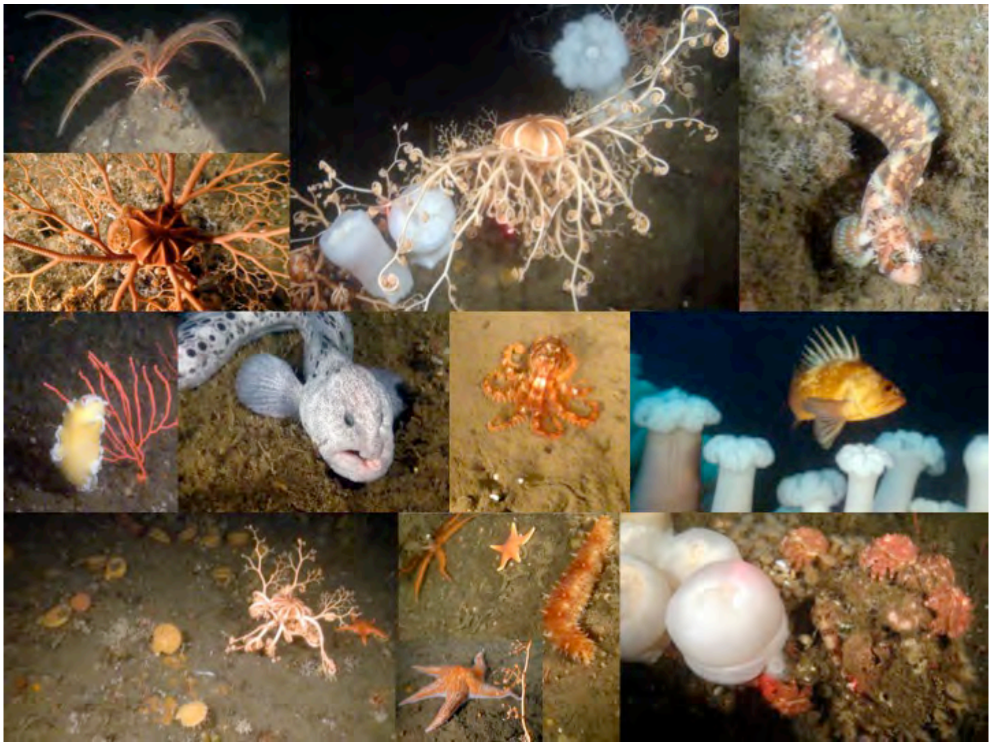
OCS Study
BOEM 2014-662

Benthic Habitat Characterization Offshore the Pacific Northwest Volume 2: Evaluation of Continental Shelf Benthic Communities



US Department of the Interior
Bureau of Ocean Energy Management
Pacific OCS Region

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BOEM 2014-662

Benthic Habitat Characterization Offshore the Pacific Northwest

Volume 2: Evaluation of Continental Shelf Benthic Communities

Authors

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Survey of Benthic Communities near Potential Renewable Energy Sites Offshore the Pacific Northwest

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Abbreviations and Acronyms

AT&SML	Active Tectonics and Seafloor Mapping Lab
BOEM	Bureau of Ocean Energy Management
CEOAS	College of Earth Ocean and Atmospheric Sciences
CMECS	Coastal and Marine Ecological Classification Standard
COR	Contracting Officer’s Representative
CSE	Council of Science Editors
CTD	Conductivity, Temperature, Depth
DOI	US Department of the Interior
EFH	Essential Fish Habitat

EIS	Environmental Impact Statement
EPA	US Environmental Protection Agency
ESP	Environmental Studies Program
ESPIS	Environmental Studies Program Information System
FRAM	Fisheries Resource Analysis and Monitoring
GIS	Geographic Information System
GPS	Global Positioning System
HMSC	Hatfield Marine Science Center
IMU	Inertial Motion Unit
MMI	Marine Mammal Institute
MHK	Marine Hydrokinetic
MLC	Maximum Likelihood Classification
NAMSS	National Archive of Marine Seismic Surveys
NGDC	National Geophysical Data Center
NMFS	National Marine Fisheries Service
NNMREC	Northwest National Marine Renewable Energy Center
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
OCNMS	Olympic Coast National Marine Sanctuary
OCS	Outer Continental Shelf
ODFW	Oregon Department of Fish and Wildlife
ONR	Office of Naval Research
OSU	Oregon State University
PO	Project Officer
PMEC	Pacific Marine Energy Center
RMS	Root Mean Square
ROV	Remotely Operated Vehicle
SETS	South Energy Test Site
SGH	Surficial Geologic Habitat
SWMP	State Waters Mapping Program
TPI	Topographic Position Index
USGS	United States Geological Survey
VRM	Vector Ruggedness Measure
WEC	Wave Energy Capture

4. Patterns of Benthic Mega-Invertebrate Habitat Associations (ROV Report)

4.1 Introduction and Background

Although the oceans provide a variety of valuable goods and services, societies sometimes fail consider the damage that such resource exploitation may cause to marine ecosystems over time (Jackson et al. 2001). Examples of anthropogenic impacts and over-exploitations of these ecosystems are numerous, and hard continental shelves and rocky reefs are among marine ecosystems the most impacted (Lotze et al. 2006; Halpern et al. 2008). Fisheries using bottom gear such as trawls and dredges are by far the most damaging for the seafloor, acting like forest clear-cutting (Watling and Norse 1998). Due to technological improvements during the last decades, bottom-fishing gears are now used from polar to tropical waters on every type of seafloor; only few places on the world's continental shelves remaining non-impacted (Watling and Norse 1998; Halpern et al. 2008). Other human uses of the oceans like aquaculture, mining or tourism activities threaten continental shelf ecosystems (Rossi 2013) and their effects, both direct and indirect, are synergistic (Jackson et al. 2001; Kaplan et al. 2013). Although the intensity and extent of effects on seafloor communities by marine renewable energy developments, like wave energy or offshore wind farms are as yet uncharacterized (Henkel et al. 2014) past studies of oil platforms have shown that these installations can affect invertebrate communities locally by providing surface for fouling invertebrates to establish, and in some cases, facilitating species invasions (Page et al. 2006). Wave and/or wind installations could similarly alter the habitat since they could act as artificial reefs with large surface area for new colonies of sessile invertebrates to establish (Wolfson et al. 1979). In addition, bringing new colonies of sessile invertebrates could also alter the ecological niches and change food web dynamics (Langhamer et al. 2009).

One of the major threats to continental shelf ecosystems is a reduction of habitat complexity and heterogeneity by damage to or smothering of slow-growing structure-building organisms like sponges or gorgonians (Watling and Norse 1998; Kaiser et al. 2006; Sheehan et al. 2013), typically found on rocky outcrop, as well as damage to or sedimentation of a rocky outcrop or reef itself. The preferred wave energy installation sites are sedimentary habitats with flat or low relief. As currents flow around installed devices, greater volumes of sediments will be sent into the water column, possibly exposing nearby rocky habitats to increasing sedimentation. Increasing sedimentation in some coral reefs have shown to exert negative effects by smothering the colonies, which reduces recruitment, decreases net productivity, and decreases calcification (Rogers 1990). If the rate of sedimentation on nearby reefs increased due to offshore installations, this could pose a threat to sponges, gorgonians, and crinoids, as their colonies could be smothered by increased sedimentation rates. Habitat heterogeneity can be a major driver of variability in the abundance and diversity of marine species (Benedetti-Cecchi and Cinelli 1995; García-Charton et al. 2004), supporting global species diversity by increasing niche availability and community complexity and facilitating the formation of distinct species assemblages (Cerame-Vivas and Gray 1966; García-Charton et al. 2004; McClain and Barry 2010).

The Pacific Northwest (PNW) continental shelf, especially the northern part (i.e. off Oregon and Washington), is mostly characterized by mud and gravel habitats, but rocky outcrops and reefs occur in several areas (Romsos et al. 2007), supporting structure-building invertebrates that increase the habitat complexity of the seafloor (Strom 2006). This region has a long history of fisheries with a variety of fleets using bottom gears dedicated to groundfishes, dermersal rockfishes, crabs and shrimps. Moreover, it is becoming a focus area for offshore wave and wind energy installations on the continental shelf and slope. However, despite the abundance (and some documentation) of invertebrate bycatch, little is known about mega-invertebrate assemblages on this part of the continental shelf. Hixon and Tissot (2007) and Hannah et al. (2010, 2013) compared trawled versus untrawled mud assemblages at two location sites on the Oregon continental shelf, and Tissot et al. (2007) described the invertebrate and fish assemblages at a single outer continental shelf reef off Oregon. Only Strom (2006) has summarized the distribution of structure-forming invertebrates at multiple sites along the continental margin off Oregon. Off southern California, different invertebrate assemblages have been distinguished based on the physical structure of the habitats: habitats composed of high-relief consolidated rocky outcrops are associated with greater densities of sessile and structure-forming mega-invertebrates including sponges and gorgonians while habitats composed of unconsolidated fine sediments are associated with motile mega-invertebrates including sea stars, crustaceans, bivalves, and sea cucumbers (Allen and Moore 1996; Allen et al. 1997; Stull et al. 1999; Tissot et al. 2006). Large sized, structure-forming mega-invertebrates such as sponges, corals, crinoids, and basket stars have been suggested to provide shelter and additional resources for both fish and other invertebrates by increasing the availability of microhabitats through their large surface area (Tissot et al. 2006).

4.1.1 Study Purpose and Objectives

The purpose of this study was to distinguish mega-invertebrate communities living on or near consolidated rocky outcrops across the Pacific Northwest. The objectives of this study were to determine first if it is possible to distinguish finer resolution habitat differentiation (beyond high-relief and unconsolidated sediment classification groups) based on substrate types; and second, to characterize the diversity and composition of mega-invertebrates found in those habitats. We hypothesized that mega-invertebrate assemblages found on pure mud substrata differ from assemblages found on mud mixed with rocks (hereafter called mixed mud-rock), which in turn differ from assemblages living in habitats primarily composed of rocks. Within rocky habitats we hypothesized that the slope of the rock (i.e. flat versus ridge rock) and the cover (i.e. consolidated rock with a cover of unconsolidated smaller rocks, hereafter called rubble, versus a cover of sediment veneer or no cover) affect the composition of associated epifauna. To test these hypotheses, we separately analyzed two sets of underwater video footage from three different sampling areas along the Washington (Grays Bank) and Oregon (Siltcoos Reef and Bandon-Arago) coasts, identifying and enumerating the sessile and motile mega-invertebrates from the images, and characterizing the encountered substratum types. The primary footage analyzed for this project was collected in 2011-2012 via ROV with a sampling plan purposefully designed to cover a maximum diversity of available habitats at study sites with regularly spaced stations comprised of three parallel transects. Additionally, we analyzed footage from the mid to early 1990's collected via the submersible *Delta*, consisting of long dives focused on the sediment and rock structure but not on the benthic invertebrates inhabiting these reefs, so the speed and the height of the submersible varied which is not ideal for mega-invertebrate identification and enumeration. The observations from the two studies thus were not directly compared; we sought to determine if the habitat distinctions and invertebrate assemblage associations determined via the systematic ROV surveys were similarly distinguished in the more 'exploratory' *Delta* dives.

4.2 Methods

4.2.1 Study Sites

Our study comprises two series of data: a first series of dives from the early to mid-1990s, and a series of more recent dives (2011-2012) (Figure 1). In the early to mid-1990s, Oregon State University geologists surveyed the seafloor at sites from Washington to northern California using a manned-submersible, *Delta*, to explore regions of tectonic and faulting activities off Oregon and Washington coast and to visually confirm and complement the geological structures highlighted by sidescan sonar and seismic reflection data (Goldfinger et al. 1997). The submersible was equipped with a Hi-8 camera attached on the starboard side, sizing lasers, depth, and temperature sensors. We reviewed 19 geologic survey dives from three sites that had not been fully reviewed for invertebrate counts and identification: Grays Bank (GB, n= 4, offshore of Grays Harbor, Washington, September 1994), Siltcoos Reef (SC, n = 7, offshore of Charleston, Oregon, September 1995), and Bandon-Arago (BA, n = 8, offshore Bandon, Oregon; September 1993).

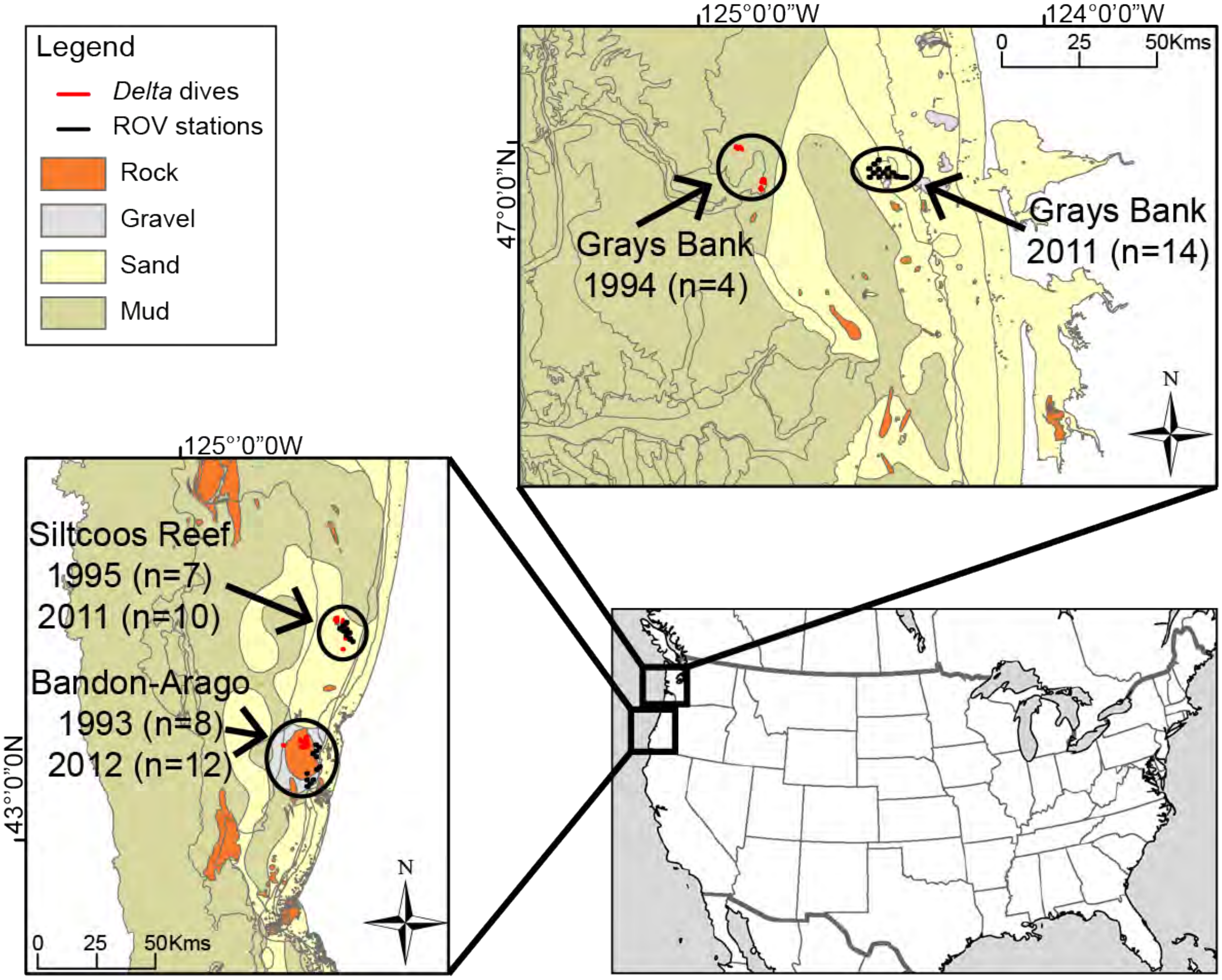
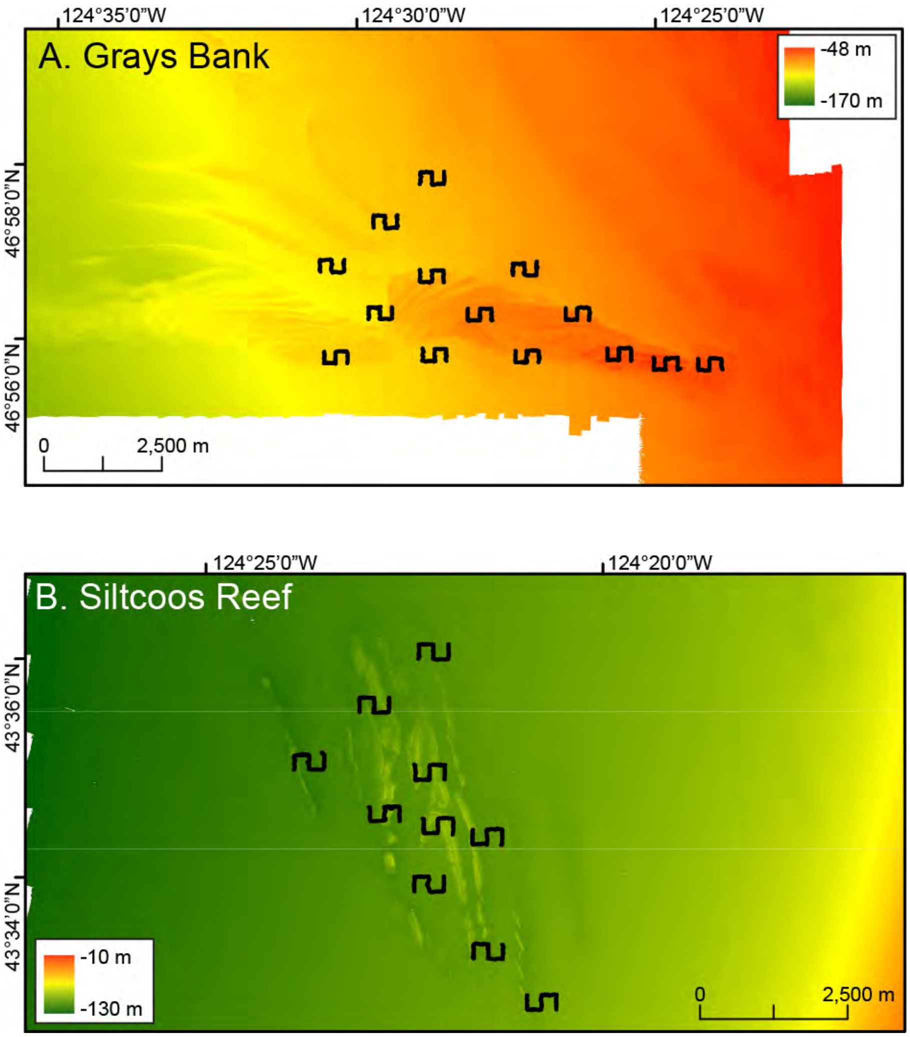


Figure 1. Location of the three ROV and Delta study areas
Tracklines are overlain on surficial lithologic habitats on the Pacific Northwest continental shelf, listed with the number of ROV stations (black lines) and *Delta* dives (red lines) per site.

In late August 2011 and September 2012, we used the remotely operated vehicle (ROV), *Hammerhead*, a modified deep-ocean *Phantom*, to survey habitat and mega-invertebrates at the same three sites: Grays Bank (n = 14; Figure 2A) and Siltcoos Reef (n = 10; Figure 2B) in 2011, and Bandon-Arago (n = 12; Figure 2C) in 2012. For this survey, the Grays Bank stations were on a reef shallower than the one surveyed in 1994; at Siltcoos Reef, ROV stations were slightly further south but overlapped with the stations from 1995; at Bandon-Arago, the northern ROV stations were very close to (but shallower) the stations from 1993 (Table 1). Each ROV station was composed of three transects, each approximately 250 meters long separated 250 meters apart), along which the ROV was kept at a regular speed and a regular height from the bottom to provide images of good quality to identify and enumerate the mega-invertebrates. The ROV was equipped with two cameras attached at the front of the ROV: one facing downward and perpendicular to the sea surface, and the other camera facing outward, angled roughly 30 degrees from the dorsal surface of the ROV. The ROV was equipped with sizing lasers for both cameras, a CTD that measured depth (meters), temperature (Celsius), and salinity (PSU) continuously, and was integrated with a navigation system that measured latitude and longitude every second.


124°35'0"W
124°30'0"W
124°25'0"W
A. Grays Bank
-48 m
-170 m
46°58'0"N
46°56'0"N
0
2,500 m
124°25'0"W
124°20'0"W
B. Siltcoos Reef
43°36'0"N
43°34'0"N
-10 m
-130 m
0
2,500 m

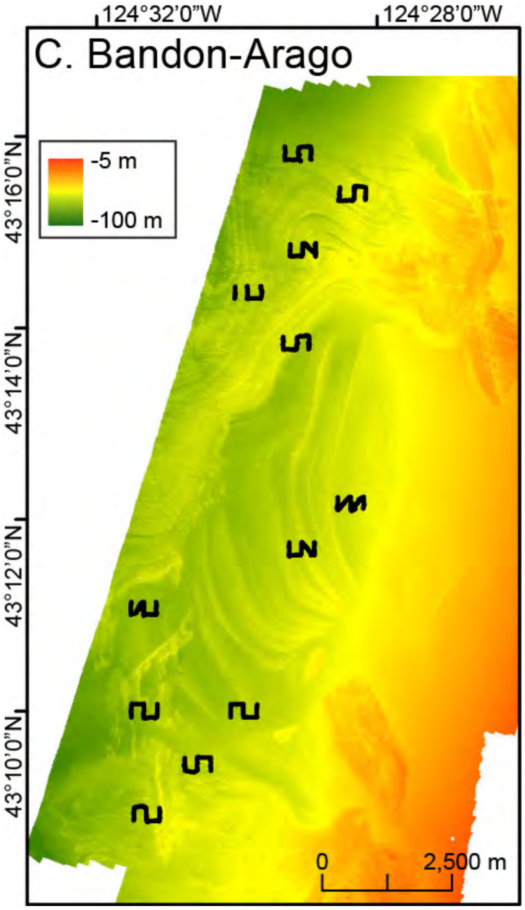


Figure 2. Tracklines of station covered during the ROV surveys at Grays Bank (A), Siltcoos Reef (B) and Bandon-Arago (C)
The bathymetry color shading is at the same scale for the three maps (red = shallow, green = deep).

4.2.2 Video Analyses

Each video was watched a minimum of three times: one for substratum identification, one for sessile mega-invertebrate identification and enumeration, one for motile mega-invertebrate identification and enumeration. Only benthic epifauna and some endofauna taxa showing recognizable body parts above the sediment were recorded. In the ROV *Hammerhead* footage, both the outward and downward facing cameras were used to identify substratum patches and invertebrates. Since one camera faced downward at a fixed angle from the vehicle, all footage viewed by the downward-facing camera was considered "on-transect" and this view was used to count the invertebrates. Generally, video analysis followed guidelines established by Tissot (2008). Each invertebrate entry was accompanied with a time code that was used to determine in which substratum patch a particular invertebrate was found.

In the *Delta* videos, the "on-transect" designation was used to lessen the effects of changing transect widths by variation of seafloor elevations and the height of the submersible off the seafloor with the side-mounted camera providing an oblique view (Strom 2006). "On-transect" was defined as the seafloor appearing below the sizing lasers on the screen; thus, substratum patch identification and invertebrate counts were based on what appeared below the lasers. Substratum patches were identified first then invertebrates were identified within each substratum patch. Based on the average height of the camera off the seafloor and the distance between the sizing lasers and the submersible, the transect width for *Delta* stations was estimated at 2 meters.

Substratum: Substratum patches were identified based on the grain size class and, for consolidated rocks, relief angle, with the start and end times of each substratum patch recorded. Each substratum patch was coded with two letters; the first letter indicated the primary substratum (comprising 50-80% of the duration of the patch) and the second letter indicated the secondary substratum (comprising 20-50% of the duration of the patch): R for ridge rock (angle >30°), F for flat rock (distinguishable from surrounding sediment, angle <30°), B for boulder (> 25.5 cm), C for cobble (6.5 – 25.5 cm), P for pebble (2 – 6.5 cm), G for gravel (4 mm - 2 cm), and M for mud (not distinguished from sand), refined from Stein et al. (1992). If the substratum patch was comprised of two substrata in equal proportions, the patch was coded with the first letter indicating the substratum with larger grain size. If a patch was comprised over 80% of a single substratum type the patch was coded with the same two letters (e.g. MM). See figures in Appendix 4 for screen grabs of example patch types.

Sessile mega-invertebrate: Sessile invertebrates taller than 5 cm were identified and enumerated, as recommended by Riedl (1971) and Tissot et al. (2006) because smaller individuals were difficult to see and identify on the images. Sponges and gorgonians, difficult to identify on video, were characterized based on their morphology and sometimes color (e.g., branching sponge, shelf sponge, branching red gorgonian). Encrusting ascidians and bryozoans, impossible to distinguish on video from encrusting sponges, were all gathered under the name shelf sponge, while possible branching bryozoans were counted as branching sponges. These two names thus describe a life form more than a systematic group.

Motile mega-invertebrate: Motile invertebrates taller than 5 cm were identified to the lowest possible taxonomic level and enumerated. Some taxa were only identified to the family or genus level, since many species in these families / genera have overlapping morphological features and are difficult to distinguish without specimens to analyze. When the abundance of motile invertebrates was high, one to three additional viewings were needed to identify and enumerate all the individuals. In the Bandon-Arago (BA) 2012 footage, small orange brittle stars were too abundant to be counted all along each transect and were only enumerated every 30 seconds.

While reviewing video footage recorded during these two surveys, several identifications were not able to reach the species level without actual specimens to check and dissect for diagnostic morphological characters. For example, the different species of the sea star genera *Henricia* and *Solaster* are impossible to differentiate without a clear check of the aboral plates, the adambulacral spines and the pedicellariae (Lambert 2000; C. Mah, pers. comm.); thus all the encountered individuals were listed as *Henricia* sp. and *Solaster* sp. respectively. Species identification is nearly impossible on video and still images for organisms like sponges, as shapes vary a lot within a species and sponges are usually identified on the structure of their spicules. In the present work, all round-shaped sponges were gathered as a morphologic group under the name "ball sponges", except a common yellow one, which was called "yellow ball sponge" and could be related to the species *Tethya aurantia* or *T. californiana*. The branching and encrusting organisms were difficult to enumerate and discriminate between sponges, bryozoans, and colonial ascidians (in the case of encrusting organisms). All the encountered individuals were counted by tufts (for branching forms) or patches (for encrusting forms) and gathered as functional groups under the names "branching sponge" and "shelf sponges" respectively, even if these groups included more than just sponge species. These taxonomic limits do not allow us to be extremely precise on the identity of some of the characteristic species for each assemblage but it gives an idea of the type of organisms and could encourage going back to those habitats to sample these organisms, particularly the sessile invertebrates, and identify them to species.

4.2.3 Segment Area and Taxon Density

The ROV *Hammerhead* was integrated with a navigation system that was used to calculate the transect width and approximate the distance traveled every second (ranging from 0.001 to 1.36 meters traveled in a second, depending on speed of the ROV and the support vessel). Based on the transect width per second (dependent on the height of the ROV above the seafloor) and the distance it traveled from the previous second, the transect area covered was determined for every second. Therefore, the area of each substratum patch was calculated by adding all area entries from one second after the start time of the segment to the end time of the patch. The density (individuals/m^2) of each taxon per substratum patch was calculated by dividing the sum of a particular invertebrate taxon count by the total area the ROV had covered along this substratum patch. The *Delta* was not equipped with a navigator beam so the area covered by each substratum patch was derived from the average speed of 0.75 knots, or 0.38 m.s^{-1} (Strom 2006). The transect width being fixed at 2 m, the substratum patch area was calculated by multiplying the total time of the segment by the average speed and the patch width. The density of each invertebrate taxon per substratum patch was then calculated as the number of each invertebrate taxon divided by the patch area.

4.2.4 Statistical Analyses

Analyses were performed for the *Delta* and ROV *Hammerhead* datasets separately. The sample units considered here were the different patch types in a whole site: data from all the same substratum patches were pooled at the site level. Only patch types observed longer than one minute in total for a whole site were kept in the analyses. A matrix of Bray-Curtis similarities between patch types was calculated on log-transformed density (# individuals/m^2) data. Nonmetric multidimensional scaling (nMDS), analyses of similarities (ANOSIM), SIMPER, and DIVERSE were performed using PRIMER 6th Edition (Clarke and Gorley 2006). The nMDS analysis plotted sample units (patch types) on a two-dimensional ordination plane based on taxa composition similarities and dissimilarities. Groups of patch types (hereafter 'habitat types') were discerned from the nMDS plot and an ANOSIM was performed to test the strengths of similarities within and differences between these habitat type groups, using permutation and randomization methods on the resemblance matrix. SIMPER (Similarity of Percentage) was used to determine which taxa and their densities contributed to defining each group and the percent contribution of each defining taxon. DIVERSE was used to calculate the diversity indices (average number of taxa S, average density N, Pielou's evenness J') on the untransformed abundances for each habitat group, and a series of ANOVAs and Tukey's HSD tests was performed in the open-source software R (R Development Core Team 2013) to test whether or not the indices were significantly different among habitat groups.

4.3 Results

4.3.1 Site Characteristics

The six sites showed slightly different physical characteristics (Table 1). Bandon-Arago (BA) 2012 and Grays Bank (GB) 2011 were the shallowest, while Grays Bank 1994 was the deepest and the three others were at a similar depth range. The temperature was the coldest at the northern deep stations (GB 1994). The temperature at SC was colder in 1995 than in 2011 and the same trend was observed at BA. The salinity was not recorded during the *Delta* dives but no bathymetric or latitudinal variation in salinity was noticed in the ROV surveys.

Table 1. Metadata associated with the ROV stations and *Delta* dives for all three sites
GB = Grays Bank, SC = Siltcoos Reef, BA = Bandon-Arago. Average duration (n) is the average time per transect for the ROV data and per dive for the *Delta* data with the total number of transects/dives.

		Depth (m)	Temp. (°C)	Salinity (PSU)	Avg. duration (n)	Total area surveyed	Year
ROV	GB	55 - 82	7.25 - 7.33	33.76 - 33.83	13:48 ± 02:46 (42)	225,321 m^2	2011
	SC	97 - 119	7.75 - 7.92	33.84 - 33.88	17:49 ± 04:46 (30)	213,043 m^2	2011
	BA	54 - 68	8.29 - 8.94	33.72 - 33.78	17:59 ± 03:11 (36)	147,607 m^2	2012
Delta	GB	167 - 204	6.45 - 6.61	-	85:18 ± 15:38 (4)	13,074 m^2	1994
	SC	108 - 120	7.39 - 7.42	-	86:05 ± 24:15 (7)	23,175 m^2	1995
	BA	85 - 116	7.75 - 8.11	-	86:27 ± 35:45 (8)	25,363 m^2	1993

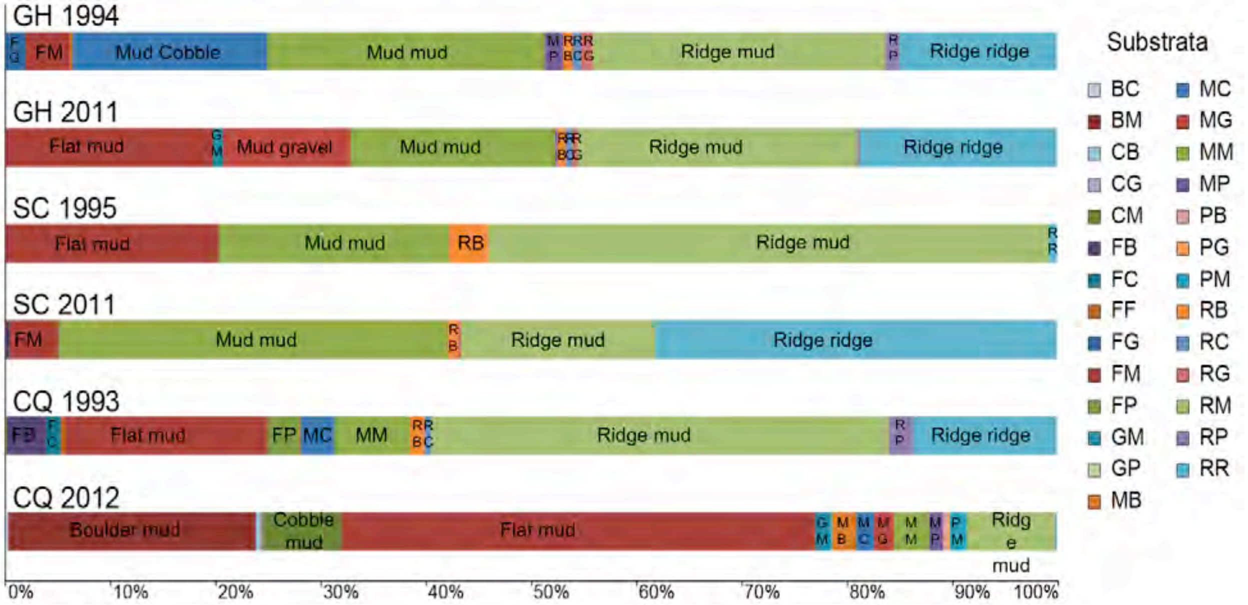


Figure 3. Proportion of substratum patch types per study site

A total of 18 and 28 different substratum patch types were identified in the *Delta* and ROV stations respectively. Considerably greater areas were covered by the ROV surveys (Table 1), contributing to the greater numbers of patch types observed. From 8 to 19 substratum patch types were found per site; however depending on the site, up to eight substratum types were not analyzed because of durations shorter than a minute. The fewest different substratum patch types were observed and analyzed at Siltcoos Reef in both years (5, 6), intermediate patch type diversity was observed and analyzed at Grays Bank in both years (12, 11), and the greatest numbers of substratum patch types were observed and analyzed at Bandon-Arago in both years (14, 17) (Table 2). Substratum types that were found in large proportion across all sites were ridge rock-mud (average = 30%), mud-mud and flat rock-mud (average = 19% each), and ridge rock-ridge rock (average = 14%) (Figure 3). Twelve substratum types were found only once across all six sites, like cobble - gravel found only at BA 2012; four of these lasted less than a minute and were removed before the analyses.

Table 2. Total count of patches of each substratum type observed and analyzed at each site, sorted by descending occurrence across all six sites

Substratum patch types are shown as two letter codes in first column and survey across the top. The fewest different substratum patch types were observed at Siltcoos Reef (SC) in both years (5, 6). The most diversity of substratum patch types was observed at Bandon-Arago (BA) in both years (14, 17). Patches seen for less than one minute are excluded.

	GB 1994	GB 2011	SC 1995	SC 2011	BA 1993	BA 2012
RM	76	146	390	125	281	80
FM	21	108	36	35	183	213
RR	27	107	3	172	50	2
MM	68	71	12	101	22	37
BM	-	-	-	-	-	145
MG	-	72	-	-	-	17
MC	44	-	-	-	17	25
RB	3	3	27	8	21	-
CM	-	-	-	-	1	54
MB	11	-	-	-	4	34
FB	-	-	-	1	44	-
RP	7	3	-	-	30	-
FP	-	-	-	-	35	-
MP	7	3	-	-	-	21
RC	4	6	-	-	13	-
FC	-	-	-	-	22	-
GM	-	8	-	-	-	9
PM	-	-	-	-	-	13
RG	3	8	-	-	-	-
FF	-	-	-	-	6	-
CB	-	-	-	-	-	4
FG	4	-	-	-	-	-
CG	-	-	-	-	-	3
PB	-	-	-	-	-	3
BC	-	-	-	-	-	2
PG	-	-	-	-	-	2

B = boulder, C = cobble, F = flat rock, G = gravel, M = mud, P = pebble, R = ridge rock.

4.3.2 Community Structure

A total of 91 taxa representing eight phyla were found across all six sites (Table 3 and Appendix 4), with more taxa recognized and individuals counted in footage from the ROV survey than the *Delta* survey. The phyla Porifera, Echinodermata and Cnidaria together comprised over 91% of all the invertebrates encountered in the ROV survey and over 99% in the *Delta* survey, Echinodermata being the most abundant in ROV and Porifera in *Delta* (Table 3). Porifera and Echinodermata were the most abundant at

BA (both years), the high numbers of Echinoderms driven by many *Florometra serratissima* observed in 1993 and the highly abundant small orange brittle stars and greater numbers of small sea cucumbers observed in 2012; cnidaria were the most abundant at GB 2011 (Figure 4).

Table 3. Total number of mega-invertebrate taxa and individuals per phylum across all sites in the *Delta* and ROV stations

Includes total counted (n = 252,884) and each phylum's percent contribution to the total count; details of taxa are given in Appendix 4.

Taxon	GB 1994	GB 2011	SC 1995	SC 2011	BA 1993	BA 2012	Total	%
ANNELIDA								
N taxa	0	0	0	0	0	2	2	
N individuals	0	0	0	0	0	83	83	0.03
ARTHROPODA								
N taxa	3	8	3	6	0	8	9	
N individuals	140	698	14	5388	0	102	6342	2.51
CHORDATA								
N taxa	1	1	1	1	1	1	1	
N individuals	1	212	1	48	4	1976	2242	0.89
CNIDARIA								
N taxa	6	13	8	10	8	11	17	
N individuals	1754	12592	3307	5133	6285	6736	35807	14.16
ECHINODERMATA								
N taxa	16	22	18	26	17	24	32	
N individuals	3178	8562	2625	14043	40522	31249	100179	39.61
MOLLUSCA								
N taxa	2	12	1	6	1	10	12	
N individuals	4	257	5	90	1	2543	2900	1.15
NEMERTEA								
N taxa	0	1	0	1	0	1	1	
N individuals	0	12	0	5	0	4	21	0.01
PORIFERA								
N taxa	7	11	7	7	6	13	17	
N individuals	2797	5561	1232	6692	52598	36430	105310	41.64
GRAND TOTAL NO. OF TAXA							91	
GRAND TOTAL NO. OF INDIVIDUALS							252884	

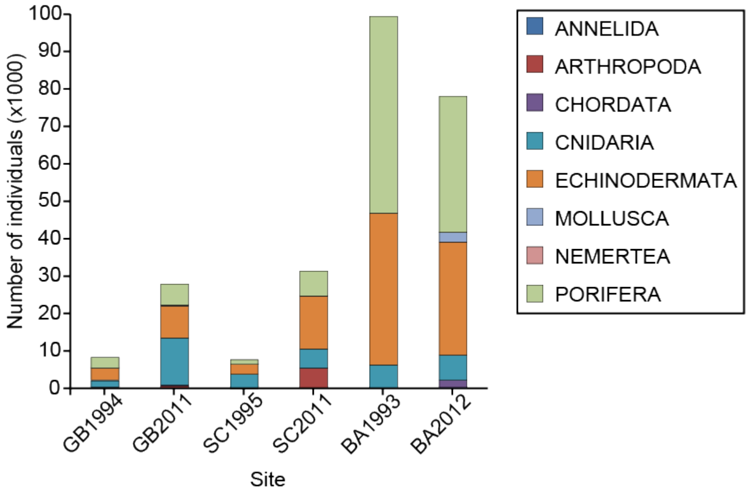


Figure 4. Abundances of benthic macroinvertebrate phyla at the study sites

4.3.2.1. Assemblages Inferred from the ROV Hammerhead Dataset

Based on their taxa composition, six habitat types (groups of patch types hosting similar invertebrate taxa) were identified on two ordination plans of the nMDS for the ROV dataset (Figure 5). The groups (hereafter 'habitat types') were mostly organized by substratum characteristics (e.g. pure mud, mixed mud-rock, consolidated/rubble rock) and subsequently by sites. Unconsolidated sediment patches from the sites split into three groups: group MM-GBSC consisted of pure mud (not distinguished from sand) patches from GB and SC; group Mx-GBSC was made of mixed mud-rock patches from GB and SC; and group Mx-BA gathered pure and mixed mud-rock patches from BA only. Rock-based patches clustered into two main groups: cR made of consolidated rocks, both bare and covered with a veneer of mud (BM, FM, RM, RR), from the three sites; and group rR made of rubble rocks (e.g. BC, FB, RG) from the three sites. Group PG (pebble-gravel), is a patch type found only at BA in a single transect and will not be discussed further. Table 4 identifies which substratum patch types are grouped into each of the five described habitat types.

The ANOSIM performed on these six groups demonstrated significant differences in the taxa compositions overall between the habitat types (Global R statistic = 0.700, with a significance level of 0.1%). In the pairwise test, comparisons were considered reliable when more than ten permutations were possible. Nine of the 12 possible pairwise comparisons showed significant differences between groups (Table 5). The non-significant pairwise comparisons were MM-GBSC vs. Mx-GBSC (6.7%) and PG vs. other groups. However, this was not surprising because of the low number of permutations possible for these pairwise comparisons. Despite these few non-significant ANOSIM comparisons, the SIMPER analysis gave a high percent of dissimilarity between each pairwise comparison, ranging from 70.81% to 99.47% of difference in the taxa composition of the groups (Table 6). Significant differences also were found among the various habitat types based on the univariate analyses of number of taxa (S), density (N), and evenness (J') (Figure 6).

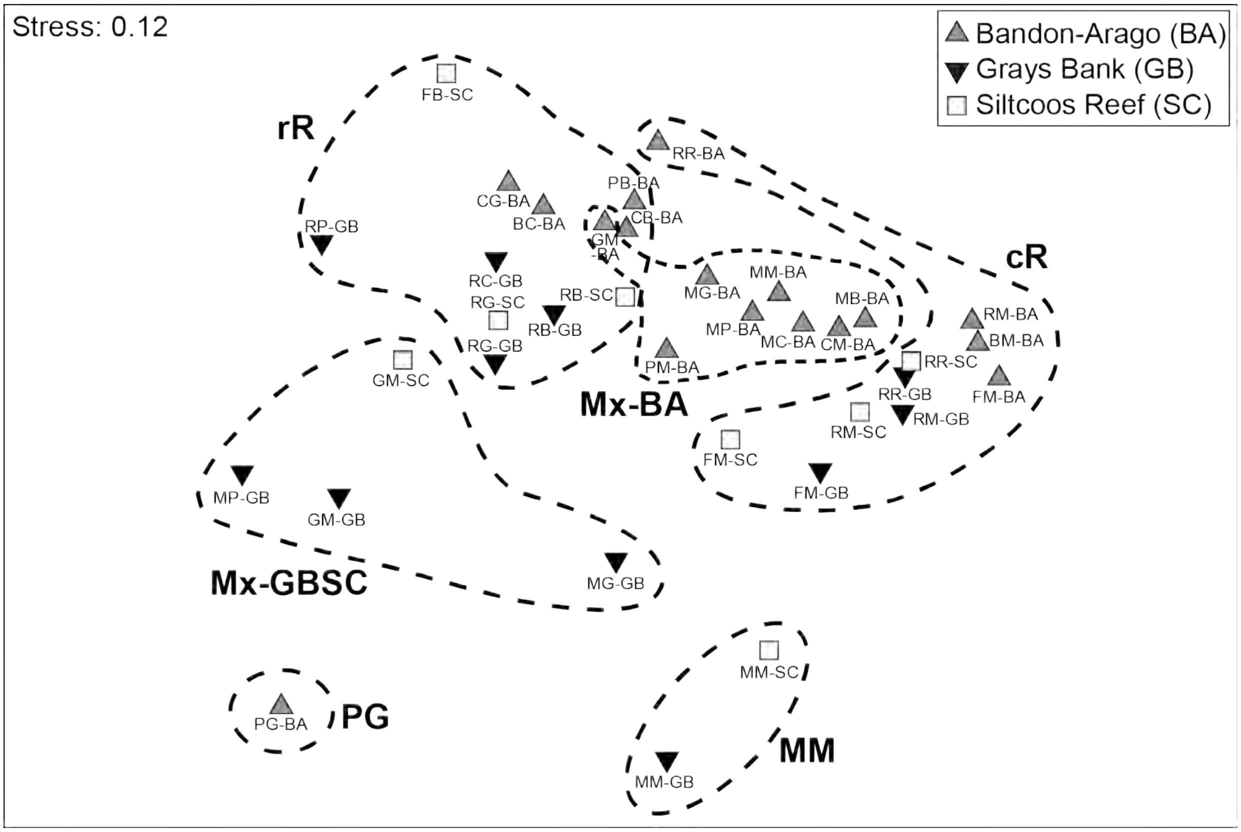


Figure 5. Two-dimensional nonmetric multidimensional scaling (nMDS) ordination of the patch types based on invertebrate community data from the ROV Hammerhead survey forming 4 distinct habitat types (MM, Mx, cR, rR) with some site differences resulting in 6 total groups
Groups distinguished with dotted lines were tested using ANOSIM to investigate within group similarity and between group dissimilarities. MM = pure mud at Grays Bank and Siltcoos Reef, Mx-GBSC = mixed mud-rock at Grays Bank and Siltcoos Reef, Mx-BA = mixed mud-rock at Bandon-Arago, cR = consolidated rocks, rR = rubble rocks, PG = pebble – gravel (found only at BA).

Table 4. General habitat codes determined by analysis of ROV and *Delta* datasets
The two-letter code patch types that are aggregated into each of the habitat codes are listed along with a general description of the habitat type.

Habitat Code	Substrate Types Included	Description
MM	MM	Pure mud/sand (distinct at Grays Bank and Siltcoos, not a unique habitat at Bandon-Arago) for *Delta* and ROV sites.
Mx	MG, MP, MC, MB, GM, PM, CM	Mud mixed with small rocks or boulders (when mud primary) for *Delta* and ROV sites. BA distinguished from GB & SC.
cR	FM, RM, RR, BM	Consolidated rock (flat or ridge), bare or covered with a thin layer of sediment, includes BM (boulders primary) for ROV sites
rR	RG, RP, RC, RB, FB, PB, CB, CG, BC	Rubble rocks, includes mixed smaller rocks (e.g. gravel, pebble) as well as consolidated rock (flat and ridge) and boulders covered with smaller rocks for ROV sites
R/F-BA	RR, RM, RP, RC, RB, FF, FM, FP, FC, FB,	All patch types with consolidated rock (ridge or flat) as primary substrata for *Delta* observations at Bandon-Arago
R/F-SC	FF, RM, RB, FM	All patch types with consolidated rock (ridge or flat) as primary substrata for *Delta* observations at Siltcoos
R-GB	RR, RM, RG, RP, RC, RB	All patch types with ridge rock as primary substrata for *Delta* observations at Grays Bank
F-GB	FM, FG	All patch types with flat rock as primary substrata for *Delta* observations at Grays Bank

Table 5. Pairwise comparisons and significance of major groupings of substrate patch types into habitat types based on identity and densities of mega-invertebrates within the patch types
ANOSIM performed on the habitat types (**Table 4**) derived from the nMDS analyses of patch types of ROV *Hammerhead* dataset (**Figure 5**). Upper matrix is the R-values of the test; lower matrix is the associated p-value (in percent). Pebble Gravel group (PG) was excluded from ROV dataset because the habitat type represented a single group.

ROV	**Global R = 0.700**				
p \ R	**cR**	**Mx-BA**	**rR**	**MM**	**Mx-GBSC**
cR		0.337	0.829	0.828	0.892
Mx-BA	0.5		0.548	1	0.921
rR	0.1	0.1		0.994	0.692
MM	1.5	2.2	1.3		0.714
Mx-GBSC	0.1	0.2	0.3	6.7	

Table 6. Percent dissimilarity between assemblages characteristic of the habitat types by the SIMPER analyses on ROV *Hammerhead* dataset

ROV	**cR**	**Mx-BA**	**rR**	**MM**	**Mx-GBSC**
Mx-BA	70.81				
rR	90.47	77.74			
MM	91.91	93.54	95.64		
Mx-GBSC	95.24	93.18	86.17	93.33	
PG	99.47	98.37	96.38	99.19	93.90

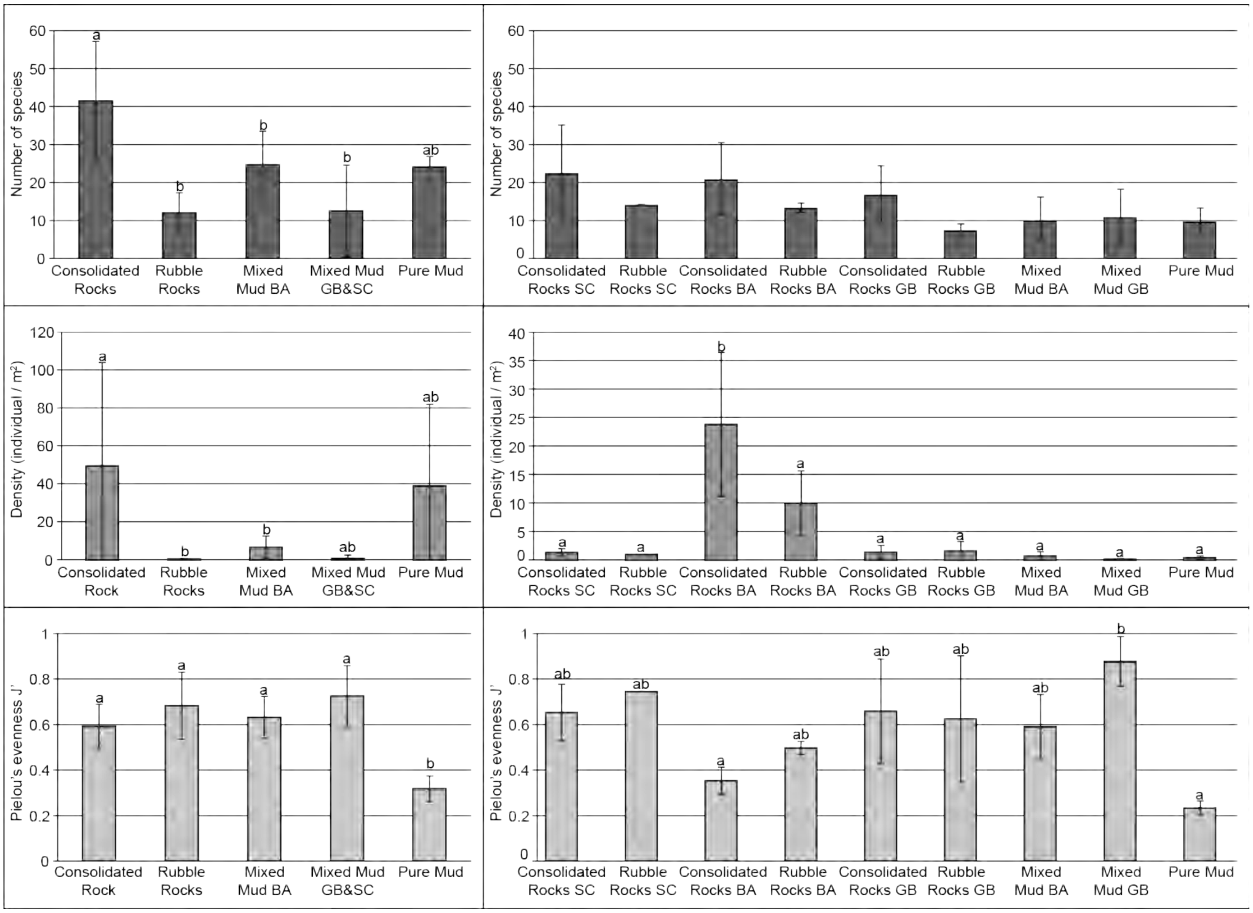


Figure 6. Diversity indices (mean ±SD) for each habitat type and membership from the Tukey test for ROV sites (left) and *Delta* sites (right)
Top left = ROV's number of species (ANOVA p-value < 0.001), mid left = ROV's density (ANOVA p-value = 0.007), bottom left = ROV's Pielou's evenness (ANOVA p-value = 0.003), top right = *Delta*'s number of species (ANOVA p-value = 0.072), mid right = *Delta*'s density (ANOVA p-value = < 0.001), bottom right = *Delta*'s Pielou's evenness (ANOVA p-value = 0.005).

