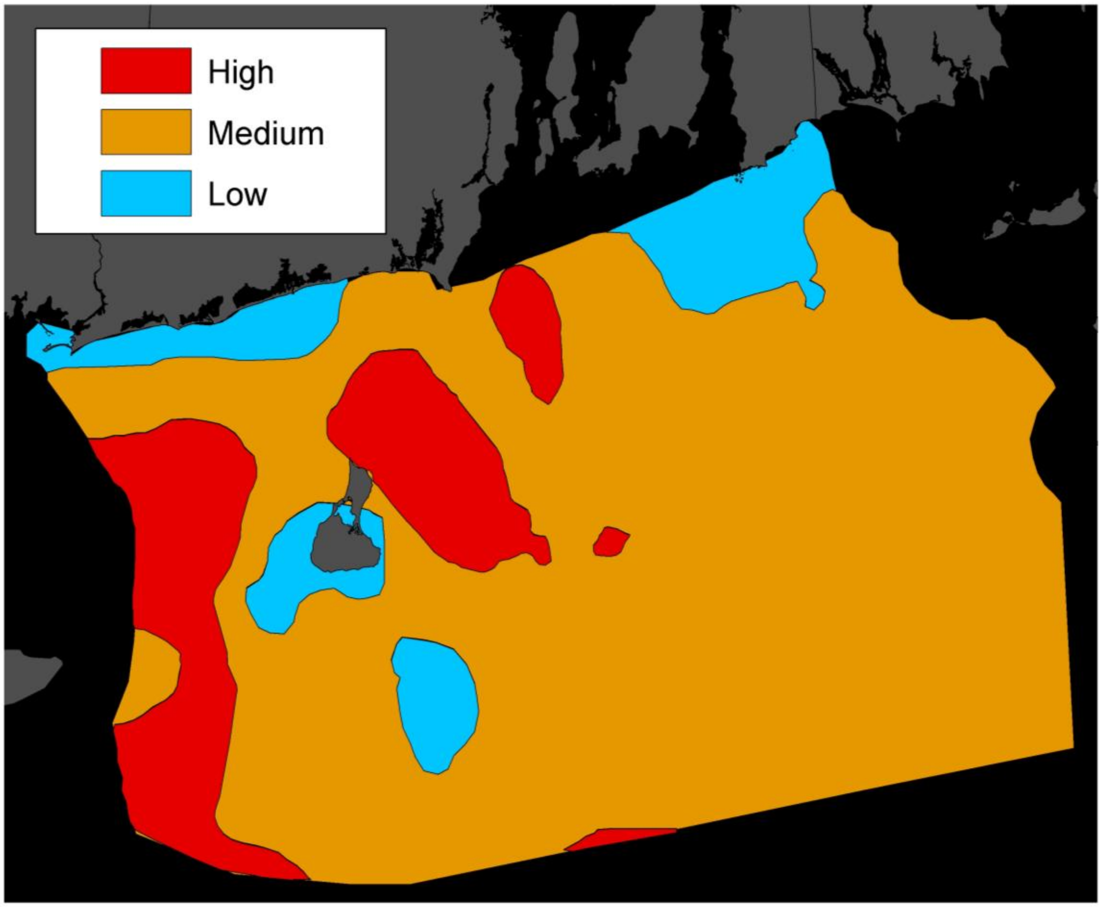

Figure 10. Biodiversity hotspots in the RIOSAMP study area. “High”, “Medium” and “Low” refer to the degree of biodiversity as shown in Figure 2.