While there were no significant differences in diversity or density of organisms (**Figure 6**) among the identified mud habitats (pure versus mixed mud-rock from the various sites), we did detect some trends and were able to identify what members of the assemblages distinguished them. Pure mud at GB & SC (33 % similar) showed a medium number of taxa and a high density of individuals with a significantly lower Pielou's evenness than all the other habitat types. Pure mud habitat was characterized by high density of burrowing brittle stars and Subselliflorae (sea whips). Mixed mud-rock habitats at GB and SC showed lower number of taxa and density of individuals than the same habitat types at BA and were characterized by medium to high abundance of anemones and low abundance of sponges with the lowest within group similarity (16 %; **Table 7**). Mixed mud-rock habitats at BA (which included pure mud at this site; patches 46 % similar) showed a medium number of taxa, a low density of individuals (**Figure 6**) and were characterized by many of the same taxa as the consolidated rocks (minus the anemones and squat lobsters) but in much lower densities. What made the two mixed mud-rock assemblages 93.18% dissimilar (**Table 6**) was the higher density of several echinoderm species (particularly the previously mentioned small orange brittle stars and sea cucumbers as well as sea stars), sponges, branching gorgonians and tunicates at BA than GB and SC, and a higher density of sea anemones at GB and SC than BA (**Table 8**).

Table 7. Within each major habitat type, assemblage characteristics determined by the SIMPER analysis on the ROV dataset

% Sim = percent of similarity of patches within a habitat type, Av den = average density of the taxon within that habitat type, Cum % = cumulated percent of contributions of the species to the characterization of a the habitat type.

Habitat Type	% Sim	Species	Av den	Cum %
Pure Mud (MM-GBSC)	32.88	Burrowing brittle star	2.57	63.59
		Subselliflorae	1.13	85.48
Mixed mud-rock GB & SC (Mx-GBSC)	16.03	*Stomphia coccinea*	0.28	30.86
		Metridium farcimen	0.09	49.84
		Urticina spp.	0.11	68.74
		Shelf sponge	0.02	81.94
Mixed mud-rock BA (Mx-BA)	46.03	Shelf sponge	1.00	35.91
		Branching sponge	0.52	49.01
		Small orange brittle star	0.51	58.79
		Mediaster aequalis	0.24	65.91
		Branching red gorgonian	0.26	72.63
		Parastichopus californicus	0.23	78.95
		Cucumaria spp.	0.14	82.73
Consolidated Rocks (cR)	37.13	Shelf sponge	1.60	19.34
		Branching sponge	1.56	31.93
		Branching red gorgonian	1.35	44.46
		Small orange brittle star	1.57	54.28
		Metridium farcimen	0.72	61.28
		Parastichopus californicus	0.57	66.58
		Munida quadrispina	0.50	71.81
		Mediaster aequalis	0.56	75.70
		Foliose sponge	0.62	78.59
		Henricia spp.	0.42	81.40
Rubble Rocks (rR)	35.83	Shelf sponge	0.22	56.68
		Parastichopus californicus	0.05	71.67
		Branching sponge	0.04	82.04

Table 8. Dissimilarities between mixed mud-rock (Mx) habitats at Bandon-Arago (BA) versus Grays Bank/Siltcoos (GBSC) in the ROV surveys

Av den = average density of the species within a particular rock habitat type and Cum % = cumulated percent of contribution of the species in the dissimilarity between the two rock habitat types

Average dissimilarity = 93.18 Species	Mx-BA Av den	Mx-GBSC Av den	Cum %
Shelf sponge	1.0	0.0	24.2
Branching sponge	0.5	0.0	34.7
Small orange brittle star	0.5	0.0	44.4
Stomphia coccinea	0.0	0.3	50.7
Branching red gorgonian	0.3	0.0	56.2

Mediaster aequalis	0.2	0.0	61.5
Parastichopus californicus	0.2	0.0	66.3
Metridium farcimen	0.1	0.1	70.1
Urticina spp.	0.1	0.1	73.4
Cucumaria spp.	0.1	0.0	76.4
Foliose sponge	0.2	0.0	79.4
Transparent tunicate	0.2	0.0	82.4

Table 9. Dissimilarities between consolidated rock (cR) and rubble rock (rR) habitat types from ROV surveys

Av den = average density of the species within a particular rock habitat type and Cum % = cumulated percent of contribution of the species in the dissimilarity between the two rock habitat types

Percent dissimilarity = 90.47	**cR**	**rR**	**Cum %**
Species	**Av den**	**Av den**	
Shelf sponge	1.60	0.22	12.07
Small orange brittle star	1.57	0.01	22.88
Branching sponge	1.56	0.04	33.19
Branching red gorgonian	1.35	0.03	42.39
Munida quadrispina	0.50	0.03	48.06
Metridium farcimen	0.72	0.03	53.49
Parastichopus californicus	0.57	0.05	57.28
Foliose sponge	0.62	0.01	61.00
Mediaster aequalis	0.56	0.01	64.57
Single stalk red gorgonian	0.38	0.00	67.36
Henricia spp.	0.42	0.00	69.79
Pentamera sp.	0.27	0.00	72.10
Transparent tunicate	0.43	0.00	74.27
Burrowing brittle star	0.15	0.00	76.28
Urticina spp.	0.21	0.02	77.98
Leptosynapta cf. *clarki*	0.10	0.00	79.59
Cucumaria spp.	0.34	0.00	81.00

Consolidated rocks showed 37 % within-group similarity (Table 7), supported the highest number of taxa and density of individuals (Figure 6), and were characterized by high abundance of sponges, branching gorgonians, giant plumose anemones, echinoderms (brittle stars, sea cucumbers and sea stars) and squat lobsters (Table 7). In contrast, rubble rocks supported significantly lower number of taxa (three-fold) and density of individuals (88-fold) and were characterized by low density of sponges and sea cucumbers with nearly 36 % within-group similarity (Table 7). What made the consolidated rock assemblage 90.47 % different than the rubble rock assemblage was higher density and number of taxa (Figure 6) of sponges, gorgonians, echinoderms (brittle stars basket stars, sea stars, and sea cucumbers), anemones, squat lobsters and tunicates on the consolidated rock (Table 9).

4.3.2.2 Assemblages Inferred from the Delta Dataset

Based on their taxa composition, seven habitat types (groups of substratum patch types) were identified on the projection on two ordination plans of the nMDS on the *Delta* dataset (Figure 7). As previously, groups were organized by substratum characteristics. As with the ROV observations, pure mud patches from GB and SC grouped together while pure mud and mixed mud-rock patches at BA differed from mixed mud-rock patches at GB (no mixed mud-rock at SC). However, in the *Delta* dataset rocky habitats differentiated more by site in the nMDS plane than by the characteristics of the rock. In these data we identified unique rock habitats for each site. At Siltcoos there was some further separation between ridge and flat rock, although we still analyzed them as one group; whereas at Grays Bank the distinction between flat and ridge rocks was enough to analyze them as different groups.

The ANOSIM performed on these seven groups demonstrated significant differences overall between the groups of substratum types (Global R statistic = 0.923, with a significance level of 0.1%). Fourteen of the 18 possible pairwise comparisons showed significantly difference between groups (Table 10). Non-significant pairwise comparisons (significance level = 6.7% for all) were not surprising because of the low number of permutations possible for these four pairwise comparisons (from 15 to 35); however, SIMPER analysis gave a high percent of dissimilarity between each pairwise comparison, ranging from 75.85% to 99.48% of difference in the species composition of the assemblages (Table 11).

Pure mud at GB & SC showed lower number of taxa and density of individuals than in the ROV dataset, had the lowest Pielou's evenness (Figure 6) and was characterized by a high abundance of Subselliflorae (Table 12). Mixed mud-rock at GB and at BA had similar diversity and densities (Figure 6). At BA, moderate evenness was observed in mixed mud-rock (Figure 6) and high densities of both branching and stalked gorgonians characterized the assemblage (Table 12). In mixed mud-rock habitats at GB, the highest Pielou's evenness was observed (Figure 6); a moderate abundance of sponges and Subselliflorae and a low density of sea stars (2 species; Table 12) characterized the assemblage. The two mixed mud-rock assemblages differed due to the presence of gorgonians (both branching and single stalked) and feather stars at BA but not GB, and the presence of sea stars, shelf sponges and Subselliflorae at GB but not BA.

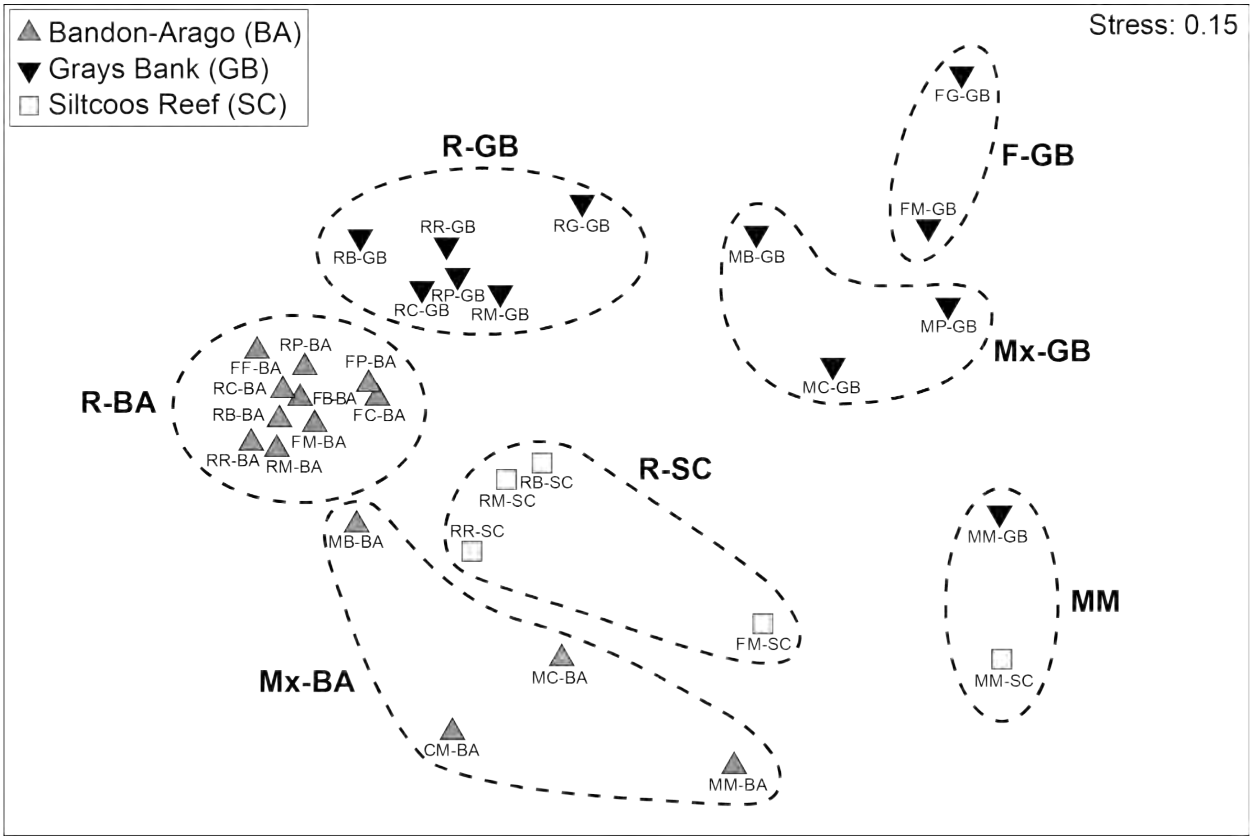


Figure 7. Two-dimensional nonmetric multidimensional scaling (nMDS) ordination of the patch types based on invertebrate community data from the *Delta* survey forming four distinct habitat types (MM, Mx, R, F) with some site differences
Dotted lines represent the seven habitat groups tested with ANOSIM to investigate within group similarity and between group dissimilarities. MM = pure mud, Mx-GB = mixed mud-rock at Grays Bank, Mx-BA = mixed mud-rock at Bandon-Arago, R/F-BA = ridge and flat rocks at Bandon-Arago, R-GB = ridge rocks at Grays Bank, F-GB = flat rocks at Grays Bank, R/F-SC = ridge and flat rocks at Siltcoos Reef.

Table 10. Pairwise comparisons and significance of major groupings of *Delta* substrate patch types into habitat types based on identity and densities of mega-invertebrates within patch types
ANOSIM performed on the habitats (**Table 4**) derived from the nMDS analyses of patch types of *Delta* dataset (**Figure 7**). Upper matrix is the R-values of the test; lower matrix is the associated p-value (in percent); dashes show pairwise comparisons without enough possible permutations to perform the test.

Delta	**Global R = 0.923**						
p \ R	**MM**	**Mx-BA**	**Mx-GB**	**R-SC**	**R-BA**	**R-GB**	**F-GB**
MM		1	-	0.786	1	1	-
Mx-BA	6.7		0.889	0.417	0.967	0.750	0.964
Mx-GB	-	2.9		0.722	0.999	0.920	-
R-SC	6.7	2.9	2.9		0.958	0.817	1
R-BA	1.5	0.1	0.3	0.3		0.945	1
R-GB	3.6	0.5	1.2	0.5	0.1		1
F-GB	-	6.7	-	6.7	1.5	3.6	

Table 11. Percent dissimilarity between assemblages characteristic of the habitat types by the SIMPER analyses on *Delta* dataset

Delta	MM	Mx-BA	Mx-GB	R-SC	R-BA	R-GB
Mx-BA	98.2					
Mx-GB	85.85	95.38				
R-SC	87.75	77.93	88.82			
R-BA	99.03	87.23	97.46	83.91		
R-GB	99.16	84.45	90.31	83.06	75.85	
F-GB	94.83	97.19	78.11	97.42	99.48	96.51

Table 12. Within each major habitat type, assemblage characteristics determined by the SIMPER analysis on the *Delta* dataset

% Sim = percent of similarity within the group, Av den = average density of the species within the group, Cum % = cumulated percent of contribution of the species within the group.

Habitat type	% Sim	Species	Av den	Cum %
Pure Mud (MM-GBSC)	54.38	Subselliflorae	0.33	97.24
Mixed mud-rock BA (Mx-BA)	36.99	Branching red gorgonian	0.23	56.03
		Single stalk red gorgonian	0.10	83.85
Mixed mud-rock GB (Mx-GB)	26.88	*Mediaster aequalis*	0.04	33.12
		Subselliflorae	0.03	60.28
		Unidentified sponge	0.02	79.24
		Luidia foliolata	0.00	84.40
Rocks SC (R/F-SC)	42.48	*Parastichopus californicus*	0.23	27.84
		Branching red gorgonian	0.24	49.94
		Shelf sponge	0.18	66.92
		Parastichopus leukothele	0.12	79.35
		Mediaster aequalis	0.06	85.15
Rocks BA (R/F-BA)	68.81	*Florometra serratissima*	1.91	45.15
		Branching sponge	1.67	76.98
		Gorgonocephalus eucnemis	0.37	84.38
Ridge Rock GB (R-GB)	51.28	*Florometra serratissima*	0.71	61.43
		Unidentified sponge	0.17	75.85
		Shelf sponge	0.24	90.15
Flat Rock (F-GB)	39.64	*Allocentrotus fragilis*	0.01	45.70
		Stomphia coccinea	0.01	68.59
		Poraniopsis inflata	0.00	89.52

While rocky habitats at the three sites separated in the nMDS plane, there were no differences in the number of taxa on rocky habitats among the sites (data not shown). When consolidated rock and rubble rocks were differentiated within each site, the number of taxa was higher for consolidated rock than rubble rocks across all sites (Figure 6), but not statistically. Rocks at SC (all rock-based patch types together; 42 % similar) supported the lowest density of organisms compared to rock habitats at other sites and were characterized by sea cucumbers, branching red gorgonians and shelf sponges (Table 12). Rocks at BA (69 % similar) supported the highest density of individuals and lowest Pielou's evenness (Figure 6) among rock groups within the *Delta* dataset and were characterized by high density of feather stars, branching sponges and basket stars (Table 12). Ridge rocks at GB supported low densities of individuals, moderately high Pielou's evenness, and were characterized by high density of feather stars and sponges while the flat rocks at GB were characterized by high density of sea urchins and anemones (Table 12). In addition to the large density differences observed among rock habitats at the three sites, the sites differentiated based on the abundances of branching sponges, shelf sponges, feather stars, and the sea star *Mediaster aequalis* as well as the presence of basket stars at BA only (Table 13).

Table 13. Dissimilarities of rock habitat types between and within *Delta* sites Siltcoos (SC), Bandon-Arago (BA) and Grays Bank (GB)

Av den = average density of the species within the group, Cum % = cumulated percent of contribution of the species in the dissimilarity between groups.

Average dissimilarity = 83.91 Species	R/F-SC Av den	R/F-BA Av den	Cum %
Florometra serratissima	0.04	1.91	36.00
Branching sponge	0.05	1.67	65.77
Gorgonocephalus eucnemis	0	0.37	73.1
Branching red gorgonian	0.24	0.21	77.69
Mediaster aequalis	0.06	0.25	81.56

Average dissimilarity = 83.06 Species	R/F-SC Av den	R-GB Av den	Cum %
Florometra serratissima	0.04	0.71	31.07
Parastichopus californicus	0.23	0	41.94
Branching red gorgonian	0.24	0	52.55
Shelf sponge	0.18	0.24	61.95
Unidentified sponge	0	0.17	70.71
Parastichopus leukothele	0.12	0.01	76.74
Foliose sponge	0.11	0.06	81.92

Average dissimilarity = 75.85 Species	R/F-BA Av den	R-GB Av den	Cum %
Branching sponge	1.67	0.02	32.38
Florometra serratissima	1.91	0.71	57.71
Gorgonocephalus eucnemis	0.37	0	65.56
Parastichopus californicus	0.31	0	72.41
Shelf sponge	0.01	0.24	77.31
Mediaster aequalis	0.25	0.02	81.99

Average dissimilarity = 96.51 Species	R-GB Av den	F-GB Av den	Cum %
Florometra serratissima	0.71	0	48.94
Shelf sponge	0.24	0	65.98
Unidentified sponge	0.17	0.01	80.87

4.4 Discussion

Our study aimed to distinguish benthic habitat types that support unique mega-invertebrate assemblages on temperate continental shelves. Specifically, we described the assemblages of benthic mega-invertebrates from three rocky reefs and the surrounding soft sediments off the Oregon and Washington coast and associated them with the substrata on which they were observed. In addition to building an understanding of the diversity, density, and taxa different habitats support, this study provides data on benthic mega-invertebrate abundances and distributions on the Pacific Northwest continental shelf at two time points, which may be used for assessments of the effects on the distribution of such taxa of global warming, fisheries management and marine renewable energy development.

The two surveys were designed for different purposes and their videos reviewed by two different observers, which partially limited the results. The 2011-2012 ROV survey was purposely designed for this study, so the stations were positioned on the three rocky reefs and the surrounding soft sediments, thanks to a good knowledge of the bathymetry and topography of the areas, to cover the best variability of available habitats with good quality images. On the other hand, the 1992-1995 *Delta* survey was carried out by geologists to explore regions of tectonic and faulting activities off Oregon and Washington coast (Goldfinger et al. 1997). Each reef was covered by several stations, each of which was comprised of one long dive focusing on the sediment and rock structure but not on the benthic invertebrates inhabiting these reefs, so the speed and the height of the submersible varied along the dives, and were not ideal for mega-invertebrate identification and enumeration. However, Strom (2006) reviewed 27 of these dives and showed that they were accurate enough for benthic communities' description. We thus decided to review the *Delta* dives recorded nearby our ROV surveys: Grays Bank (Washington), Siltcoos Reef and Bandon-Arago (Oregon). With these two different surveys, we were able to compare the results obtained from a survey purposely designed for benthic communities' description and the results obtained from images recorded for a different purpose, to determine if our habitat classifications based on species assemblages were consistent regardless of survey method.

Pure Mud

As hypothesized, the mega-invertebrate assemblages found along patches of pure mud (not distinguished from sand) were very different from the assemblages found in other types of habitats for both data sets. The diversity and evenness of taxa living on the mud or partially burrowed in it were quite low while the abundance of some of these taxa numbered in the hundreds. The pure mud community was thus largely dominated by a very few taxa, like Subselliflorae sea whips and burrowing brittle stars with occasional sea anemones and sponges. This dominance of the sea whips on mud communities previously has been noted along the Oregon coast (Hixon and Tissot 2007; Hannah et al. 2010, 2013), as well as on the southern California shelf (Tissot et al. 2006; de Marignac et al. 2009), the Gulf of Alaska and the Bering Sea (Malecha and Stone 2009). This type of mega-invertebrate can live in dense populations and may provide structure and habitat heterogeneity for other invertebrates in this otherwise flat and non-complex environment (Tissot et al. 2006; Malecha and Stone 2009). However, Subselliflorae are adapted to life in very homogenate and stable habitats and are more vulnerable to habitat alteration like those generated by bottom-fishing gears than benthic communities found in less consolidated coarse sediments like the mixed mud-rock (Collie et al. 2000; Malecha and Stone 2009). Nonetheless, despite the relatively high number of shrimp-trawl records in the vicinity of Siltcoos Reef (R. Hannah, pers. comm.), the observed high abundance of Subselliflorae indicates that either this area is not too impacted, yet, by human activities or that the Subselliflorae are resilient to bottom-fishing disturbance, managing to maintain a sustainable population.

Regarding the motile taxa, the mud community is dominated by burrowing brittle stars extending their arms out of the sediment. The burrowing brittle stars were also identified in central California (de Marignac et al. 2009) as a dominant taxon along what they called the fishing 'recovering transects'. Our study is the first to notice such a high abundance of this taxon in the pure mud assemblage on the PNW continental shelf, probably because this burrowing brittle star is quite cryptic and novice observers can easily miss these individuals on underwater images, probably explaining the absence of these brittle stars from the dataset of the *Delta* survey. This may contribute to some of the differences seen between the two datasets. Other motile taxa that contributed to the similarity of this habitat type include sea stars, sea cucumbers, squat lobsters and octopuses, for both data sets. Dungeness crabs, ocean shrimps and weather-vane scallops were only observed at Siltcoos Reef, and in high density for the shrimps.

In contrast to Siltcoos Reef and Grays Bank, the pure mud habitat type at Bandon-Arago was not differentiated in benthic assemblage from the mixed mud-rock (in both the *Delta* and ROV observations) and was comprised of very few to no Subselliflorae and burrowing brittle stars. The Bandon-Arago area is a large and old rock outcrop on the mid Oregon shelf (Romsos et al. 2007) and the pure mud and mixed mud-rock patches were found within the reef complex: the pure mud substratum type representing only 15% of the total area covered by what is described as the mixed mud-rock habitat, mostly in short patches. The 'pure mud' at Bandon-Arago might rather be a thin layer of mud on the bedrock, probably not really stable and not suitable enough for the species characteristic of pure mud communities to settle. Contrastingly, Siltcoos Reef and Grays Bank are smaller rock outcrops and pure mud and gravel-mud were mostly found in large areas around the reefs.

In general, we describe the pure mud habitat on the outer continental shelf in temperate waters as one hosting an assemblage dominated by a few abundant species. The characteristic mega-invertebrate assemblage is comprised primarily of sessile Subselliflorae sea whips and mobile burrowing brittle stars, with the addition of certain sea star and sea cucumber species and patches of high abundances of crabs and/or shrimp.

Mixed mud-rock

Mixed mud-rock habitats are made of mud more or less assorted with coarser sediments like gravel, pebble, cobble or even boulder; these unconsolidated rocks act as physical supports for sessile organisms like sponges, gorgonians, tunicates or sea anemones. Some of the most abundant motile taxa in this habitat are partially burrowing organisms such as the sea cucumbers, *Cucumaria* spp., or the small orange brittle stars that live with the body hidden in tiny cracks in the mud or between small rocks and the arms extending out. At Siltcoos Reef and Grays Bank, in addition to some structure-forming sessile organisms (gorgonians and sponges), the benthic mega-invertebrates inhabiting the mixed mud-rock habitats were mostly sea anemones and a few motile species such as sea stars. The species inhabiting the mixed mud-rock at Bandon-Arago for both datasets were sessile organisms like gorgonians and sponges (both shelf and branching), which add complexity and heterogeneity to this habitat and supply support, shelter, or food to motile invertebrates like sea stars, sea cucumbers and nudibranchs. High abundance of gorgonians at Bandon-Arago is consistent with other *Delta* observations in the region (Strom 2006) where gorgonians were found in the highest abundances on Coquille Bank (close to Bandon-Arago). Additionally, Strom (2006) observed that gorgonians tended to dominate the species composition in regions where a thick sediment layer was present atop a rocky substrate. On Heceta Bank in Oregon "unidentified gorgonians" were most abundant in cobble habitats (Tissot *et al.* 2004) while at California's Cordell Bank, gorgonians were in greatest densities in the transition between high-relief rock and boulder habitats (Pirtle 2005). While these authors did not identify "mixed mud-rock" habitat as we did in this study, it is apparent that gorgonians are not restricted to rocky ridges and seem tolerant of surrounding sediment. Strom (2006) hypothesized that the gorgonians' association with thick sediment layers was due to the gorgonians being suspension feeders and thus highly concentrated in depositional areas, which deliver food as well as sediment.

Mixed mud-rock has not been described as a major benthic habitat type on the PNW continental shelf in previous studies. However, updates to SGH Version 4 have made it now possible to distinguish these areas but still not to the degree of specificity that we see for the organisms. The single SGH_Prefix field has been split into SGH_Pref1 and SGH_Pref2. SGH_pref1 is the physiographic feature type, or Greene et al. (1999) “Macrohabitat”. SGH_pref2 now matches the Greene et al. “Seafloor Induration” definition (hard/mixed/soft). So, patchy habitats that include all hard types (including consolidated rock) and any soft type (smaller than boulder) are now coded as mixed. Within the Joint Nature Conservation Committee (JNCC) classification scheme (Connor et al. 2004; used for European temperate continental shelves) mixed mud-rock habitat is described similarly to our classification in this chapter. Brown and Collier (2008) describe macrofaunal and epifaunal communities for “cobbles, pebbles and coarse gravel overlying muddy sand” at the Loch Linnhe artificial reef site on the west coast of Scotland. In the Bay of Biscay and the English Channel, Brind’Amour et al. (2014) describe different mega-invertebrate assemblages depending on the size and abundance of the unconsolidated rocks involved. Within our study, the differences between mixed mud-rock at Bandon-Arago and the other two sites (observed both in the *Delta* and ROV footage) similarly may be related to the difference of the size and abundance of the rocks. At Siltcoos Reef and Grays Bank, the mud was mixed with gravels and occasionally pebbles (small rocks). At Bandon-Arago the mixed mud-rock also included cobbles and boulders. It is thus not certain whether the differences observed between the two mixed mud-rock assemblages we described are locally-induced differences from a broad mixed mud-rock habitat, or if there are really two habitats different in terms of sediment characteristics which support different mega-invertebrate assemblages. With more occurrences of each substratum type across sites we might have been able to highlight differences in benthic assemblages related to the size of the unconsolidated rocks mixed in the mud.

Consolidated Rock

Most of the taxa diversity and individual densities were associated with consolidated rock substrata, which included boulders, flat and ridge rock with a veneer of mud or bare ridge rock. Across all sites and surveys, this habitat type had the highest abundance of sessile and structure-forming invertebrates such as sponges (ball, branching, foliose, shelf, tube, etc.), gorgonians (branching and single stalked), giant plumose anemones, sometimes in very dense aggregations, and other sea anemones. The motile mega-invertebrates are very diverse, with an average of forty taxa within a substratum type, including a variety of crabs, echinoderms (basket stars, brittle stars, feather stars, sea cucumbers and sea stars), nudibranchs, octopuses, scallops and squat lobsters. This diversity has been attributed to the physical complexity of high-relief substrata where there may be greater variation in depth, temperature, current direction and velocity, nutrient transport, and the substrata may be composed of different elements (Taylor & Wilson 2003). Furthermore, the large diversity of structure-forming sessile invertebrates increases the habitat complexity and heterogeneity and provides a variety of shelters, refuges, spawning grounds and ecological niches for both invertebrates and fishes (Cerame-Vivas and Gray 1966; Benedetti-Cecchi and Cinelli 1995; Tissot et al. 2006). Basket stars and feather stars also contribute to the heterogeneity of the habitat, their arms spread above the rock acting as supports and shelters for smaller species.

Rubble Rock

On the other hand, although some of the major taxa were the same, the substrata composed of rubble rocks, i.e. flat or ridge rocks with a cover of unconsolidated rocks or mixed smaller rocks, showed distinct assemblages with less diversity and abundance of species, with an average of only ten different species within a substratum type. Despite these substrata being rock-based, they do not support the greater densities of sessile and structure-forming mega-invertebrates and greater diversity generally attributed to high-relief rocks (Allen and Moore 1996; Allen et al. 1997; Stull et al. 1999; Tissot et al. 2006). Within the ROV surveys, these substrate types had the lowest diversity and densities across all three sites. This difference might be due to the weak stability of the unconsolidated rocks on a consolidated rock substratum, probably engendered by hydrodynamic movements due to the strong internal tidal currents found on the Oregon continental shelf (Kurapov et al. 2003; Osborne et al. 2014). This instability of the substratum then results in frequent disturbance not suitable for the establishment of dense populations of structure-forming mega-invertebrates able to attract a variety of motile invertebrates. The role of natural disturbance in structuring marine communities has been well described in the intertidal (Dayton 1971; Lubchenco and Menge 1978; Sousa 1979, 1984; Paine and Levin 1981) and shallow subtidal, especially for algae (Airoldi et al. 1996; Airoldi 1998; Scheibling et al. 2008). We propose that disturbance by the movement of rubble rocks across the consolidated rocks similarly affects the recruitment and persistence of mega-invertebrates in this habitat. This habitat type will be challenging to map using sonar, but we suggest it should be classified as a separate habitat type since it certainly supports a different species assemblage than consolidated rocks without associated rubble.

The distinction between consolidated rocks and rubble rocks was less obvious for the *Delta* surveys than for the ROV surveys, although significant differences in diversity indices were found when the rock observations from the *Delta* surveys were categorized into those two habitat types. The historic dives at Grays Bank and Bandon-Arago were recorded at greater depths than the recent ones and the disturbance induced by the rubble rocks might be weaker at those depths, resulting in less distinction between consolidated rocks and rubble rocks. In the particular case of Siltcoos (where depths were similar between the two surveys), the lower number of rubble rock substratum types observed in the *Delta* survey (1) as compared with the ROV survey (3) likely contributed to the inability to distinguish between rubble and consolidated rock in the *Delta* data. The main pattern in the *Delta* survey was a clear distinction of rocky habitats among the three sites that we did not find in the ROV survey. Because of fewer disturbance impacts due to moving rubble rocks at the *Delta* sites, the species constituting each of these assemblages might be more specialized and adapted to the very local conditions or specific depth ranges of the sites, causing site differences to be more prominent and detectable than in the ROV survey sites. We propose that generally mega-invertebrate assemblages associated with high-relief habitats on the continental shelf can be differentiated first in regard to the depth of the reef and then the composition of the rocks.

4.4.1 Conclusions

Despite some taxonomic and technical limitations, the review of the video footage and the statistical analyses performed on taxa densities allowed us to discriminate different assemblages on particular substrata based on their taxonomic composition as well as which assemblage-habitat associations were more or less shared between the historic and the new data. As in previous studies (Allen and Moore 1996; Allen et al. 1997; Stull et al. 1999; Tissot et al. 2006), we observed differences between habitats composed of higher relief consolidated rock (supporting greater densities of sessile and structure-forming mega-invertebrates and greater diversity) versus unconsolidated fine sediment habitats (more motile mega-invertebrates). We also characterized finer distinctions within both unconsolidated low-relief habitats (between pure and mixed mud-rock) and among rock types as described above. Although we hoped to describe habitat types that were generalizable across sites and held up between the two surveys, we did observe some differences between the two datasets and among sites. Among sites, the main difference we observed was the uniqueness of Bandon-Arago in terms of the organisms living in primarily mud areas (however, we attribute this to the likelihood that the sediment layer is not as deep there as other site and the mixed-in rocks are larger). Between the datasets, the main discrepancy was that that ridge and flat rock did not differentiate (based on observed mega-invertebrate densities) in the recent ROV surveys while they did in the *Delta* observations. These differences likely stem from the different depths covered by the ROV versus *Delta* surveys (particularly at Grays Bank where some *Delta* dives were on the continental slope rather than the shelf).

Because of the high diversity of groundfish species associated with rocky habitats, rocky reefs are areas of the PNW continental shelf most targeted by fishing activities, and repeated contacts of bottom-trawls on the reefs have damaged, or even eradicated slow-growing structure-forming sessile invertebrates and the motile species they attract (Watling and Norse 1998; Kaiser et al. 2006; Sheehan et al. 2013). Nevertheless, because of the decline in rockfish stocks along the PNW coast at the end of the 20th century (see review in NRC 2002), the Pacific Fishery Management Council established in the early 2000's new regulations leading to a decrease of the fishing pressure on part of the rocky reefs on the continental shelf, especially the outer shelf (Hannah 2003; Bellman et al. 2005; Bellman and Heppell 2007). Since that time, some studies have focused on the recovery of rockfish populations on reefs (Bellman et al. 2005; Bellman and Heppell 2007) or invertebrate populations on mud substrata (de Marignac et al. 2009;

Hannah et al. 2010, 2013), but much remains to be done on the status of structure-forming invertebrate species on rocky reefs. The three reefs in our ROV study are not included in the Essential Fish Habitat conservation areas (NMFS 2013) and are thus still open to bottom trawling, as evidenced by fishing gear debris seen on the video footage at Grays Bank and Siltcoos Reef. Although the fishing pressure is relatively moderate on these three inner shelf reefs (R. Hannah, W. Wakefield, pers. comm.), it is not the case for all the non-protected rocky reefs on the PNW continental shelf, and a comprehensive description of the benthic assemblages is needed to understand the effects of bottom-contact ocean-use activities (e.g. fishing, renewable energy development) and integrate this benthic component into conservation and management plans.

Before management decisions about the ocean can be made (for example, where to allow renewable energy installations), we need to know what resources have the potential to be impacted. While biological communities are shaped by a variety of bottom-up, top-down, and species interaction factors, a major driver structuring mega-invertebrate communities is substrate type. Thus, more precise habitat mapping is necessary to understand their distributions. We identified at least four habitat types for mega-invertebrate assemblages: (1) Pure Mud dominated by sea whips and burrowing brittle stars; (2) Mixed Mud-Rock (which may be further divided based on size of mixed-in rocks) characterized by various species in low density; (3) Consolidated Rocks characterized by high diversity and density of sessile and motile mega-invertebrates; (4) Rubble Rocks showing less diversity and density than the consolidated rocks, probably due to the disturbance generated by the unconsolidated rocks. The two rocky habitats might not be as distinct at deeper depths where reefs might have their own local assemblages due to the predominance of locally-induced conditions and deep species recruiting. We believe with existing data it may be possible to map mixed mud-rock separately from other unconsolidated sediment. We propose that future mapping efforts attempt to distinguish rubble-rock from consolidated rock.

4.4.2 Next Steps

Given our findings, we propose that ‘mixed mud-rock’ be mapped as a distinct habitat type characterized by low densities of a diversity of species, particularly sponges, gorgonians, anemones, and burrowing echinoderms. Future studies should be designed to obtain thorough video coverage of transition areas between consolidated rock and mud habitats to discern whether the different sizes of the rocks support distinct mega-invertebrate assemblages. Some of the sessile taxa present in mixed mud-rock function similarly to taxa in consolidated rock in that they are structure-forming, supporting other invertebrate taxa and thought to attract fishes. Thus, understanding the distribution and extent of mixed mud-rock habitats could be important for spatial planning (marine reserves, renewable energy development, Essential Fish Habitat) in order to effectively preserve these important invertebrate taxa. Studying the fishes in these videos and other areas could determine if this habitat type is related to particular fish assemblages. Additionally, we recommend future mapping and videographic surveys attempt to sample more rubble-rock and consolidated rock areas in an attempt to improve mapping capabilities, characterize species differences, and refine hypothesizes about drivers of observed differences.

Because the *Delta* survey and our ROV survey were not designed for the same purpose and not conducted at the exact same locations, our data cannot be compared to estimate impacts of ocean-use or climatic changes across these three localities. However, our results could encourage the design of a video survey on rocky reefs now protected from fishing activities (mostly the outer shelf reefs but also some inner shelf reefs like Heceta Bank and Nehalem Bank), to compare the mega-invertebrate assemblages of reefs now recovering from bottom-gear disturbance to those of reefs still impacted by bottom-fishing activities and to get an estimate of the benthic epifauna recovering more than ten years after the fishing closure.

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5. Benthic Macrofauna Distributions and Habitat Associations

5.1 Introduction and Background

Sedimentary (soft bottom) seafloor is the predominant habitat on the continental shelf and it is likely to be the habitat targeted for offshore renewable energy development; thus, investigation of species distributions in sedimentary habitat is a major focus of this project. Determining baseline habitat associations of potentially affected organisms constitutes a first step in making informed ocean use decisions. Siting offshore renewable energy facilities, offshore aquaculture, dredge disposal, and marine reserves all require an understanding of species distributions and habitat associations to evaluate effects of such space use changes. With increasing interest in using environmental variables as surrogates to describe and predict spatial patterns in benthic diversity and distributions (e.g. McArthur et al. 2010), determining current species- and assemblage-habitat associations provides a baseline from which to make predictions and assess impacts.

The spatial distribution patterns of benthic invertebrates found on or in seafloor sediments (macrofauna) result from interactions with a host of environmental variables. Multiple studies have found significant associations between macrofaunal composition of soft-bottom communities and sediment characteristics (percent silt-clay, organic carbon, grain size) (Weston 1988, Hoey et al. 2004, Jayaraj et al. 2008, Labrune et al. 2008). The importance of sediment for benthic species begins early in the life cycle: sediment affects the settlement of benthic larvae (Gray 1974, Woodin 1986, Butman 1987, Snelgrove and Butman 1994), as well as the growth and burrowing rate of juvenile and adult bivalves (de Goeij and Luttikhuizen 1998, de la Huz et al. 2002) among other species. Other studies have found that benthic assemblages are associated with particular water temperatures and/or dissolved oxygen levels (Cerame-Vivas and Gray 1966, Cimberg et al. 1993, Carroll and Ambrose 2012). Still other surveys have noted that differences in benthic assemblages are most related to differences in depth (Hyland et al. 1991, Oug 1998, Bergen et al. 2001). Based on a series of macrofaunal invertebrate surveys in southern California, depth was considered to be the primary variable structuring species distributions with other factors such dissolved oxygen, grain size, and total organic carbon secondary (SAIC 1986, Hyland et al. 1991, Allen et al. 2007).

Energy conversion by large arrays of wave-energy capture (WEC) devices or the installation of large, hard structures in previously “featureless” habitats may result in changes in local hydraulics (current patterns and water mixing) (Cada et al. 2007). Such changes can affect organisms by altering the patterns or rates of food delivery, the mixing of eggs and sperm, the dispersal of spores and/or larvae and how temperature varies throughout the water column, all of which may impact benthic species distributions and/or abundances. Changes in water movement resulting from wave-energy capture or the presence of devices inducing scour also may affect how sediment is moved, resulting in differing distribution of grain sizes and impacting benthic species that are strongly tied to specific sediment characteristics. During construction and decommissioning, the movement of anchors, substations and underwater power cables also may directly disturb sedimentary habitats and populations.

The effects of seabed installations and/or energy removal may go beyond the spatial extent of the installation, so the extent of potential effects on the sediment and associated invertebrates may be greater than the project footprint; however, the extent of such changes is as yet unknown. Benthic changes will be observed mainly near installations in nearshore water with effects likely to be highly localized. For example, sand adjacent to an artificial reef installed at 13 m water depth offshore La Jolla, CA, was scoured out to 15 m from the reef (Davis et al. 1982), and grain-size analysis of sediment collected along a transect from Oil Platform “Eva” off Huntington Beach, CA, in 18 m of water indicated coarse sand out to 20 m from the platform with very fine sand beyond that (Wolfson et al. 1979). It is less certain how the installation of multiple devices could extend the impact footprint or how much scour should be expected from installation in deeper waters on the Outer Continental Shelf. Studies of offshore platforms in the

Mediterranean observed that benthic macrofaunal assemblages varied with distance from a platform and that the spatial extents of the differences varied with depth of the platform (30 m vs. 90 m water depth; Terlizzi et al. 2008) and over time (Manoukian 2010).

In 1988, the US Minerals Management Service conducted benthic reconnaissance surveys for invertebrates on soft and hard bottom substrata of central and northern California's outer continental shelf areas in four geological basins in preparation for oil and gas exploration in those regions. For soft-bottom invertebrate assemblages, the main patterns were related to depth; sediment size characteristics had a secondary influence, and other inter-basin differences appeared to have only a minor influence (Lissner 1989). These results from central and northern California suggest there are few within-region differences in benthic invertebrate assemblages and that communities could potentially be predicted if depth and sediment type were characterized at a site.

The most extensive study of benthic macrofaunal communities on the US west coast was conducted by the US Environmental Protection Agency (EPA). The EPA National Coastal Assessment (NCA; the coastal component of the nationwide Environmental Monitoring and Assessment Program – EMAP) has traditionally assessed embayments and estuaries; however, one west-coast shelf assessment was conducted in 2003. The 2003 EPA-NCA sampling was spatially comprehensive and randomly distributed along the shelf; thus it provides data from areas in between our eight sites.

5.1.1 Study Purpose and Objectives

The purpose of this study was to determine species- and assemblage-habitat associations and provide a baseline in the Pacific Northwest from which to make predictions and assess impacts. The objectives of this portion of the project were to:

- Compare macrofaunal communities within and across eight sites.
- Compare 2010-2012 survey findings to EPA survey data from 2003.
- Identify species that are particularly representative of various communities or distinguish between communities.
- Develop understanding of physical drivers shaping community patterns.

5.2 Methods

5.2.1 New Sample Collection

In 2010, we sampled 118 stations, grouped into six distinct sites from northern California to Washington: North San Andreas Fault (NSAF, n=21), Eureka (n=20), Siltcoos (n=19), Newport (n=22), Nehalem (n=22), and Grays Bank (n=14). Station locations were generated using a Generalized Random Tessellation Stratified (GRTS) survey design, which stratified the sites by depth bin and stations were randomly assigned within each depth bin, proportional to the overall area in that depth bin (Stevens and Olsen 2004). In summer 2012 we added 35 stations across two additional sites, again using the GRTS design across those two sites for a total of 153 stations (see Figure 8 and Table 14 for distributions of stations). This sampling strategy allowed us to investigate the degree of spatial heterogeneity within a site as well as similarities and differences between distinct sites. This type of analysis is consistent with 2003 regional sampling and is helpful in informing the degree of sampling necessary for site selection or ecological monitoring of offshore renewable energy installations.

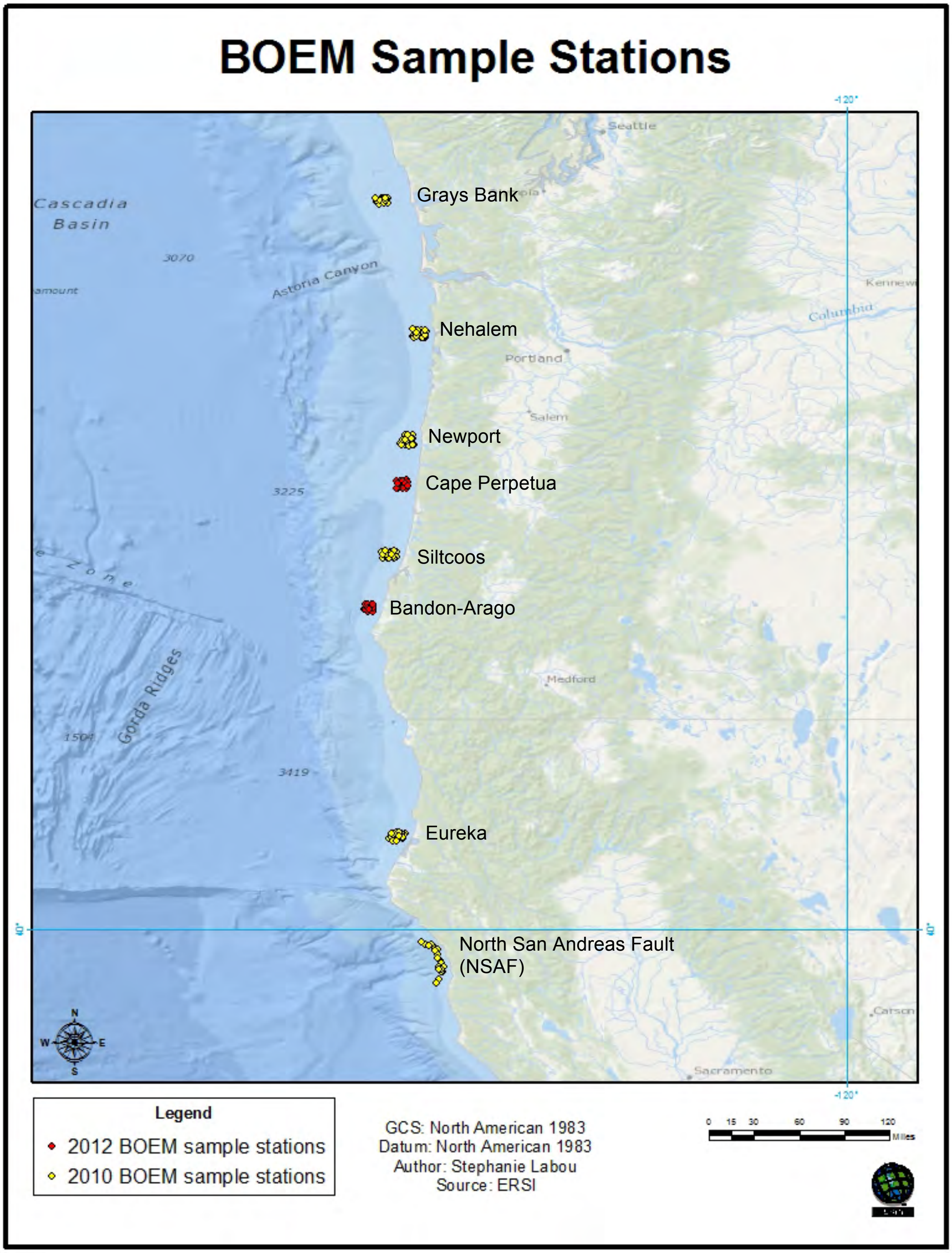

Figure 8. Box core stations sampled in 2010 (yellow) and 2012 (red) across eight sites

Table 14. Depth and site distribution of sampling stations
Sites are listed north (off the coast of Washington State) to south (off northern California). Sampling dates are 2010 unless otherwise noted.

Depth Bin	Grays Bank (GB)	Nehalem (NEH)	Newport (NPT)	Cape Perpetua (CP)	Siltcoos (SC)	Bandon-Arago (BA)	Eureka (EUR)	N. San Andreas Fault (NSAF)	Total Stations
40-50 m			2						**2**
50-60	3		3	2			5		**13**
60-70	5	6	11	8			3		**33**
70-80	5	4	6	9		1	6		**31**
80-90	1	5		1		5	1		**13**
90-100		7			2	1	1	2	**13**
100-110					5	3	2	2	**12**
110-120					5	2	1	9	**17**
120-130					7	3	1	8	**19**
Site Total	**14**	**22**	**22**	**20**	**19**	**15**	**20**	**21**	**153**
Sample Dates	20-21 Sept 2010	22 Sept 2010	15 Oct 2010	5 Oct 2012	23-24 Aug & 8 Oct	30 Aug - 1 Sept 2012	7 Oct 2010	6-7 Oct 2010	
Vessel	*Miss Linda*	*Miss Linda*	*Elakha*	*Elakha*	*Miss Linda* & *Pacific Storm*	*Baylis*	*Pacific Storm*	*Pacific Storm*	

At each station, sediment samples were obtained with a modified Gray-O'Hare 0.1 m^2 box core. One grab sample was taken at each station. Subsamples of sediment from the undisturbed surface layer and then from mid-core were collected and later used to determine percent silt-clay of sediment and median grain size (MGS). The mid-core sample also was used to determine total organic carbon (TOC) and total nitrogen (TN). Samples then were sieved onboard through a 1.0 mm screen, and all collected organisms (both infauna living in the sediment and small epifauna which may have been on the surface – hereafter called macrofauna) were preserved in a mixture of 10 % buffered formalin and seawater. At each station vertical water-column profiles of conductivity, temperature, dissolved oxygen, and depth were obtained with a Sea-Bird Electronics CTD unit with additional sensors.

5.2.2 Sample Processing

Upon return to the laboratory, organisms were transferred to 70% ethanol then sorted into major taxonomic groups by Oregon State University staff in the Henkel laboratory. Kristin Politano (laboratory manager) identified species from most groups (except crustaceans and polychaetes). Jeff Cordell at the University of Washington identified crustacean samples. Kathy Welch of AquaMarine Environmental Services in Edmonds, WA, identified polychaetes and other worms. Additionally, identified molluscs from California were sent to Susan Weeks of Oikos in Corvallis, OR, to confirm species identification. These individuals are the same contracted 'taxonomic experts' used for the 2003 EPA-NCA samples; thus we are confident in the consistency of identification between the datasets. These experts provided us with lists and counts of species per sample and also provided voucher specimens. After obtaining voucher specimens from the contractors, a second set of vouchers was made in accordance with procedures learned by Politano and Gilbane during their visit to the Smithsonian in November 2011 and sent to the

Smithsonian in 2014.

Grain sizes of the sediment from the top and middle of the core (mid-core only for 2012 samples due to personnel/processing constraints) were analyzed using a Beckman Coulter Laser Diffraction Particle Size Analyzer (LD-PSA) to determine median grain size and percent silt/clay (portion less than 62.5 μm; Wentworth 1922). In most cases, the percent sand (62.5 μm to 2 mm) was the balance of the sample. Where grain sizes larger than 2 mm (maximum size for the LD-PSA) were encountered, these samples (n=11) were fractioned and the percent gravel (that fraction greater than 2 mm) was determined. The balance of the fraction was then analyzed by the LD-PSA to determine % sand and silt/clay (also called mud). It was not possible to determine median grain sizes for those few fractionated samples. Samples were analyzed for percent total organic carbon and total nitrogen using an NA1500 Elemental Analyzer operated by staff in the College of Earth Ocean and Atmospheric Sciences at OSU.

5.2.3 Processing of Historical Data

Data from the 2003 EPA study (detailed description of the methods for sample collection can be found in Nelson et al. 2008) were downloaded from the EPA National Coastal Assessment Coastal Data Search Engine (http://oaspub.epa.gov/coastal/coast.search). Station location, station visit, water quality, benthic grab, benthic abundance, and sediment grain composition data files were downloaded. These data were then merged such that the water quality, sediment composition, and organism abundance were associated with each station. Data were then filtered to only include stations within the BOEM study region (Fort Bragg, California, to Grays Harbor, Washington). This resulted in 20 Washington stations (south of the Olympic Coast National Marine Sanctuary), 49 Oregon stations (a sample for macrofauna was not obtained at one Oregon station), and 10 northern California stations for a total dataset of 79 grab samples (Figure 9).

5.2.4 Data Analysis

5.2.4.1 Univariate Analyses

Physical attributes (depth, sediment characteristics, CTD data) of the sites were compared using one-way ANOVAs with Tukey's HSD post-hoc tests. The Shannon-Weiner diversity index (H') was calculated for each of the 153 BOEM grabs, and then the average diversity was calculated for each of the eight BOEM sites and compared among sites using one-way ANOVAs with Tukey's HSD post-hoc tests. Both the individual H' values and the mean H' values for each site were plotted against depth, percent silt/clay, and median grain size. Shannon-Weiner diversity also was calculated for each of the 79 EPA stations and was plotted against depth and percent silt/clay (median grain size not available for EPA stations).

5.2.4.2. Multivariate Analyses

A variety of multivariate analyses were undertaken using PRIMER 6th Edition. Species density data, count/area of core (0.1 m^2), were first ln(x+1) transformed and a Bray-Curtis similarity matrix was created for 152 BOEM stations (one station with a large rock component was excluded since the species were so different) and the 79 EPA stations (total = 231). In previous reports for this project, data were transformed using square or fourth root, as those are the most common transformation for species density data. However, after careful consideration we have determined that log transformation is more appropriate, as the ratio of the largest to the smallest organism abundance within a station was usually greater than 10 (frequently 100). Square root is the least drastic and used when the variance is equal to the mean, whereas the logarithmic transformation is applicable to data that depart more widely from a normal distribution (Legendre & Legendre 2012). Further, the stress (a goodness of fit measure) on the nMDS plots was lowest for log transformation as compare to square or fourth root. Nonmetric multidimensional scaling (nMDS) was used to plot the 231 stations on a two-dimensional ordination plane based on taxa composition similarities & dissimilarities. The EPA data separated from the BOEM data in the nMDS plane (Figure 10); thus, subsequent multivariate analyses were conducted on these two datasets separately.

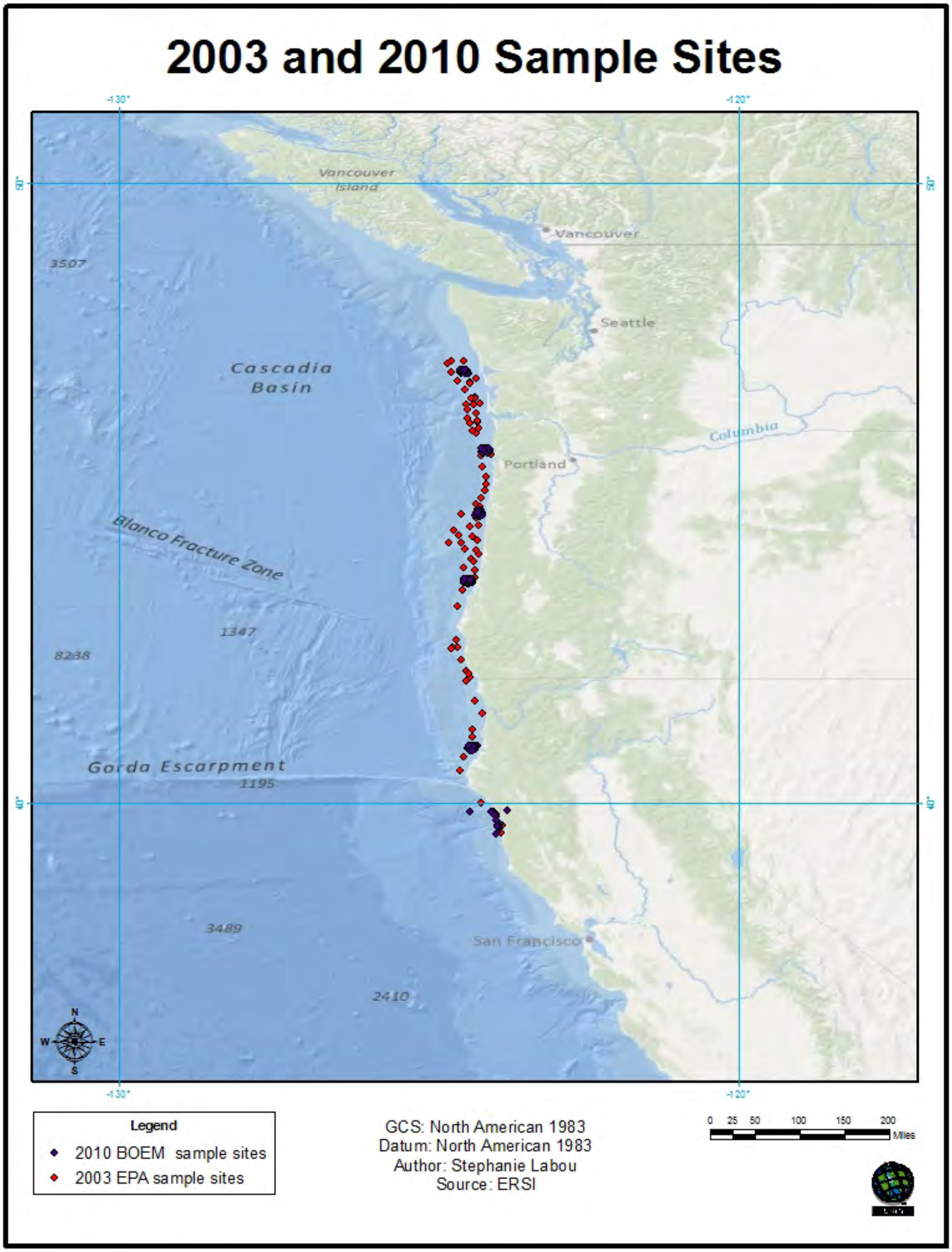

Figure 9. BOEM box core stations sampled in 2010 (blue) and EPA stations sampled in 2003 (red)

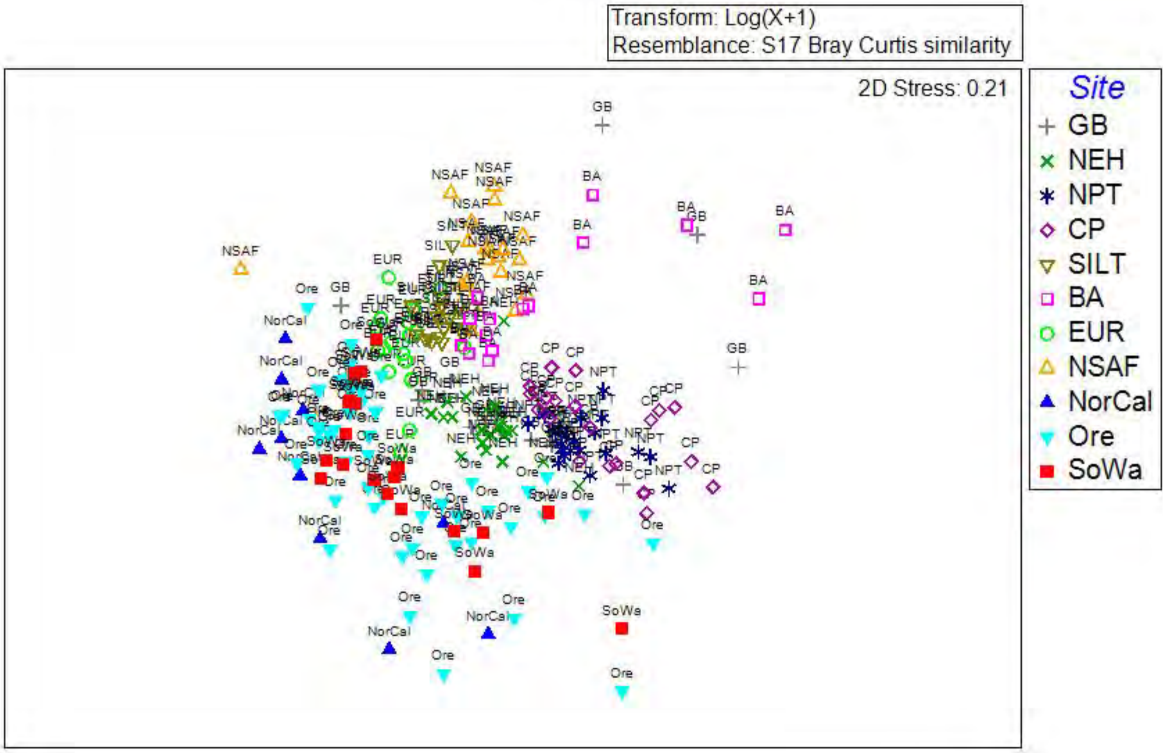

Figure 10. nMDS plot of BOEM (2010 & 2012) and within-region EPA stations (2003)
Stations from the eight BOEM sites (n=152) are labeled with 'open' symbols. The EPA stations, grouped into northern California (NorCal), Oregon (Ore) and southern Washington (SoWa), have filled symbols. The EPA samples cluster together in the lower left of the nMDS plane, with very little overlap with the BOEM samples. ANOSIM test comparing the two datasets resulted in a global R statistic of 0.398 at the 1% significance level. Thus, for further analyses, these two datasets were handled separately.

For each dataset, separate Bray-Curtis similarity matrices were created and cluster analyses (CLUSTER) were run along with the SIMPROF (Similarity of Profile) routine to identify statistically significantly different groups of sample stations based on an assumption of no prior structure of the taxa composition similarities and dissimilarities. SIMPER (Similarity of Percentage) was used to evaluate how much contribution each species made one assemblage unique, or significantly different, from other assemblages in order to identify potential 'characteristic' species for each assemblage.

To determine what environmental factors describe the distribution of macrofaunal invertebrates across the study region, the BIO-ENV (BEST) procedure was used to find a subset of environmental variables that best correlated with overall species assemblage patterns. Following BIO-ENV analysis, LINKTREE was run using the best subset of environmental variables and the biological resemblance matrix to find the most effective way of describing the biological-environment relationships relative to the successive use of single variables. Starting with the group of all samples, LINKTREE divides the stations into two groups (a binary split), determined by the most influential environmental variable(s) at a value of that variable that results in groups of stations with the most similar species assemblages. By iteratively repeating this procedure on the resulting groups, the samples are divided into a number of groups, within which all the samples have similar biological and physical characteristics (MESH 2014). An ANOSIM was performed to test the strengths and statistical significance of differences between LINKTREE groups, using permutation and randomization methods on the resemblance matrix. The SIMPER routine was run on the transformed biological matrix using the LINKTREE groups to determine the species and their abundances contributing to the similarities within and differences between groups. Stations were coded with the LINKTREE groups and visualized on an nMDS plane.

5.3 Results

5.3.1 BOEM Survey Data

The full list of species identified from the 153 box cores and their abundances as well as physical data corresponding to each box core sampling station visit have been submitted as separate .csv files to the project manager. These files have been checked for successful import into PRIMER. A full list of species collected and total abundances at each site are included in Appendix 5.

Significant differences were found among the eight surveyed sites in every physical metric measured. Box plots of physical parameters at the sites with Tukey groups can be found in Appendix 5. NSAF and Siltcoos were, on average, the deepest sites, while Newport and Grays Bank were the shallowest (Table 15). Eureka had the highest percent of silt/clay in the sediment, followed by NSAF (Table 15; Figure in Appendix 5). In contrast, sediments at Nehalem, Newport, and Cape Perpetua were almost entirely sand, with very low percent silt/clay. Penetration depth of core varied between sites, ranging from 7 to 30 cm, but since the small macrofaunal invertebrates of interest are most likely within the top few centimeters of sediment, no further analysis was conducted regarding penetration depth. Average temperature (7.3 – 9.2°C) and dissolved oxygen (1.05 – 3.58 ml/L) showed variation among sites: NSAF was the warmest (avg. = 9.0°C) while Grays Bank was the coolest (avg. = 7.3°C) on average, and Eureka had the highest DO (avg. = 2.91 ml/L) while Cape Perpetua had the lowest DO (avg. = 1.34 ml/L).

Overall polychaetes (Annelida) and bivalves (Mollusca) dominated the assemblages at each site (Figure 11); annelids ranged from a high of 53 % at Grays Bank to a low of 10 % at Newport. Molluscs ranged from a low of 33 % at NSAF to a high of almost 79 % at Newport. At Newport (as at all sites) bivalves comprised the majority of the molluscan proportion, making up 71% of total taxa. Although bivalves numerically dominated the Newport assemblage (116 bivalves per 0.1 m^2) only 10 species of bivalves were collected at Newport (the lowest bivalve richness across all sites), and the site was dominated by two species: *Nutricola lordi* (nearly 63% of bivalves) and *Axinopsida serricata* (34%). Contrastingly, at Siltcoos (the second highest proportion of molluscs) 20 bivalves species were collected. Additional sampling in 2012 at Cape Perpetua and Bandon-Argo found three additional bivalve species and one new snail (*Haminoea vesicular*, white bubble snail). The most prevalent (present at 134 of 252 stations) and abundant species overall was the bivalve, *Axinopsida serricata.* The most abundant polychaete species was *Magelona berkeleyi* while the most prevalent polychaete (present at over two-thirds of the stations) was *Onuphis iridescens*. Twenty-eight species of polychaetes were found in the 2010 sampling and fourteen additional polychaete species were identified from the two new sites in 2012. The most prevalent and abundant crustacean was the Gammaridian amphipod, *Ampelisca careyi*, present at over half the stations. In terms of crustaceans, sampling at Cape Perpetua and Bandon-Arago yielded four new Gammaridian amphipods and a sea louse (*Argulus* sp.). The most prevalent and abundant echinoderm was the brittle star, *Amphioplus strongyloplax*, present at one-third of the stations. No additional echinoderms were identified in 2012.

Table 15. Habitat and diversity metrics for the eight BOEM sites (upper table) and three EPA states (lower table)
*Median grain size means are for stations that did not have gravel. EPA did not measure mgs (μm).

	Mean Depth (m)	Mean Median Grain Size (μm)	Mean % Silt/Clay	Average H’ (diversity) per grab	Average # species per grab	SIMPROF Groups per site
Grays Bank	67.86 (±8.88)	223.69* (±102.40)	12.91 (±15.35)	2.14 (±0.49)	31.21 (±14.95)	5
Nehalem	82.04 (±13.59)	217.28 (±26.83)	1.48 (±0.55)	3.23 (±0.30)	39.64 (±8.60)	9

Newport	65.54 (±6.96)	273.44 (±58.59)	0.05 (±0.15)	1.83 (±0.32)	22.18 (±5.22)	6
Cape Perpetua	69.39 (±7.35)	431.67 (±80.09)	0.53 (±0.45)	2.26 (±0.49)	22.45 (±5.80)	3
Siltcoos	114.89 (±12.10)	60.42 (±12.55)	52.18 (±7.83)	2.79 (±0.40)	37.11 (±8.05)	4
Bandon-Arago	100.40 (±20.00)	79.42* (±51.41)	36.02 (±26.61)	2.13 (±0.66)	23.87 (±11.43)	6
Eureka	77.60 (±21.34)	26.39 (±17.08)	82.41 (±15.50)	2.86 (±0.27)	37.35 (±9.21)	6
NSAF	116.43 (±9.44)	52.00* (±14.76)	67.05 (±12.87)	2.82 (±0.28)	20.38 (±10.43)	3

	Mean Depth (m)	Mean Median Grain Size (µm)	Mean % Silt/Clay	Average H' (diversity) per grab	Average # species per grab	SIMPER Groups per state
Southern Washington	70.85 (±23.30)	NA	22.98 (±16.89)	3.01 (±0.37)	59.05 (±21.38)	12
Oregon	87.02 (±21.94)	NA	13.96 (±13.77)	3.18 (±0.53)	53.69 (±19.87)	19
Northern California	79.9 (±24.20)	NA	49.18 (±26.54)	3.48 (±0.39)	71.3 (±27.45)	6

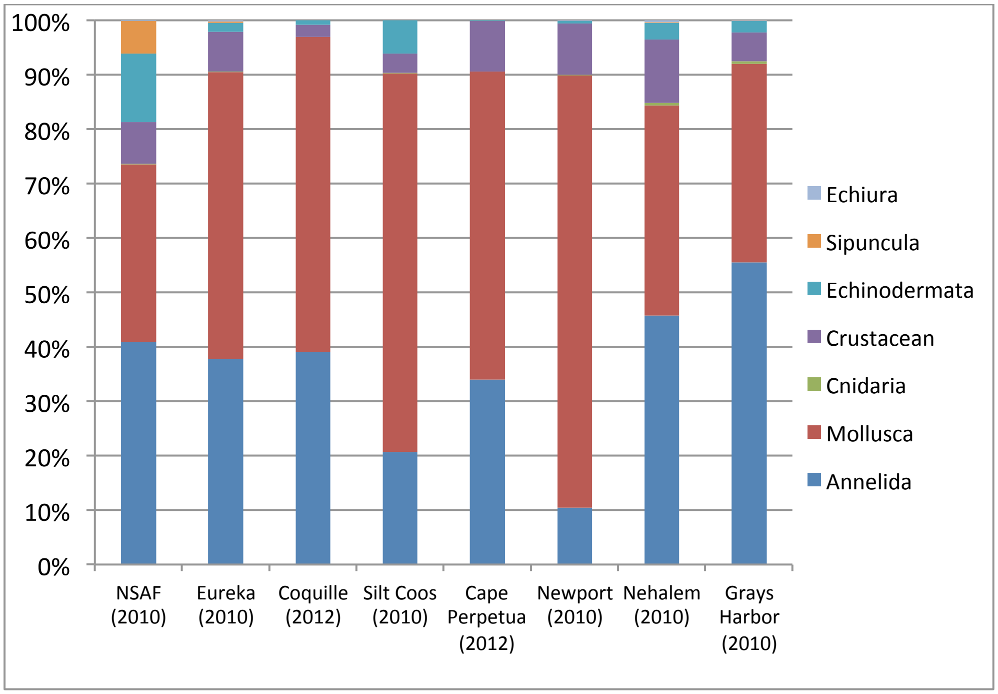

Figure 11. Proportions of major taxa at each site surveyed for the BOEM project from northern California (two left sites), offshore of Oregon (next five sites), and Washington (Grays Harbor)

5.3.1.1 BOEM Diversity Indices

The site with the highest average Shannon-Weiner diversity was Nehalem with an average H’ of 3.2 and an average of 39.6 different species collected per core (Table 15). The lowest average diversity (1.825) was found at the Newport site with an average of 22.2 different species collected per core. The greatest ranges in number of species among stations as well as in H’ diversity among stations were found at Grays Bank and Bandon-Arago; this was expected as these sites encompassed the greatest variety of sediment types (including gravel).

Shannon Diversity had a 2nd degree polynomial relationship with depth. When average diversity at a site was compared the depth, the relationship was weakly significant with an $R^2 = 0.316$. With respect to median grain size (gravel stations removed), the relationship was best described by a logarithmic function ($R^2 = 0.259$). As traditionally observed, diversity did increase with smaller grain sizes. However, based on the parabolic curve, there appeared be ‘optimal’ depths where macrofaunal invertebrate diversity should be highest; the regression equation indicated maximum diversity of macrofaunal invertebrates should be found at ~ 99 m.

5.3.1.2 BOEM Biological Assemblages

The SIMPROF routine determined that stations grouped into 29 significant clusters (2 – 19 stations per cluster) and nine singletons (stations that didn’t cluster with any others) based on invertebrate species abundances. Significant macrofaunal invertebrate assemblages typically clustered within each of the eight Pacific Northwest shelf sites with a few exceptions. Notably, gravelly stations clustered together, regardless of site, and some sandy stations clustered across sites: one cluster included a single Nehalem and ten Newport stations while another included four Newport and 11 Cape Perpetua stations. Cluster similarity of invertebrate assemblages ranged from 10 to 25 % for stations with gravel sediments and 36 – 62 % similarity for invertebrate assemblages within sandy/muddy station groups (BOEM SIMPER Table in Appendix 5). Even within sites, a number of significantly different groups of stations were found. Overall, crustaceans were highly contributing characteristic species only at the sandy sites: Nehalem, Newport, and Cape Perpetua; gastropods were highly contributing characteristic species for all groups in Newport and in a single group each at Siltcoos and Eureka (BOEM SIMPER Table in Appendix 5). Spatial heterogeneity (number of SIMPROF groups per site) was highest at about 90 m depth (similar to the depth of highest taxa diversity) and 247 µm. Each of these sites, with the significant clusters of stations described below, is pictured in the figures in Appendix 5.

Grays Bank: Grays Bank stations varied greatly among groups, as was expected with the diversity of substrates sampled at this site (i.e. stations ranging from all sand to nearly 50 % silt and some with gravel). Differences between groups AF and AG illustrate the importance of subtle differences in percent silt in largely sandy sediment. Stations from both groups averaged 61 m deep. However, Group AG stations averaged less than 1% silt/clay while Group AF stations had an average silt/clay portion of 8.75%. Generally, the bivalve species differed between these two groups but the rest of the contributing species were rather similar, indicating that small differences in the amount of silt largely impacted which bivalves were present at a station. Group Z stations were the deepest and comprised greater than 15% silt/clay. This additional increase in fine grains resulted in a different bivalve and different polychaetes making up the top characteristic species for group Z. Group A was comprised of stations that were greater than 60% gravel and were highly characterized by a single polychaete, *Prionospio steenstrupi*. Group B included only one Grays Bank station along with 4 Bandon-Argo stations (which were comprised of 10 to 30% gravel).

Nehalem: Nehalem was largely sandy with a few transition zones, resulting in the highest within-site macrofaunal heterogeneity (8 significantly different species groups). This unique sediment distribution pattern was reflected in the assemblages. There were three major groups of stations (V, W, X) within the sandy planes, then three singleton groups (S,T,U), two doublets (Y, AA), and one station that grouped with Newport (Group AD). At Nehalem, an ostracod, *Euphilomedes carcharodonta*, a gammaridian amphipod, *Ampelisca careyi*, and a phoxocephalid amphipod, *Rhepoxynius dabouis*, were among the top contributors to differences among station groups.

Newport: High heterogeneity in species assemblages also was observed at Newport, a mostly medium sand site with some pockets of coarse sand. Six significantly different assemblages were determined at this site, two of which were singletons. Group AI was made up of 5 Newport stations and 11 Cape Perpetua stations. Group AI was the shallowest at the sites and had the largest median grain size (although some stations did have a small percent of silt). The ubiquitous *Axinopsida serricata, Nutricola lordi* (a bivalve that seems to be restricted to very sandy stations) and the gastropod, *Cylichna attonsa***,** were characteristic of all the 'pure' Newport station groups. In terms of the top 5 species, these groups differed only in which polychaete (*Magelona sacculata*/*Ophelia assimilis*/*Aphelochaeta* sp.) was highly contributing and whether the 5th species was another gastropod or a crustacean.

Cape Perpetua: Closest in latitude, sediment type, and depth to Newport was Cape Perpetua, which had one singleton and only two other station groups (one of which, AI, was shared with Newport). The group AK was slightly deeper ($\dot{z}$ = 76 m) and siltier (0.87%) than group AI with many fewer *Nutricola lordi* and *Tellina nuculoides* and increased numbers *A. serricata* and *Acila castrensis*. The singleton station 542 (group AJ) was distinct mostly because of the large abundances of Isaeidae amphipods and *Synidotea* isopods.

Siltcoos: Siltcoos was a fairly uniform site in terms of depth and grain size (excluding a rocky reef present at this site); four significant station groups were found at this site and seemed to vary more with depth than percent sand, as groups that had the same sand percent (G & E) but different depth bins were distinct. Group F was shallowest ($\dot{z}$ = 104 m) with an average of 46% sand. In group F, the bivalves *A. serricata, Macoma carlottensis, Acila castrensis,* and *Ennucula tenuis* were the most characteristic species, followed by the brittle star, *Amphioplus strongyloplax*. Group G was made of stations averaging 119 m deep and 52% sand; *A. serricata, M. carlottensis,* and *Acila castrensis* were still the most characteristic with the addition of the polychaete *Sternapsis fossor* and gastropod *Astyris gausapata*. Group H stations averaged 120 m deep and 41% sand, and finally group E was 130 m and 53% sand. In these deeper groups *M. carlottensis and A. serricata* were still characteristic along with the brittle star, *Amphioplus strongyloplax,* and the scaphopod *Rhabus rectius*.

Bandon-Arago: At Bandon-Arago, group B stations were all comprised of 10 – 30 % gravel and nine of the top 10 characteristic species were worms: eight polychaetes and a nematode. The clustering of this group with station 4 from Grays Bank indicates how the presence of gravel drives this assemblage, as the depths and percent silt of the Bandon-Arago stations were considerably different from the GB station; however, the mean gravel percent was nearly the same. Likewise, station 568 is in group AL with the gravel station from NSAF. Groups I, J, and L varied in both % sand and depth. The sandier stations both at the shallow and deep ends of the site were characterized by bivalves, while the pair of stations with < 50 % sand was characterized by both bivalves and polychaetes.

Eureka: Stations at the Eureka site largely fell within five station groups that varied with bathymetry and sediment type with one single station making up the sixth group. All station groups were characterized by relatively high abundances of the bivalve *Axinopsida serricata*, with the shallower groups of stations having approximately 3 times the density of *A. serricata* as the deeper groups of stations. The shallow (54 m), sandy mud (48.5 % sand) group (M) was additionally characterized by high abundances of the amphipod, *Ampelisca careyi*, and the Lumbrinerid polychaete, *Lumbrinereis luti*. This differs from the species found in group O (59 m; 26.3% sand) where the bivalve, *Ennucula tenuis*, is the second most contributing species, followed by the Lumbrinerid polychaete, *Ninoe gemmea*. Moving deeper (70 m) into the mud (10.5% sand; Group Q), *A. serricata* is again followed by *E. tenuis*; however a Sternapsid polychaete, *Sternaspis fossor (africana)*, is the third most characteristic species. Deeper still (98 m) with slightly more fines (9.7% sand) is group N where *A. serricata* is still the most characteristic species, but abundances decrease and another polychaete, *Onuphis iridescens*, becomes characteristic. Finally, at the deepest group of stations (120.5 m; group R), where the sediment is slightly finer still (9.6% sand) *O. iridescens* is the most characteristic, followed by *A. serricata*, and then another polychaete, *Nephtys punctata*. Thus, we see a decrease of bivalves and increase of polychaetes at deeper stations with more silt/clay fraction.

Northern San Andreas Fault: There were few significantly different macrofaunal clusters at the Northern San Andreas Fault site, likely due to the fact that stations were uniformly deep and for the most part composed of sandy silt or silt. Nearly all the stations at NSAF clustered within group D. These stations averaged 30% sand and were characterized by the brittle star *Amphioplus strongyloplax* followed by bivalves *A. serricata* and *Acila castrensis*. Group AL was made of NSAF station 100 (where a large number of Sipunculid worms were collected) and Bandon-Arago station 568, both of had gravel and were characterized by a Leptochitonid chiton, the bivalve *Cyclocardia ventricosa*, and the polychaete, *Terebellides reishi*. Group C, consisting only of station 120, had greater than 50% sand and was the only station in the dataset at which the snail, *Lacuna vincta*, was collected.

Overall, macro-invertebrate assemblages collected from the 152 stations formed into 29 distinct groups, largely site-specific and demonstrating within-site heterogeneity; therefore it is challenging to gain a clear regional perspective on habitat types for macrofaunal invertebrates. Subsequent analyses, reported below, that combine the biological and habitat data help draw wider generalizations about habitat types supporting similar macrofaunal assemblages.

5.3.2 EPA Data

A total of 644 taxa were identified in the region considered for this analysis. The EPA stations were not grouped into sites; they were randomly distributed along the coast; thus, in the original EPA report (Nelson et al. 2008) and here analyses are conducted at the state level. Comparisons of relative abundances of major taxonomic groups among sites did reveal differences among the three states (Figure 12). In the stations analyzed for this report (northern California, Oregon, southern Washington), northern California stations had the largest percentage of polychaetes and the smallest percentage of molluscs while Oregon had the lowest percentage of polychaetes and the highest percentage of molluscs. Crustaceans and echinoderms made up similar percentages of the collections across all three states.

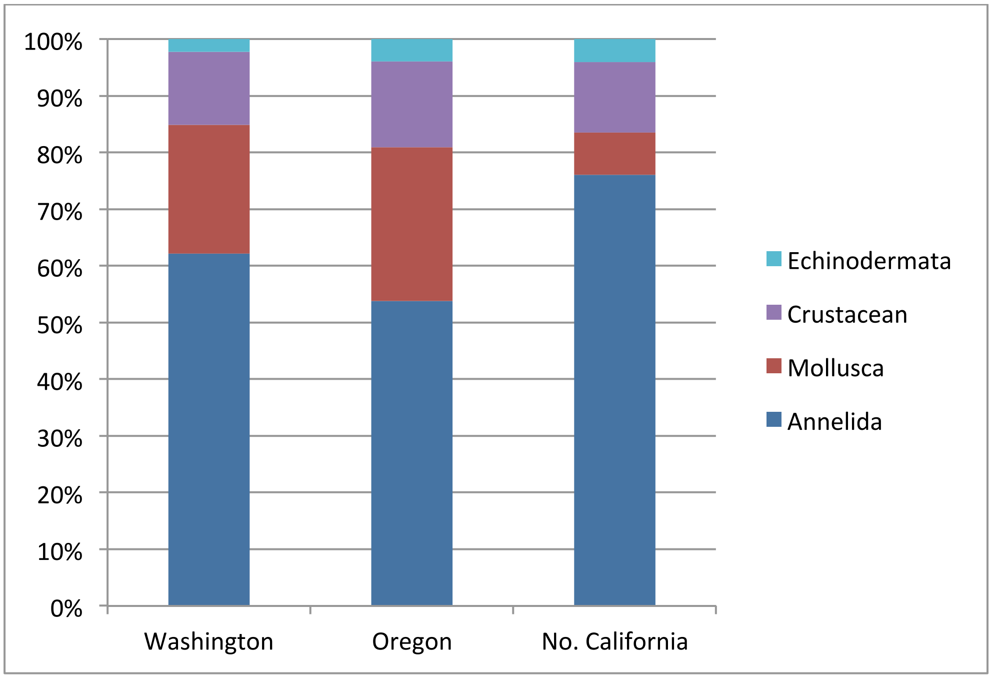

Figure 12. Proportions of major taxa within the selected areas of the EPA dataset grouped by state

5.3.2.1 EPA Diversity Indices

The macrofaunal species diversities found at EPA sampled stations in northern California on average were significantly higher than in southern Washington (ANOVA with Tukey post-hoc p = 0.039), but diversities at Oregon stations did not differ from either northern California or southern Washington (Table 15). When the diversity indices of the 79 stations from 2003 EPA data were plotted against depth, a similar 2nd degree polynomial relationship was observed (not presented). Although the relationship did not seem to indicate a peak diversity at the same depth as indicated by the BOEM samples (~99 m), the single EPA station with the highest H' was at 95 m depth.

5.3.2.2 EPA Biological Assemblages

Cluster analysis of the densities of all taxa across all 79 analyzed stations revealed two major groups of stations and 16 stations that fell outside the two main clusters (Figure 13); stations from all three states were dispersed between the two clusters. Two-sample t-tests revealed that stations making up those clusters differed significantly in depth, percent fines (% silt/clay) in the sediment, percent total organic carbon in the sediment, water temperature, and salinity; however, they did not different in latitudinal range. One cluster of stations (n = 22, orange box, Figure 13) was shallower ($\dot{z}$ = 64.0 m), lower in silt/clay (9 %), lower in TOC, warmer, and lower salinity while the other cluster (n = 41 stations, blue box, Figure 13) was the deeper ($\dot{z}$ = 98.7 m) with higher silt/clay (33.2 %), more TOC, colder, and saltier (Table 16). In terms of organisms, the deeper cluster contained more species (n = 89) that were rare (≤ 3 occurrences) or not present in the shallower cluster of stations than there were in the shallow stations that were rare or not present in the deep (n = 45) (Table 17).

Table 16. Average physical parameters of the two major clusters of stations (based on macrofaunal species abundances) in the EPA dataset

Values are means for each cluster ± standard deviation. P-values represent significance of differences in the means of the physical parameters between clusters (n = 79 stations) as determined by a t-test.

	Cluster 1	Cluster 2	p-value
Depth (m)	67.2 ± 19.2	98.7 ± 16.1	< 0.001
% Silt/clay	8.96 ± 7.57	33.19 ± 22.5	< 0.001
% TOC	0.246 ± 0.143	0.748 ± 0.340	< 0.001
Temperature (c)	7.509 ± 0.066	7.100 ± 0.524	< 0.001
Salinity (psu)	33.779 ± 0.178	33.912 ± 0.090	0.001
Transmissivity	84.54 ± 3.32	80.15 ± 18.25	0.066
Dissolved Oxygen (ml/L)	3.246 ± 0.77	3.192 ± 1.62	0.814

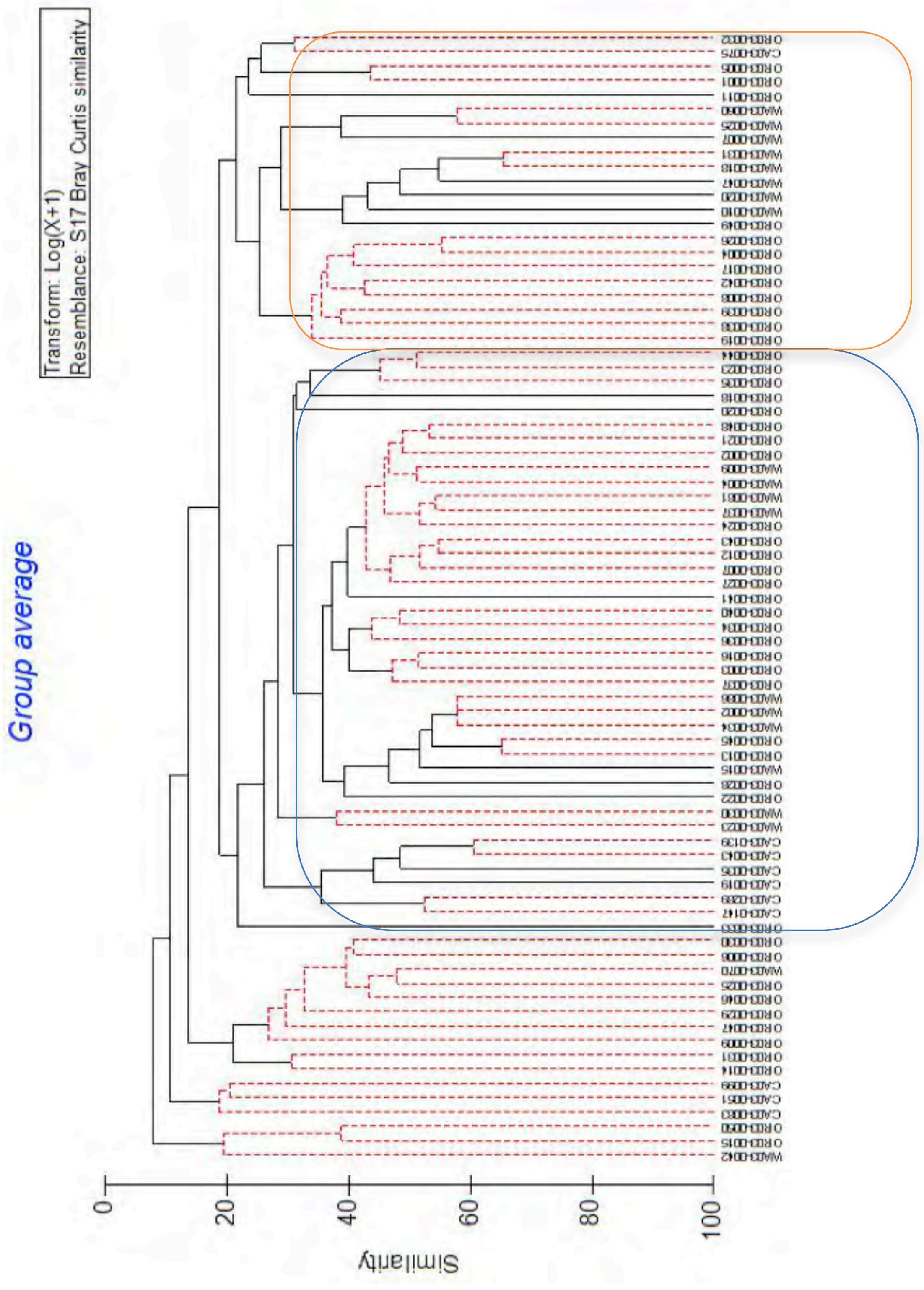

Figure 13. Cluster analysis of the regional EPA stations (n = 79) based on macrofaunal densities Solid black lines indicate significant clusters (anything connected by dotted red lines are not significantly different). Cluster 1 (orange box, n = 22) is comprised of stations that are shallower and lower percent silt/clay while Cluster 2 (blue box, n = 41) is comprised of deeper station with higher percent silt/clay. The deeper, siltier stations have more unique species than the shallower stations.

Table 17. Species that are abundant in one cluster but rare or absent in the other for the EPA dataset

'Cluster 1' is the shallower (z = 64 m) group of stations and 'Cluster 2' is the deeper (z = 99 m) group of stations.

Cluster 1	Cluster 2	
Amaeana occidentalis	*Adontorhina cyclia*	*Maldane sarsi*
Americhelidium rectipalmum	*Ampelisca brevisimulata*	*Melinna cristata*
Ampelisca agassizi	*Ampharete finmarchica*	*Melinna oculata*
Aricidea (acmira) cerrutii	*Amphicteis scaphobranchiata*	*Metaphoxus frequens*
Axiothella rubrocincta	*Amphioplus macraspis*	*Metasychis disparidentatus*
Bathycopea daltonae	*Anobothrus gracilis*	*Microclymene caudata*
Boccardia pugettensis	*Aphelochaeta glandaria*	*Monticellina serratiseta*
Carinoma mutabilis	*Aphelochaeta monilaris*	*Monticellina tesselata*
Chaetozone bansei	*Aphelochaeta tigrina*	*Musculus discors*
Chaetozone columbiana	*Apistobranchus ornatus*	*Myriochele gracilis*
Dendraster excentricus	*Apistobranchus tullbergi*	*Myriochele olgae*
Diastylis bidentata	*Araphura breviaria*	*Nemertea*
Euchone hancocki	*Aricidea (acmira) simplex*	*Neotrypaea californiensis*
Glycera oxycephala	*Aricidea (allia) ramosa*	*Nephtys cornuta*
Halcampa decemtentaculata	*Asabellides lineata*	*Nephtys punctata*
Hemipodia borealis	*Brisaster latifrons*	*Nereis procera*
Hesionura coineaui difficilis	*Cadulus* sp	*Nicippe tumida*
Heteropodarke heteromorpha	*Cerebratulus* sp	*Ninoe gemmea*
Macoma calcarea	*Chaetoderma* sp	*Nuculana hamata*
Magelona pitelkai	*Chaetozone nr setosa*	*Oligochaeta*
Magelona sacculata	*Chaetozone spinosa*	*Orchomene decipiens*
Mesochaetopterus sp	*Chirimia similis*	*Paradiopatra parva*
Mesochaetopterus taylori	*Chloeia pinnata*	*Paraphoxus communis*
Microphthalmus sp	*Cirratulidae*	*Pionosyllis articulata*
Micropodarke dubia	*Clymenura gracilis*	*Pista wui*
Nassarius fossatus	*Compsomyax subdiaphana*	*Praxillella gracilis*
Nutricola lordi	*Cossura bansei*	*Praxillella pacifica*
Olivella baetica	*Cossura candida*	*Praxillella* sp
Olivella pycna	*Cossura pygodactylata*	*Proclea graffi*
Ophelia limacina	*Cyclocardia ventricosa*	*Rhabdus rectius*
Orchomene pacificus	*Diastylis paraspinulosa*	*Rhepoxynius barnardi*
Pentamera pseudocalcigera	*Dougaloplus amphacanthus*	*Rhodine bitorquata*
Phoronis sp	*Echiurus echiurus alaskanus*	*Sigambra bassi*
Polycirrus californicus	*Eudorella pacifica*	*Solamen columbianum*
Polygordius sp	*Exogone lourei*	*Solemya reidi*
Protodorvillea gracilis	*Foxiphalus similis*	*Spio filicornis*
Rhepoxynius fatigans	*Heterophoxus affinis*	*Sternaspis cf fossor*
Rhepoxynius menziesi	*Heterophoxus ellisi*	*Sthenelais tertiaglabra*
Rhepoxynius stenodes	*Huxleyia munita*	*Tellina carpenteri*
Saccocirrus sp	*Jasmineira pacifica*	*Terebellides californica*
Sigalion spinosus	*Levinsenia gracilis*	*Terebellides reishi*
Siliqua patula	*Lysippe labiata*	*Thyasira flexuosa*
Spio cirrifera	*Macoma carlottensis*	*Trichobranchus glacialis*
Tellina modesta		

The SIMPROF routine determined 18 significant clusters of stations (2 – 12 stations per cluster) and 15 singletons (stations that didn't cluster with any others) among the 79 analyzed. Within cluster similarity ranged from 19 – 66 % (EPA SIMPER Table in Appendix 5). Three groups were made of all California stations; for each of these groups, the top four contributing species were all either polychaetes or amphipods. One group was made of a single California station and a single Oregon station, which included polychaetes, the amphipod, *Ampelisca careyi*, and the snail, *Astyris gausapata*. Six groups consisted of only Oregon stations. Three groups had mixed Oregon and Washington stations. Three groups consisted of only Washington stations, two of which had the ostracod, *Euphilomedes carcharodonta*, as one of the top contributing species.

5.3.3 EPA and BOEM comparison

As previously stated, the EPA data separated from the BOEM data in the nMDS plane (Figure 10); an ANOSIM test comparing the two datasets resulted in a global R statistic of 0.398 at the 1% significance level. The main difference observed between the 2003 EPA and BOEM data sets was greater relative and absolute molluscan abundance in the BOEM dataset. The molluscan increase is due primarily to an increase in bivalves – while bivalve species composition was fairly similar between the datasets, abundances of the species present were higher in the BOEM collections than the EPA, primarily due to increased abundances of three species of bivalve: *Axinopsida serricata*, *Ennucula tenuis*, and *Nutricola lordi*. This change was especially pronounced in Newport, where molluscs comprised approximately 80 percent of collected macrofaunal invertebrates at this 2010 BOEM site. To investigate whether observed differences were due to sampling different areas on the coast or actual temporal changes, we compared only the EPA stations that fell within the same region of the coast (as defined by capes and headlands) as the BOEM sites. Even within geographic region, the BOEM stations showed higher average abundances of bivalves (Figure 14). Drawing conclusions about drivers temporal changes is difficult with only two time points and a limited number of stations that overlap the same sampling areas. However, historical Army Corps data for dredge spoils off Newport (USACE and EPA 2001 and 2011) combined with more recent bi-monthly benthic sampling in the same area (Henkel 2011a) provide a longer time series data set for Newport in particular. Preliminary analysis corroborates the observed shift to bivalve-dominated communities in the EPA/BOEM comparison with more bivalves collected in recent samples off Newport (2010 – 2014) than in previous surveys at and around the dredged material disposal site (1984 – 2008).

In order to investigate possible causes for the observed difference in bivalves, we compared physical conditions between the datasets and within each dataset we compared spatial variations in temperature, dissolved oxygen, percent silt, chlorophyll *a* (WEMAP) and fluorescence (BOEM) to spatial trends in bivalve density. Neither temperature nor dissolved oxygen displayed large variations between 2003 and 2010. Although silt/clay % did vary at the stations surveyed in the different years, the pattern in percent silt distribution observed for the BOEM sites was not reflected in bivalve densities across stations; similarly, the patterns for chlorophyll a/fluorescence do not explain the trends in bivalve density. Since neither changes in the physical environment nor changes in prey abundance (via chlorophyll) seem to explain the increase in bivalves, release from predation may help explain observed trends. However, we did not conduct surveys of higher trophic levels in this project.

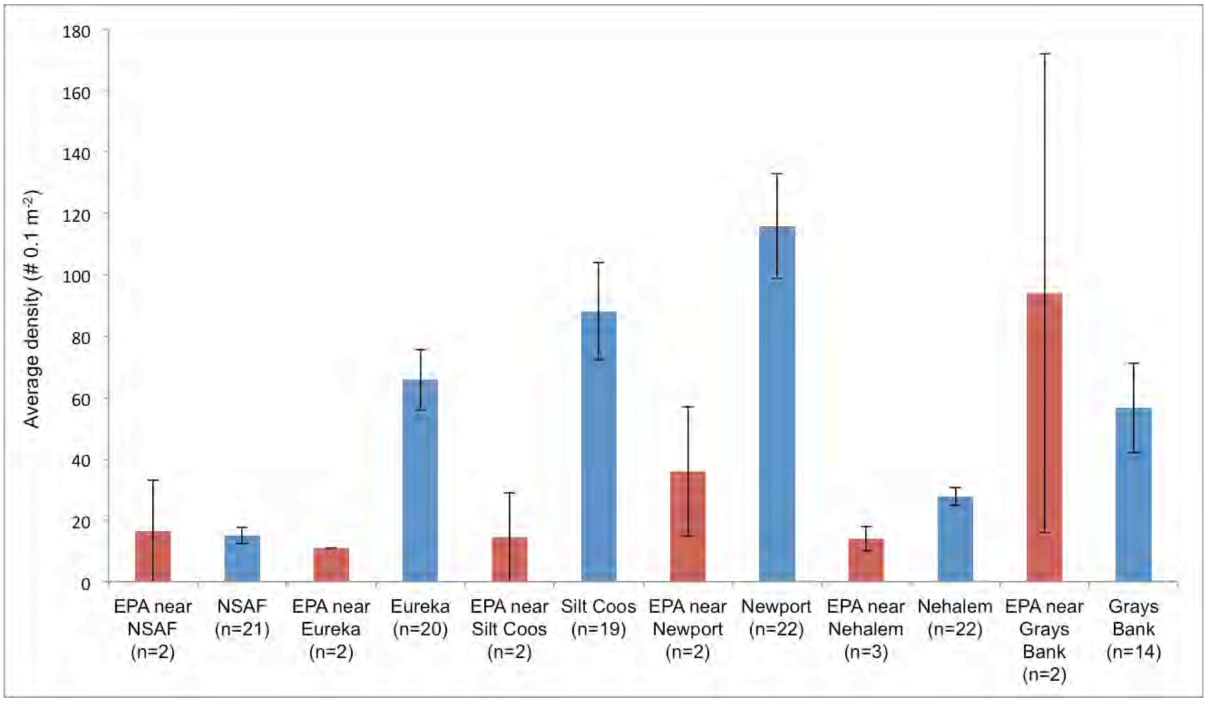

Figure 14. Bivalve densities from EPA stations (red bars) that fell near 2010 BOEM sites (blue bars)

Even within close proximity, collections made in 2010 mostly had higher abundances of bivalves than collections made in 2003. Stations from the two datasets do not directly overlap.

5.3.4 Linking Biological and Physical Patterns

The BIO-ENV routine in Primer indicated that the subset of measured environmental variables that correlated best with the distribution of BOEM stations based on the macrofaunal invertebrate assemblages included depth, % sand, % gravel and median grain size with a correlation of 0.709. In this case, no water quality variables (temperature, salinity, dissolved oxygen) were strongly correlated with organism distributions. For the EPA dataset, depth and % sand, along with TOC, salinity, and latitude were the strongest correlates. However, the relationship to the biological distribution was not as strong with an overall correlation of only 0.472.