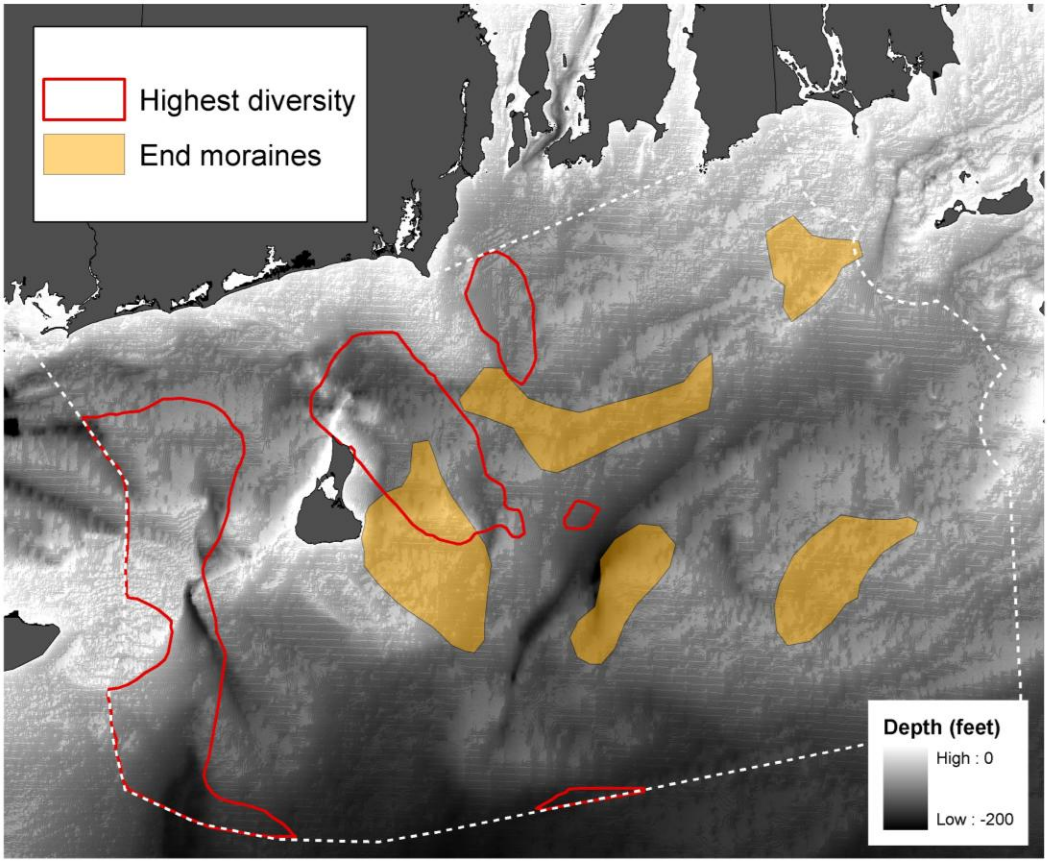

Figure 11. Areas of highest biodiversity shown with location of end moraines and bathymetry values.

4 Interpretation

4.1 Habitat Typology

- The typology clearly separates the RI Sound (East of Block Island) from the BI sound (West of Block Island), based on the fresh colder water inflow and higher tidal velocities associated to the Long Island Sound tidal hydrodynamics (West of the BI Sound).
- Inside each sound, the analysis identifies 2 major factors controlling the marine landscape:
  - *<u>The offshore-ness, coastal-ness gradient.</u>*
    - This factor is associated to depth and distance to coast. It differentiates offshore from coastal waters.
    - Upwelling might be a significant sub-factor.

- *<u>The sedimentology and geomorphology</u>*
  - The sedimentology factor reflects the sediment grain size, coarse to fine sand, clay presence or not.
  - The geomorphology factor reflects the sea bottom roughness; large scale as well as fine scale roughness are clearly identified as driving factors.

4.2 Habitat Template

Like the Habitat Typology, the spatial patterns in the SG and ND indices suggest that there is an important distinction among habitat types related to offshore versus near shore conditions and the underlying geomorphology of the RIOSAMP area. For example, ND tends to be higher further offshore and lower in bathymetric depressions; SG tends to be higher over areas of complex bathymetry (compare Figures 7 and 11) and lower in the most coastal waters. However, the quadrants of the Habitat Template show a more latitudinal separation in ocean landscapes or habitat zones than the Habitat Typology method. This may be due to the fact that the Habitat Template method incorporates a measure of biological variability (i.e., Food Availability) and the Habitat Typology does not include a type of biotic variable, and that this is driven mostly by depth and distance to shore.

In terms of ecosystem value, the locations of biodiversity hotspots derived from the Habitat Template show a wide variety of geomorphologies as potentially valuable habitats. For example, the western-most hotspot is an area of very complex bottom, whereas the northernmost hotspot is on a relatively flat area of seafloor. This finding is interesting because it indicates that geologic habitat is not the only determinant of biological value (i.e., “some moraines are more valuable than others”).

- Future studies using the Habitat Template approach in the RIOSAMP area will focus on:
- Incorporating sediment grain size and geomorphology in order to improve the model of natural disturbance
- Increasing the resolution of the model
- Expanding the spatial domain beyond the stark boundaries of the RIOSAMP study area
- Testing the biodiversity predictions of the model

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