The LINKTREE routine iteratively divided the stations into two groups with similar macrofaunal assemblages for each of the influential variables determined by the BIO-ENV routine. For the BOEM dataset, this resulted in nine splits and 10 groups of similar stations (Figure 15). The 11 gravel stations split off first and into two groups: high gravel and moderate gravel, characterized by different groups of polychaetes (BOEM LINKTREE Table in Appendix 5). However, the similarity of invertebrates among gravel stations is relatively low (BOEM LINKTREE Table in Appendix 5). The next split was at ~ 85 % sand. All stations (n = 70 across 5 sites) that were less than 84 % sand (> 16 % silt) formed a significantly similar group (Group C, left branch; Figure 15), which was not further subdivided, indicating that silty habitats support similar macrofaunal assemblages regardless of latitude or depth. This ‘silty’ group was characterized by moderate abundances of three bivalves, a brittle star, and two polychaetes (BOEM LINKTREE Table in Appendix 5). Within stations that had > 87 % sand, stations were further split on the basis of depth (with significant breaks at 72 m, 83 m, and 92 m deep), median grain size (with significant breaks at ~343 um and 219 um), and finally a break between 99.2 and 100 % sand. The shallower high sand stations with the largest grain sizes as well as the 100 % sand stations were characterized by high abundances of the bivalve *Nutricola lordi* – this seems to be a very specialist species, which defines and dominates this habitat type. In high sand stations with smaller grain sizes, amphipods such as *Ampelisca* *careyi* and *Rhepoxynius* sp. become characteristic. At the deepest sand stations, brittle stars again because part of the assemblage.

For the EPA dataset, when LINKTREE analysis of the stations was run with all the 'best' correlating environmental variables, the inclusion of salinity resulted a tree that differed by only one station from a tree that did not include salinity. So, for simplicity and consistency (neither the BOEM BEST nor the BayesNet models [Chapter 6] indicated water column variables were explanatory factors), we ran the LINKTREE analysis without salinity. In the resulting tree (Figure 16), high sand stations (>95 %) split off first (there were no gravel stations in the EPA dataset). That high sand group of stations was then further divided into two groups which differentiated at ~ 42 ° N latitude. Southern high sand stations were characterized by polychaetes and a single crustacean while northern high sand stations required many more species to characterize the assemblage (EPA LINKTREE Table in Appendix 5) These two groups were nearly 87 % dissimilar with differences driven by the dominant polychaete species: *Amaeana occidentalis* in the south and *Spiophanes norrisi* in the north, as well as the occurrence of many more amphipod species in the southern stations than the north. Stations that had less than 95 % sand further divided based on depth (with significant breaks at 70 m and 81 – 102 m) and twice more at ~ 42 ° N latitude. A second sand break occurred at ~ 81 % sand. Overall, most stations (n = 55) fell into two major clusters: stations with greater than 95 % sand (H), and a group of less than 95 % and greater than 71 m deep (B-R) (Figure 16).

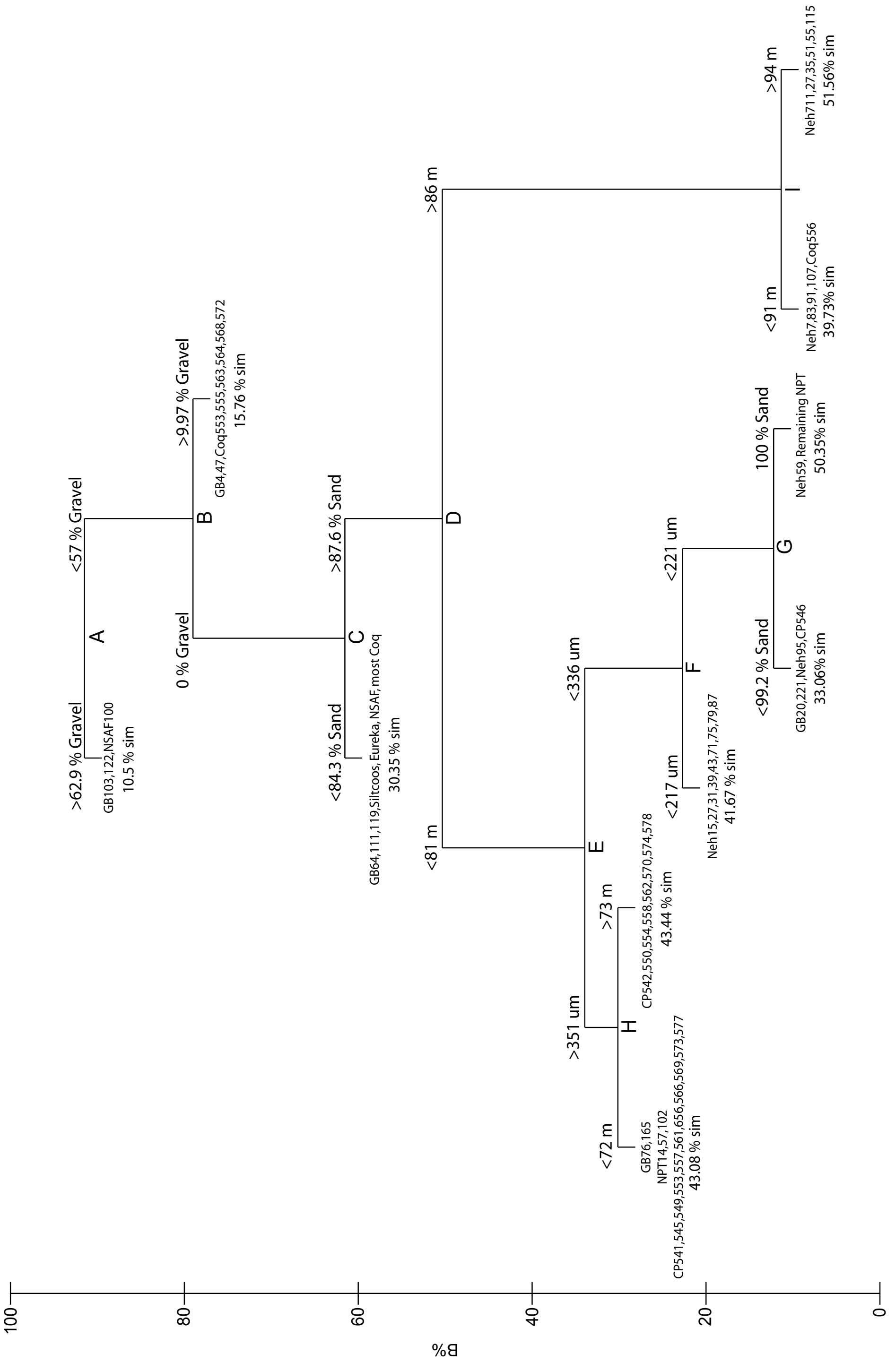

Figure 15. LINKTREE grouping and physical characteristics of BOEM stations developed using the BEST correlating (% gravel, % sand, median grain size, and depth) environmental variables. Y-axis shows the percent similarity (%B)

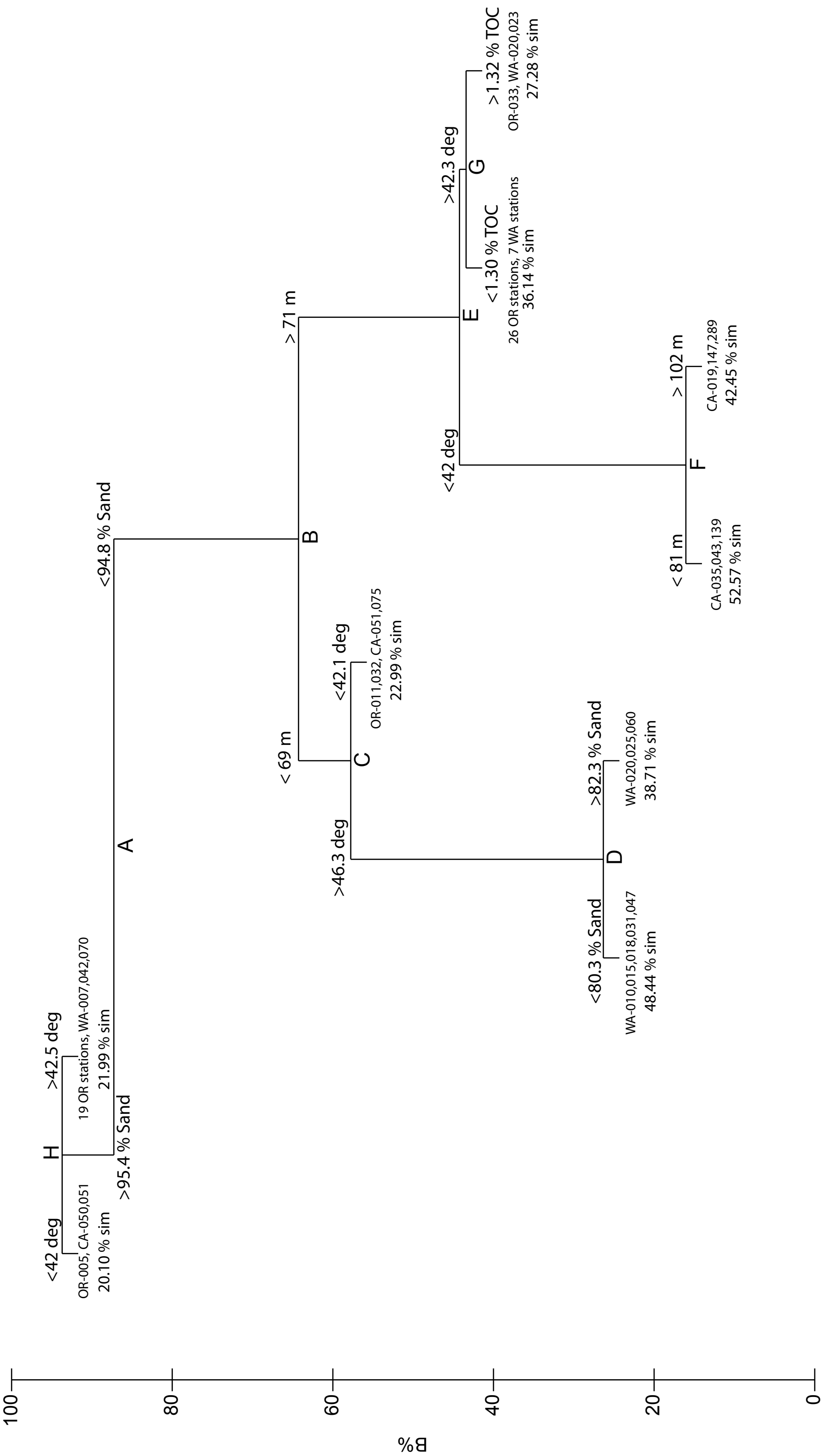

Figure 16. LINKTREE grouping and physical characteristics of EPA stations developed using the BEST correlating (% sand, depth, TOC, and latitude

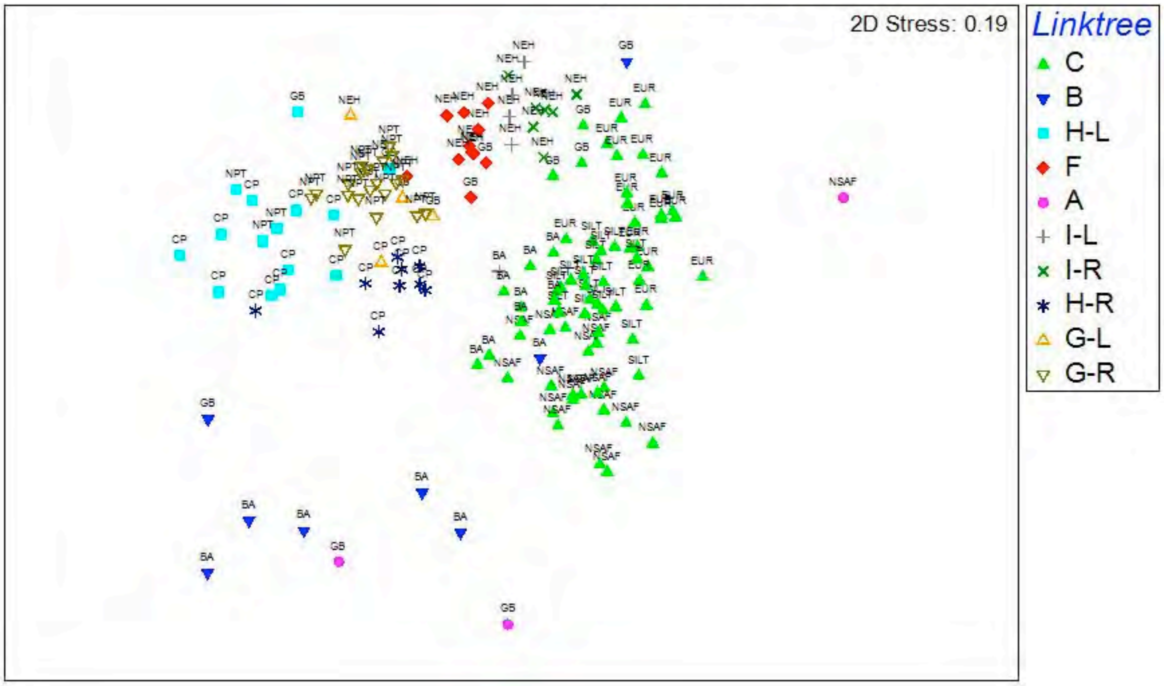

Figure 17. nMDS ordination of BOEM stations
Distribution of stations in the ordination plane is based on organism abundance resemblance matrix. Letter codes above symbols represent site names. Symbols represent how stations grouped primarily by sediment types and depth in the LINKTREE analysis. For instance, three stations (group A) have distinct assemblages from the remaining stations; this group is defined by the fact that these stations are composed of >62.9% gravel. However, while Group A is distinct from other stations, the three stations in group A have a low degree of similarity among stations and are therefore distant from each other.

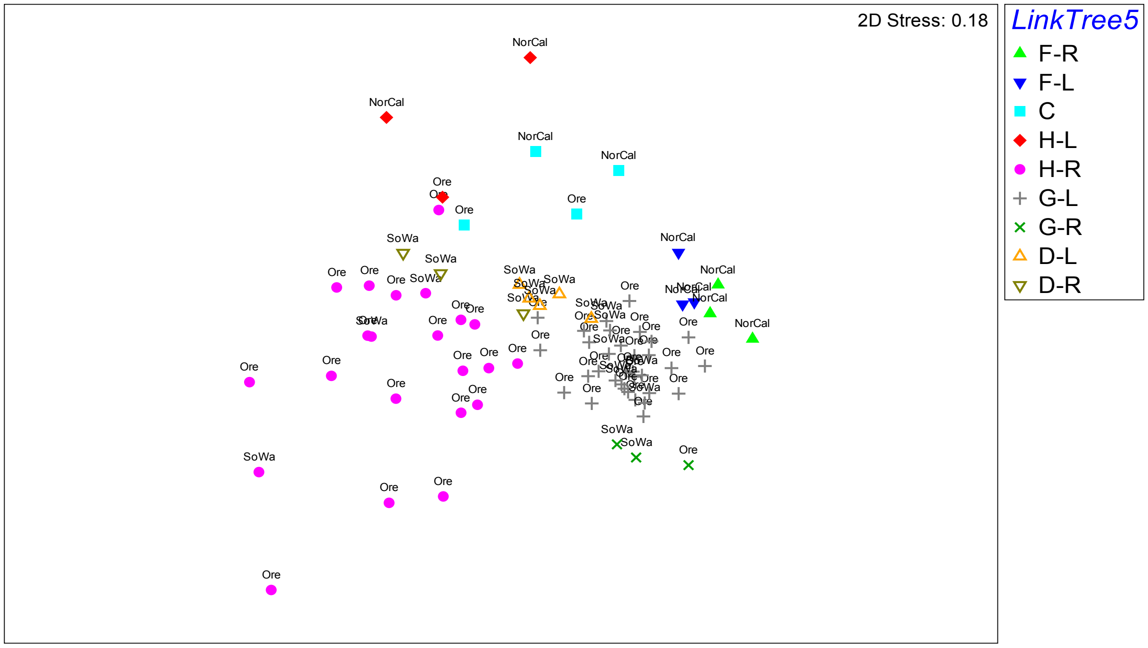

Figure 18. nMDS ordination of EPA stations
Distribution of stations in the ordination plane is based on organism abundance resemblance matrix. Letter codes above symbols are the states where the samples were taken. Symbols represent the LINKTREE groups.

5.4 Discussion

In this comprehensive survey, we analyzed the macrofaunal assemblages from 153 grabs at eight sites across three states and related the abundances of different species to environmental conditions observed at those grab stations. Strong site specific and within-region patterns are clearly detected in the BOEM and to a lesser extent in the EPA data. This is not surprising given that most of the BOEM sites represented a unique depth-sediment combination and the literature suggests macrofauna communities are driven primarily by grain size and depth. Where sediment and depth conditions were similar (Cape Perpetua, Newport, and Nehalem) macrofaunal assemblages grouped across site boundaries.

Analyses based on the species and their counts without considering physical variables at the sample stations (CLUSTER & SIMPROF) detected significantly different species distributions within and among the eight sites surveyed for this project. However analyses grouping stations based on both similar species abundances and benthic conditions (LINKTREE) resulted in discernable broad-scale patterns. Generally, stations containing greater than 15 % silt/clay grouped together, regardless of depth or latitude, indicating that silty habitats support rather homogeneous assemblages. The fine discrimination in the cluster analysis of stations in silty habitats was largely due to differences in the abundances of species, with the mostly the same organisms found across groups within a site. Thus, it seems that within particular depth and % silt/clay conditions, certain groups of species can be expected to be present, even if their relative abundances vary. Thus, a species occurrence list from one silty site within the region would likely apply to another site of similar depth and grain size in the area. On the other hand in sandy areas (> 87 % sand, e.g. Nehalem, Newport, Cape Perpetua), small changes in depth and percent silt/clay resulted in statistical differentiation of stations. Within sandy regions, assemblages were more depth-specific, and more detailed information about the sediment characteristics (specific grain size distributions) is necessary to predict macrofaunal species assemblages. Additionally, we analyzed data from 79 stations in the same region collected by the US EPA in 2003. Consistent with the analyses of the BOEM dataset, the percent sand in the sediment was the primary factor associated with differences in macrofaunal assemblages, which then further differentiated by depth strata. Therefore, the lithological classification of sand (< 25% silt/clay; *sensu* Shepard 1954) can only be considered a geologic group and does not adequately define a 'habitat' for macrofaunal invertebrates.

These findings from both collections seem slightly in contrast with observations in southern California, where depth is considered to be the primary structuring variable with other factors such dissolved oxygen, grain size, and total organic carbon secondary (SAIC 1986, Hyland et al. 1991, Allen et al. 2007). However, this could be due to the somewhat limited zone of these studies (BOEM & EPA), which did not include samples from the inner continental shelf (few stations less than 50 m) or samples deeper than 130 m. Based on other sampling in Oregon state waters (Henkel 2011a,b), we hypothesize that across the shelf, depth may be the primary factor structuring assemblages (consistent with other studies), with the inner shelf (< 50 m) differentiating from the mid to outer-shelf (this study), which is secondarily structured by sediment composition (% sand) with finer resolution depth differentiation occurring within sediment types. In the LINKTREE analysis of both datasets, significant depth breaks were detected at approximately 70 m and 80 m. In the BOEM dataset, a third break was observed at ~90 m, and within the EPA data the third break was observed at >102 m. It should be noted that in sandy areas where these ~10 m depth bins are most distinct, the shelf is gently sloping such that a 70 m station may be kilometers away from an 80 m station.

The focus region for this study is very similar to the "Oregon, Washington, Vancouver Coast and Shelf" ecoregion based on the Marine Ecosystems of the World (MEOW) biogeographic schema (Spalding et al. 2007); however, the Northern San Andreas Fault (NSAF) site and three of the EPA California stations fall into the "Northern California" ecoregion (below 40° N). In our surveys, we did not observe the NSAF stations to differ significantly from the rest of the dataset, nor were the three southern-most EPA California stations distinct. Thus, for macrofaunal invertebrates, it does not appear that 40° N latitude represents a strong break in species distributions or abundances. However, in the EPA dataset, breaks in species assemblages were determined at 42 – 42.5° N within multiple percent sand and depth bins. Since this break was reiterated within various sediment/depth bins, it reinforces the hypothesis that sediment composition is the primary driver of species assemblages; then, within major assemblages associated with different sediment types, we see further differentiation in species distributions related to latitude. These latitudinal breakpoints are between the Rogue River in Oregon and the California border, which also is within the biggest gap between sites surveyed for this BOEM study. BOEM sites to the south of this break (EUR and NSAF) were not distinct from sites in Oregon and Washington with similar sediment characteristics. However, in our survey all the (non-gravel) stations from EUR and NSAF had less than 84 % sand, suggesting that the latitudinal break observed in the EPA survey may only hold for assemblages associated with high sand (>84 % sand) environments. A second latitudinal break in the EPA stations was determined at > 46.3 ° N within the shallower (<70 m) stations. Both these observations are consistent with our overall findings that greater spatial heterogeneity is found in shallower sandy areas than silty areas. Latitudinal trends in species diversity (richness) are in general well documented and well accepted, with diversity highest at the tropics and decreasing towards the poles (Fischer 1960, Gaston 1996, Willing et al. 2003, Hillebrand 2004). However, marine macrofauna present a taxonomic area where debate about this diversity gradient is still ongoing. Thorson (1957) argued that this trend was not reflected in infauna because of the burrowing nature of infaunal species in soft bottom habitats: unlike epifauna, infauna were not as exposed to large scale latitudinal variation in environmental parameters; their homogeneous habitats sheltered them and species richness was independent of latitude.

There are multiple possible explanations for spatial differences in species occurrences and abundances. Generally, factors driving community composition can be considered bottom-up forces, such as resource availability or environmental factors, or top-down forces, such as predation (Hairston et al. 1960); however, these two types of forces are not mutually exclusive and communities are impacted by a combination of both types of drivers (Hunter and Price 1992). In this project, focused on abiotic (bottom-up) factors, top-down/biotic forces constitute important missing parameters, since competition and predation can have a large effect on the spatial distribution of soft-sediment macrofauna (Wilson 1990). It should be noted that along with all biotic factors, some potentially important environmental parameters are also missing. Wave action and/or currents influence larval distribution and affect feeding rates for suspension feeding organisms. In the case of some polychaetes, wave action and/or currents can impact not only feeding rates but also feeding behavior (i.e. suspension or deposit feeding) (Taghon et al. 1980, Dauer et al. 1981, Taghon and Greene 1992. Depth can be considered a rough proxy for wave action, with deeper sample stations less likely to be impacted by wave action; however, within our survey area most stations would be considered below the influence of wave action. It has been argued that bottom flow, rather than grain size or sediment type, is the main determinant of spatial distribution for macrofaunal species. In a review paper, Snelgrove and Butman (1994) contend that since grain size is a "super parameter" (Jansson 1967) with covariates including amount of organic matter, pore-water chemistry, and microbial presence, these factors, rather than grain size, may be the actual casual factors influencing distribution. Furthermore, because these covariate factors are all impacted by the hydrological regime – particularly boundary-layer and near-bed flow – flow conditions ultimately drive spatial distribution. Even if bottom flow isn't responsible for spatial distribution via impacts on grain size covariates, it might account for the strong relationship between species distribution and sediment in another way. Snelgrove and Butman (1994) note:

> "Another explanation for the association between particular species and a given sediment type is that larvae may be deposited onto the seabed as passive particles…if characteristics of passive larvae and transported sediment grains (e.g. size, specific gravity, and gravitational fall velocity) are similar, then larvae and sediment could be hydrodynamically sorted in a similar manner…resulting in distinct animal-sediment associations. This mechanism…explicitly accounts for correlations between macrofaunal and grain-size distributions, but grain size per se is irrelevant in producing the pattern."

So, variability in larval forms and larval transport may also constitute a missing parameter, important in explaining spatial distribution of benthic macrofauna. Of course, there are top-down factors such as predation that also likely affect the community composition and abundances of macrofaunal invertebrates.

Components of offshore renewable energy devices are expected to affect the benthic environment. Effects beyond direct smothering of small areas by bottom-mounted components include the alteration of the local hydrological regime, which may alter sediment transport dynamics, as well as resuspension and movement of sediments, which will increase turbidity (Gill 2005, Cada et al. 2007), potentially beyond the project footprint. This disturbance, somewhat analogous to dredging/bottom-contact fishing disturbance, will likely cause a loss of some sedentary macrofauna at local scales (Gill 2005). Additionally, sediment transport, which alters neighboring habitats, has the potential change the spatial distribution of local species as well as attract new species to the area. It is important to note that these impacts are not just limited to benthic macrofauna: decreases in abundance or changes in the spatial distribution of lower trophic levels sources will also impact higher level predatory species (Gill 2005). These impacts are generally applicable to benthic environments; however, it must be noted that exact ecological responses will necessarily be site-specific. For some areas, impacts due to WEC projects will be small compared to natural spatial and temporal variations (Langhamer 2010).

Although impacts due to WEC devices themselves may be small compared to “naturally” occurring variation, these impacts are not occurring in a vacuum – ocean conditions are changing globally, regionally, and locally, not only in response to changes in seasonal or inter-annual environmental parameters but also in response to anthropogenic effects (Boyd and Hutchins 2012). Benthic communities are predicted to be under considerable pressure with predicted changes in seawater pH and temperature. Hale et al. (2011) concluded that “ocean acidification induced changes in marine biodiversity will be driven by differential vulnerability within and between different taxonomical groups,” with molluscs displaying the greatest vulnerability, in terms of both abundance and diversity, to decreased pH and increased temperature. Furthermore, benthic responses are also predicted to vary according to habitat sediment type, with impacts occurring faster and to a greater extent on organisms in sandy sediment than organisms in muddy sediment (Widdicombe et al. 2009). In addition to the impacts of climate change, coastal zones (the locations of WEC sites) are often already highly impacted by human activities such as fisheries development, oil and gas production, nutrient pollution and eutrophication, and hypoxic events. Given the large number of pressures already affecting potential WEC sites, cumulative impacts are an important aspect of WEC that will need to be considered (Cada et al. 2007).

5.4.1 Conclusions

Regional surveys about spatial variation of invertebrates can provide baseline data as well as inform possible outcomes of WEC impacts by understanding how macrofaunal communities may differ with changes in sediment characteristics. Characterizing benthic habitats and communities is useful not only for providing a snapshot of current benthic composition, as discussed here, but also for providing baseline data useful for future environmental assessments and environmental impact statements. For example, alterations in local benthic substrate may change available habitat at a small scale. If species-specific relationships with sediment are known, possible changes in local communities can potentially be predicted. For instance, species such as *Nutricola lordi,* which are sensitive to even small amounts of silt-clay in sediment, may be expected to be more vulnerable to or impacted by changes in local substrate. Conversely, species with broad tolerances to sediment types, such as *Axinopsida serricata*, may be expected to be robust to localized sediment alterations.

Furthermore, site selection, baseline data collection, and continual monitoring are expensive and labor-intensive tasks, so the “transferability” of sample data – whether the collected data would be applicable to or representative of another site with similar environmental parameters – is of great interest. It is in this context that understanding the drivers, or primary characteristics, of assemblages and/or individual species becomes important. In the BOEM survey, the Newport/Nehalem difference serves as a cautionary tale about using general sediment type as a defining characteristic for a bivalve assemblage: although both contain sediment which is nearly all sand, the small percentage of silt present at Nehalem resulted in significant faunal differences (particularly in the bivalve assemblages) between the sites, primarily due to the presence of a single species, *Nutricola lordi*. On the other hand, the Newport/Cape Perpetua comparison shows that when both sediment and depth conditions are uniform macrofaunal assemblages are also uniform across sites. The results of this study demonstrate that characterizing macrofaunal invertebrate distributions and abundances requires fairly detailed knowledge of depth and sediment conditions at a site (potentially requiring site-specific physical surveys with relatively high spatial intensity). However, if those parameters are known, habitat suitability for particular macrofaunal species or assemblages may be predictable without biological sampling.

The overall aim of environmental assessments is to develop a robust study design capable of detecting environmental changes while keeping costs associated with environmental monitoring appropriately scaled to the cost of a project. We expect that the high intensity sampling conducted by our academic institution to assess the effort required to characterize habitats, species, and detect and understand potential changes will inform the development of appropriately scaled standards for the consenting process.

5.4.2 Next Steps

In this study we compared macrofaunal communities within and across the region, identified the physical factors most associated with different communities, and identified species that are particularly representative of various communities or distinguish between communities. Initially, the most unexpected finding of this project was the significant differences in macrofaunal assemblages among sites. Based on surveys in other parts of the California Current System as well as the 2003 EPA survey in the region, such strong site differences were not expected. However, once the physical characteristics of the sites are understood and taken into account, the faunal differences between them are not so surprising. The eight sites fell into four significantly different depth groups and six significantly different percent silt/clay groups. Only Newport and Cape Perpetua were statistically similar for both metrics (and macrofaunal communities did span across these sites). Thus, it cannot be determined by the samples collected to date if there are actual site-specific macrofaunal communities or if the apparent site specificity in biological assemblages is a result of site specificity in habitat parameters. In order to investigate this question, future studies should endeavor to sample areas with similar depth and sediment characteristics across latitude throughout the region. The areas sampled for this project focused on regions of the coast where offshore renewable energy projects had been proposed at the initiation of this study (bounded by jurisdictional and logistical constraints). Thus, the somewhat site-specific findings of this study are relevant to those areas of potential offshore renewable energy development. However, if a broader understanding of local versus regional variability in macrofaunal distributions is desired, future studies must survey more areas along the coast in order to replicate habitat conditions across space.

In order to use the information on species/community relationships with physical habitat characteristics gained by this study to understand how WEC development might affect macrofauna communities, a next step is to identify species or assemblages that would most be affected by the impacting factors identified in renewable energy development. For example, changes in water movement, resulting from both anchors in place and, potentially, energy removal, can cause benthic sediment scouring (Boehlert and Gill 2010). This scouring will result in localized changes to the percent silt and median/mean grain size (as small grains are likely to be scoured away first). Thus, species that have been identified in this study as being characteristic of discriminating between groups associated with small differences in percent silt/sand may be those most likely to sensitive to WEC installations.

Once species of interest (those that might be most likely to respond to WEC project-related changes) have been identified, they are good candidates for regional geologically based habitat modeling efforts. These regional models can support spatial planning efforts by identifying areas with high versus low probably of suitable habitat for species of concern. We have provided models for seven species of interest in the next chapter: *Axinopsida serricata, Ennucula tenuis, Astyris gausapata, Callianax pycna, Magelona berkeleyi, Onuphis iridescens,* and *Sternaspis fossor*. Some of these species were chosen because they do represent ones that might be expected to change distributions based on sediment changes due to WEC installations. Others were chosen because of other characteristics about their distributions that may present challenges to the modeling effort, as the goal of the modeling described in Chapter 6 is to demonstrate the utility of the tool across a spectrum of species. The seven species and their reason for inclusion in the modeling are described below. Future work should apply the developed model tool to specific taxa of interest as related to WEC installations.

- The gastropod, *Astyris gausapata*, was observed at about 45 % of the stations but was characteristic of (abundant at) stations with the largest grain sizes (LINKTREE group H-R); thus, this is a species that might be expected to have higher habitat suitability in places experiencing scour due to WEC installations and reduced habitat suitability in areas downstream where scoured silt ultimately gets deposited.
- The polychaete, *Sternaspis fossor*, was observed at 30 % of the stations and was a characteristic species for the silty-sand group (LINKTREE group C), being seven times more abundant in this group than in other groups. Thus, scouring away of fine sediment might be expected to reduce habitat suitability locally for this species.
- The bivalve, *Ennucula tenuis,* was characteristic of the deep stations (LINKTREE groups I-L and I-R) and highly contributed to distinguishing those groups from all the others. Similarly, the gastropod, *Callianax pycna*, was characteristic only of shallow stations. WEC installations are not expected to affect distributions of these species (since WECs aren't going to dramatically change depth), but these were chosen as candidates for regional modeling efforts to observe how models differ for species with different drivers.
- The polychaete, *Magelona berkeleyi*, has very patchy distributions. While it was only observed at 16 % of the stations, where it did occur, it was highly abundant (max = 265 in a single grab). Thus, it is interesting to see if the model can discern what makes some places highly suitable for this species.
- The bivalve, *Axinopsida serricata*, and the polychaete, *Onuphis iridescens*, were highly prevalent across all stations; thus variations in their abundances helped define differences between assemblages (e.g. *A. serricata* was in the top 5 species for 35 of 44 pair-wise comparisons). These were chosen to see if the habitat suitability models can capture and model variations in habitat suitability for broadly distributed species.

While we have initiated regional modeling efforts with the above seven species, there are still a number of areas on the coast that are under-sampled, so model outputs are weak for those areas. A better understanding both of regional distributions of habitat types (depth-sediment combinations) and species distributions would improve habitat suitability models and WEC siting efforts. Thus, a next step for new data collection would be to conduct a series of cross-shelf surveys particularly in areas of 'low experience' (few data points) to strengthen regional maps and models. In particular, areas around the mouth of the Columbia River represent a unique sediment-depth area. While a number of surveys have been conducted near the mouth related to dredge material disposal, the middle and outer continental shelf are less well characterized. Additionally, southern Oregon (below Cape Arago) is particularly data-poor and may represent a distinct region.

Finally, to gain a more ecological understanding of factors that influence macrofaunal assemblages and that could be affected by renewable energy development, future studies should survey other assemblages (epibenthic megafauna, fish) that interact with/prey upon the macrofaunal invertebrates surveyed here.

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6. Bayesian Modeling of Macrofauna Report

6.1 Introduction and Background

The distribution of a species over a landscape has strong associations to the patterns of its environment, allowing scientists to inferentially predict regional distributions of species from limited sample data (Guisan and Zimmermann 2000). This can be incredibly beneficial when studying and managing for elusive species (Sauer et al. 2013), such as benthic marine invertebrates. Understanding their ecology and distribution is strongly limited by the cost and time associated with collecting data of species living several to hundreds of meters under the surface of the ocean (e.g., Schonberg et al. 2014). Yet despite unknowns related to benthic invertebrate ecology, development of the benthic environment is progressing, increasing the risk of exposing benthic invertebrates to disturbance from human impact in the form of resource extraction, energy device development, and climate change.

This report will focus primarily on benthic macrofauna that live within marine soft bottom sediment, and are highly affected by the size of substrate particles (Gray 1974). Changes to sediment patterns on the seafloor can therefore impact the species living within the sediment. While it is unknown how renewable energy devices will impact benthic macrofauna, it is anticipated they will disturb communities, either through direct (i.e. anchor attachment, cable laying etc.), or indirect (i.e. changes to the local current and sediment patterns, acoustic and electromagnetic effects etc.) disturbance (Boehlert and Gill 2010). Therefore, a preliminary assessment of likely macrofauna suitable habitat is informative prior to the installation of multiple renewable energy devices off the western coast of the United States.

The continental shelf of the Pacific Northwest, United States is a high-energy wave system, which results in broad scale sedimentation patterns. Shallow regions, impacted by wave energy, tend to be dominated by coarse, sandy sediment with low organic content. As depth increases and wave disturbance decreases, there is a transition to finer, muddier sediment with high organic content (Snelgrove and Butman 1994; Snelgrove 1999; Byers and Grabowski 2013). While benthic macrofauna communities living within the sediment tend to organize around these sedimentary patterns, Snelgrove and Butman (1994) caution against relying on grain size alone to understand benthic macrofauna species distribution across a seascape. They discuss other factors, linked by fluid dynamics, which are likely at play. Examples include organic and microbial content within the sediment, food supply, larval dispersal and trophic interactions. Given that many of these factors co-vary throughout the continental shelf warrants careful model design to account for environmental variable correlation.

Habitat Suitability Probability (HSP) models apply statistical inference on species-environment relationships, drawn from sample data, to create regional maps with a prediction of the probability of suitable habitat for every given location (Guisan and Zimmermann 2000; Franklin 2009). Suitability can be determined by a range of methods. A straightforward method is based on the examination of species presence and absence from sampling efforts with coincident environmental correlates and remotely sensed environmental data. When sampling data are insufficient, suitability may be inferred from literature, expert opinion or other means. Final suitability maps are a continuous surface expressing the probability that the given, regional environmental conditions describe suitable habitat for the species of interest. The probability of suitable habitat is not a measure of abundance or any ordinal measure of habitat quality; rather, it is a static, empirical measure of probability in which environmental conditions are correlated with the observations of species presence (Franklin 2009). Inference occurs when predictions are made beyond sample collection sites; the model can apply what has been learned from these data and make a prediction of the probability that a particular combination of regional environmental parameters are suitable habitat for the species of interest.

Statistical habitat suitability models find their basis in the ecological niche and ecological gradient theories (Hutchinson 1957; Whittaker 1960; Whittaker et al. 1973; Franklin 1995), which state that a species is thought to have a unique set of environmental parameters in which it can survive and reproduce. Multiple HSP modeling techniques have been developed over the last decade, each with their own strengths and weaknesses (Guisan and Zimmermann 2000; Franklin 2009). Several limitations are known to occur for most of the modeling frameworks currently in use. One limitation is that of multi-collinearity, or variable correlation (Graham 2003). Most multivariate statistical modeling methods (that is, most principle-component and related data-reduction methods) cannot handle environmental parameters that are highly correlated (Heckerman 1995). This can become a problem when modeling in the marine benthic environment, where many of the environmental variables used to predict suitable habitat are highly correlated (Snelgrove and Butman 1994). A second issue is missing data. For most modeling tools, if a certain location in space is missing information about the environment, then a prediction cannot be made for this location, and if a sampled location is missing the measurement of even one covariate, the location record cannot be used to develop the overall model.

The final issue is uncertainty. A model is a representation of reality and therefore must contain some level of uncertainty. While the goal of a good model is to limit uncertainty, it cannot be eliminated completely. Sources of uncertainty include (but are not limited to) human error, precision of measurements, natural variability that occurs over space and time and error within the model itself (Guisan and Thuiller 2005; Franklin 2009). Species distribution maps are created to aid in the management of endangered, threatened and invasive species. They are also increasingly used in climate change and environmental impact assessment scenarios, predicting how a species will respond to future changes in the environment (Guisan and Thuiller 2005). Clearly communicating uncertainty is essential so that managers may better understand the spatial distribution of uncaptured variability and error, allowing for more scientifically informed decisions (Cleaves 1995).

Bayesian networks are a graphical modeling tool that applies Bayes' theorem to a network of linked variables to calculate posterior probabilities of outcome states (Jensen and Nielsen 2007). Bayes' theorem, in the application of habitat suitability modeling, states that the probability of the hypothesis (i.e. H = species presence) given the evidence (i.e. E = habitat data) is equal to the product of the conditional probability of E given H and the unconditional probability of H, divided by the unconditional probability of E, or: $\Pr(H|E) = \frac{\Pr(E|H)\Pr(H)}{\Pr(E)}$ (de Laplace 1812). Bayesian networks are used to address the three issues listed above; they can handle small datasets, multi-collinearity and missing data (Heckerman 1995; Kontkanen et al. 1997; Myllymäki et al. 2002; Uusitalo 2007). Bayesian networks are also designed to track and propagate uncertainty through the system (Gelman et al. 2013; Sivia 1996; Uusitalo 2007) and, in the context of this report, can provide a final habitat suitability surface along with an uncertainty surface (Norsys, Netica®). With maps of habitat suitability and projection uncertainty, environmental managers can be better informed to make decisions that progress human interests while considering impact on species of interest. Bayesian networks provide a robust method for tracking uncertainty through the HSP modeling process.

6.1.1 Purpose and Objectives

Mitigating for increased human impact in US coastal waters associated with offshore renewable energy device deployment can benefit from an understanding of the distribution of sensitive marine benthic species. For managers to make informed decisions that advance societal development while lessening the impact on species of interest, integrative models that consider interactions between various parts of the ecosystem and impacts are needed. The purpose of this study was to develop predictive methods as a tool to understand the regional distribution of rare or elusive benthic macrofauna species. Bayesian networks were developed to statistically infer suitable habitat for seven species of benthic macrofauna along the continental shelf of the United States, Pacific Northwest. The species were selected because their relative abundances were important for defining distinct macrofauna communities observed in the region. Models were learned from benthic sampling data collected from sites along the Pacific Northwest shelf, spanning from Northern California to Washington State, south of the Olympic Coast National Marine Sanctuary. We used Netica® software to implement the design and analysis of the statistical models, and to apply a cross-validation model selection technique. A generalized benthic macrofauna model structure for invertebrates living within marine sediment was developed for reusability and update capacity. Three regional maps were produced for each species, communicating habitat suitability, prediction uncertainty and the empirical basis for the habitat suitability map (equivalent sample size). With the three maps, environmental managers will be better equipped to make decisions that progress human interests while minimizing impact on species of interest. Methods developed and presented here also are broadly applicable to a wide range of other species and ecosystem models, particular in under-constrained settings where detailed sampling over large regions is not practical.

6.2 Methods

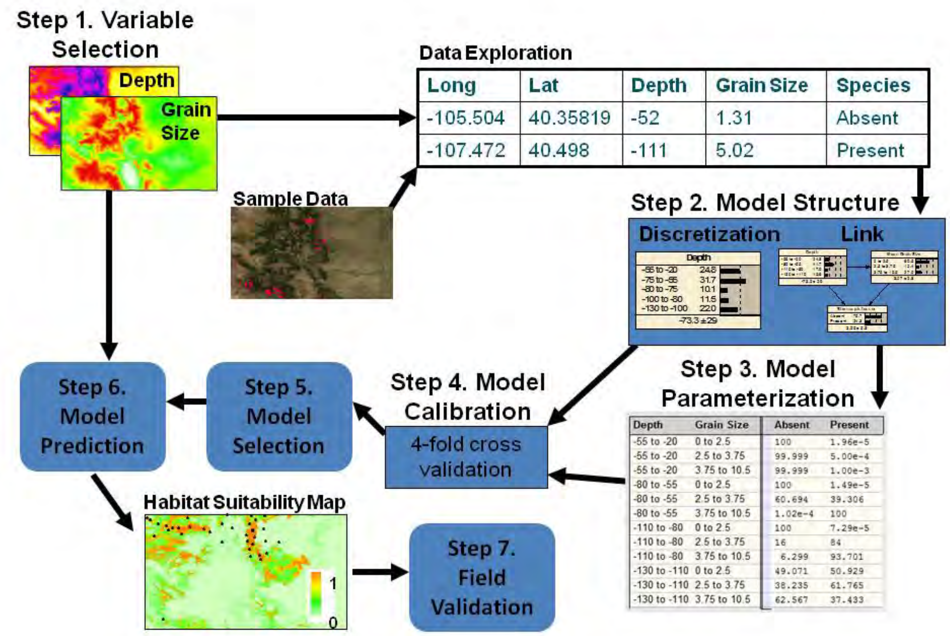
6.2.1 Overview

Seven benthic macrofauna species were selected for habitat suitability modeling: *Axinopsida serricata, Aystris gausapata, Callianax pycna, Ennucula tenuis, Magelona berkeleyi, Onuphis iridescens* and *Sternaspis fossor*. These species were collected as part of the effort described in Section 5 and sample processing methods are described in Section 5.2.1. Species chosen for modeling were based on the Primer SIMPER analysis, which determines which taxa and their densities contribute to defining distinct groups of stations hosting similar assemblages group (analysis methods are detailed in Section 5.2.4.2). The seven species modeled were those whose variations in densities highly contributed to distinctions between assemblages at multiple sites (Figure 19). Two species were chosen due to expected changes in distribution based on sediment changes due to offshore installations*: Aystris gausapata* and *Sternaspis fossor*. The other five species were chosen due to unique characteristics of their distributions, warranting further investigation with habitat suitability models to help determine the utility of the tool across a spectrum of species.

Figure 19. Benthic macrofauna species chosen for habitat suitability models
From top left to bottom right: *Aystris gausapata, Sternaspis fossor, Ennucula tenuis, Callianax pycna, Magelona berkeleyi, Axinopsida serricata* and *Onuphis iridescens*. Two species were chosen due to expected changes in distribution based on sediment changes due to offshore installations: *Aystris gausapata and Sternaspis fossor*. The other five species were chosen due to unique characteristics of their distributions, warranting further investigation with habitat suitability models to help determine the utility of the tool across a spectrum of species.

Databases on presence and absence of the seven benthic macrofauna species were loaded into ArcGIS 10.1 and were joined to raster databases on water depth and distance to shore. A final database resulted, containing data on species presence, absence, and environmental parameters (depth, grain size, distance to shore, total organic carbon, total nitrogen, percent silt and percent sand) for each sample location, which was brought into the modeling environment Netica®, to construct the Bayesian networks.

Benthic macrofauna models for all seven species were designed using guidelines for creating ecological Bayesian network models described by Marcot et al. (2006) and Uusitalo (2007). The overall habitat suitability modeling steps used include: 1) variable selection, 2) development of model structure, 3) model parameterization of probability values, 4) model calibration, 5) model selection, 6) model prediction and when data were available 7) field (or model) validation (Figure 20).



Long	Lat	Depth	Grain Size	Species
-105.504	40.35819	-52	1.31	Absent
-107.472	40.498	-111	5.02	Present

Depth	Grain Size	Absent	Present
-55 to -20	0 to 2.5	100	1.96e-5
-55 to -20	2.5 to 3.75	99.999	5.00e-4
-55 to -20	3.75 to 10.5	99.999	1.00e-3
-80 to -55	0 to 2.5	100	1.49e-5
-80 to -55	2.5 to 3.75	60.694	39.306
-80 to -55	3.75 to 10.5	1.02e-4	100
-110 to -80	0 to 2.5	100	7.29e-5
-110 to -80	2.5 to 3.75	16	84
-110 to -80	3.75 to 10.5	6.299	93.701
-130 to -110	0 to 2.5	49.071	50.929
-130 to -110	2.5 to 3.75	38.235	61.765
-130 to -110	3.75 to 10.5	62.567	37.433

Figure 20. Diagram of the process used to create Bayesian Network-based model for seven benthic macrofauna species
Step 1) Variable selection: variables of interest are selected for the modeling process and linked with sample data either through *in situ* observation or GIS analysis. Step 2) Model Structure development: this step consisted of 2 phases in Bayesian networks which are Discretization Structure development and Link Structure development. Step 3) Model Parameters: conditional probabilities were calculated using Norsys, Netica® expectation maximization algorithm. Step 4) Model Calibration: using four-fold cross validation. Step 5) Model Selection: final models were selected by analyzing performance metric results. Step 6) Model Prediction: final HSP maps were created using regional prediction layers and Norsys, Netica® software. Step 7) Field Validation: final models were evaluated with new field data.

Possible options for model development (Steps 1-3) include automated machine learning from the empirical datasets (e.g., Acid et al. 2004; Liang and Zhang 2009), knowledge-based model design from expert judgment (Cain 2001) or a combination (Darwiche 2009). The combination approach, in which computer algorithms define the model structure and probabilities that are modified through supervision to minimize black box effects, provides a useful opportunity to accurately represent complex ecological relationships that would not emerge from a strictly automated machine-learning approach (Uusitalo 2007). Models within this study were developed primarily using such a supervised technique.

A general benthic macrofauna model structure was developed for species living within marine sediment from Steps 1-2. Species-specific model structures were then created from this general model by modifying species-environment discretization breakpoints. Models were then parameterized using the sample data (Step 3). Multiple models were developed for each species using various subsets of covariates, and compared using performance metrics in model calibration (Step 4). In model selection (Step 5), performance metrics from Step 4 were used to choose a final model that balances model complexity and performance and under- and overfitting, discussed by Anderson (2008) as the Principle of Parsimony (Figure 21).

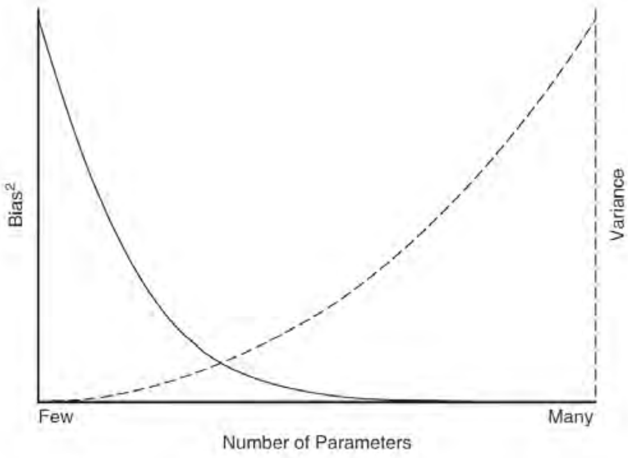


Figure 21. Principles of Parsimony
The most parsimonious model maximizes the tradeoff between certainty and precision. Precision and variance increase along with model complexity while bias increases as model complexity decreases. Graphic from Anderson (2008). Curves shown here are generalized to represent concepts, and were not derived from the benthic macrofauna models.

An "underfit" model does not provide enough structure to the data, leading to an over-generalized model with high certainty but low precision. The opposite scenario: an overfit model, where noise in the data is considered real, leads to spurious results with high precision of fit to the training data set, but low certainty of accurate application to unstudied sites (Anderson 2008). An ideal model is the simplest one that appropriately fits the data, optimizing both precision and certainty. A more complex model must significantly improve a model's classification accuracy score to warrant its additional complexity. To select a final model, modeling metrics or model performance scores are compared using model validation techniques. In the Bayesian network modeling environment, the tools used to determine model complexity and model comparison are not as clear as in the frequentist paradigm (Watanabe 2010). Also, as a Bayesian network is more than just the dataset in hand (prior knowledge informing structure, improvement of model with new data), a more complex network with small improvements to performance may remain the best choice.

Final habitat suitability maps were created in the model prediction phase (Step 6). For this study, maps were created for seven species of benthic macrofauna that spanned the continental shelf region from northern California to southern Washington (**Error! Reference source not found.**). The region was bounded by the southernmost and northernmost sampling locations (39º 30′ 25.668″ to 47º 01′ 2.64″), and along east to west by the shallowest and deepest marine sampling locations (-20 m to -130 m). Regions of rock, cobble and gravel were masked from the final predictive maps as the model was developed only for soft sediment habitats. Field validation (Step 7) was used to analyze the classification success of each model (Guisan and Zimmermann 2000). We compared model outputs (predictions of habitat suitability) to new data (observations of species presence representing suitable habitat) to assess the quality of the models' predictions. Given the discrepancy in units between habitat suitability predictions (probabilities) and observations (presence or absence), thresholds were predetermined to translate the two units (i.e. prediction probabilities of suitable habitat above 50% HSP represented species presence, and below 50% HSP represented species absence). Field validation is only meaningful for the site within which data were collected. As more data are collected throughout the region, the models can be further tested and updated.

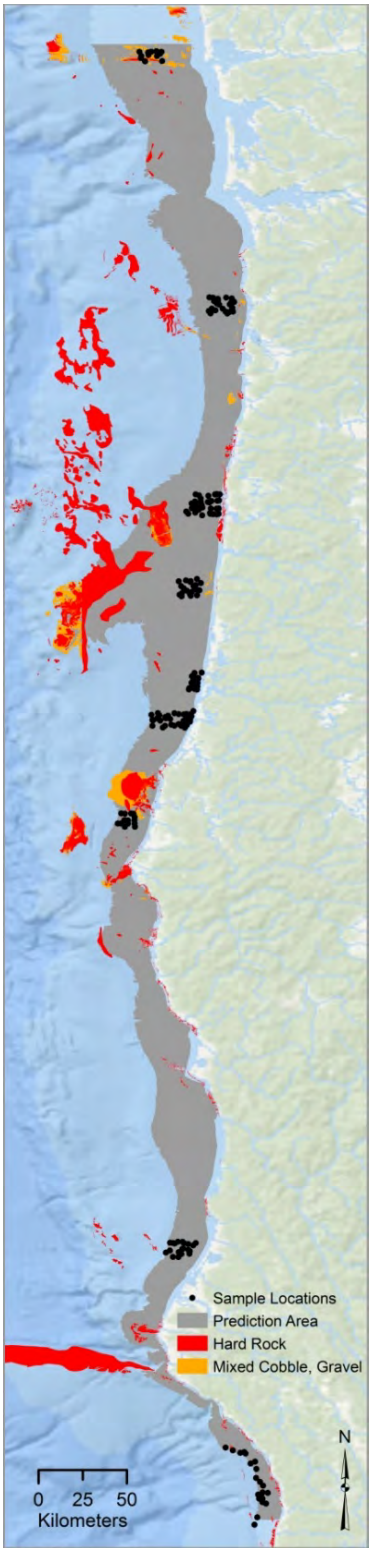


Figure 22. Study region
Southern and northern bounds defined by macrofauna sampling locations described in Section 5 (39º 30' 25.668" to 47º 01' 2.64"). Eastern and western bounds defined by shallowest and deepest samples (-20 to -130 meters). Areas of hard rock (red), cobble and gravel (yellow) are described in Section 3.

6.2.2 Components of a Bayesian Network

A Bayesian network modeling structure consists of nodes containing each explanatory (covariate or prediction) variable and response variable (Figure 23). These variables are connected by links (arrows) signifying correlative or assumed causal relationships or logical dependence. In models developed from supervised expert judgment, arrows typically point from a prediction node (the "parent") to a response node (the "child"). When a relationship between two prediction variables consists of a correlative relationship without causality, the direction of the arrow is not as important (Norsys, Netica®).

Each node is broken into a number of states or bins. As an example, in Figure 23, the *Sternaspis fossor* node has two states: Absent (observations in which the species abundance was equal to zero) and Present (observations in which the species abundance was greater than zero). The Depth node has four states: depth values which range from -20 to -55 m, -55 to -80 m, -80 to -110 m and -110 to -130 m. The Mean Grain Size node has three states: grain size values which range from 0 to 2.5 phi, 2.5 to 3.75 phi and 3.75 to 10.5 phi. Numbers to right of the states indicate their respective probabilities; child nodes contain posterior probabilities calculated using Bayes' theorem given the data (Norsys, Netica®). Posterior probabilities are the probabilities after the model has been updated with (has "learned from") data. All probabilities within a node add to 100 and numbers represent overall probabilities for the entire data set.

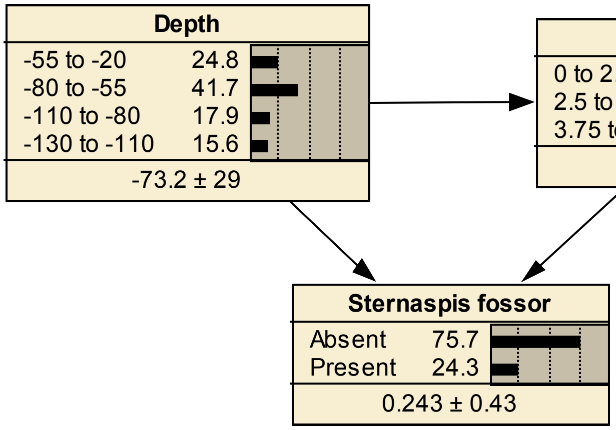


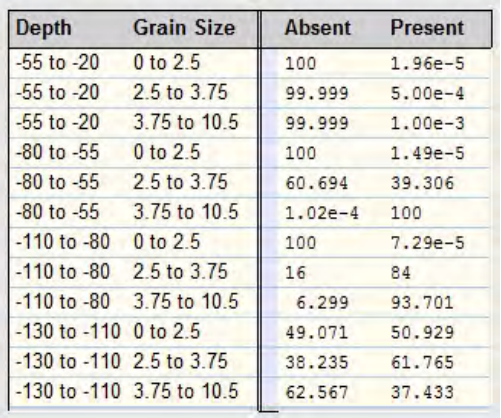
Figure 23. A sample Bayesian network modeling structure
This model describes an example relationship between species and environment, where Mean Grain Size (right node) is informed by Depth (left node) and the macrofauna species (*S. fossor*; bottom node) is dependent on both Depth and Mean Grain Size.

The numbers in the bottom of the node box indicate the expected value ($\bar{X}$) plus or minus its standard deviation ($\sqrt{V}$). The expected value is calculated via the Mean Value Theorem in calculus, which states that the mean value of a smooth curve is where its derivative is equal to, or parallel to the secant, or x-axis (Norsys Netica®). This expected value is not the value most likely to occur, as is the case with the frequentist mean, but rather the center of the probabilistic curve that is bounded by the start and end state values and weighted by the respective probabilities of each state. The standard deviation describes the symmetric Gaussian error distribution, and the standard deviation is equal to the square root of the variance. Table 18 calculates the expected value for each node from Figure 23.

Table 18. Steps for calculating expected values ($\overline{X}$) of nodes displayed in Figure 23
The expected mean is the bottom number in each continuous-value node. The midpoint of each state is multiplied by its posterior probability. Each weighted value is summed together to derive the node's expected value.

Node	State Midpoint	Posterior Probability	Weighted Value
Depth (m)	-37.5	0.248	-9.3
	-67.5	0.417	-28.15
	-95	0.179	-17.01
	-120	0.156	-18.72
	Expected Value:		-73.18
Mean Grain Size (phi)	1.25	0.605	0.76
	3.125	0.124	0.39
	7.125	0.27	1.92
	Expected Value:		3.07
Sternaspis fossor	0	0.757	0
	1	0.243	.243
	Expected Value:		.243

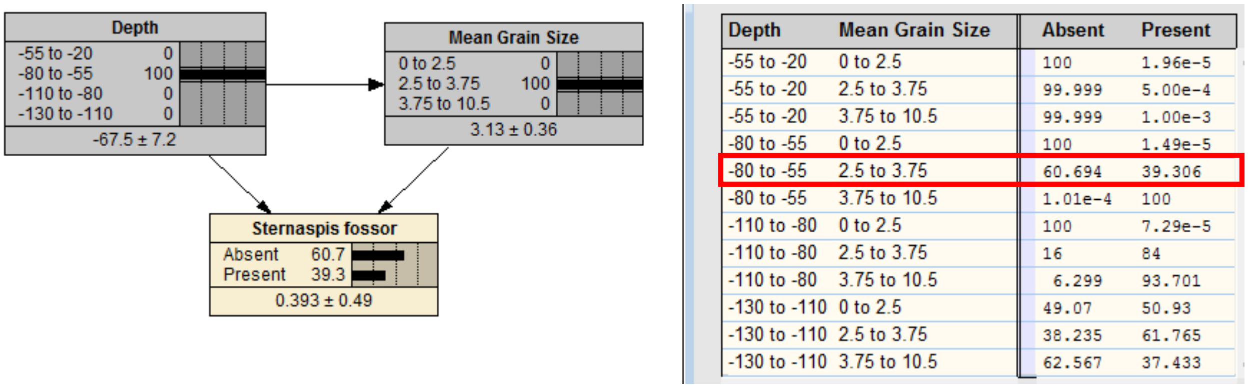
Within each child node is a conditional probability table (CPT) that contains all possible combinations of parent states (Figure 24). For each unique combination of parent states, a resultant probability is calculated for each child state using Bayes' theorem when the probabilities are calculated using machine-learning algorithms; otherwise, in supervised models, CPT values can be calculated from frequencies of outcomes given observed conditions, or can be assigned based on best professional judgment.



Depth	Grain Size	Absent	Present
-55 to -20	0 to 2.5	100	1.96e-5
-55 to -20	2.5 to 3.75	99.999	5.00e-4
-55 to -20	3.75 to 10.5	99.999	1.00e-3
-80 to -55	0 to 2.5	100	1.49e-5
-80 to -55	2.5 to 3.75	60.694	39.306
-80 to -55	3.75 to 10.5	1.02e-4	100
-110 to -80	0 to 2.5	100	7.29e-5
-110 to -80	2.5 to 3.75	16	84
-110 to -80	3.75 to 10.5	6.299	93.701
-130 to -110	0 to 2.5	49.071	50.929
-130 to -110	2.5 to 3.75	38.235	61.765
-130 to -110	3.75 to 10.5	62.567	37.433

Figure 24. Bayesian Network Conditional Probability Table (CPT)
The CPT shows all possible variable combinations from relationships of nodes presented in **Table 18**. For absent and present columns (right side), each row must add up to 100% probability.

When an environmental condition is entered into the Bayesian Network, the network reports the resultant probabilities of absent and present from the CPT (Figure 25). The probability of presence translates scientifically to the probability of suitable habitat since models were trained from a minimal dataset establishing relationships between species presence/absence and physical parameters alone.



Depth	Mean Grain Size	Absent	Present
-55 to -20	0 to 2.5	100	1.96e-5
-55 to -20	2.5 to 3.75	99.999	5.00e-4
-55 to -20	3.75 to 10.5	99.999	1.00e-3
-80 to -55	0 to 2.5	100	1.49e-5
-80 to -55	2.5 to 3.75	60.694	39.306
-80 to -55	3.75 to 10.5	1.01e-4	100
-110 to -80	0 to 2.5	100	7.29e-5
-110 to -80	2.5 to 3.75	16	84
-110 to -80	3.75 to 10.5	6.299	93.701
-130 to -110	0 to 2.5	49.07	50.93
-130 to -110	2.5 to 3.75	38.235	61.765
-130 to -110	3.75 to 10.5	62.567	37.433

Figure 25. Integrating absent/present probabilities
When environmental conditions are entered into the Bayesian Network, absent/present probabilities are pulled from the CPT. The "probability of present" translates scientifically to the "probability of suitable habitat" since probabilities were trained from a minimal dataset establishing relationships between species presence/absence and physical parameters. This is an example network and not a final model for *S. fossor*.

To create final predictive maps, Netica® processes a case file where each row is a cell on the map and each column represents a raster layer (i.e. Depth, Latitude, Mean Grain Size and Distance to Shore). Netica enters each raster value into the net for every cell location and reports the final probability of habitat suitability. This table is then converted into a raster within ArcGIS 10.1 with a continuous surface indicating the probability of habitat suitability given known environmental conditions.

6.2.3 Variable Selection

Of the physical parameters considered for habitat suitability models (Table 19) six *in situ* variables were used in the analysis: Latitude, Mean Grain Size, Percent Silt, Percent Sand, Total Organic Carbon (TOC) and Total Nitrogen (TN). An initial exploration of variables indicated minimal variability in Salinity (range: 33.1 – 33.9 PSU) and Temperature (range: 7.3 – 9.8 ˚C), warranting their exclusion in the modeling process as it was anticipated that these two variables would contribute little explanatory power. Further, pH, Fluorescence and Turbidity were excluded due to likely measurement errors encountered during the sampling process. Due to potential error in depth measurements made by the vessel at the time of sample collections, high resolution bathymetry data (detailed in Section 3) were extracted for each sampling location within ArcGIS 10.1. An additional parameter, Distance to Shore was calculated using a Euclidean Distance analysis on a polyline shoreline within ArcGIS 10.1. Values from this raster were extracted for each sampling location to be used in the analysis.

The inclusion of Latitude, Distance to Shore and local sediment characteristics (Percent Sand, Percent Silt, TOC and TN) were further analyzed by comparing all Bayesian network model results with and without these variables, and by conducting sensitivity analyses in the Bayesian network model. The latter technique reports how a finding at one node will likely change the probabilities of the target node (Norsys, Netica®). Resulting metrics from model comparisons plus results from Netica®'s Sensitivity to Findings analysis guided the process in selecting final models. When model performance metric results were identical, the model with fewer variables was selected.

Table 19. Environmental variables considered for Benthic Macrofauna Model for Habitat Suitability Analysis

Data were either collected *in situ* with species as part of this study (Section 5) or calculated as a raster in ArcGIS. Models were parameterized with *in situ* variables and high resolution rasters. Variables not included in the model were excluded either due to being insignificant or having insufficient data. Variables used for prediction were all generalized to a 250 meter cell size or predicted within the network.

Variables	Data Source	Model Parameterization	Model Prediction	Units of Variable
Mean Grain Size	Collected *in situ* Regional Raster (Section 3)	*in situ*	Regional Raster – 250m	phi
Latitude	Collected *in situ*	*in situ*	Regional Raster – 250m	degrees
Percent Silt	Collected *in situ*	*in situ*	Predicted in Network	percent
Percent Sand	Collected *in situ*	*in situ*	Predicted in Network	percent
Total Organic Carbon (TOC)	Collected *in situ*	*in situ*	Predicted in Network	percent by weight
Total Nitrogen (TN)	Collected *in situ*	*in situ*	Predicted in Network	percent by weight
Salinity	Collected *in situ*	Excluded – insignificant	Insignificant Variable	PSU
Temperature	Collected *in situ*	Excluded – insignificant	Insignificant Variable	degrees Celsius
pH	Collected *in situ*	Excluded – Insufficient data	Insufficient Data	pH
Fluorescence	Collected *in situ*	Excluded – insufficient data	Insufficient Data	ug/l
Turbidity	Collected *in situ*	Excluded – insufficient data	Insufficient Data	NTU
Depth	High Resolution Raster (Section 3)	High Resolution Raster (Section 3)	Regional Raster – 250m	meters
Distance to Shore	ArcGIS Raster	ArcGIS Raster	Regional Raster – 250m	meters

6.2.4 Development of Model Structure

Bayesian networks have a two-step process in developing model structure: variable discretization structure and node link structure (Step 2 in Figure 20). The former is a process where continuous variables are binned into incremental categories. The latter is a process where environmental nodes are connected with arrows (or links) depicting a correlative or causal relationship.

6.2.4.1 Node Discretization Structure

As the Netica® Bayesian network platform relies on a categorical approach, an additional step in the modeling process was necessary to discretize, or categorize continuous variables. Several automated techniques exist, yet no satisfactory discretization method, in the specific context of ecological datasets, has been developed within a Bayesian network (Uusitalo 2007). Myllymäki et al. (2002) recommend methods which use ecologically significant breakpoints and minimizing the number of states so that each interval contains enough data to run the model.

As there is no expert prior knowledge about ecological breakpoints for the seven species being modeled, a supervised technique was developed by visually inspecting frequency-value histograms and comparing presence and absence of each species in relation to values of each variable. Breakpoints were identified at the minimum and maximum range of a species presence response in the frequency-value histograms, or where density histograms changed from/to a greater density present to/from a greater density absent. Minimization of state intervals was attempted by only selecting what visually appeared to be the most relevant breakpoints in the variable's data that correspond to presence or absence of a species. Multiple breakpoint schemes were compared within Netica® using the species and single environmental node to optimize breakpoint locations and number of states. Models designed with this supervised approach were compared to an equal frequency binning technique, where breakpoints were identified so that an equal number of sample data (field records) points fell into each state (Figure 26). Model performance was compared for the two discretization approaches. Supervised discretization histograms for each species are listed in Appendix 6.1.

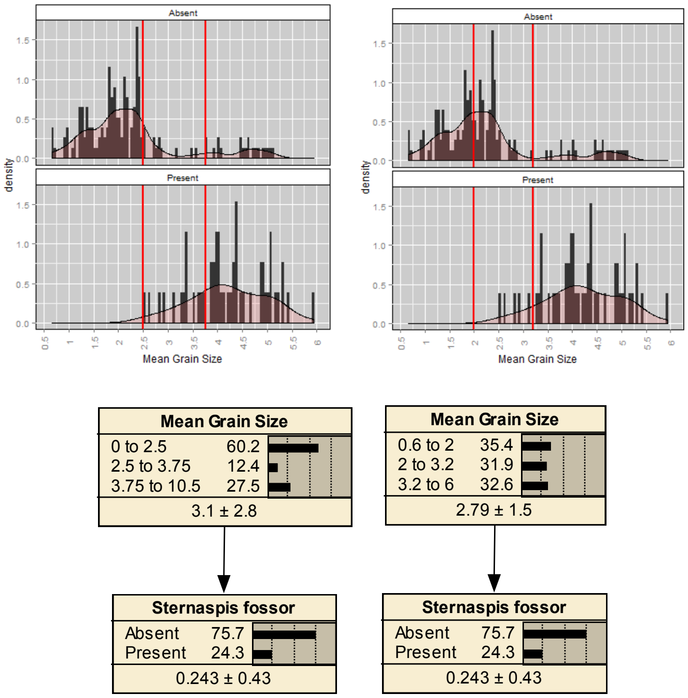


Figure 26. Supervised Discretization (Left) and Equal Frequency Discretization (Right) techniques to select breakpoints and state parameters for building the HSP Model (Top Left)
Supervised breakpoints (red lines) are determined by visually inspecting histograms of mean grain size at sites where a species was absent (top graph) and present (bottom graph). For Equal Frequency Discretization (Top Right), a computer algorithm assigns an equal number of data points to each state. Underneath the four histogram boxes are corresponding nodes. Notice the Equal Frequency Technique corresponds to a node with an approximate equal probability for each grain size state. In this example, node values for Mean Grain Size change while values for *Sternaspis fossor* remain the same (75.7% absent, 24.3% present, expected value 0.243 ± 0.43) because expected values and standard deviations are dependent on state breakpoints. Since the state breakpoints for *Sternaspis fossor* remain the same, the statistics within the node do not change. Mean Grain Size posterior probabilities, expected values, and standard deviations change because breakpoints have been altered. This is an example using *S. fossor* and does not represent this species' final model.

6.2.4.2 Link Structure Development

The simplest link structure is the naïve Bayesian network, which consists of a target node (i.e. variable of interest, which in this case is the benthic macrofauna species) pointing towards each explanatory variable. At its simplest, a naïve Bayesian network assumes no correlation among explanatory variables and thus lacks links between explanatory nodes (Figure 27).

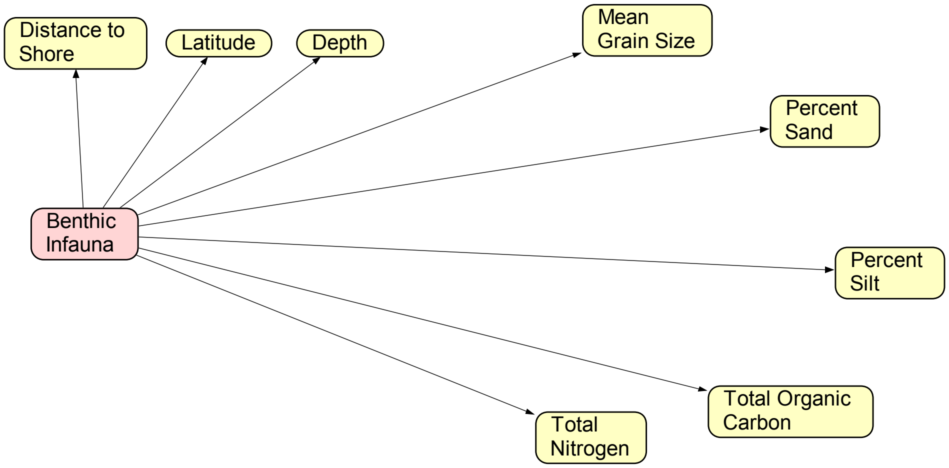


Figure 27. Naïve Bayesian Network
Effects of each node on target node are considered in isolation, correlations between explanatory variables are not taken into account.

The Bayesian Network software program, Netica®, contains the Tree Augmented Naïve (TAN) algorithm (Figure 28) for learning the Bayesian link structure when no prior knowledge is available to guide the design of the Bayesian Net (Friedman et al. 1997, e.g., as used by Aguilera et al. 2010 and Dlamini 2011). Lockett (2012) demonstrated that this technique outperforms the simple Naïve net when modeling benthic macrofauna species. See Lockett (2012) for a detailed description of applying the TAN modeling approach to create habitat suitability maps of benthic macrofauna at local sites. However the TAN structure limits the number of parents for any given node to two in order to minimize model complexity. Therefore, this link structure is not as desirable when more than three variables are correlated with each other. Additionally, relationships are learned directly from the sample data set. When no other information is available, this is an appropriate technique. However, when prior knowledge about correlations among variables exists, a more robust model structure may result from applying supervised techniques to identify and designate link structures around known interdependencies (Uusitalo 2007).

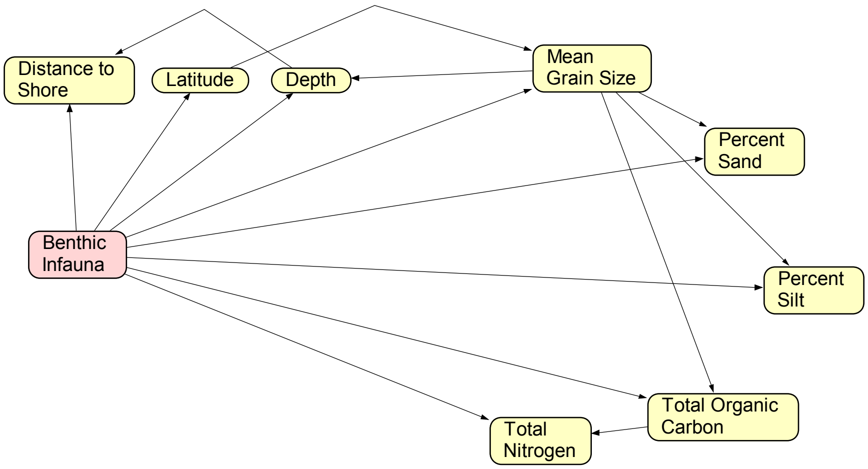


Figure 28. Tree Augmented Naïve Bayesian Network
Algorithm within Netica® software that calculates a network structure from the data.

For these reasons, a supervised link structure approach was adopted where a combination of expert knowledge and correlations between variables within the dataset were applied to design the link structure. The measurements of grain size, percent silt and percent sand are known to be different types of measurements of the same phenomenon and are therefore known to be highly correlated. Total Organic Carbon (TOC) and Total Nitrogen (TN) are known to be highly correlated with percent silt. Therefore, a Bayesian network was designed to account for known dependencies among all sediment variables. Further, sample data was inspected for correlations among variables. This step confirmed the high correlation among sediment variables and also suggested a correlation between depth and grain size, percent silt, percent sand, TOC and TN. As suggested by Marcot (Pers. Comm. 2013), links were added between Depth and sediment variables to account for the correlation within the data set (Figure 29).

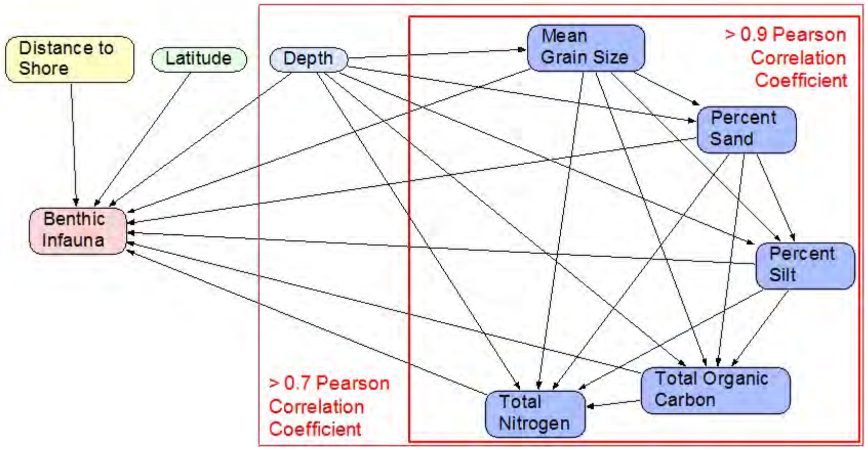


Figure 29. Supervised Net Link Structure
The links between nodes is this structure are developed based on a prior understanding of the environment and confirmed by correlations in the data. Mean Grain Size, Percent Sand, Percent Silt, Total Organic Carbon and Total Nitrogen are all highly correlated with a Pearson Correlation Coefficient greater than 0.9. Depth is correlated with each of the above variables with a Pearson Correlation Coefficient greater than 0.7

6.2.4.3 Final Net Structure

Within the Bayesian network structure established above, there are two levels of explanatory environmental variables: regional variables, or those that correspond with regional raster datasets and represent continuous coverage of information throughout the region of interest; and *in situ* variables, or those whose values are known only at sediment sample locations yet remain in the network due to their significance to benthic macrofauna species. Due to their correlative relationships with regional variables, *in situ* variables can be predicted in the network prior to calculating final habitat suitability predictions. Since the *in situ* variables are being predicted in the network, uncertainty of their actual values exists in their output, which is carried through the network into the uncertainty of the final suitability prediction (expressed as the posterior probability distribution of the benthic macrofauna absence and presence states). As a final step in model structure development, therefore, intermediate nodes were inserted into the network to re-discretize regional variables (Distance to Shore, Depth, Latitude and Mean Grain Size) to best predict *in situ* variables (Percent Silt, Percent Sand, TOC and TN: Figure 30).

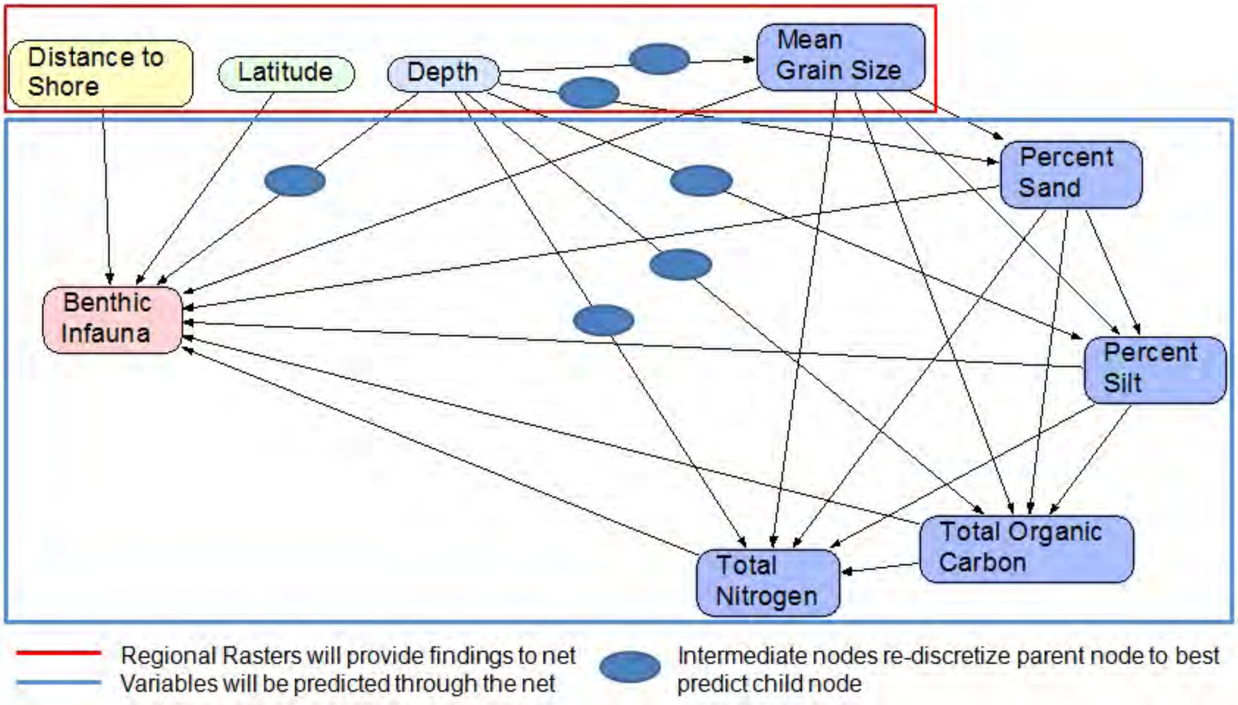


Figure 30. Regional raster and local in situ variables
Regional raster variables predict local in situ variables, which all combine to predict habitat suitability. Blue circles indicate intermediate nodes, their function being to re-discretize the parent node to best predict the child node.

Percent Sand was left as a variable predicted from Depth and Mean Grain Size. While a raster layer was designed for Percent Sand, the range of error reported from the Inverse Distance Weighted analysis (Section 3) was larger than the significant state width important for a species. Using this regional raster layer to inform the probability of the Percent Sand node would do so with 100 % certainty and not capture the error from the IDW analysis. Therefore, this node was predicted through the network to propagate the uncertainty throughout the model.

The result of this process was a benthic macrofauna model framework for invertebrates living within marine sediment, that is both adaptable to new species and updateable (Figure 31). This model framework was applied to the seven benthic macrofauna species with modifications to each species' discretization breakpoints. It can be adapted to new benthic macrofauna species, believed to be influenced by the suite of environmental variables presented here, with only slight modifications to species-environment discretization breakpoints. The model can be updated with new information about either a species of interest or relationships between explanatory variables (e.g., Percent Silt and TOC).

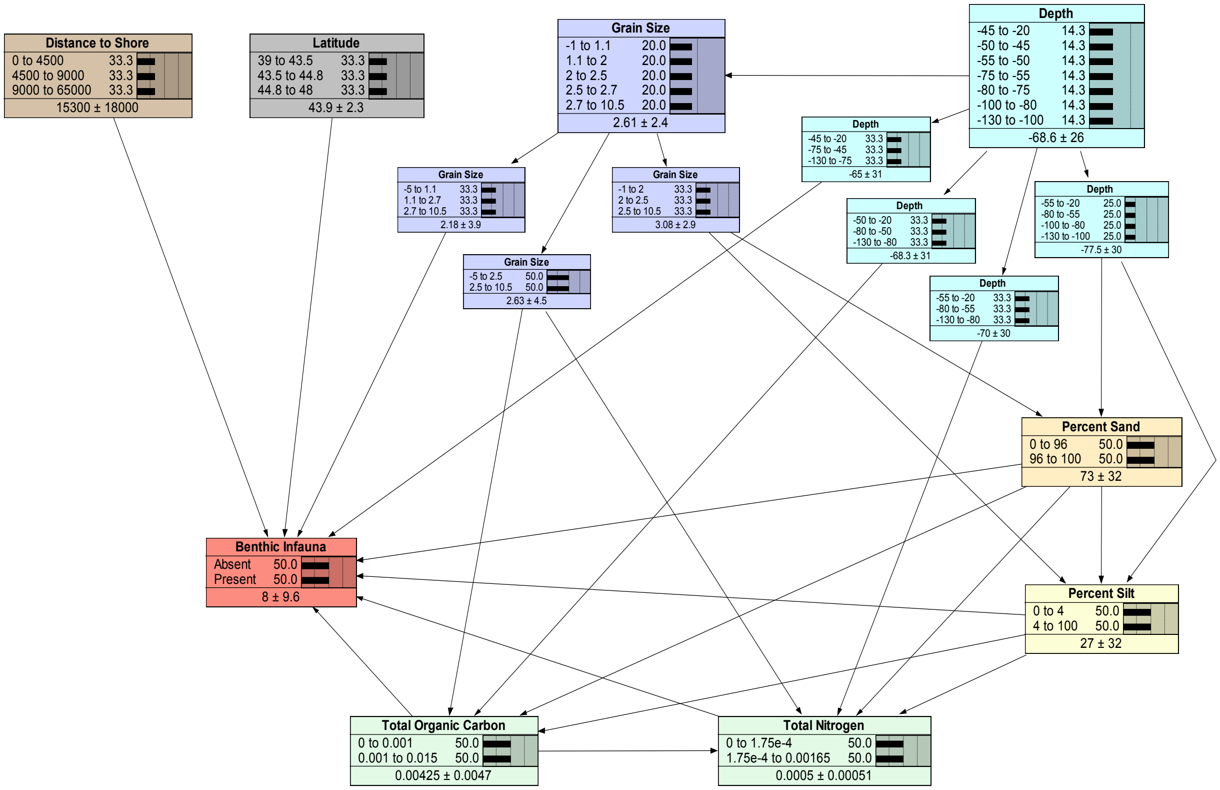


Figure 31. Example of a re-useable and updateable Bayesian network for benthic macrofauna living within marine sediment
This framework was applied to each of the seven macrofauna species within this report and can be updated.

6.2.5 Model Parameterization

After initial models were established with uniform prior probability distributions, CPTs were defined using Netica®'s Expectation-Maximization (EM) algorithm. This algorithm applies a convergent log-likelihood function (Norsys, Netica®). Statistically, log likelihood calculations optimize model parameters (conditional probabilities in a Bayesian network) in order to create a model that best fits the data. The EM technique starts with a candidate net, calculates its log likelihood, and then processes these data to find a better Bayesian network. This is repeated iteratively until there is no longer an improvement in log likelihood values. The probabilities propagate through the net to learn probabilities of the presence or absence of a species given different environmental scenarios (Marcot et al. 2006).

Prior to learning CPTs from the species sampling data, CPTs of Grain Size, Depth, Percent Silt and Percent Sand were learned from the US Seabed sampling database (Reid et al. 2006). This step improved the knowledge of the relationships between depth and sediment size measurements throughout the study region prior to learning the species-environment relationships.

6.2.6 Model Calibration, Selection, and Prediction

Final Models were selected by evaluating three performance metrics: confusion matrix error rates, spherical payoff and true skill statistic (TSS) (Table 20; Marcot 2012).

Table 20. Performance Metrics
Each metric used to measure model performance is listed on the left. Details of its Application, Metric Potential Values, and descriptions of assumptions or considerations are listed for each metric.

Model Performance Metric	Application	Metric Potential Values	Assumptions or Considerations
Confusion Matrix Error Rate	Percent predictions that are Type I and Type II errors	[0, 100] 0% = Best Performing Model 100% = Worst Performing Model	Based on highest probability state, which may oversimplify the utility of the model
Spherical Payoff	Index to measure classification performance	[0, 1] 1 = Best Performing Model 0 = Worst Performing Model	Influenced by number of states in the response variable Outperforms AUC
True skill statistic (TSS)	Index to measure classification performance	[-1, 1] 1 = Model with No error 0 = Model with Random error -1 = Model with Total error	Conflates error types Assumes 2-state outcomes Independent of Prevalence

The confusion matrix error rate (Figure 32) is the simplest metric and is basically a calculation of the percent classification error in a model. In the current models, this metric is calculated as the quotient of the number of all incorrect classifications (of known-outcome records of species absence or presence) divided by all records. When the model predicts presence in a particular habitat when, in fact, the species was absent, a false positive occurs, otherwise known as a Type I error. When the model predicts absence in a particular habitat, when in fact, the species is present, a false negative occurs, otherwise known as a Type II error.

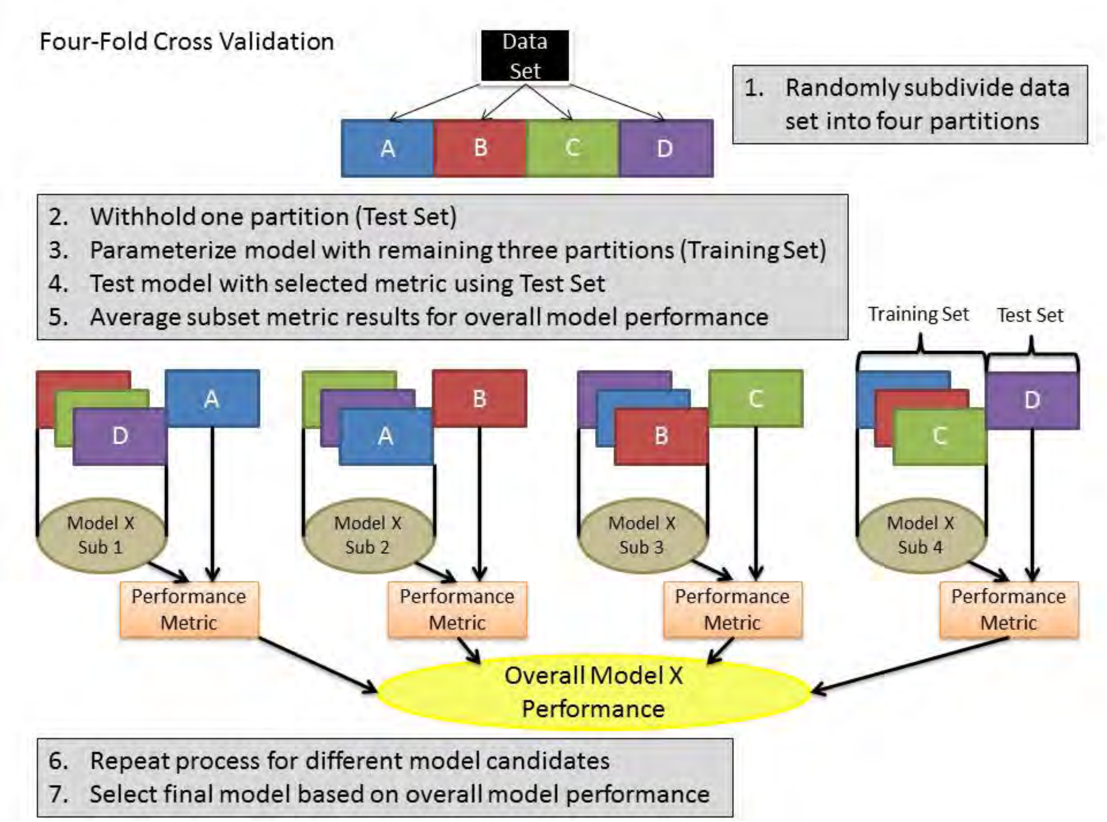
Confusion Matrix		Predicted	
		Absent	Present
Observed	Absent	True Negative	False-Positive Type I error
	Present	False Negative Type II error	True-Positive

Figure 32. Confusion Matrix that is used to calculate the confusion matrix error rate
The confusion matrix compares what the model predicted to what was actually observed. The confusion matrix error rate is calculated by a ratio of the number of false negatives (type II error) and false positives (type I error) to the total number of all observations.

Confusion matrix error rates are based on the highest probability state of the species node, which can oversimplify the utility of the model. For example, a species is considered to be predicted as “present” if the probability value of presence is above 50%. Oversimplification occurs because (1) in this example, a probability of 52% is given the same weight as a probability of 100%, and (2) no other threshold values for “highest” probability can be applied (e.g., if there was reason to accept any model projection of >40%

presence as usefully predicting potential presence). There is no distinction between models where all classification errors occur in regions of uncertainty (close to 50%) as compared to a model where all classification errors occur in regions of high certainty (close to 100%). For this reason, it is best to also consider other modeling metrics, which may help to clarify the performance of a model. Spherical payoff was chosen as it out-performs AUC (Area Under the Curve)), a popular and highly used modeling metric (Marcot 2012). TSS was chosen, as it is independent of prevalence (e.g., a species with a high probability of occurrence) (Allouche et al. 2006; Marcot 2012). This can be important when modeling very common or rare species. For example, one can predict the presence of a common species with low error rates, regardless of the quality of the model. TSS, due to its prevalence independence, helps discriminate which model has the best performance for common or rare species (Allouche et al. 2006).

Confusion matrix error rate values range from 0 to 100%, spherical payoff ranges from 0 to 1, and TSS ranges from -1 to 1. The best performing model (where all classifications are correct) has the following scores for each metric: confusion matrix error rate = 0, spherical payoff = 1and TSS = 1. The worst performing model (where all classifications are incorrect) has the following scores for each metric: confusion matrix error rate = 100, spherical payoff = 0 and TSS = -1. Metrics were compared 1) using all data to learn CPTs and 2) following a four-fold cross validation approach where a portion (1/4) of these data were withheld prior to learning CPTs. The model was tested against this withheld portion for each ¼ of the data withheld; and each model performance metric were calculated for, and averaged over, each of the four “fold” analyses (Figure 33).



1. Randomly subdivide data set into four partitions
2. Withhold one partition (Test Set)
3. Parameterize model with remaining three partitions (Training Set)
4. Test model with selected metric using Test Set
5. Average subset metric results for overall model performance
6. Repeat process for different model candidates
7. Select final model based on overall model performance

Figure 33. Graphical representation of the Four-Fold Cross Validation process
Data were partitioned into four components. A model was trained with three partitions and then tested against the fourth, withheld partition. This was repeated four times, withholding a different partition in each instance. Results were averaged together.

Multiple models were tested for each species. Final models were selected by evaluating performance metrics from the cross validation results. If more than one model resulted in similar performance, the one with the least number of variables was selected to account for model parsimony.

6.2.7 HSP Bayesian Net Model Outputs

A database consisting of regional latitude, depth, grain size and distance to shore at 250 m resolution cell size was supplied to Netica® for final predictive HSP maps. This particular resolution was constrained by the coarsest regional raster layer, Mean Grain Size, and represents a much finer resolution than has been previously published for regional benthic habitat suitability studies along the US West Coast (Copps et al. 2007; Guinotte and Davies 2014). Identifying a more ecological significant scale requires more extensive knowledge of habitat use than was available for this study. Regions of rock, cobble, and gravel were masked from the final predictive maps as the model was developed only for soft sediment habitats.

For each location, Netica® calculated a probability of suitable habitat for each species being modeled. Output HSP maps (250 m resolution) were shaded from low to high probability of habitat suitability. Blue shades ranged in probability score from 0 to 0.49, indicating a progression of probabilities from an area being highly unsuitable (HSP = 0) to somewhat unsuitable (HSP = 0.49). Red shades ranged in probability scores from 0.51 to 1, indicating a progression of probabilities from an area being somewhat suitable (HSP = 0.51) to highly suitable (HSP = 1). Green indicated a probability of suitable habitat between 0.49 and 0.51. This HSP score represents either an unknown probability, in which case no data was available to update the prior probability of 0.5 to something greater or lesser; or an even probability, in which case a lot of data was used but the given combination of regional environmental variables was neither suitable nor unsuitable (observations were 50% present and 50% absent). The data format for model output is ESRI floating-point grid format (valid HSP range: 0-1).

In addition, uncertainty maps were produced to spatially communicate areas of the map that are either high or low in statistical uncertainty. Uncertainty maps were derived from Netica®'s standard deviation output (Section 6.2.2) and shaded from low uncertainty or high precision (light color) to high uncertainty or low precision (dark color).

Finally, we developed a novel product termed an Experience Map, which spatially communicates the amount of data, or equivalent sample size, behind probability predictions. Values were reported as a percentage of the overall sample size, with dark colors indicating little to no data were used to inform probabilities and light colors indicating a large percentage of data were used to inform probabilities. Novel python code was developed to create a map product from Netica®'s experience table, which contains an experience value for each row (unique combination of environmental states).

6.2.8 Field Validation

An additional 14 box core grab samples were collected from the Northwest National Marine Renewable Energy Center's (NNMREC's) Pacific Marine Energy Center South Energy Test Site (SETS; **Error! Reference source not found.**) in August and again in October of 2013 (Pers. Comm. Henkel 2014). Observations of presence or absence were compared with model results from the SETS region developed without SETS data. An observation was recorded as a true positive if the species was observed to be present and the model predicted suitable habitat with a score above 0.51. An observation was recorded as a true negative if the species was observed to be absent and the model predicted unsuitable habitat with a score below 0.49. An observation was recorded as a false positive if the species was observed to be absent but the model predicted suitable habitat with a score above 0.51. An observation was recorded to be a false negative if the species was observed to be present but the model predicted unsuitable habitat with a score below 0.49. Using this information, performance metrics were calculated. Because of the proximity to the Newport sample study region, this field validation study does not necessarily sample a new, unseen environment. Also, this field validation study is limited by the small number of samples collected.

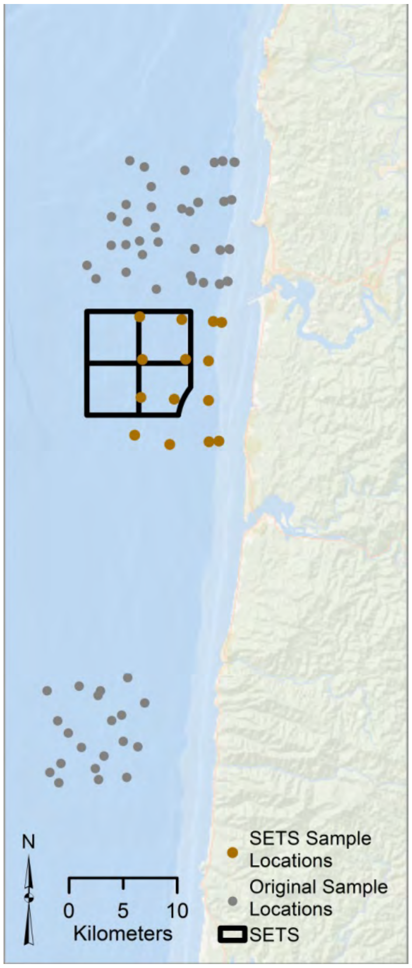


Figure 34. Study area of field validation
SETS sampling stations (brown dots) indicate box core samples taken August and October 2013 and used in field validation. Grey dots indicated the closest sample locations (Section 5, sites Newport and Cape Perpetua) used to train predictive models

6.3 Results

The model structure development phase resulted in a Benthic Macrofauna model framework for species living within marine sediment (Figure 31). The model can be updated with new information about either a species of interest or relationships between explanatory variables (e.g., Percent Silt, TOC). Final Bayesian network models for each of the seven benthic macrofauna species are listed in Appendix 6.2 while Appendix 6.3 provides detailed instructions on applying the model framework to a new species of interest and updating existing nets with new information.

The following results are reported for each species: 1) Model performance metrics; 2) Habitat Suitability Maps; 3) Uncertainty Maps; 4) Experience Maps and 5) SETS field validation results. Each component of the results warrants a different interpretation. Model performance metrics (confusion matrix error rates, spherical payoff, and true skill statistic) are a measure of how well the model predicts the sample data. Model performance metrics do not provide any information about how well the model extrapolates to areas outside sampling locations. Habitat Suitability Maps provide regional predictions of suitable habitat given the regional environmental variables (Depth, Mean Grain Size, Distance to Shore and Latitude) occurring at the resolution of 250 meters raster cell size. Uncertainty Maps communicate the posterior distribution of the habitat suitability prediction, which is a measure of certainty in the probability predictions. Experience Maps describe the percentage of the benthic macrofauna sampling dataset used to inform probabilities. High experience can occur outside sampling locations if environmental conditions mirror those of regions heavily sampled. Finally, field validation is a measure of how well the model predicts a new region. If the field validation site falls within a region of high experience, however, results are less compelling than if the site is within a region of low experience.

Performance metrics were compared to select final models. Supervised discretization structures consistently produced better performing models than those calculated through automated equal frequency techniques. Due to the small difference in performance (Figure 35) between supervised link structures and TAN structures, it was decided to use the supervised link structure approach for final models for two reasons: 1) Supervised link structures are more likely to reflect the natural phenomenon being modeled and will therefore hold up over time to new data while TAN structures will likely change with each data update. 2) Supervised structures provide a user-friendly interface for modeling new species or updating models with new information.

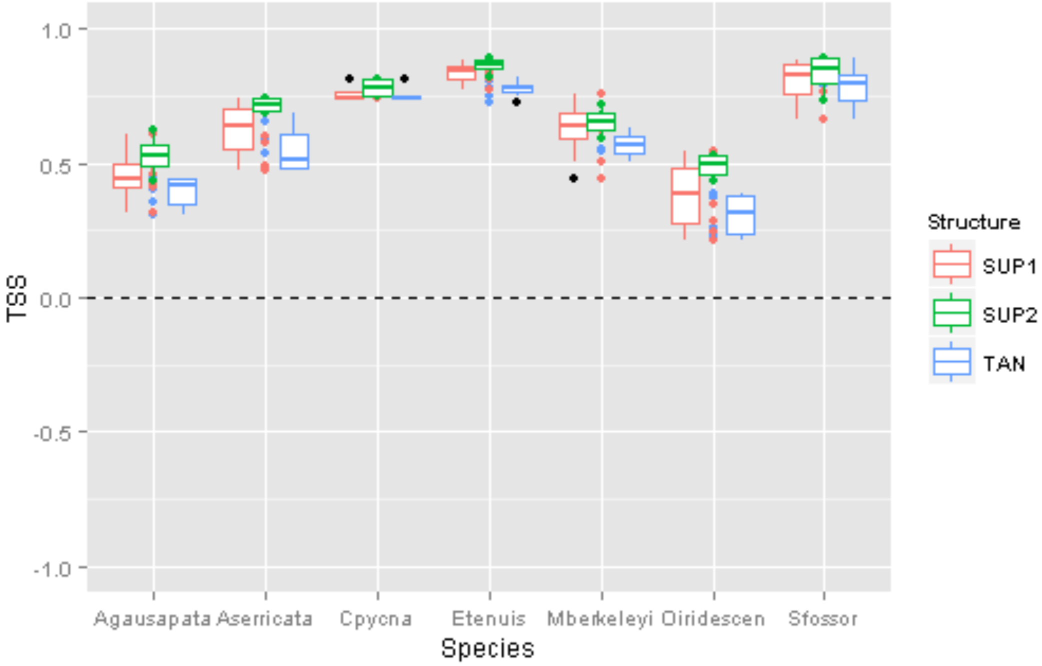


Figure 35. Overall Model Comparison of True Skill Statistic (TSS) performance scores
TSS results for all models tested were plotted by species to compare supervised link structures with Tree Augmented Naïve (TAN) Bayesian Network models. SUP1 refers to a supervised link structure without intermediate nodes. SUP2 refers to a supervised structure with intermediate nodes. TAN refers to a link structure learned with Netica®'s Tree Augmented Naïve algorithm. TSS ranges from -1 (total error) to +1 (no error). The dotted line indicates random error. Overall, models show high performance (close to 1) and small differences among the three methods. *Sternaspis fossor*, *Ennucula tenuis* and *Callianax pycna* perform the best when comparing across all link structures or variable permutations. Spherical payoff and confusion matrix error rates show similar patterns with smaller variation among models tested per species.

6.3.1 Bivalvia

6.3.1.1 Axinopsida serricata

This bivalve species was common throughout the region (present in 82.6% of the samples). While models with Percent Silt, Percent Sand, TOC and TN performed best with all data included, their performance dropped significantly under a four-fold cross validation analysis, indicating that their inclusion resulted in an overfit model. Sensitivity to findings analysis indicated that the Bayesian network for this species was most sensitive to Grain Size and Depth (nearly equal), followed by Latitude. The network was least sensitive to Distance to Shore. Further analysis of metrics supported removing Distance to Shore from the model. Final model performance metrics (Table 21) are reported. Confusion matrix error rates and Spherical payoff scores indicate better model performance than true skill statistic. However, the latter, being independent of prevalence, is a better metric when predicting presence of a common species.

The HSP map (Figure 36) depicts high probability of habitat suitability throughout most of the region with small pockets of moderately unsuitable habitat found near shore in shallow regions. An area of completely unknown probability is found in the northern, shallow region of the study area. This corresponds with the output of the Columbia River, a unique sedimentary environment which wasn't sampled in this study. The uncertainty map (**Error! Reference source not found.**) is strongly correlated with the HSP maps: regions of highly suitable habitat correspond with higher precision (low uncertainty) around the posterior probability whereas areas of the map with somewhat suitable/unsuitable to unknown habitat correspond with regions of lower precision (high uncertainty). The experience map (**Error! Reference source not found.**) indicates the largest percentage of data went to inform probabilities from the southern, deep region; followed by the shallow to mid depth, mid latitude region; with the least amount of data informing probabilities in the northern, deep region, and shallow to mid depth regions of the most northern and southern extents.

Field validation analysis at the SETS site (Figure 36) indicates *Axinopsida serricata* was more likely present at deeper stations and more likely absent at shallow stations, following similar patterns to suitable habitat predictions. Seven SETS observations were in error (Table 21) compared to model predictions: five false positives (model predicted presence but the species was absent in SETS sample data) and two false negatives (model predicted absence but the species was present in SETS sample data). While error rates did not change after applying mean grain size observations from SETS sampling effort, probability predictions of suitable habitat declined through much of the region from highly suitable (HSP value = 1) to unknown to somewhat suitable (HSP value = 0.58). Three of the five false positive observations fell within this region and station samples indicated the species to be present one season and absent another season, indicating an even probability of suitable habitat. The remaining observation errors occurred on the boundary between suitable and unsuitable habitat.

Table 21. Performance Metrics of HSP model for *Axinopsida serricata*
A good performance score has a low confusion matrix error rate (Error Rate), high spherical payoff (SP) and True Skill Statistic (TSS). The HSP models were trained using either the full benthic macrofauna sampling data excluding SETS observations (All Data) or a training set specified in the four-fold cross validation (4-fold CV Training Set) methods (Section 6.2.6). Models were tested four ways: using All Data; a specified test set (4-fold CV methods); samples from South Energy Test Sites (SETS) combined with modeled Mean Grain Size (prior MGS) values; and SETS samples combined with *in situ* Mean Grain Size values (updated MGS).

Train	Test	Error Rate	False Positive	False Negative	SP	TSS
All Data	All Data	11 %	6 %	5 %	0.94	0.58
4-fold CV Training set	4-fold CV Test set	15 %	7 %	8 %	0.88	0.55
All Data	SETS – prior MGS	26 %	19 % - 5 instances	7 % - 2 instances	0.74	0.51

All Data	SETS – updated MGS	26 %	19 % - 5 instances	7 % - 2 instances	0.74	0.51

Habitat Suitability (Left) ranges from 0 (blue: very unlikely probability of suitable habitat) to 0.5 (green: unknown/even probability) to 1 (red: very likely probability of suitable habitat). Uncertainty (Middle) ranges from 0 (light: high precision and low uncertainty in probability estimate) to 0.5 (dark: low precision and high uncertainty in probability estimate). Experience (Right) ranges from 1 (light: high percent of data inform probabilities) to 0 (dark: low percentage of data inform probabilities). SETS (Bottom) sample site locations of observed species presence/ absence over HSP model predictions. Labels indicate updated HSP predictions given new grain size data.

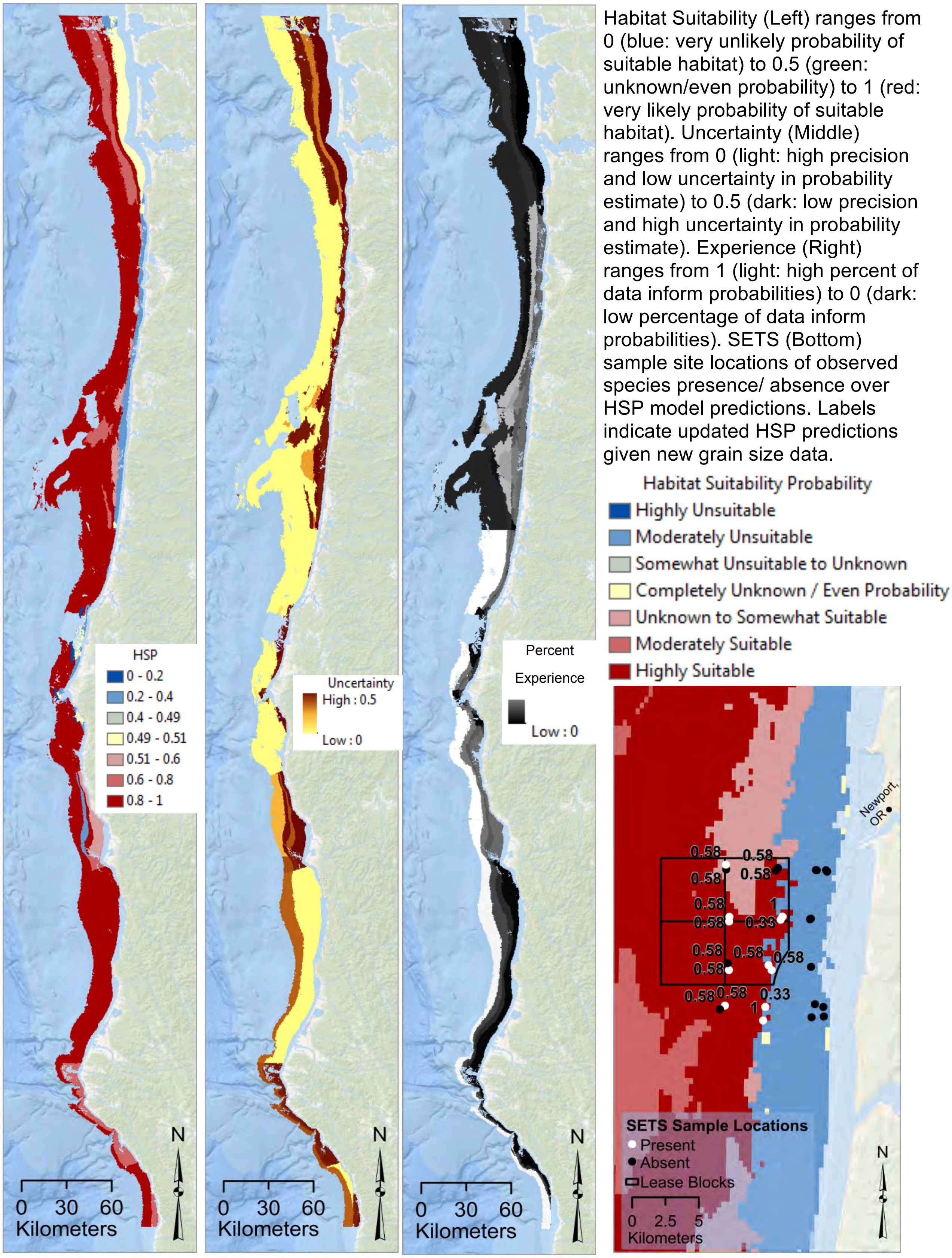


Figure 36. ***Axinopsida serricata***

6.3.1.2 *Ennucula tenuis*

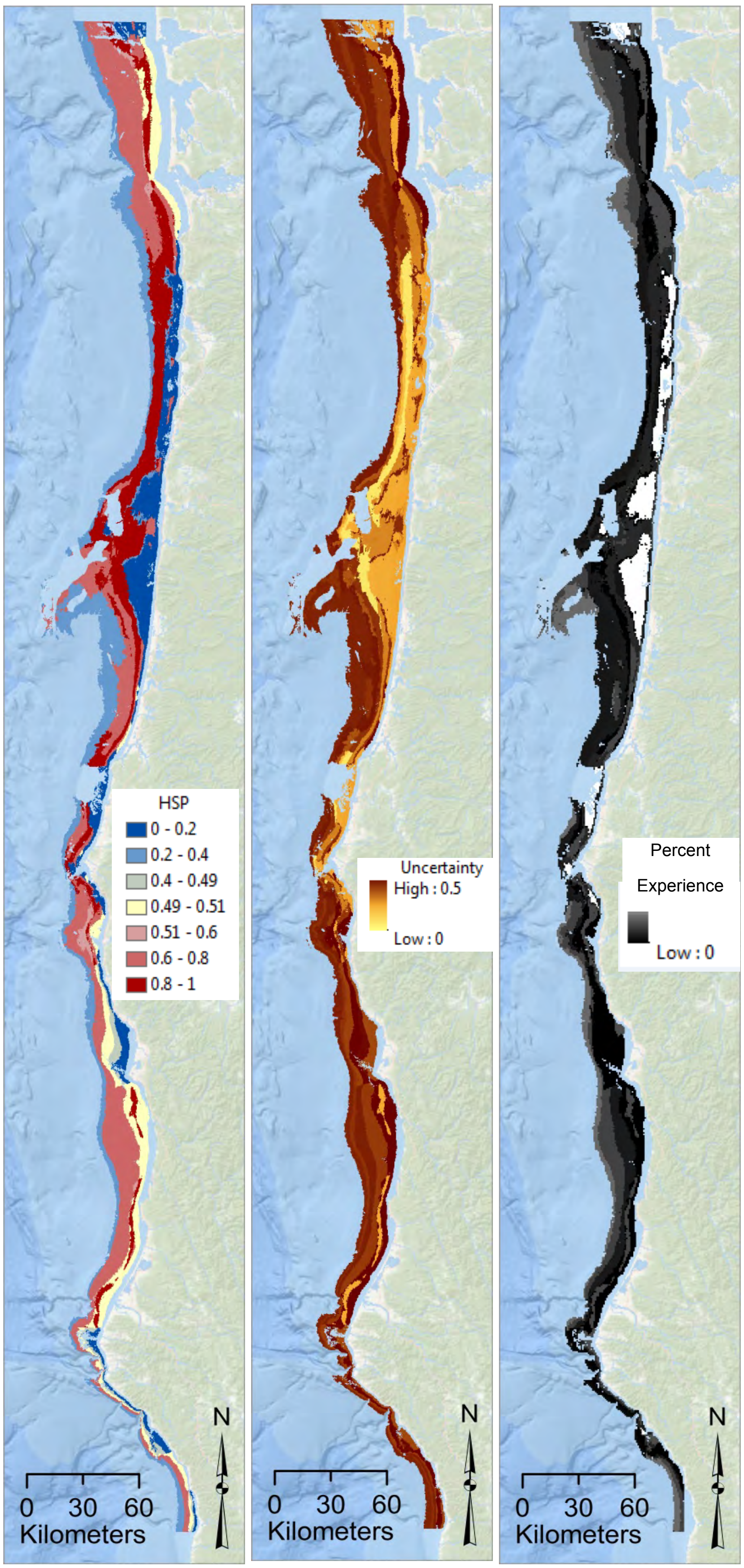
This second bivalve species was present in 44.5% of samples collected. A sensitivity to findings analysis indicated that the Bayesian network for this species to be most sensitive to Percent Silt, followed by TOC, Percent Sand, Grain Size, TN and Depth. The network was least sensitive to Latitude and Distance to Shore. Further analysis of metrics supported removing Latitude and Distance to Shore from the model. Final model performance metrics (Table 22) indicate good performance for all metrics.

The HSP map (**Error! Reference source not found.**) depicts suitable habitat throughout the mid depth region of the study area that corresponds to silty habitat. Unsuitable regions were found in sandy, shallow regions as well as deeper, silty regions. The uncertainty map (**Error! Reference source not found.**) is nicely correlated with the HSP maps: regions of highly suitable habitat correspond with higher precision (low uncertainty) around the posterior probability whereas areas of the map with somewhat suitable or unsuitable to unknown habitat correspond with regions of lower precision (high uncertainty). The experience map (**Error! Reference source not found.**) indicates the largest percentage of data went to inform probabilities from the mid latitude, shallow to mid depth region as well as the Grays Bank site.

Field validation analysis at the SETS site (**Error! Reference source not found.**) involves two levels of interpretation due to discrepancies in mean grain size model predictions and field observations. Given the mean grain size model used to predict HSP, nine false positives were observed (Table 22), where the model predicted presence, yet the species was absent in the SETS sampling data. However, if observed mean grain size values from SETS sampling effort were used in the model, it correctly predicts absence for SETS samples, with no error.

Table 22. Performance Metrics of the HSP model for *Ennucula tenuis*
A good performance score has a low confusion matrix error rate (Error Rate), high spherical payoff (SP) and True Skill Statistic (TSS). The HSP models were trained using either the full benthic macrofauna sampling data excluding SETS observations (All Data) or a training set specified in the four-fold cross validation (4-fold CV Training set) methods (Section 6.2.6). Models were tested four ways: using All Data; a specified test set (4-fold CV Test set) methods; samples from South Energy Test Sites (SETS) combined with modeled Mean Grain Size (prior MGS) values; and SETS samples combined with *in situ* Mean Grain Size values (updated MGS).

Train	Test	Error Rate	False Positive	False Negative	SP	TSS
All Data	All Data	8 %	3 %	5 %	0.93	0.82
4-fold CV Training set	4-fold CV Test set	12 %	4 %	8 %	0.90	0.73
All Data	SETS – prior MGS	33 %	33 % - 9 instances	0 %	0.74	-
All Data	SETS – updated MGS	0 %	0 %	0 %	1.0	1.0



Habitat Suitability (Left) ranges from 0 (blue: very unlikely probability of suitable habitat) to 0.5 (green: unknown/even probability) to 1 (red: very likely probability of suitable habitat). Uncertainty (Middle) ranges from 0 (light: high precision and low uncertainty in probability estimate) to 0.5 (dark: low precision and high uncertainty in probability estimate). Experience (Right) ranges from 1 (light: high percent of data inform probabilities) to 0 (dark: low percentage of data inform probabilities). SETS (Bottom) sample site locations of observed species presence/ absence over HSP model predictions. Labels indicate updated HSP predictions given new grain size data.

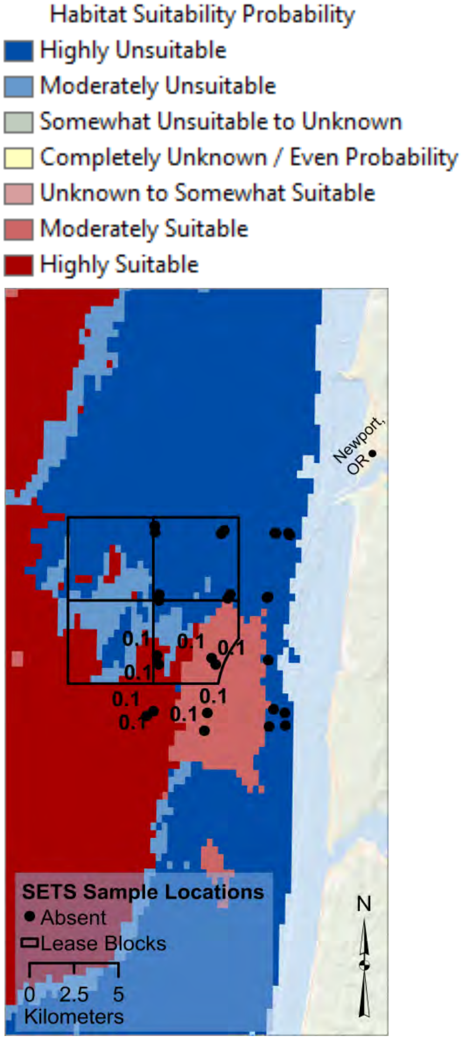


Figure 37. ***Ennucula tenuis***

6.3.2 Gastropoda

6.3.2.1 Aystris gausapata

This species of snail was present in 43.1% of samples collected and did not show a strong response to any particular environmental variable. Uncertainty in this model tended to be high (**Error! Reference source not found.**) and model metrics performed worse than other species (Table 23), indicating larger error in the model. Sensitivity to findings analysis indicated that the Bayesian network for this species was most sensitive to Percent Sand, followed by Percent Silt, TN, Depth, TOC, Grain Size and Distance to Shore. The network was least sensitive to Latitude. Further analysis of metrics supported removing Latitude from the model.

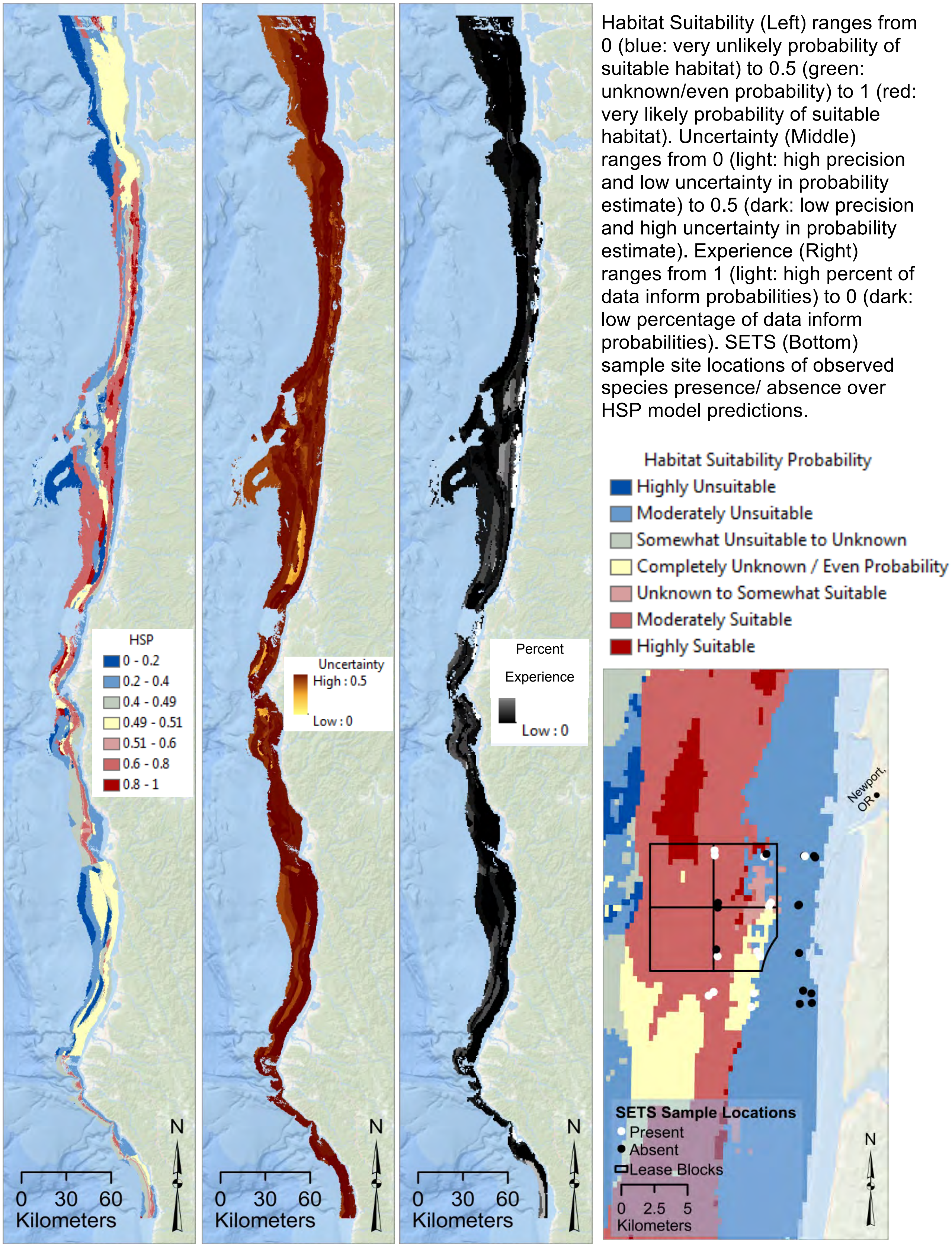
The HSP map (**Error! Reference source not found.**) depicts a large region of somewhat to moderate probabilities of suitable/ unsuitable habitat throughout the region compared to the maps of other species examined. High probabilities of unsuitable habitat were found in deeper, offshore areas. In addition, large regions were classified as completely unknown or even probability of suitable habitat, including the region off the Columbia River mouth. The uncertainty map (**Error! Reference source not found.**) expresses low precision (high uncertainty) throughout the region. The experience map (**Error! Reference source not found.**) indicates small pockets in the shallow, mid latitude regions where probabilities were informed by a higher percentage of data. In general, the majority of predictions were informed by little to no data, likely due to the complexity of the best performing model.

Field validation analysis at the SETS site (**Error! Reference source not found.**) indicates *Aystris gausapata* was more likely present at deeper stations and more likely absent at shallower stations, although there was slightly more error between observations and habitat suitability patterns than other species. Ten SETS observations were in error (Table 23) compared to model predictions: three false positives (model predicted presence but the species was absent in SETS sample data) and seven false negatives (model predicted absence but the species was present in SETS sample data). Five of the seven false negatives occurred in an area predicted as an unknown probability (HSP value = 0.49 – 0.51). The remaining two false negatives occurred in areas predicted to be moderately unsuitable. The three false positives occurred in areas predicted to be moderately suitable.

Overall, metric results from cross validation and field validation (Table 23) indicate this model to have poorer performance than other species modeled. However, corresponding maps help to communicate this error, uncertainty, and lack of data inherent in the model.

Table 23. Performance Metrics of the HSP model for *Aystris gausapata*
A good performance score has a low confusion matrix error rate (Error Rate), high spherical payoff (SP) and True Skill Statistic (TSS). The HSP models were trained using either the full benthic macrofauna sampling data excluding SETS observations (All Data) or a training set specified in the four-fold cross validation (4-fold CV Training set) methods (Section 6.2.6). Models were tested four ways: using All Data; a specified test set (4-fold CV Test set) methods; samples from South Energy Test Sites (SETS) combined with modeled Mean Grain Size (prior MGS) values; and SETS samples combined with *in situ* Mean Grain Size values (updated MGS).

Train	Test	Error Rate	False Positive	False Negative	SP	TSS
All Data	All Data	22 %	8 %	13 %	0.85	0.55
4-fold CV Training set	4-fold CV Test set	42 %	12 %	30 %	0.68	0.09
All Data	SETS – prior MGS	37 %	11 % - 3 instances	26 % - 7 instances	0.76	0.24
All Data	SETS – updated MGS	37 %	11 % - 3 instances	26 % - 7 instances	0.76	0.24



Habitat Suitability (Left) ranges from 0 (blue: very unlikely probability of suitable habitat) to 0.5 (green: unknown/even probability) to 1 (red: very likely probability of suitable habitat). Uncertainty (Middle) ranges from 0 (light: high precision and low uncertainty in probability estimate) to 0.5 (dark: low precision and high uncertainty in probability estimate). Experience (Right) ranges from 1 (light: high percent of data inform probabilities) to 0 (dark: low percentage of data inform probabilities). SETS (Bottom) sample site locations of observed species presence/ absence over HSP model predictions.

Figure 38. ***Aystris gausapata***

6.3.2.2 Callianax pycna

Callianax pycna, the second snail species*,* is uncommon in the depth ranges sampled throughout the study region (13.3% prevalence). It demonstrated a strong association with sandy, shallow habitat. Sensitivity to findings analysis indicated that the Bayesian network for this species was most sensitive to Depth, followed by Percent Silt, Percent Sand, TOC, Grain Size, TN and Distance to Shore. The network was least sensitive to Latitude. Further analysis of metrics supported removing Latitude from the model. Final model performance metrics (Table 24) indicate good performance. While confusion matrix error rates and spherical payoff scores indicate excellent model performance, it is important to note that this is an uncommon species on the outer continental shelf. The TSS score is a slightly more indicative metric of predicting the absence of an uncommon species. The final model predicted SETS data with little error, further supporting the model's validity.

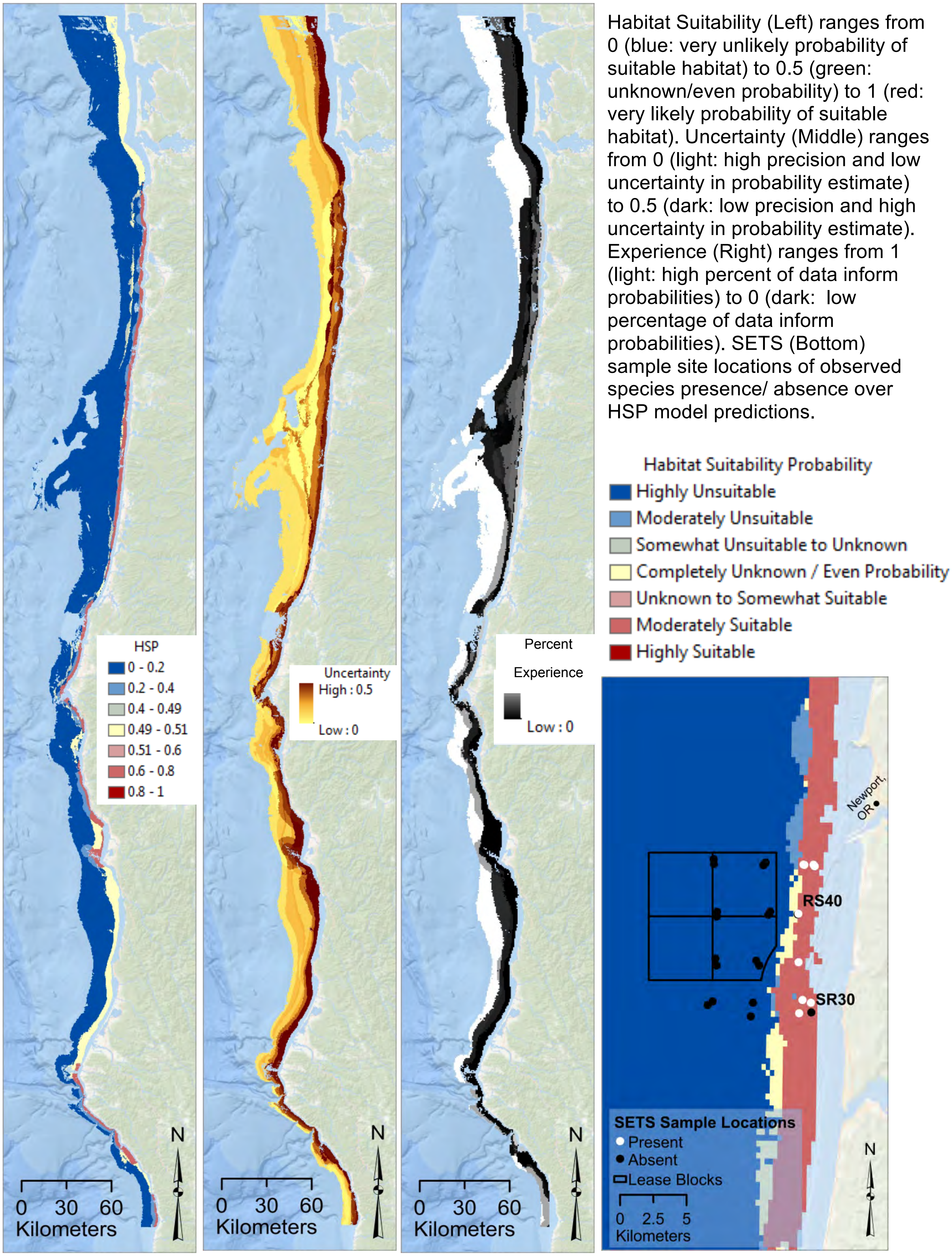
The HSP map (Figure 39) depicts high probability of habitat unsuitability throughout most of the region with small pockets of somewhat to moderately suitable habitat found near shore in shallow regions. The uncertainty map (Figure 39) is nicely correlated with the HSP maps: regions of highly unsuitable habitat correspond with higher precision (low uncertainty) around the posterior probability whereas areas of the map with somewhat suitable/unsuitable to unknown habitat correspond with regions of lower precision (high uncertainty). The experience map (Figure 39) indicates the largest percentage of data went to inform probabilities associated with unsuitable habitat while suitable habitat probabilities were informed by little to no data. This is likely because this species occupies a specialized niche in sandy, shallow habitat, an under sampled combination in this study.

Field validation analysis at the SETS site (Figure 39) involves two levels of interpretation due to discrepancies in mean grain size model predictions and field observations. Overall, *Callianax pycna* was found to be absent at deeper stations and present at shallowest stations, following similar patterns to suitable habitat predictions. Given the mean grain size model used to predict HSP, two false positives were observed (Table 24), where the model predicted presence, yet the species was absent in the SETS sampling data. One false positive occurred at station RS40, right on the boundary between an HSP prediction of 0.5 and 0.7. *Callianax pycna* was not observed at this station in August, but was observed at this station in October. Mean grain size values and sampling locations were consistent between the two seasons, yet this area likely represents an even probability of suitable habitat for this species. Another false positive prediction occurred at station SR30, a region predicted to be suitable with a probability of 0.7. *Callianax pycna* was observed at this station in August, but was not observed at this station in October. Sampling locations and mean grain size values were slightly different between these two locations. If actual mean grain size values from SETS sampling effort were used in the model, the location where *Callianax pycna* was observed to be absent changed from an HSP value of 0.7 to 0.5, decreasing the SETS false positive rate from 7% to 4%. Overall, metric results from cross validation and field validation indicate this model to have good performance.

Table 24. Performance Metrics of HSP model for *Callianax pycna*

A good performance score has a low confusion matrix error rate (Error Rate), high spherical payoff (SP) and True Skill Statistic (TSS). The HSP models were trained using either the full benthic macrofauna sampling data excluding SETS observations (All Data) or a training set specified in the four-fold cross validation (4-fold CV Training set) methods (Section 6.2.6). Models were tested four ways: using All Data; a specified test set (4-fold CV Test set) methods; samples from South Energy Test Sites (SETS) combined with modeled Mean Grain Size (prior MGS) values; and SETS samples combined with *in situ* MGS values (updated MGS).

Train	Test	Error Rate	False Positive	False Negative	SP	TSS
All Data	All Data	6 %	3 %	3 %	0.95	0.75
4-fold CV Training set	4-fold CV Test set	7 %	4 %	3 %	0.93	0.75
All Data	SETS – prior MGS	7 %	7 % - 2 instances	0 %	0.93	0.89
All Data	SETS – updated MGS	4 %	4 % - 1 instance	0 %	0.94	0.94



Habitat Suitability (Left) ranges from 0 (blue: very unlikely probability of suitable habitat) to 0.5 (green: unknown/even probability) to 1 (red: very likely probability of suitable habitat). Uncertainty (Middle) ranges from 0 (light: high precision and low uncertainty in probability estimate) to 0.5 (dark: low precision and high uncertainty in probability estimate). Experience (Right) ranges from 1 (light: high percent of data inform probabilities) to 0 (dark: low percentage of data inform probabilities). SETS (Bottom) sample site locations of observed species presence/ absence over HSP model predictions.

Figure 39. ***Callianax pycna***

6.3.3 Polychaeta

6.3.3.1 Magelona berkeleyi

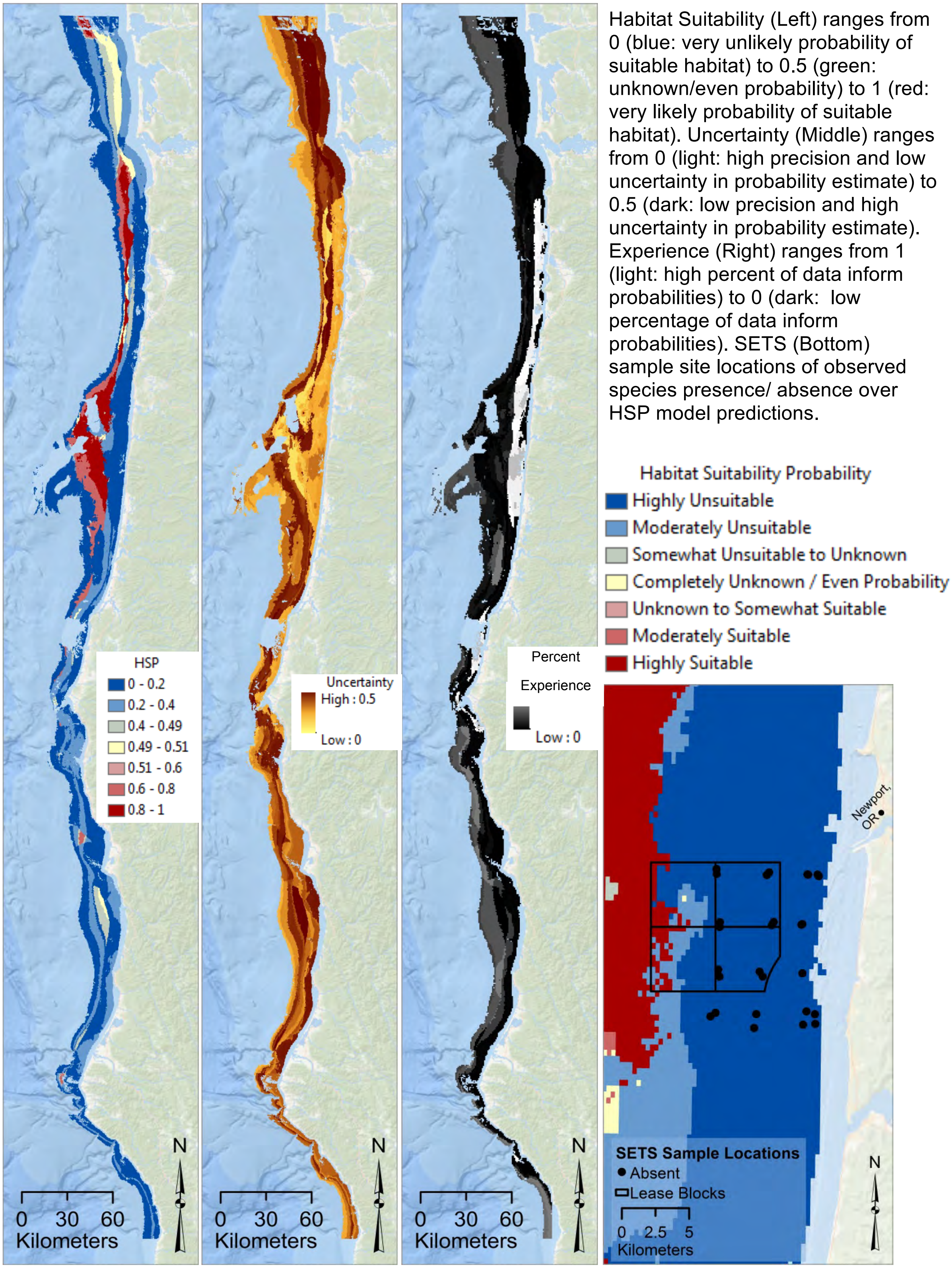
Magelona berkeleyi is one of three polychaete species tested and is not commonly found in the study region (11.5% prevalence). Sensitivity to findings analysis indicated that the Bayesian network for this species was most sensitive to Percent Silt, followed by Percent Sand, TN, TOC, Depth, Distance to Shore and Grain Size. The network was least sensitive to Latitude. Further analysis of metrics supported removing Latitude from the model. Final model performance metrics, confusion matrix error rates and spherical payoff (Table 25) indicate excellent model performance. However, because this is a rare species, the true skill statistic score is a slightly more indicative metric of predicting the absence of an uncommon species. The final model predicted SETS data with no error, further supporting the model's validity.

The HSP map (Figure 40) depicts high probability of habitat unsuitability throughout most of the region with pockets moderately to highly suitable habitat found along the mid depth, mid latitude region of the study area. The uncertainty map (Figure 40) is strongly correlated with the HSP maps: regions of highly suitable/ unsuitable habitat correspond with higher precision (low uncertainty) around the posterior probability whereas areas of the map with somewhat suitable/unsuitable to unknown habitat correspond with regions of lower precision (high uncertainty). The experience map (Figure 40) indicates the largest percentage of data went to inform probabilities associated with the mid latitude, near shore region of the study area, with much of the remaining area corresponding with little to no data. Probabilities of suitable habitat were informed by a lower percentage of data. These findings, similar to *C. pycna*, are likely because this species is uncommon throughout the study region and occupies a specialized niche, representing an under sampled combination of habitat parameters in this study.

Field validation analysis at the SETS site (Figure 40) indicates *Magelona berkeleyi* was found to be absent throughout, corresponding with a consistent prediction of absence throughout the area. Therefore, no error was observed between SETS sample observations and model predictions. Overall, metric results from cross validation and field validation indicate this model to have good performance.

Table 25. Performance Metrics of the HSP model for *Magelona berkeleyi*
A good performance score has a low confusion matrix error rate (Error Rate) and high spherical payoff (SP) and True Skill Statistic (TSS). The HSP models were trained using either the full benthic macrofauna sampling data excluding SETS observations (All Data) or a training set specified in the four-fold cross validation (4-fold CV Training set) methods (Section 6.2.6). Models were tested four ways: using All Data; a specified test set (4-fold CV Test set) methods; samples from South Energy Test Sites (SETS) combined with modeled Mean Grain Size (prior MGS) values; and SETS samples combined with *in situ* Mean Grain Size values (updated MGS).

Train	Test	Error Rate	False Positive	False Negative	SP	TSS
All Data	All Data	4 %	0 %	4 %	0.97	0.68
4-fold CV Training set	4-fold CV Test set	9 %	0 %	9 %	0.92	0.24
All Data	SETS – prior MGS	0 %	0 %	0 %	1.0	1.0
All Data	SETS – updated MGS	0 %	0 %	0 %	1.0	1.0



Habitat Suitability (Left) ranges from 0 (blue: very unlikely probability of suitable habitat) to 0.5 (green: unknown/even probability) to 1 (red: very likely probability of suitable habitat). Uncertainty (Middle) ranges from 0 (light: high precision and low uncertainty in probability estimate) to 0.5 (dark: low precision and high uncertainty in probability estimate). Experience (Right) ranges from 1 (light: high percent of data inform probabilities) to 0 (dark: low percentage of data inform probabilities). SETS (Bottom) sample site locations of observed species presence/ absence over HSP model predictions.

Figure 40. *Magelona berkeleyi*

6.3.3.2 *Onuphis iridescens*

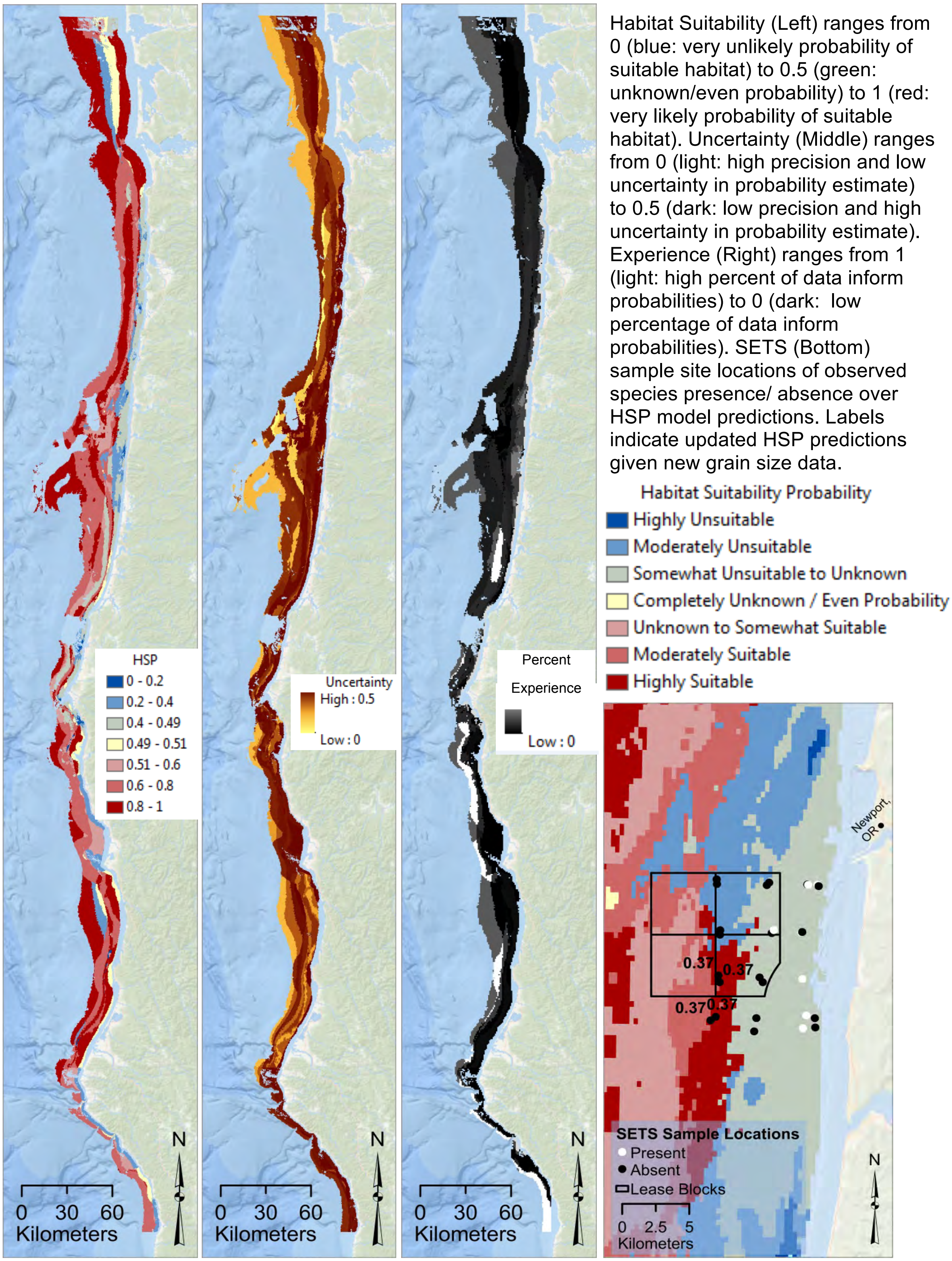
This species had a higher prevalence than other species (61.9% of samples collected). Uncertainty in this model (Figure 41) tended to be high and model metrics (Table 26) performed worse than other species. Sensitivity to findings analysis indicated the Bayesian network for this species was most sensitive to Percent Silt, followed by TN, Percent Sand, TOC, Mean Grain Size, Distance to Shore and Depth. The network was least sensitive to Latitude. Further analysis supported removing Latitude from the model.

The HSP map (Figure 41) depicts moderately suitable habitat throughout most of the region with pockets of unsuitable habitat near shore, particularly throughout the mid latitude region. The uncertainty map (Figure 41) is strongly correlated with the HSP maps: regions of highly suitable habitat correspond with higher precision (low uncertainty) around the posterior probability whereas areas of the map with somewhat suitable/unsuitable to unknown habitat correspond with regions of lower precision (high uncertainty). This map also communicates that uncertainty is high throughout most of the study area for this species. The experience map (Figure 41) indicates that most of the probabilities throughout the region were trained on little to no data, due to the complexity of the best performing model. Small pockets of high experience occur in the mid latitude, mid depth region and the deeper regions of the southern extent. The largest percentage of data went to inform probabilities associated with the mid latitude, near shore region of the study area, with much of the remaining area corresponding with little to no data.

Field validation analysis at the SETS site (Figure 41) involves two levels of interpretation due to discrepancies in mean grain size model predictions and field observations. Given the mean grain size model used to predict HSP, eleven instances of error were observed (Table 26): four false positives (model predicted presence but the species was absent in SETS sample data); and seven false negatives (model predicted absence but the species was present). If observed mean grain size values from SETS sampling effort were used in the model, the four false positive locations shifted from an HSP value of 0.90 to 0.37, decreasing the false positive rate to 0% and the overall error rate from 41% to 26%. Of the remaining false negative predictions, all seven instances occur in a region where HSP values were 0.487 and uncertainty ranged from 0.49 to 0.50. Six of the seven false negative errors occurred at sampling locations where *Onuphis iridescens* was observed to be present one season and absent the next, further supporting evidence that this region depicts an even probability of suitable habitat. Subsequently, while error rates remain high, overall predictions communicate the model's uncertainty in predicting high probabilities of suitable / unsuitable habitat. Overall, metric results from cross validation and field validation (Table 26) indicate this model to have poorer performance than other species modeled. Corresponding maps help to communicate this error, uncertainty and lack of data inherent in the model.

Table 26. Performance Metrics of the HSP model for *Onuphis iridescens*
A good performance score has a low confusion matrix error rate (Error Rate), high spherical payoff (SP) and True Skill Statistic (TSS). The HSP models were trained using either the full benthic macrofauna sampling data excluding SETS observations (All Data) or a training set specified in the four-fold cross validation (4-fold CV Training set) methods (Section 6.2.6). Models were tested four ways: using All Data; a specified test set (4-fold CV) methods; samples from South Energy Test Sites (SETS) combined with modeled Mean Grain Size (prior MGS) values; and SETS samples combined with *in situ* Mean Grain Size values (updated MGS).

Train	Test	Error Rate	False Positive	False Negative	SP	TSS
All Data	All Data	23 %	10 %	13 %	0.83	0.53
4-fold CV Training set	4-fold CV Test set	34 %	11 %	23 %	0.74	0.34
All Data	SETS – prior MGS	41 %	15 %-4 instances	26 %-7 instances	0.64	-0.2
All Data	SETS – updated MGS	26 %	0 %	26 %-7 instances	0.76	0.0



Habitat Suitability (Left) ranges from 0 (blue: very unlikely probability of suitable habitat) to 0.5 (green: unknown/even probability) to 1 (red: very likely probability of suitable habitat). Uncertainty (Middle) ranges from 0 (light: high precision and low uncertainty in probability estimate) to 0.5 (dark: low precision and high uncertainty in probability estimate). Experience (Right) ranges from 1 (light: high percent of data inform probabilities) to 0 (dark: low percentage of data inform probabilities). SETS (Bottom) sample site locations of observed species presence/ absence over HSP model predictions. Labels indicate updated HSP predictions given new grain size data.

Figure 41. ***Onuphis iridescens***

6.3.3.3 Sternaspis fossor

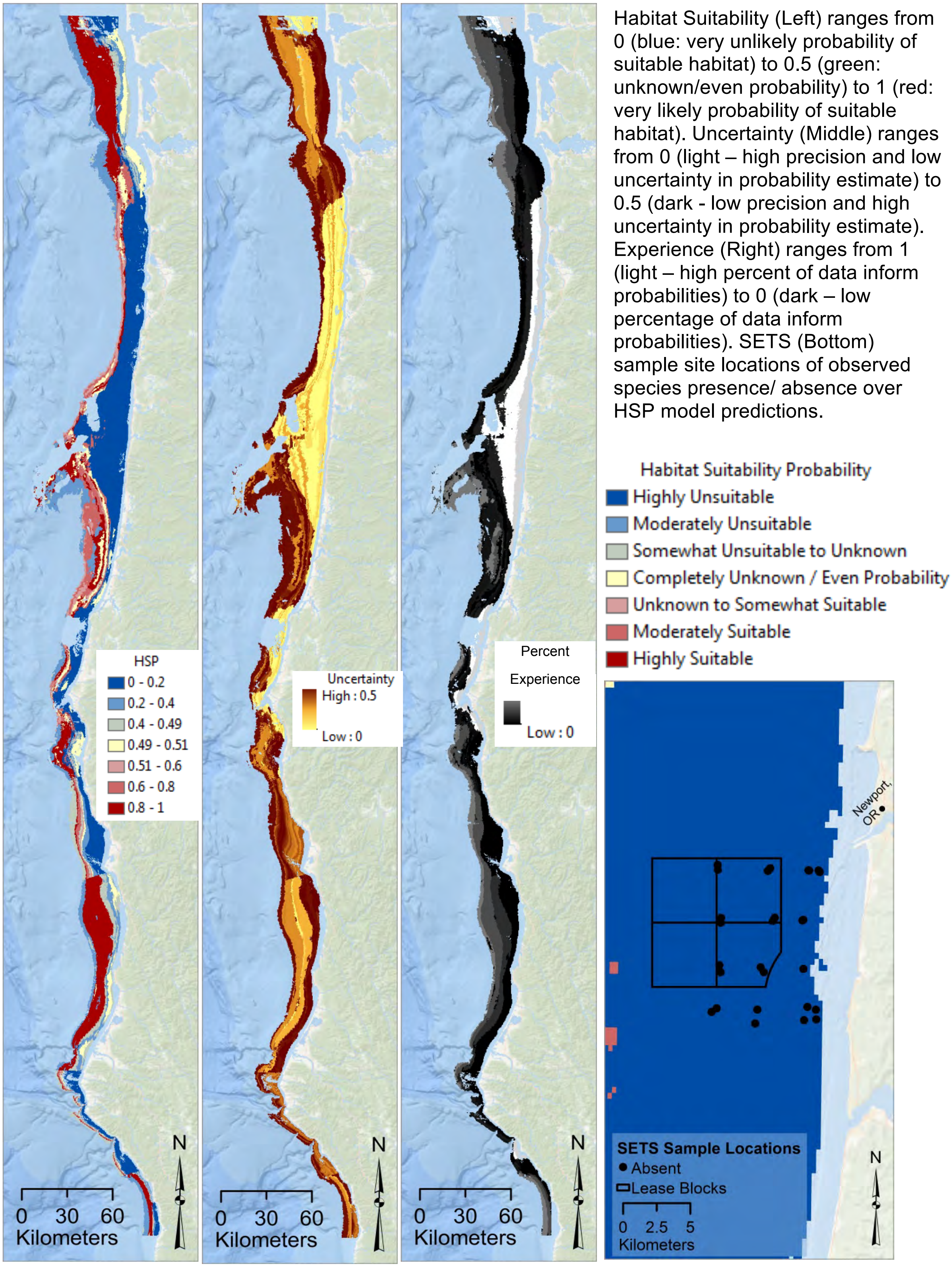
This species was present in 24.3 % of samples collected. Sensitivity to findings analysis indicated that the Bayesian network for this species to be most sensitive to Percent Silt, followed by Mean Grain Size, TOC, TN, Percent Sand and Depth. The network was least sensitive to Latitude and Distance to Shore. Further analysis of metrics supported removing Latitude and Distance to Shore from the model. Final model performance metrics (Table 27) indicate good performance. The final model predicted SETS data with no error (Table 27), further supporting the model's validity.

The HSP map (Figure 42) depicts high probability of habitat unsuitability throughout shallow, sandy regions, transitioning to suitable habitat in deeper, silty regions. The uncertainty map (Figure 42) is nicely correlated with the HSP maps: regions of highly suitable/ unsuitable habitat correspond with higher precision (low uncertainty) around the posterior probability whereas areas of the map with somewhat suitable/unsuitable to unknown habitat correspond with regions of lower precision (high uncertainty). The experience map (Figure 42) indicates the largest percentage of data went to inform probabilities associated with the mid latitude, shallow, sandy habitat regions. Much of the remaining area corresponded with little to no data. Probabilities of suitable habitat were informed by a lower percentage of data. This is likely because this rare species occupies a small, specialized niche, representing an under sampled combination of habitat parameters in this study.

Field validation analysis at the SETS site (Figure 42) indicates *Sternaspis fossor* was found to be absent throughout, corresponding with a consistent prediction of absence throughout the area. Therefore, no error was observed (Table 27) between SETS sample observations and model predictions. Overall, metric results from cross validation and field validation indicate this model to have good performance.

Table 27. Performance Metrics of the HSP model for *Sternaspis fossor*
A good performance score has a low confusion matrix error rate (Error Rate), high spherical payoff (SP) and True Skill Statistic (TSS). The HSP models were trained using either the full benthic macrofauna sampling data excluding SETS observations (All Data) or a training set specified in the four-fold cross validation (4-fold CV Training Set) methods (Section 6.2.6). Models were tested four ways: using All Data; a specified test set (4-fold CV Test set) methods; samples from South Energy Test Sites (SETS) combined with modeled Mean Grain Size (prior MGS) values; and SETS samples combined with *in situ* Mean Grain Size values (updated MGS).

Train	Test	Error Rate	False Positive	False Negative	SP	TSS
All Data	All Data	8 %	0 %	4 %	0.94	0.74
4-fold CV Training set	4-fold CV Test set	10 %	4 %	6 %	0.91	0.72
All Data	SETS – prior MGS	0 %	0 %	0 %	1.0	1.0
All Data	SETS – updated MGS	0 %	0 %	0 %	1.0	1.0



Habitat Suitability (Left) ranges from 0 (blue: very unlikely probability of suitable habitat) to 0.5 (green: unknown/even probability) to 1 (red: very likely probability of suitable habitat). Uncertainty (Middle) ranges from 0 (light – high precision and low uncertainty in probability estimate) to 0.5 (dark - low precision and high uncertainty in probability estimate). Experience (Right) ranges from 1 (light – high percent of data inform probabilities) to 0 (dark – low percentage of data inform probabilities). SETS (Bottom) sample site locations of observed species presence/ absence over HSP model predictions.

Figure 42. ***Sternapsis fossor***

6.4 Discussion

Bayesian networks provided a robust analytical tool for modeling benthic macrofauna species suitable habitat across the Pacific Northwest Continental Shelf. Results indicated that including prior knowledge improved model performance. Supervised techniques typically performed better than automated ones. Overall, models achieved TSS scores above 0, indicating better performance than what would be expected from a total random model or model with total error (Marcot 2012).

6.4.1 Interpreting Results

Habitat Suitability Probability (HSP) maps reflect static probability predictions of suitable habitat for seven benthic macrofauna species given regional raster information. Raster data used to calculate regional probabilities include: depth, mean grain size, distance to shore and latitude. A high probability of suitable/unsuitable habitat can be interpreted as: the given combination of regional environmental variables which have a high probability of being suitable/unsuitable for the species of interest. A probability of 0.5 can man either an unknown probability, in which case no data was available to update the prior probability of 0.5 to something greater or lesser; or an even probability, in which case a lot of data was used, however the given combination of regional environmental variables was neither suitable nor unsuitable (observations were 50% present, 50% absent). Using the experience map can assist in differentiating between the two.

While regional latitude and distance to shore raster data are both precise and accurate, depth and mean grain size raster data represent modeled information at a coarser scale than what occurs in nature. Regional mean grain size data is limited in scale (250 m) and is not able to represent finer habitat patches. The existence and prevalence of ecologically significant habitat patches finer than 250 meters used here in this analysis warrants further investigation, as local patches may be incorrectly predicted at the regional level. The analysis of SETS field validation samples touch on HSP error caused from errors in modeled mean grain size predictions due to fine scale patterns underrepresented in regional grain size data.

Uncertainty maps represent the level of precision in habitat suitability values, or the width of the posterior probability distribution. Uncertainty in model predictions arises from uncertainty inherent in the sampling data. Environments that are highly suitable are associated with species observations predominantly depicting species presence (100 % presence, 0 % absence). Environments which are somewhat suitable are more likely associated with species observations closer to 50% presence, 50% absence. Therefore, highly suitable or unsuitable habitats are typically associated with a higher certainty in predictions than somewhat suitable/unsuitable to unknown habitats. Uncertainties associated with predicting local *in situ* variables are also carried through to the final uncertainty surface.

Experience maps are a novel product that communicates a third piece of information: the percentage of data informing probabilities in the model. These maps help to communicate regional confidence in predictions arising from sampling effort. Experience values are associated with unique combinations of environmental parameters. This means that an area can be high in experience, even if it wasn't sampled, if it contains a combination of environmental parameters that were sampled frequently in other areas. Experience values will differ for each species, as they are dependent on the unique environmental parameters important to the species of interest. Experience values do not necessarily mirror uncertainty values. A region can be high in experience and low in precision if a large percentage of data were collected from somewhat suitable habitat versus a region with high precision and low experience, where a small percentage of data were collected from highly suitable habitat. Due to these properties, Experience maps also provide a novel interpretation in that they can be used to identify regions to target for future sampling effort. It would be disadvantageous to sample a new region if it was high in experience (e.g., shared similar environmental conditions to a region already sampled) and would provide little new information to the model. Therefore, using Experience maps to guide future effort will maximize new information for minimal effort.

By providing all three map layers, resource managers will be better informed, not only of habitat suitability predictions, but of the confidence behind these predictions, and the level of data used to calculate them.

6.4.2 Limitations

Habitat Suitability Probability (HSP) models demonstrate our best estimation of likely suitable habitat for seven benthic macrofauna species and do not represent species abundance. These models are limited by knowledge of individual species-environment associations. Given that this knowledge is predominantly dictated by geomorphic features easily measured on a regional scale, these models do not capture variability associated with biological, chemical or temporal dynamics. Improved knowledge of species-environment associations to geomorphic, biological and chemical features of the landscape can be inserted into the Bayesian networks, allowing for model improvements. Utilization of species counts from a wider sampling effort can enhance predictions with more information about abundance or ordinal habitat preferences.

HSP maps represent static suitability from a snapshot in time dictated by our sampling window. With a larger temporal dataset, more can be inferred about how habitat suitability may change over time.

Theoretically, models are also limited to a particular species unique response to its environment. Generalist species, which are easily adaptable and can withstand a wide range of environmental conditions, do not necessarily present a unique signal that can be modeled and easily visualized on a map. On the opposite extreme, specialists, or species that are limited by a narrow range of conditions, can send out a strong signal to produce maps and models with high performance metrics. Yet, in order to model such responses with high precision, more data is needed to describe the species' small environmental envelope.

Overall, models with the lowest uncertainty were based on species most sensitive to variables associated with the regional raster layers of Depth or Mean Grain Size. Many of the benthic macrofauna species showed a strong modeled response to Percent Silt, Percent Sand, Total Organic Carbon and Total Nitrogen, variables which were not provided as regional input for the final predictive map products. Improving regional predictions of these variables, will in turn, improve habitat suitability predictions and lower overall uncertainty for most macrofauna species.

Finally, an opportunity arose during the course of this study to conduct a field validation at the South Energy Test Sites (SETS), which is located in our study area and an area planned to test renewable energy devices. Findings showed that habitat suitability models had an overall additional field validation over space and time will improve models by providing new data in which to test model performance and to update networks with new information. While the data from the SETS site was useful, it was somewhat limiting due to its small sample size, its close proximity to another sampling site, and its expression of similar habitat features sampled at other sites. Experience maps indicate this region to have some level of experience for all macrofauna species, and to have high levels of experience for *Ennucula tenuis, Magelona berkeleyi* and *Sternaspis fossor.* Data used to inform these habitat suitability models are patchy over both geographic and environmental space. In order to improve models, new sampling sites should be identified to maximize geographic coverage and unique environmental areas.

6.4.3 Recommendations

6.4.3.1 Improve Environmental Data

The success of creating a habitat suitability map of any species depends on the resolution and quantity of regional environmental data from which regional predictions can be made. It must be noted that regional environmental data must either represent ecological drivers of species distribution or proxies to ecological drivers. For example, if a species distribution is primarily driven by fine scale patterns of pH on the ocean floor and no regional raster of bottom pH concentration levels exist and is not related to any environmental factor that can be measured, then regional prediction is not possible.

Improvements to environmental data can be made on two fronts: increase ocean floor coverage of direct environmental drivers and identify new regional scale environmental proxies. Models will be enhanced by a finer scale description of direct ecological driver patterns, such as TOC, TN, percent silt, percent sand and grain size. As seen in the SETS analysis, species are responding to finer scale processes in grain size than were captured by the 250 meter resolution cell size. Further, the collection of other variables not used in models, which may be important to macrofauna, is recommended. These variables may include biological (e.g., larval disbursement and recruitment patterns, species trophic interactions and food supply, etc.), chemical (e.g., dissolved oxygen, pH and concentrations of minerals, etc.) and physical drivers (e.g., bottom temperature, bottom currents and topological habitats, etc.).

Identifying new environmental proxies, which are strongly correlated with direct, ecological drivers, is also important. Proxies, which can be measured on a regional scale with little effort (e.g., remotely sensed data), can improve model performance at little cost.

6.4.3.2 Improve Sampling Effort

Larger sample size over both time and space inevitably leads to better habitat suitability predictions. However, this is a costly process in the marine environment, and therefore directed sampling effort can maximize the increase in information while minimizing the cost. Experience Maps, detailed for the first time in this study, can be used to recommend future directed sampling by highlighting spatial regions which are low in experience for a given species. Species within this study will be used as an example for how the Experience Maps can inform future sampling effort.

Aystris gausapata and *Onuphis iridescens* demonstrate low experience throughout the study area. This is likely because each species was best represented by a more complicated model, due to weak ecological responses to the environmental variables used in the modeling effort. Both species would benefit from increased sampling effort throughout the region. However, it is also possible that another environmental driver could better describe these species' habitat suitability patterns. Such drivers could be physical, biological, or chemical in nature. Better understanding these species' ecology could elucidate factors more likely affecting habitat suitability patterns observed across the study area.

Ennucula tenuis, Magelona berkeleyi and *Sternaspis fossor* all show high experience in the mid latitude, shallow, sandy, region of the study area, yet tend to be found in deeper, silty environments associated with lower experience. Therefore, more samples within deeper regions would likely increase information about these species.

Axinopsida serricata and *Callianax pycna* show more experience in offshore, deeper water. *Callianax pycna* was not observed deeper than 75 meters and was predominantly found shallower than 45 meters, a region of low experience Latitudinally, no sampling effort shallower than 50 meters occurred south of Siltcoos or north of Newport. Therefore, all data informing suitable habitat for this species came from a small latitudinal region. Subsequently, habitat suitability predictions for this species outside this region were mostly unknown in shallow, possibly suitable environments. Having samples in water shallower than 50 m at the northern and southern extent would improve habitat suitability predictions for this species.

In addition to increasing the number of samples, efforts should endeavor to uniformly sample across consistent depth ranges across the latitudinal gradient. Due to the lack of uniformity, under sampled regions in this study include the shallowest and deepest extents, the southern portion of the study site where deeper, siltier environments are found closer to shore, and the northern region surrounding the output of the Columbia River. The Columbia River plume is a large driver in sedimentary patterns in the near shore environment and can influence a broad latitudinal range, where plume effects can sometimes be seen as far south as Newport. A better understanding of this unique system will improve model predictions, which were predominantly reported as unknown probabilities for this region.

Finally, future sampling effort will improve the temporal component of this dataset. Hierarchical Bayesian modeling is capable of handling temporal data and can provide information in regards to temporal variability. A region that is susceptible to large sedimentary changes would express a higher uncertainty in static HSP predictions whereas a region with little to no temporal variability would have a lower uncertainty in static HSP predictions.

6.4.3.3 Improve Accessibility of Model Predictions

Providing managers with access to models within the framework of decision support tools will improve managers' ability to use models in marine management and spatial planning. Data products (ESRI format raster images) may be added to the Bayesian Analysis for Spatial Siting (BASS) tool as advisory datasets loaded to the BASS viewer in order to provide this service.

6.4.4 Conclusions

Bayesian networks provide a robust analytical tool for modeling species suitable habitat. Results indicated that when applicable, including prior knowledge improved model performance. Supervised techniques typically performed better than automated ones. Overall, models with TSS scores above 0 indicate better performance than what would be expected from a total random model or model with total error.

Outputs and uses for this product: The data format for model output is ESRI floating point grid format (valid HSP range: 0-1). Users may interact with the model outputs either through the BASS Viewer or by adding the dataset directly to a desktop application (e.g. ArcGIS, Matlab and R) from a local copy or live map service. In this way the user has various mechanisms to apply model outputs to activities related to managing and permitting marine renewable activities.

6.5 Next steps: Application of methods to preliminary glass sponge habitat model

Due to cost savings from partnering and good weather, additional time and money was available to research habitat suitability models for additional species. Work reported in this section outlines the work completed as of the end of this reporting period. The model results represent a preliminary analysis and should not be used for management or planning purposes, as results have not undergone a model review, refinement, or testing phase. This work was done in collaboration with Northwest Fisheries Science Center and Alaska Fisheries Science Center from NOAA.

6.5.1 Introduction

The technique laid out earlier in Section 6 has provided a framework that is currently being adapted to the hard bottom glass sponge dictyonine species group: *Aphrocallistes vastus*, *Heterochone calyx* and *Farrea occa* **(Figure 43).** These three species will be treated as one modeling unit as they can be difficult to tell apart visually and are believed to share similar habitat characteristics (Pers. Comm. Stone 2014). The species within this sponge group produce a siliceous skeleton and can grow in assemblages either as sponge reefs or grounds. Sponge reefs are found from British Columbia, Canada to Juneau, Alaska, U.S (Stone et al. 2014). Within sponge reef ecosystems, sponge skeletons remain after an organism's death (Krautter et al. 2006). This structure traps fine sediment, eventually burying the underlying rock surface and allowing the development of stable, long-lived reef complexes, considered important nursery habitat for rockfish (Cook 2005; Krautter et al. 2006; Stone et al. 2014). As glass sponge species are fragile organisms, they are very susceptible to bottom trawling fisheries (Austin et al. 2007). Sponge grounds, found south of British Columbia are less complex assemblages of dictyonine species in areas strongly associated with hard bottom substrate and high current (Pers. Comm. Stone, B 2014). As dictyonine species are filter feeders, they are highly susceptible to sediment smothering, and therefore cannot survive in regions of high wave energy and high sedimentation rates (Whitney et al. 2005). This property limits their depth range from shallow regions affected by wave turbulence. Dictyonine assemblages express themselves as sponge ground habitat when conditions are not optimal for reef formation (Pers. Comm. Stone B. 2014). Nevertheless, sponge grounds may still provide structure for benthic organisms co-habiting on sponge grounds.

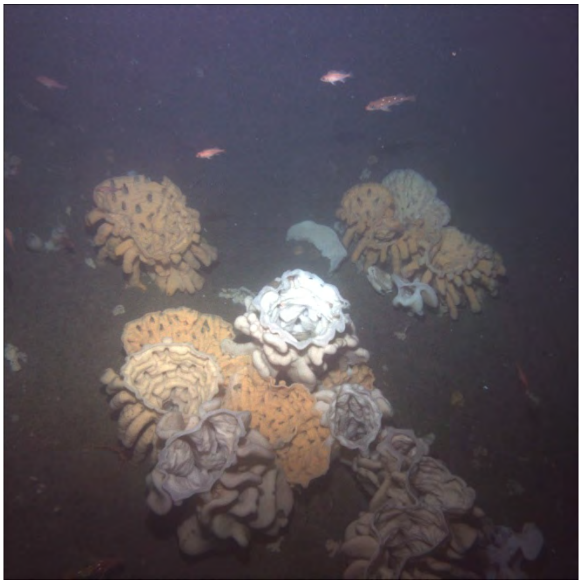


Figure 43. Dictyonine glass sponge species Image from AUV transect survey along Sponge Reef site off Washington State. Photo credit: NOAA 2010.

Dictyonine sponges, found along the continental shelf and slope of the Pacific Northwest, have previously been described off the coast of British Columbia and Washington state. Reef complexes north of British Columbia have been found in glacial sediments, moraines, and glacial promontories in regions of low sedimentation (Conway et al. 2004; Krautter et al. 2006;), in water depths of 50-550 m where bottom currents are strong (Conway et al. 2005; Cook et al. 2008; Yahel et al. 2007). Reefs are typically found in linear patterns along ridges (Conway et al. 2007) and near the heads of shelf canyons (Whitney et al. 2005). Bottom water conditions near and around reef complexes are reported to have the following oceanographic conditions: 43-75 µM silicate, 64-152 µM dissolved oxygen, 5.5-7.3 degrees Celsius, and 33.2 – 34.2 salinity (Whitney et al. 2005). Glass sponges grow at slow rates (~ 1-2 cm yr); therefore, silica uptake remains lower than measured silica background levels of sponge reef sites off British Colombia (Yahel et al. 2007). Considering silica levels are generally higher in the North Pacific, this variable may not a limiting factor. We did not include this variable from our initial analysis as a regional silica bottom concentration map had yet to be identified.

6.5.2 Methods

We began compiling species data from scientific literature and expert knowledge; NOAA's coral and sponge database (NOAA 2013); and an in-house dataset from autonomous underwater vehicle (AUV) surveys along the Washington Sponge Reef site (NOAA 2010). Only the NOAA (2013) database was incorporated into the model. NOAA's coral and sponge database has 353 presence-only records of dictyonine sponge species from trawl surveys along the US west coast from northern California to northern Washington State. The database has two unique issues not encountered in the macrofauna dataset: the data are presence-only, as absence cannot be confirmed without spatially explicit information of trawl transect surveys; and locational resolution is course to the scale of 2-km, as it is unknown at which point glass sponges were encountered along trawl surveys. Both these issues will be resolved when more spatially accurate trawl transect data is obtained from NOAA. This initial analysis integrates expert knowledge with the NOAA coral and sponge database.

In order to successfully predict habitat suitability throughout the region, environmental layers were identified to act as proxies for ecological drivers (excluding depth). Hard Substrate was predicted throughout the region using the Probability of Outcrop map along with "Ridges" identified from the Version 4 Surficial Geologic Habitat map (Section 3). Finally, we used the standard deviation of depth, calculated using a neighborhood of 50 km, to act as a proxy for regions of high current. This layer was chosen as a proxy for two reasons: broad scale patterns in bathymetry are associated with bottom current patterns (Wilson 2007); and this layer visually appeared to partially explain species observations.

A preliminary spatial examination of NOAA sponge observations and environmental regional layers highlighted a hotspot of dictyonine species in a geographic region previously described as soft sediment habitat (Figure 44). Geologically defined as the "Newport embayment," this region was previously believed to be devoid of underlying surface structure that would create hard-bottom habitat (Pers. Comm. Goldfinger 2014). While sponges require hard substrate for attachment, substrate surfaces do not need to be large or complex. Pockets of cobble or human debris could potentially explain sponge distribution in this region. Further, sponge observations appeared associated with the minimum isocore sediment thickness map, which defines regions of thick sediment and no underlying structure (Figure 44). While this association is likely to be coincidental, it is possible that sedimentary basins may host slight depressions in the seabed, allowing cobbles or other small, hard debris to accumulate. In the Klamath basin, another site with coral and sponge occurrence, the basin is underlain by an extensive low angle normal fault, and the basin itself is an extensional basin, unusual for a compressional subduction setting. The extension of the cover sequence in the basin is generating numerous normal faults that may act as fluid conduits, and in turn generate carbonate hard substrates associated with venting.

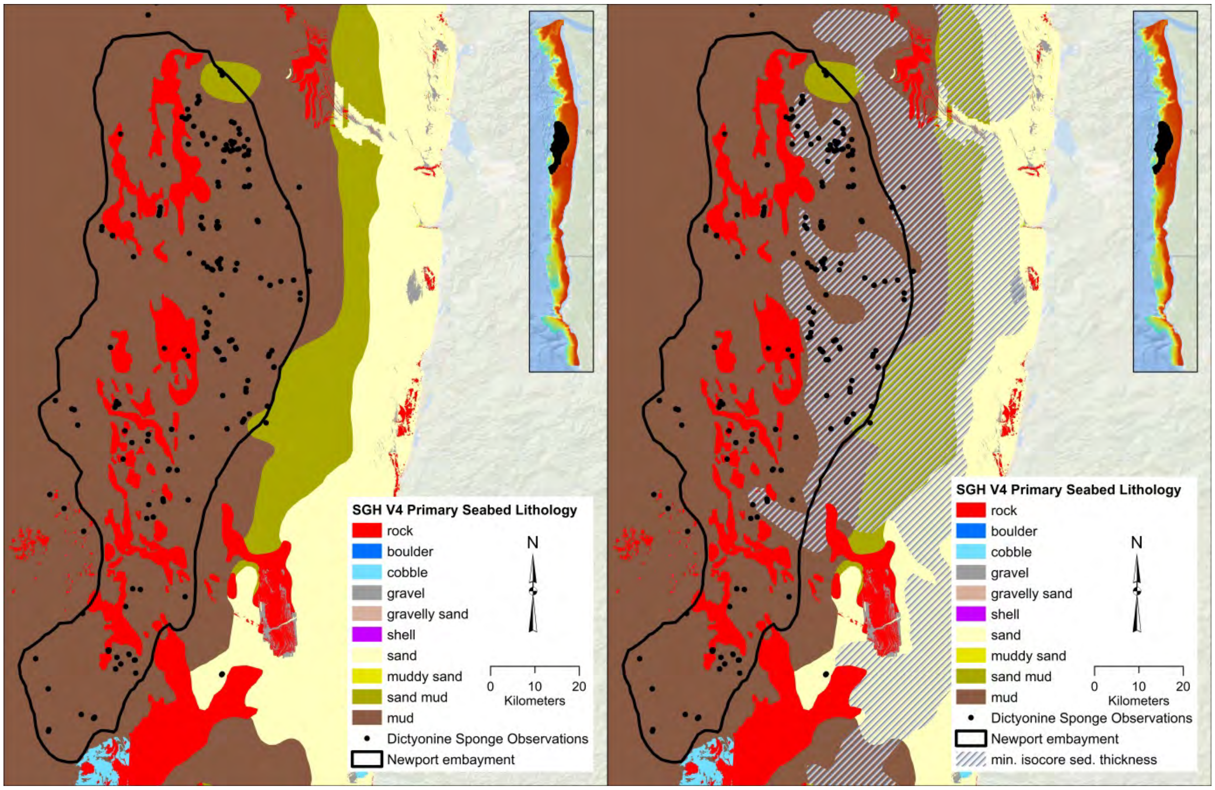


Figure 44. Newport embayment offshore of Oregon
Dictyonine sponge observations are predominantly found in areas depicted as mud. Map on right highlights the associations between observations and minimum isocore sediment thickness. Dictyonine observations from NOAA (2013).

Categorical variables (Minimum isocore sediment thickness, Newport Embayment, Ridge and Rock) were discretized by two states, "Yes" and "No." Continuous variables were discretized by supervised techniques using NOAA's coral and sponge database (Section 6.2.4.2). As absence was not available, density histograms of presence were compared against all records in the database (5069 observations).

An initial analysis of data suggested no correlation among the explanatory variables, supporting the use of a basic network structure (Figure 45). Depth, Probability of Rock, Presence of Ridge and Change (or standard deviation) in Depth represent regional raster variables. Each node, in turn point towards suitability nodes, or intermediate nodes, which capture the relationship between each explanatory variable and dictyonine sponge species observations. To account for the anomalous Newport embayment region, the model calls out locations within the Newport embayment and increases the likelihood of suitable habitat if the location falls within a region of minimum isocore sediment thickness. While this is a crude method for addressing this unique habitat that currently lacks a physical explanation, it remains an initial place holder until new research, currently underway, can better explain the processes underlying the pattern of sponge observations in what are believed to be soft sediment habitats.

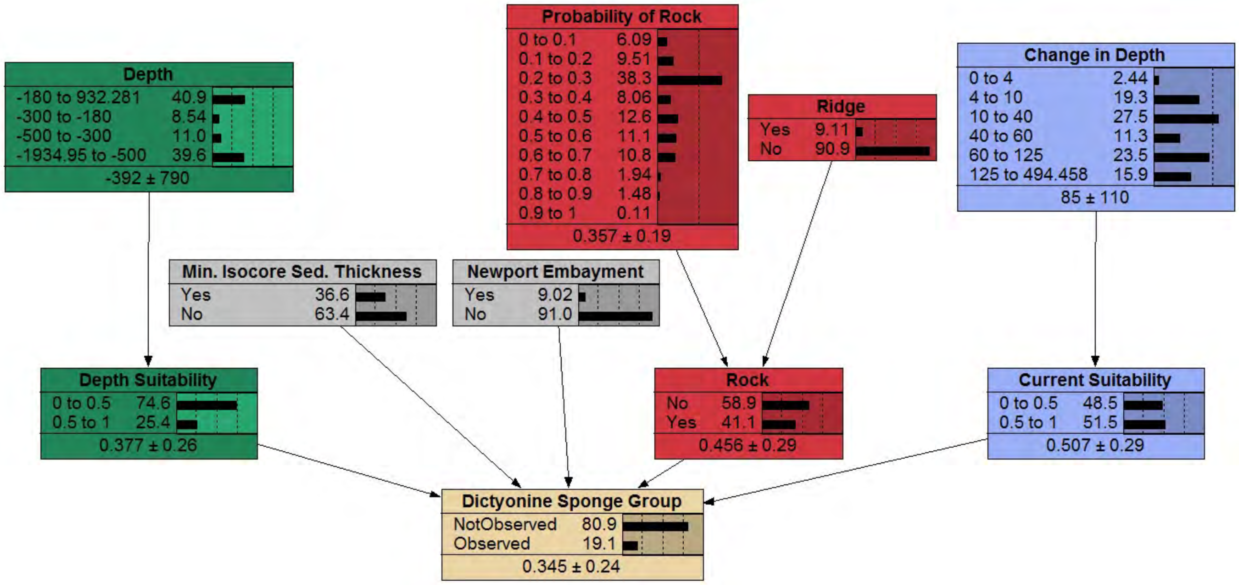


Figure 45. Preliminary Bayesian network for dictyonine sponge group
No correlations were found between continuous explanatory variables, so a basic net structure was used for the preliminary model.

Conditional Probability Tables (CPTs) were parameterized in a two-step process. First, probabilities were expertly defined using NOAA sponge observation density histograms and expert knowledge. Second, probability of occurrence of regional raster nodes (Depth, Probability of Rock, Ridge and change in Depth) were updated to reflect the frequency with which each categorical state was encountered throughout the region using NOAA's complete coral and sponge database for the northern region.

Following model structure development and parameterization, a prediction was made for the region. The southern extent was defined by that of the benthic macrofauna model. The region was bounded in the north by the NOAA bottom trawl survey extent and to south by the southern extent of the benthic macrofauna model (39º 30′ 25.668″ to 48º 30′ 4″). It was bounded on the east to west axis by the shallowest and deepest depths surveyed by NOAA's bottom trawl sampling program (-55 m to -1280 m).

6.5.3 Preliminary Results

The dictyonine sponge group was uncommon throughout the region, with 10% confirmed observations (n = 353) within the NOAA coral and sponge database (NOAA 2013), after data was gridded by 1-km to account for repeated records. However, this rate does not take into account taxonomic resolution bias. Of the same gridded data, 12% were only identified to the glass sponge taxonomic order, unknown Hexactinosida; 3% were only identified to the glass sponge taxonomic class, unknown Hexactinellida;

and 24% were only identified as an unknown sponge, Porifera. In general, dictyonine sponges are under reported throughout the region due to uncertainty in species identification, as 39% of the gridded data could potentially be a species in the dictyonine sponge group.

Sensitivity to findings analysis within the Bayesian Network indicated that this species group was most sensitive to Rock, then Depth Suitability, followed by Current Suitability. The species group was least sensitive to Newport Embayment and Minimum isocore sediment thickness. These results fit nicely with prior expectation of dictyonine sponge habitat.

Conclusions cannot be made in regards to unsuitable habitat, as absence data were unavailable for model training. Probabilities are strictly about the probability of suitability. Therefore, a habitat suitability map was generated on a single color scale, to reflect the increased probability of suitable habitat from low to high, with no threshold distinguishing between unsuitable and suitable (Figure 46). Probability scores are then interpreted in regards to habitat suitability. For example, an HSP score of 0.3 would be interpreted as: the given combination of regional environmental variables have a 0.3 probability of being suitable for the species of interest.

As the only data available to compare model performance currently comes from NOAA's coral and sponge database, performance metrics available are limited due to the presence-only nature of the data. Prediction success was reported for the percent of NOAA dictyonine sponge observations within 2 km of a cell with an HSP value above specified thresholds (Table 28).

Table 28. Prediction success reported as a percent occurrence
Column on left indicates HSP thresholds. Middle column represents the number of dictyonine observations from NOAA coral and sponge database which occurred within 2 km from a raster cell containing an HSP value at or higher than indicated by the left column. This column represents a cumulative (and not total) sum of observations. Right column expresses this cumulative count as a percent of total dictyonine records in the NOAA database.

HSP	Dictyonine Observations	Percent of NOAA Dictyonine Records
0.9	136	39 %
0.8	145	41 %
0.7	153	43 %
0.6	168	48 %
0.5	174	49 %
0.4	187	53 %
0.3	233	66 %
0.2	297	84 %
0.1	344	97 %
0.0	353	100 %

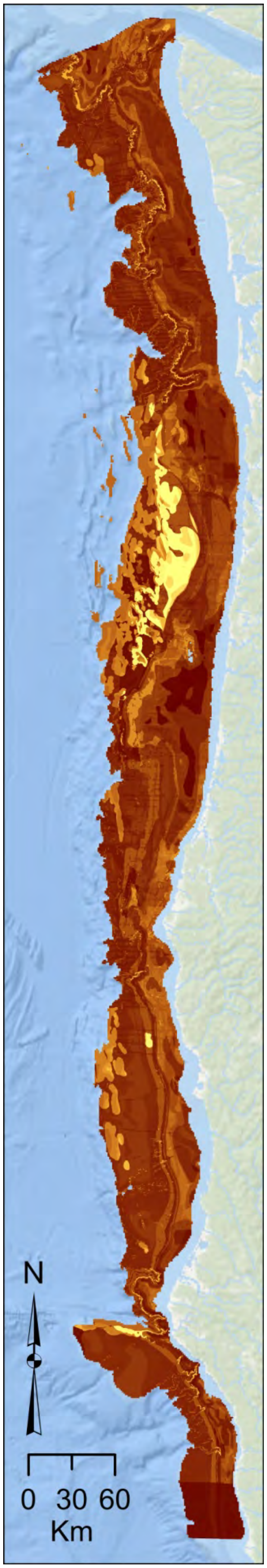


Figure 46. Habitat Suitability Probability (HSP) Map of the Dictyonine sponge group
HSP values range from 0 (dark – low probability of suitable habitat) to 1 (high probability of suitable habitat). Due to the lack of absence data training the model, nothing can be inferred about habitat unsuitability.

HSP
High : 1
Low : 0

6.5.4 Discussion

This work represents a first attempt to model the dictyonine glass sponge species group. The current model under-predicts habitat suitability and needs improvement prior to its use for management purposes. Recommendations to improve the model include: further exploring the Newport embayment region to better understand the processes producing hard bottom surfaces in the region; incorporating AUV data; incorporating NOAA spatially explicit trawl transect data to improve locational accuracy of dictyonine sponge occurrences and to incorporate absence data (trawls with no dictyonine sponge by-catch); locating a bottom current dataset to replace current suitability proxy or improving existing spatial layers with more refined techniques, such as a multi-spatial scale bathymetric position index; and refining model probabilities by communicating further with dictyonine sponge experts. After the dictyonine sponge model is refined, it will undergo a more rigorous model performance testing, review, and validation phase. After this work is complete, we hope to publish results and integrate the completed model with OSU's data viewer and BASS framework.

6.6 Literature Cited

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Appendix 4. Supplementary Material for ROV Report

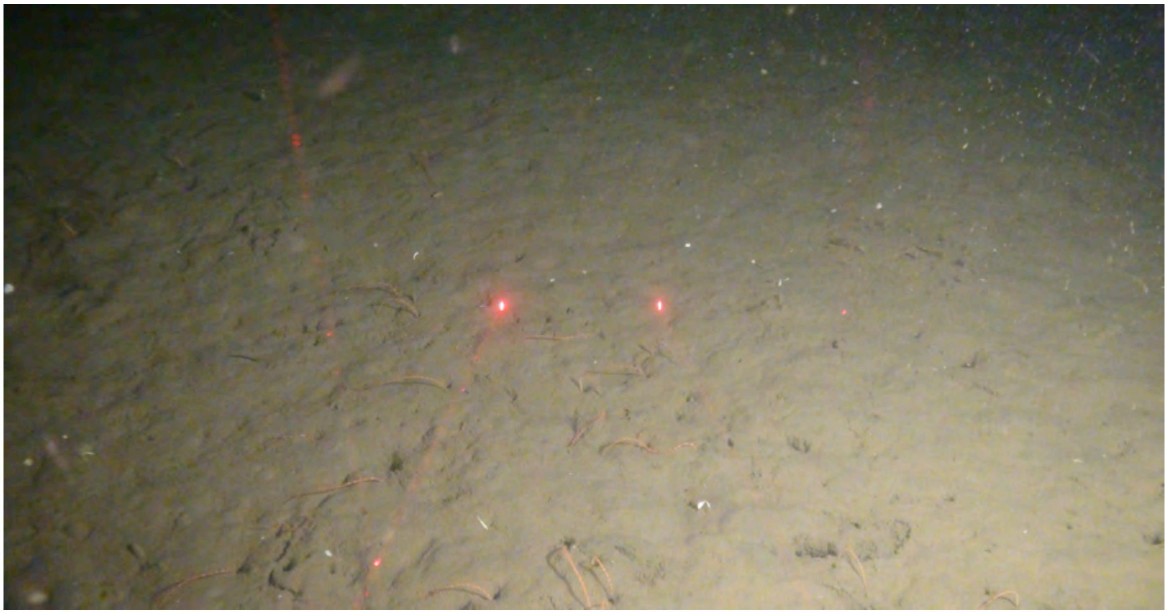


Figure 47. Example of a mud-mud (MM) patch (from Siltcoos)

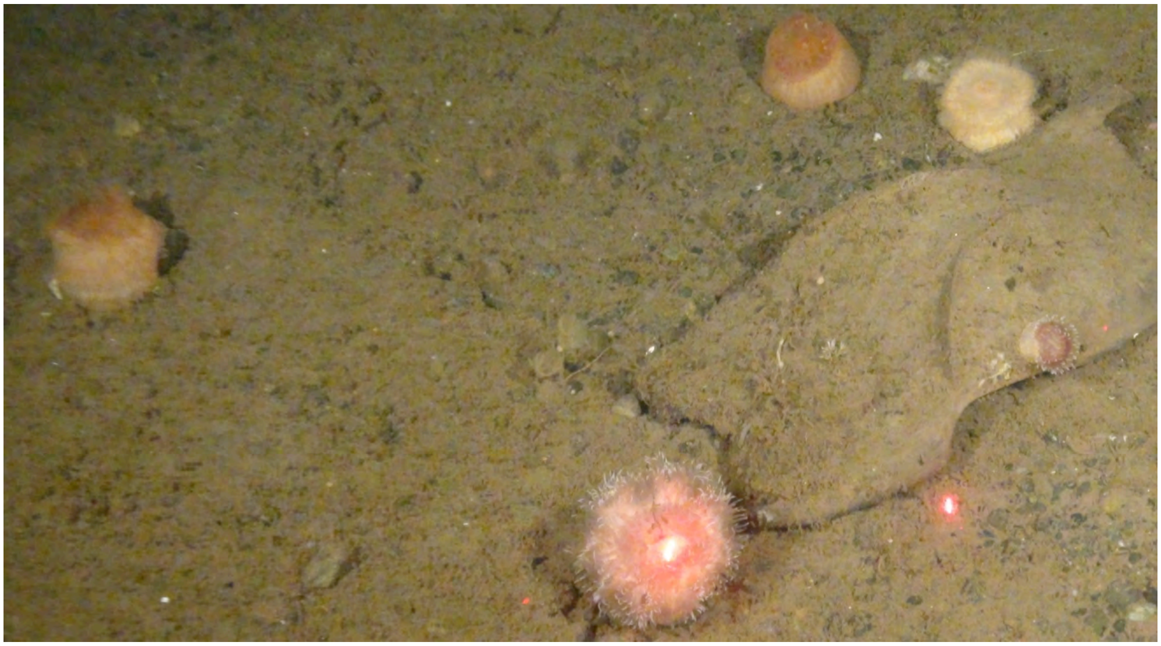


Figure 48. Example of a mud-gravel (MG) patch (from Grays Bank)

Figure 49. Example of a mud-pebble (MP) patch (from Bandon-Arago)

Figure 50. Example of a cobble-mud (CM) patch (from Bandon-Arago)

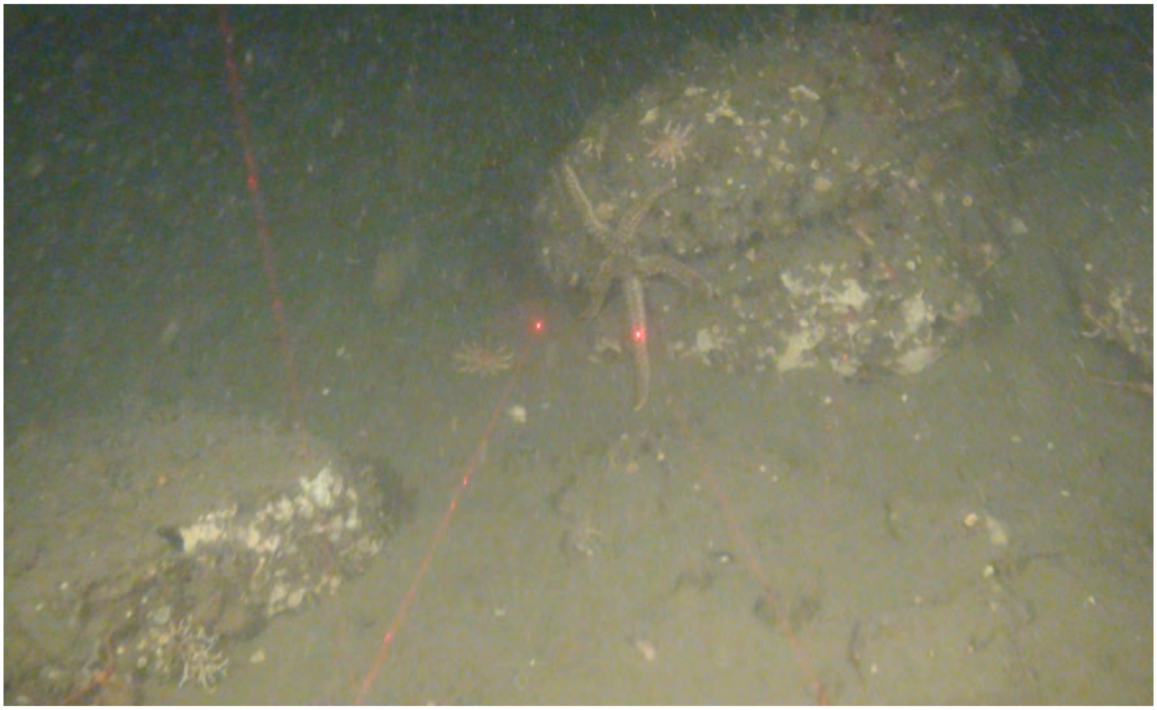


Figure 51. Example of a mud-boulder (MB) patch (from Siltcoos)

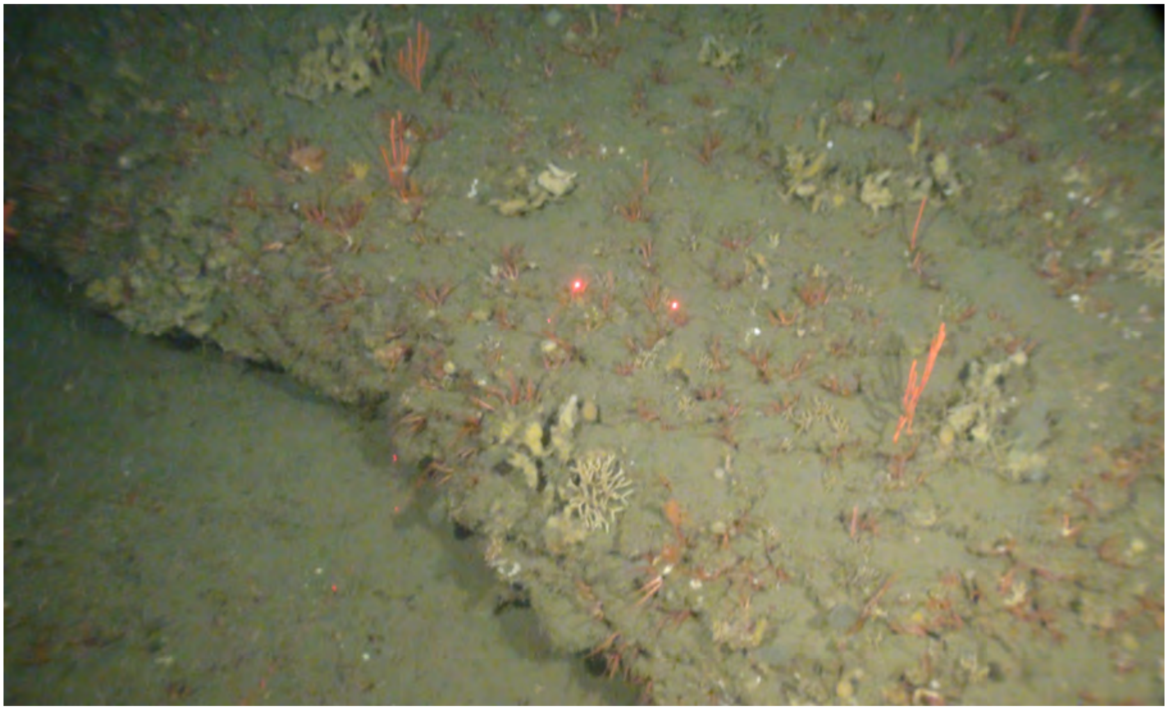


Figure 52. Example of a flat rock-mud (FM) patch (from Bandon-Arago)

Figure 53. Example of a ridge rock-mud (RM) patch (from Bandon-Arago)

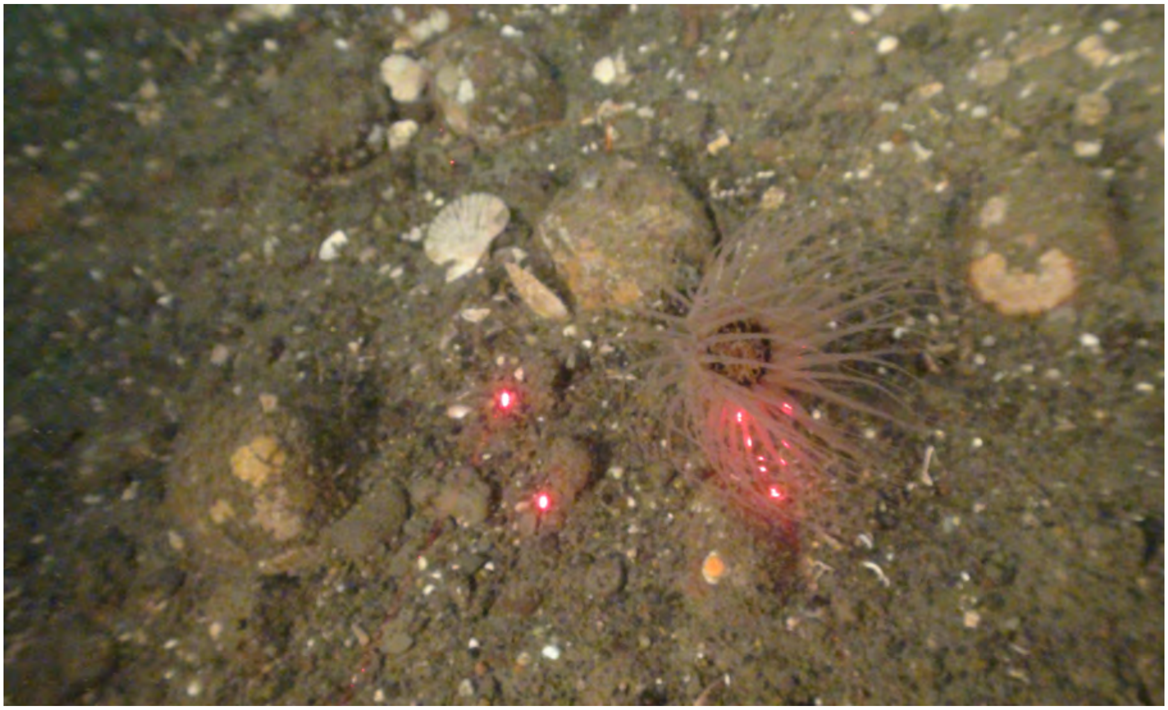


Figure 54. Example of a cobble-gravel (CG) patch (from Bandon-Arago)

Table 29. Total raw count of macroinvertebrate taxa across all six sites in the *Delta* and ROV *Hammerhead* stations

Includes total counted (n = 252,884) and each taxon's percent contribution to the total count; GB = Grays Bank, SC = Siltcoos Reef, BA = Bandon-Arago, M = motile, S = sessile.

Taxon	GB 1994	GB 2011	SC 1995	SC 2011	BA 1993	BA 2012	Total # of indiv.	% of total
ANNELIDA								
Feather-duster worm, M	-	-	-	-	-	74	74	0.03
Bamboo worm, M	-	-	-	-	-	9	9	0.00
	Total no. of Annelid individuals						**83**	**0.03**
	Total no. of Annelid taxa						**2**	
ARTHROPODA								
Pandalus sp., M	110	1	-	4617	-	3	4731	1.87
Munida quadrispina, M	-	541	1	759	-	74	1375	0.54
Hermit crab, M	2	110	8	-	-	6	126	0.05
Lithod crab, M	28	18	-	1	-	5	52	0.02
Cancer spp., M	-	15	5	9	-	1	30	0.01
Unidentified shrimp, M	-	8	-	1	-	10	19	0.01
Decorator crab, M	-	4	-	1	-	-	5	0.00
Loxorhynchus crispatus, M	-	1	-	-	-	2	3	0.00
Long-legged crab, M	-	-	-	-	-	1	1	0.00
	Total no. of Arthropod individuals						**6342**	**2.51**
	Total no. of Arthropod taxa						**9**	
CHORDATA								
Transparent tunicate, S	1	212	1	48	4	1976	2242	0.89
	Total no. of Chordate individuals						**2242**	**0.89**
	Total no. of Chordate taxa						**1**	
CNIDARIA								
Branching red gorgonian, S	111	6173	1385	3153	2649	5622	19093	7.55
Metridium farcimen, S	-	1407	27	1256	3252	695	6637	2.62
Subselliflorae, S	425	2178	1684	117	26	-	4430	1.75
Single stalk red gorgonian, S	866	1410	34	110	268	79	2767	1.09
Stomphia coccinea, S	15	682	18	82	72	142	1011	0.40
Urticina spp., S	13	671	20	11	4	166	885	0.35
Burrowing anemone, S	324	-	138	-	12	-	474	0.19
Burrowing anemone (white), S	-	11	-	270	-	2	283	0.11
Burrowing anemone (brown), S	-	8	-	116	-	22	146	0.06
Cribrinopsis fernaldi, S	-	20	-	11	-	1	32	0.01
Metridium senile, S	-	13	-	7	-	3	23	0.01
Ptilosarcus gurneyi, S	-	15	-	-	-	3	18	0.01
White sea-pen, S	-	3	-	-	-	-	3	0.00
Dromalia alexandri, S	-	-	-	-	2	-	2	0.00
Clavactinia milleri, S	-	-	-	-	-	1	1	0.00
Anthomastus ritteri, S	-	1	-	-	-	-	1	0.00
Stylaster californicus, S	-	-	1	-	-	-	1	0.00
	Total no. of Cnidarian individuals						**35807**	**14.16**
	Total no. of Cnidarian taxa						**17**	

ECHINODERMATA								
Florometra serratissima, M	2561	-	252	12	35158	78	38061	15.05
Small orange brittle star, M	12	3083	6	193	-	21532	24826	9.82
Burrowing brittle star, M	-	1583	-	10016	-	88	11687	4.62
Parastichopus californicus, M	-	796	1128	1199	1398	1664	6185	2.45
Mediaster aequalis, M	113	95	185	719	1726	1783	4621	1.83
Cucumaria spp., M	-	3	-	2	-	2760	2765	1.09
Gorgonocephalus eucnemis, M	3	38	56	191	1429	709	2426	0.96
Pentamera sp., M	-	1734	-	1	-	1	1736	0.69
Parastichopus leukothele, M	89	1	647	382	198	1	1318	0.52
Henricia spp., M	18	575	125	165	263	1157	2303	0.91
Psolus chitonoides, M	-	61	8	29	-	1137	1235	0.49
Large orange brittle star, M	-	19	-	445	-	4	468	0.19
Leptosynapta cf. *clarki*, M	-	-	-	418	-	-	418	0.17
Stylasterias forreri, M	19	148	12	109	13	89	390	0.15
Luidia foliolata, M	18	106	125	27	80	4	360	0.14
Orthasterias koehleri, M	10	7	11	15	149	76	268	0.11
Pteraster tesselatus, M	-	133	40	13	3	54	243	0.10
Allocentrotus fragilis, M	145	17	-	2	37	29	230	0.09
Psolus squamatus, M	135	-	-	-	-	-	135	0.05
Pycnopodia helianthoides, M	22	44	-	16	7	23	112	0.04
Crossaster papposus, M	-	11	6	56	21	4	98	0.04
Pisaster brevispinus, M	-	75	-	-	-	18	93	0.04
Solaster spp., M	1	29	2	9	14	26	81	0.03
Poraniopsis inflate, M	25	-	13	3	17	-	58	0.02
Hippasteria spinosa, M	2	-	3	14	5	-	24	0.01
Dermasterias imbricate, M	-	2	-	2	-	10	14	0.01
Poraniopsis jordani, M	5	-	-	-	4	-	9	0.00
Ceramaster patagonicus, M	-	-	3	4	-	-	7	0.00
Pteraster militaris, M	-	-	3	1	-	-	4	0.00
Strongylocentrotus sp., M	-	2	-	-	-	-	2	0.00
Gephyreaster swifti, M	-	-	-	-	-	1	1	0.00
Unidentified sea star, M	-	-	-	-	-	1	1	0.00
	Total no. of Echinoderm individuals						**100179**	**39.61**
	Total no. of Echinoderm taxa						**32**	
MOLLUSCA								
Chlamys sp., M	-	22	-	-	-	2185	2207	0.87
Dorid nudibranch, M	-	145	-	67	-	273	485	0.19
Dendronotid nudibranch, M	1	11	-	10	-	36	58	0.02
Octopus rubescens, M	-	40	5	5	-	3	53	0.02
Unidentified nudibranch, M	-	14	-	-	-	14	28	0.01
Aeolid nudibranch, M	-	3	-	-	-	18	21	0.01
Unidentified snail, M	3	2	-	-	1	9	15	0.01
Moon snail, M	-	8	-	-	-	3	11	0.00
Dironid nudibranch, M	-	3	-	6	-	-	9	0.00
Mud scallop, M	-	4	-	1	-	1	6	0.00
Enteroctopus dofleini, M	-	4	-	-	-	1	5	0.00
Rossia pacifica, M	-	1	-	1	-	-	2	0.00
	Total no. of Molluscan individuals						**2900**	**1.15**

	Total no. of Molluscan taxa						**12**	
NEMERTEA								
Nemertean, M	-	12	-	5	-	4	21	0.01
	Total no. of Nemertean individuals						**21**	**0.01**
	Total no. of Nemertean taxa						**1**	
PORIFERA								
Branching sponge, S	72	2128	273	825	52513	22722	78533	31.05
Shelf sponge, S	1373	2021	628	5736	3	9961	19722	7.80
Foliose sponge, S	226	207	234	92	50	2563	3372	1.33
Unidentified sponge, S	1084	-	32	-	23	-	1139	0.45
Yellow tall branching sponge, S	-	47	-	-	-	749	796	0.31
Yellow ball sponge, S	-	314	-	18	-	231	563	0.22
Tube sponge, S	-	485	-	-	-	3	488	0.19
Semisuberites cribrosa, S	-	301	-	-	-	-	301	0.12
Cliona sp., S	-	5	-	-	-	90	95	0.04
Spheciospongia confoederata, S	14	-	51	8	-	-	73	0.03
Polymastia sp., S	-	-	-	-	6	58	64	0.03
Ball sponge, S	-	14	-	-	-	47	61	0.02
Upright flat sponge, S	22	8	10	12	3	3	58	0.02
Phakellia sp., S	-	31	-	-	-	-	31	0.01
Barrel sponge, S	6	-	4	1	-	1	12	0.00
Fan-like sponge, S	-	-	-	-	-	1	1	0.00
Leucandra sp., S	-	-	-	-	-	1	1	0.00
	Total no. of Poriferan individuals						**105310**	**41.64**
	Total no. of Poriferan taxa						**17**	
	GRAND TOTAL NUMBER OF INDIVIDUALS						**252884**	**100**
	GRAND TOTAL NUMBER OF TAXA						**91**	

Appendix 5. Supplementary Material for Macrofauna Report

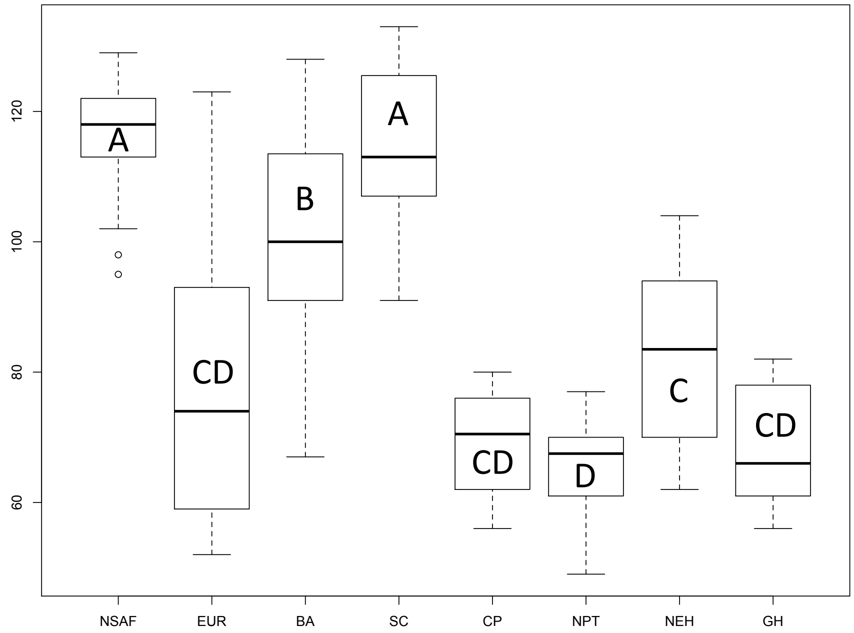


Figure 55. Depth (m) at the eight study sites
Sites differed significantly in depth (ANOVA, p < 0.001). Letters in the boxes indicate the results of Tukey post-hoc tests.

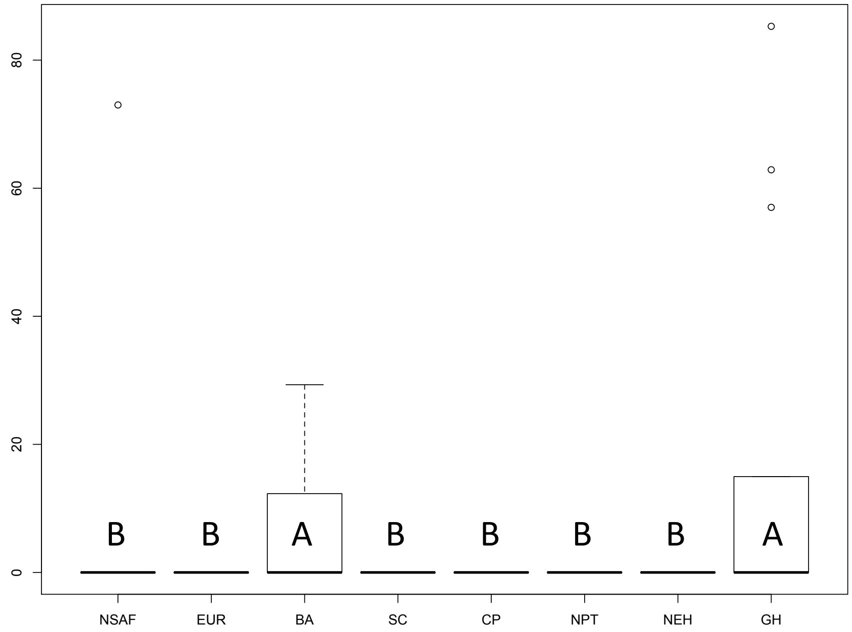


Figure 56. Percent gravel (> 2 mm) at the 8 study sites
Sites differed significantly (ANOVA, p < 0.001) in percent gravel. Letters in the boxes indicate the results of Tukey post-hoc tests.

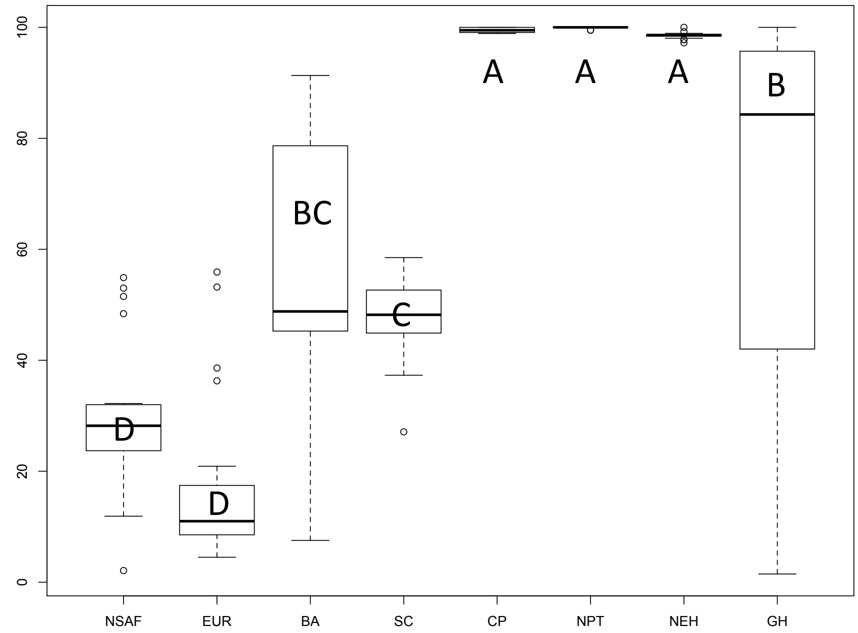


Figure 57. Percent sand (62.5 um - 2 mm) at the 8 study sites
Sites differed significantly (ANOVA, $p < 0.001$) in percent sand. Letters in the boxes indicate the results of Tukey post-hoc tests.

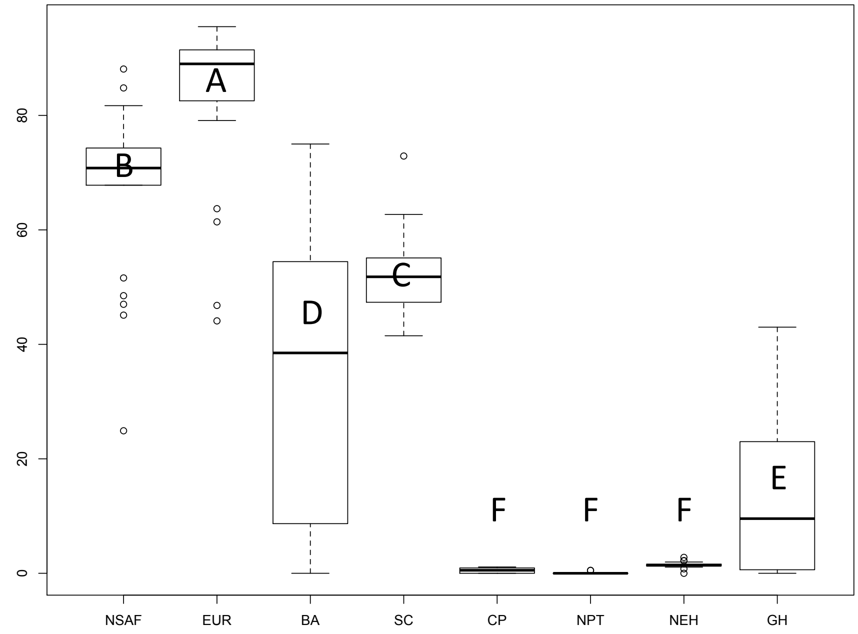


Figure 58. Percent silt/clay (fraction < 62.5 um) at the 8 study sites
Sites differed significantly (ANOVA, $p < 0.001$) in percent silt. This measured physical factor was the one that differed the most among sites with 6 significantly different groups across eight sites. Letters in the boxes indicate the results of Tukey post-hoc tests.

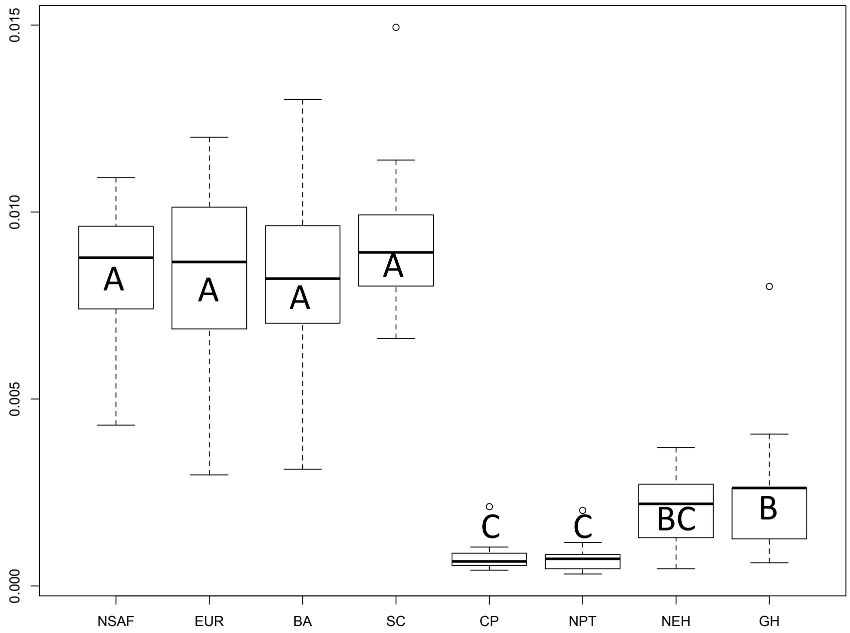


Figure 59. Percent (by weight) total organic carbon at the 8 study sites
Sites differed significantly (ANOVA, $p < 0.001$) in the percent total organic carbon in the sediment. Letters in the boxes indicate the results of Tukey post-hoc tests.

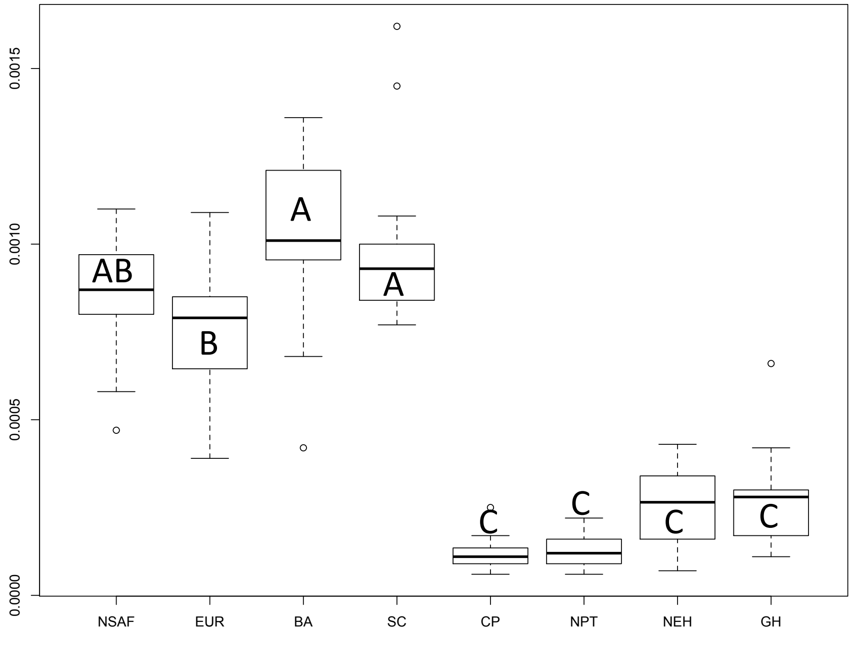


Figure 60. Percent (by weight) total nitrogen at the 8 study sites
Sites differed significantly (ANOVA, $p < 0.001$) in the percent total nitrogen in the sediment. Letters in the boxes indicate the results of Tukey post-hoc tests.

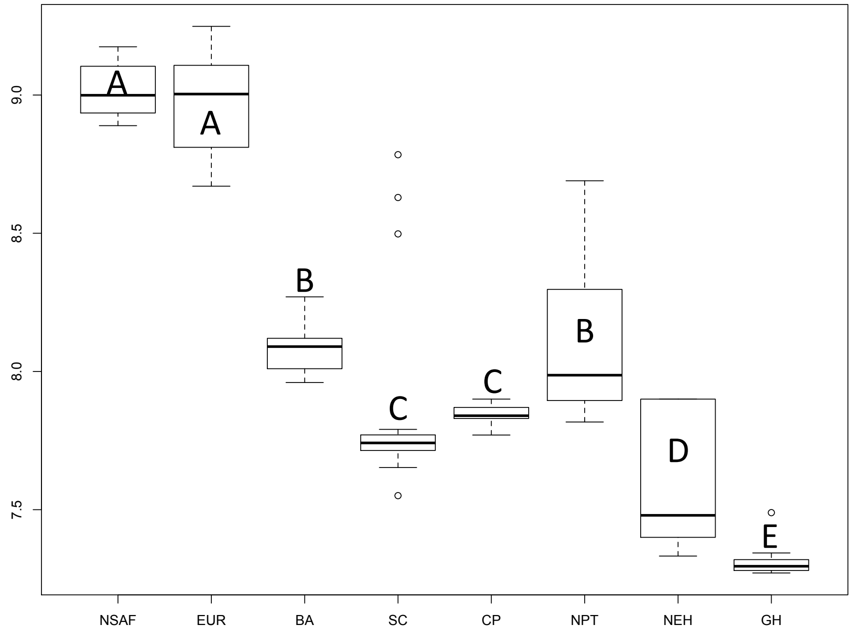


Figure 61. Temperature (degrees Celcius) at the eight study sites
Sites differed significantly (ANOVA, $p < 0.001$) in temperature. Temperature and DO were tied for the second-most variable measured physical factor with five significantly different groups across eight sites. Letters in the boxes indicate the results of Tukey post-hoc tests.

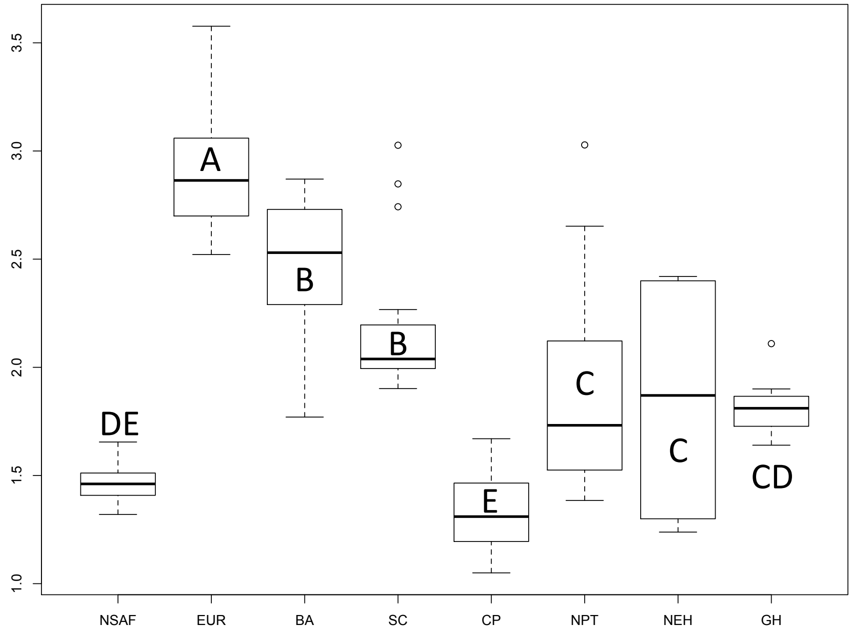


Figure 62. Dissolved oxygen (mg/mL) at the 8 study sites
Sites differed significantly (ANOVA, $p < 0.001$) in dissolved oxygen. Temperature and DO were tied for the second-most variable measured physical factor with 5 significantly different groups across eight sites. Letters in the boxes indicate the results of Tukey post-hoc tests.

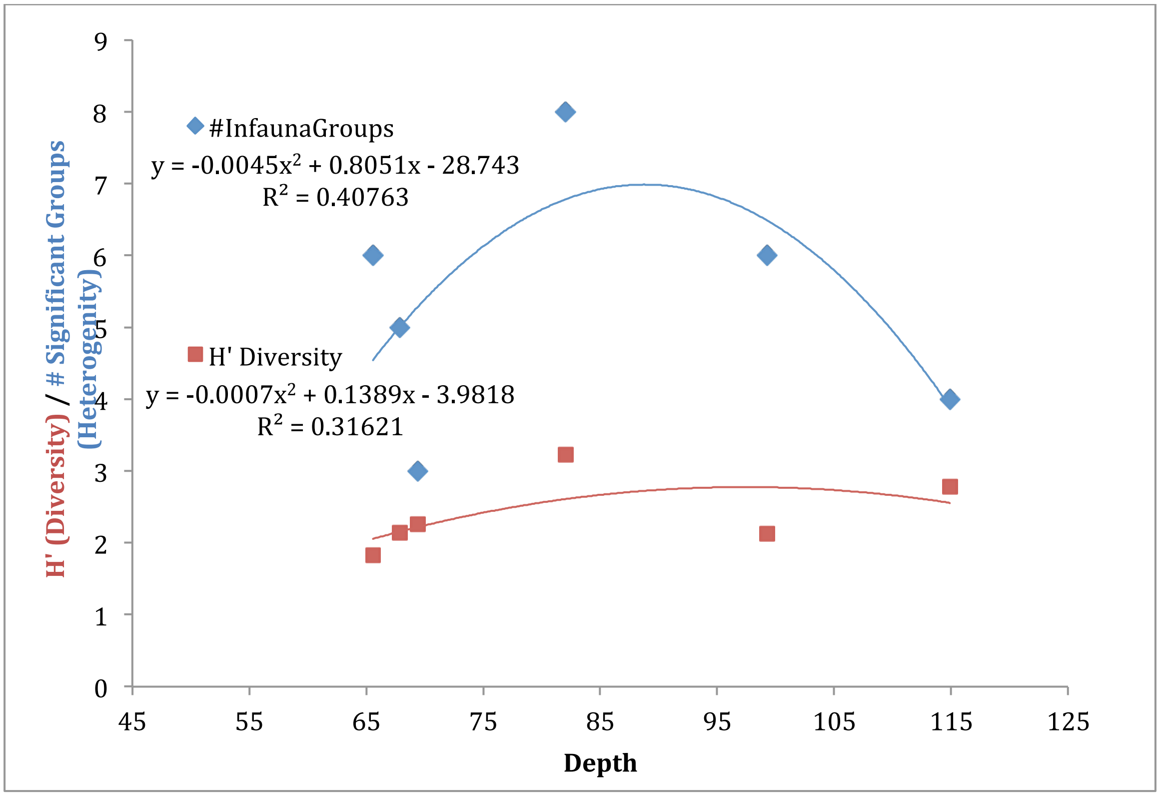


Figure 63. Macrofauna indices for the BOEM dataset compared to depth

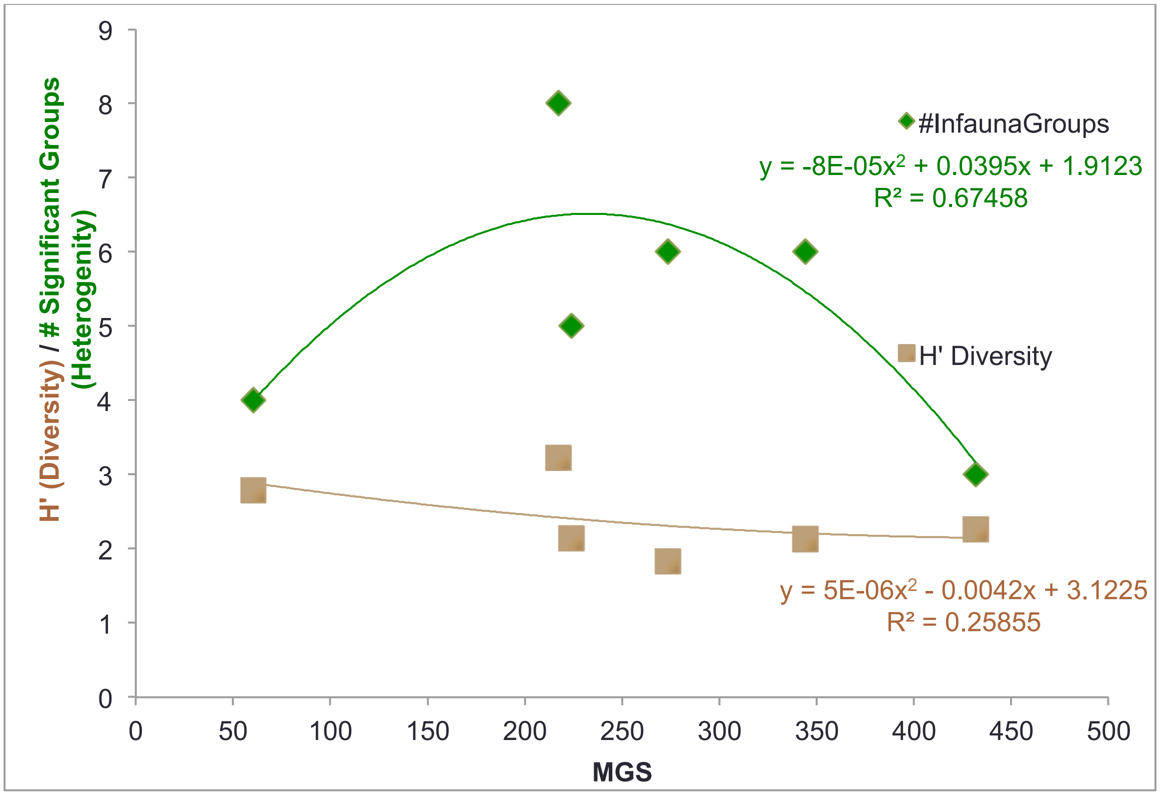


Figure 64. Macrofauna indices for the BOEM dataset compared to median grain size

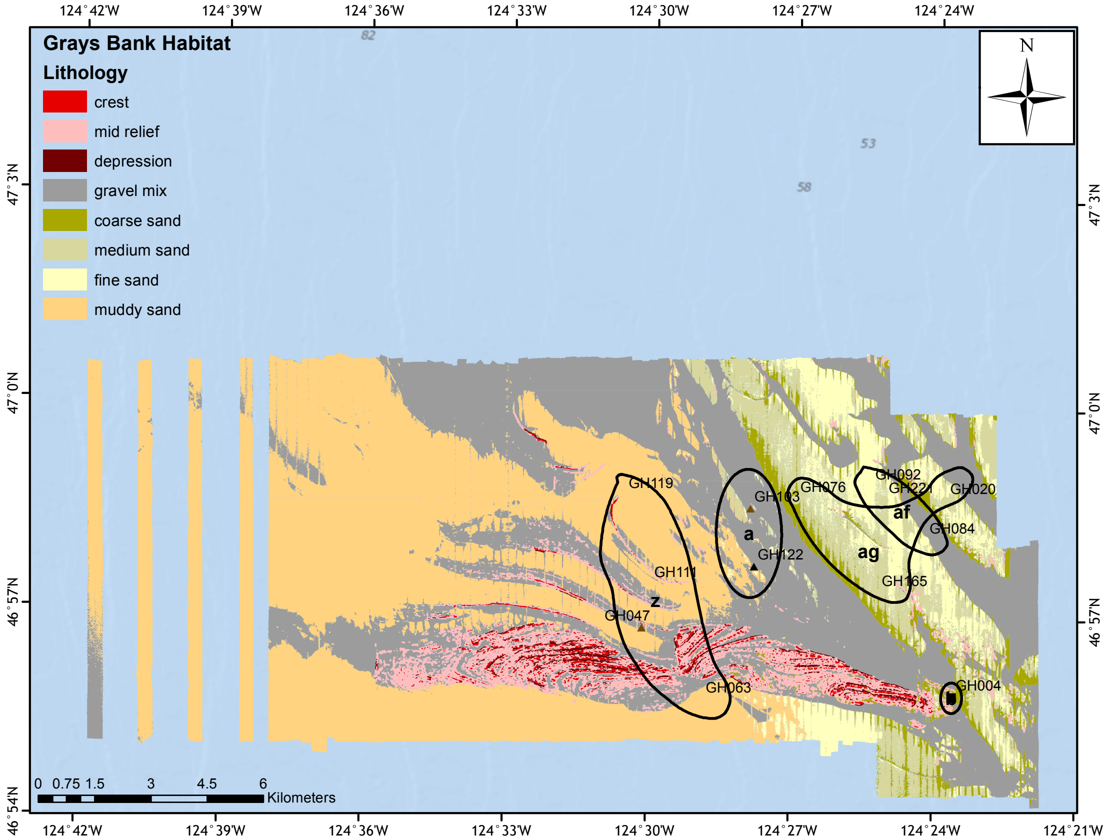


Figure 65. Macrofauna groups at Grays Bank as determined by cluster and SIMPROF analyses
The singleton station in Group B clusters with four stations at the Bandon-Arago site as these stations all have 10 – 30 % gravel in the sediment. Lithology classification in the legend is explained in Chapter 3.

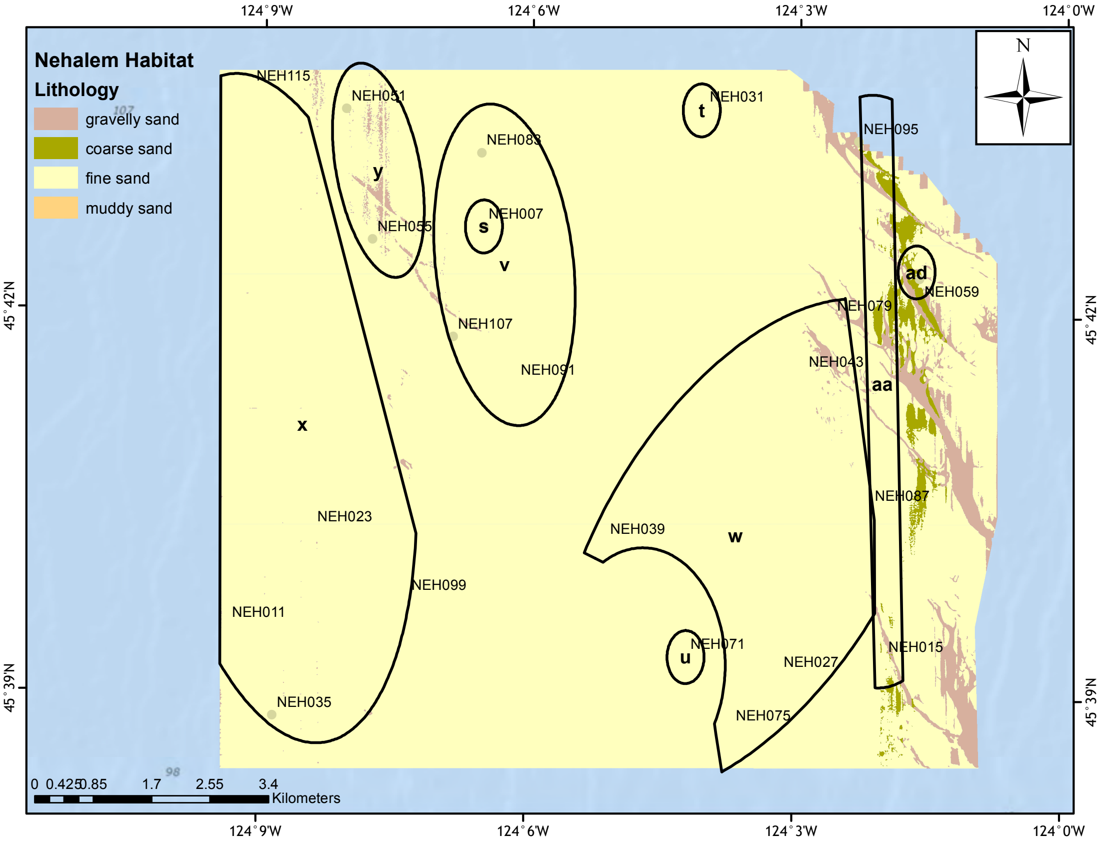


Figure 66. Macrofauna groups at Nehalem as determined by cluster and SIMPROF analyses
This site was largely sandy with a few transition zones, resulting in the highest within-site heterogeneity (most groups). The singleton in Group AD clusters with stations at Newport. Lithology classification in the legend is explained in Chapter 3.

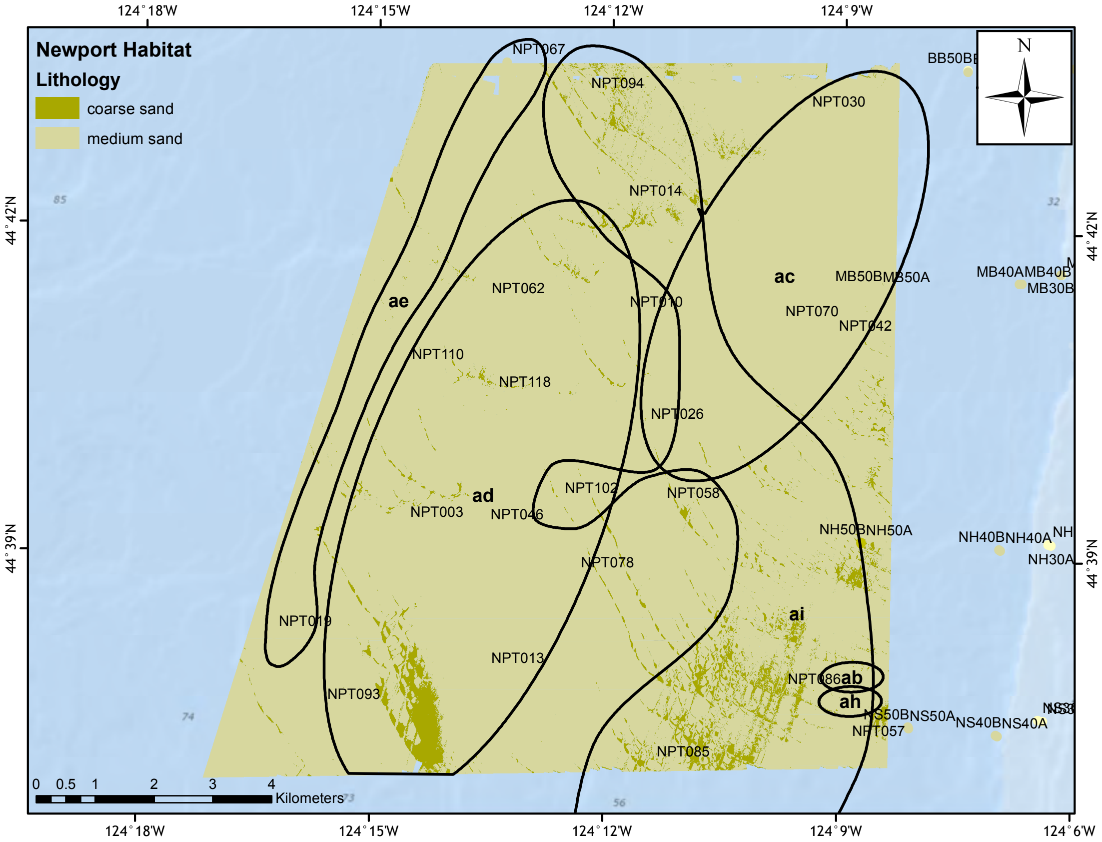


Figure 67. Macrofauna groups as determined by cluster and SIMPROF analyses at Newport Stations in Group AD cluster with a Nehalem station and stations in Group AI cluster with Cape Perpetua stations. Lithology classification in the legend is explained in Chapter 3. Stations outside the mapped area and not included in any groups are those taken for the State of Oregon for proposed wave energy activities in the Territorial Sea.

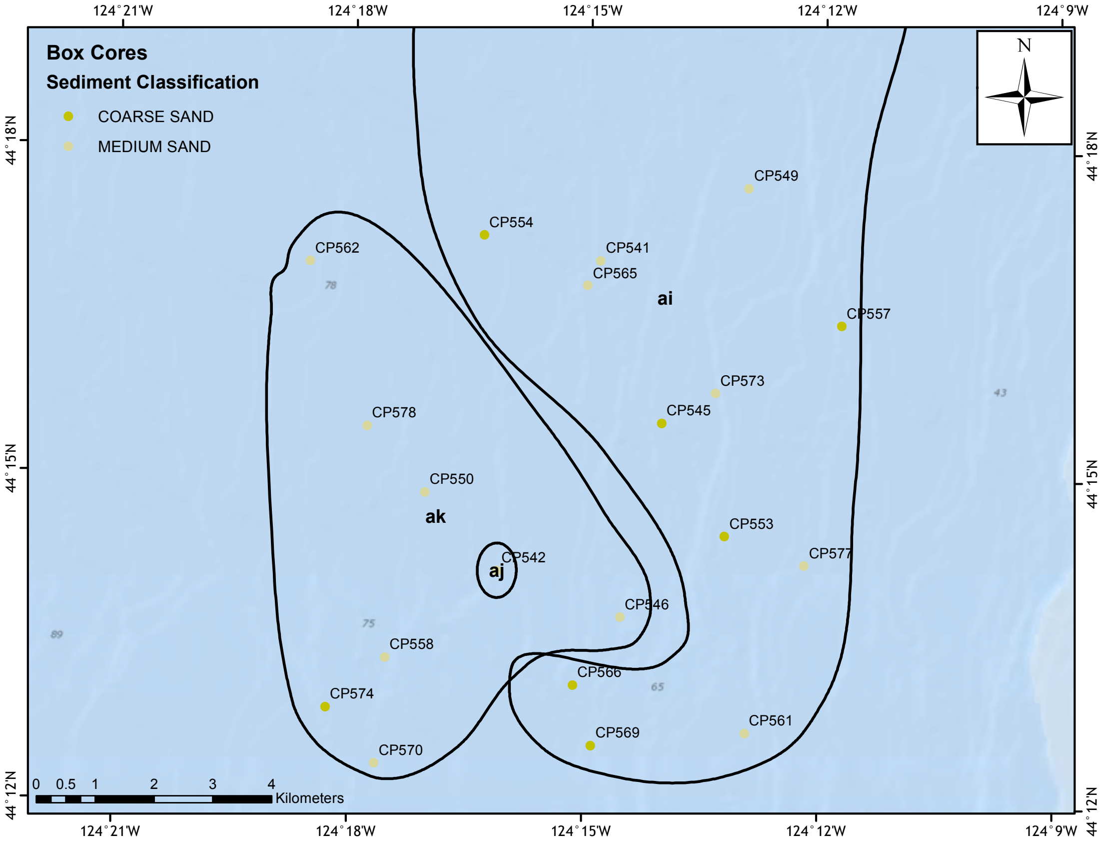


Figure 68. Macrofauna groups at Cape Perpetua as determined by cluster and SIMPROF analyses Stations in Group AI cluster with Newport stations. There is no underlying SGH map for this site as it was not one of the originally proposed areas to be surveyed. However, it was added as a box-coring site in 2012 to fill in latitudinal gaps and provide more high sand samples. The legend shows the classification of the collected sediment samples.

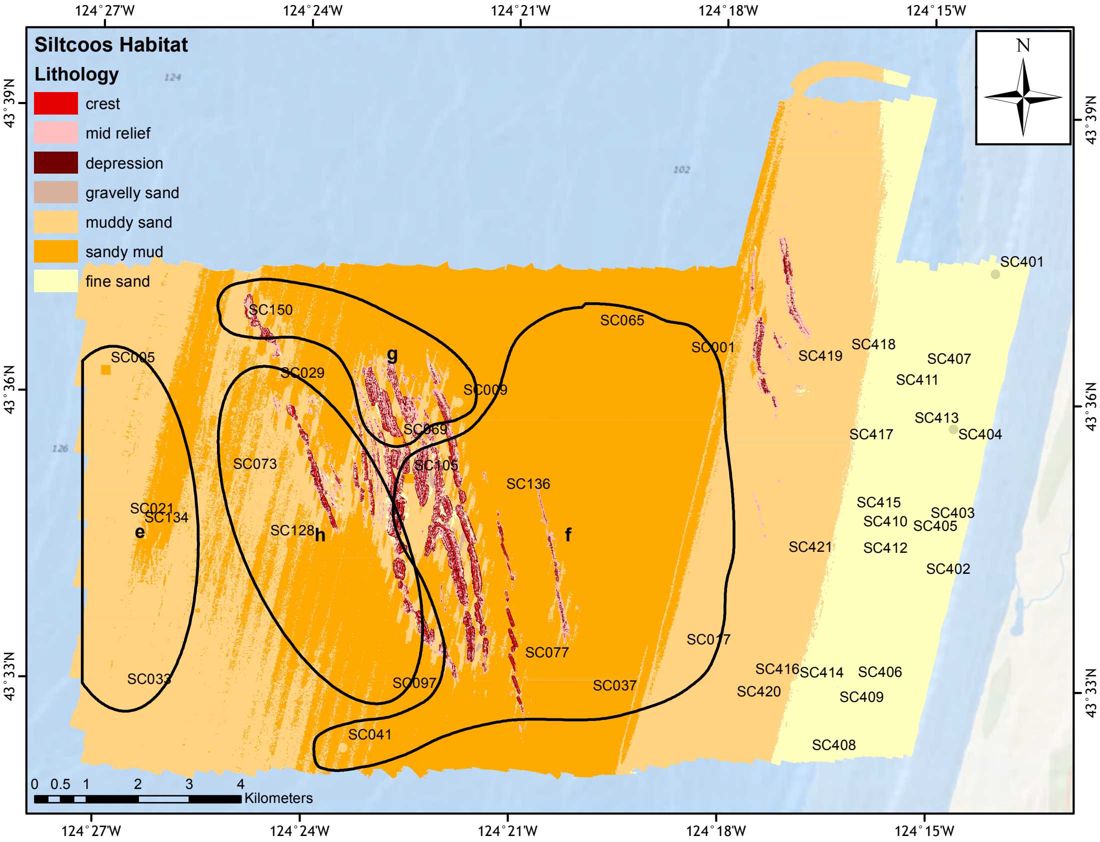


Figure 69. Macrofauna groups at Siltcoos as determined by cluster and SIMPROF analyses
Sediment at this site was fairly uniform and stations seemed to cluster according to depth. Lithology classification in the legend is explained in Chapter 3. Stations not included in any groups are those taken for the State of Oregon for proposed wave energy activities in the Territorial Sea.

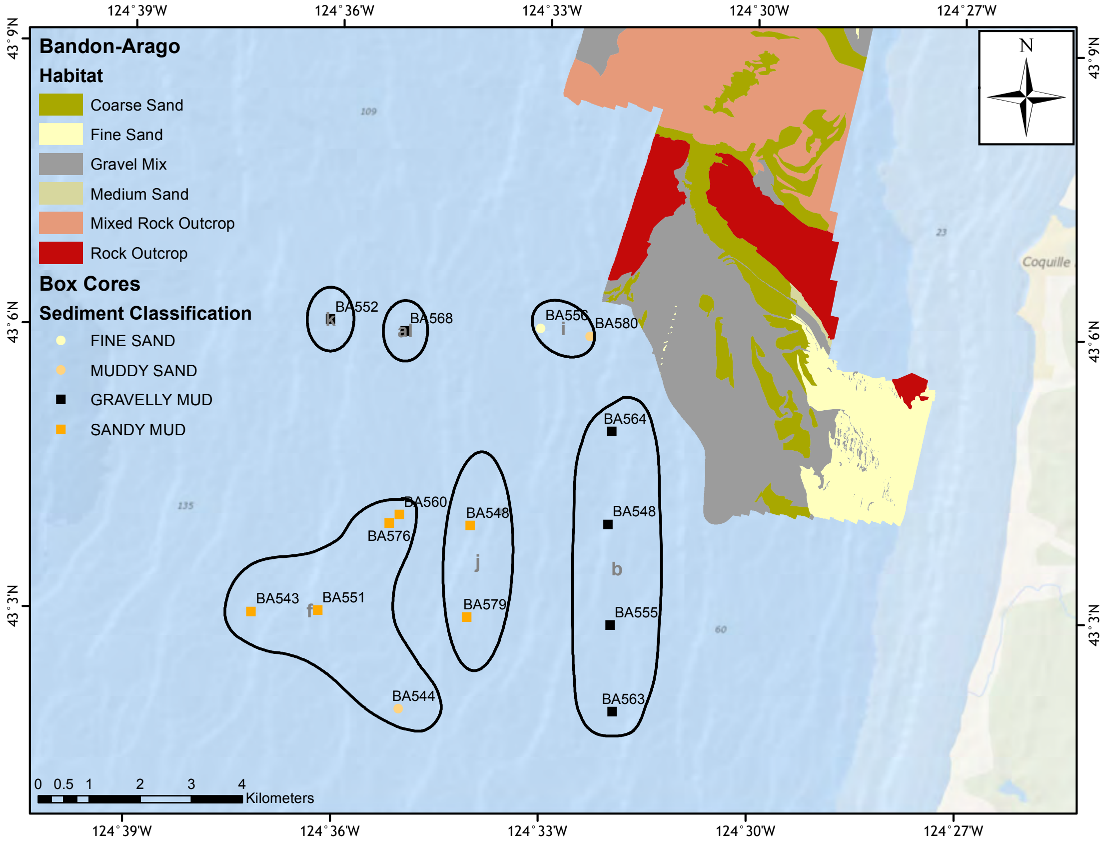


Figure 70. Macrofauna groups at Bandon-Arago as determined by cluster and SIMPROF analyses
There is no underlying SGH map for this site as it was not one of the originally proposed areas to be surveyed. However, it was added as a box-coring site in 2012 to fill in latitudinal gaps and provide more diversity of sediment types. Stations in Group B clustered with the one station at Grays Bank with a similar gravel percentage. The singleton in Group AL clustered with a gravel station at the Northern San Andreas Fault site. The legend shows the lithology for a nearby area and the classification of the collected sediment samples.

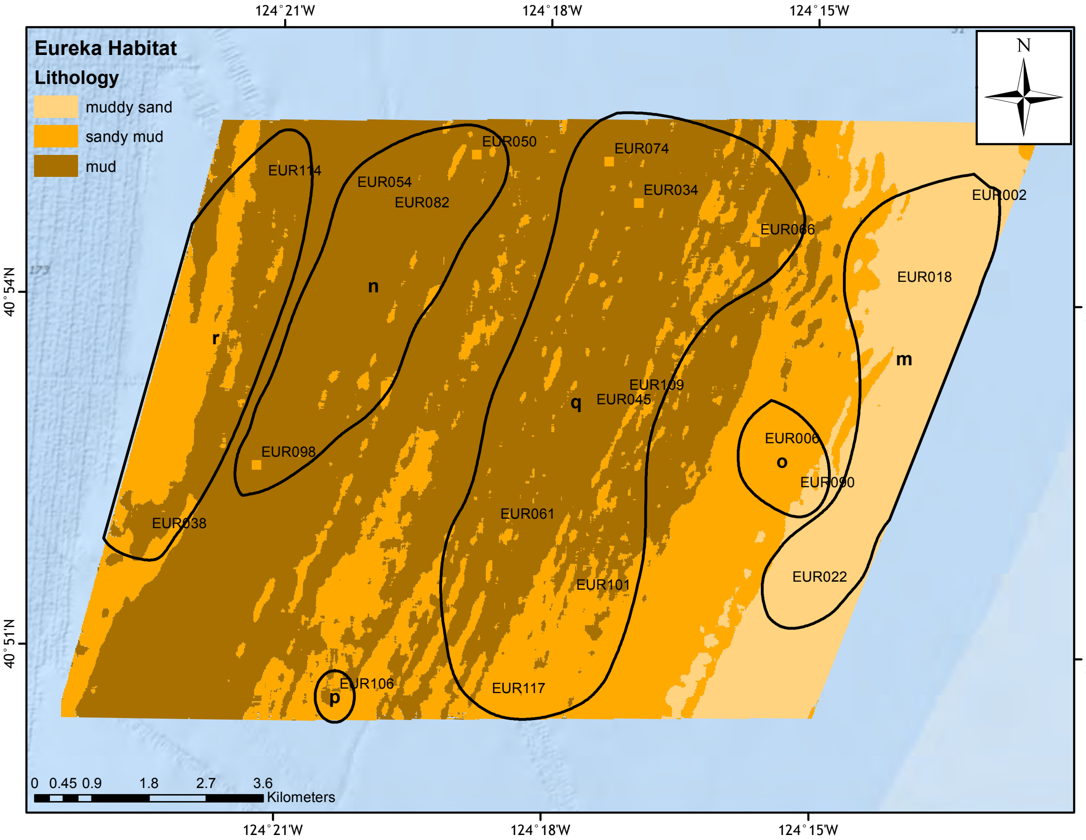


Figure 71. Macrofauna groups at Eureka as determined by cluster and SIMPROF analyses
Eureka covered the broadest depth range and thus had a relatively high number of groups. Lithology classification in the legend is explained in Chapter 3.

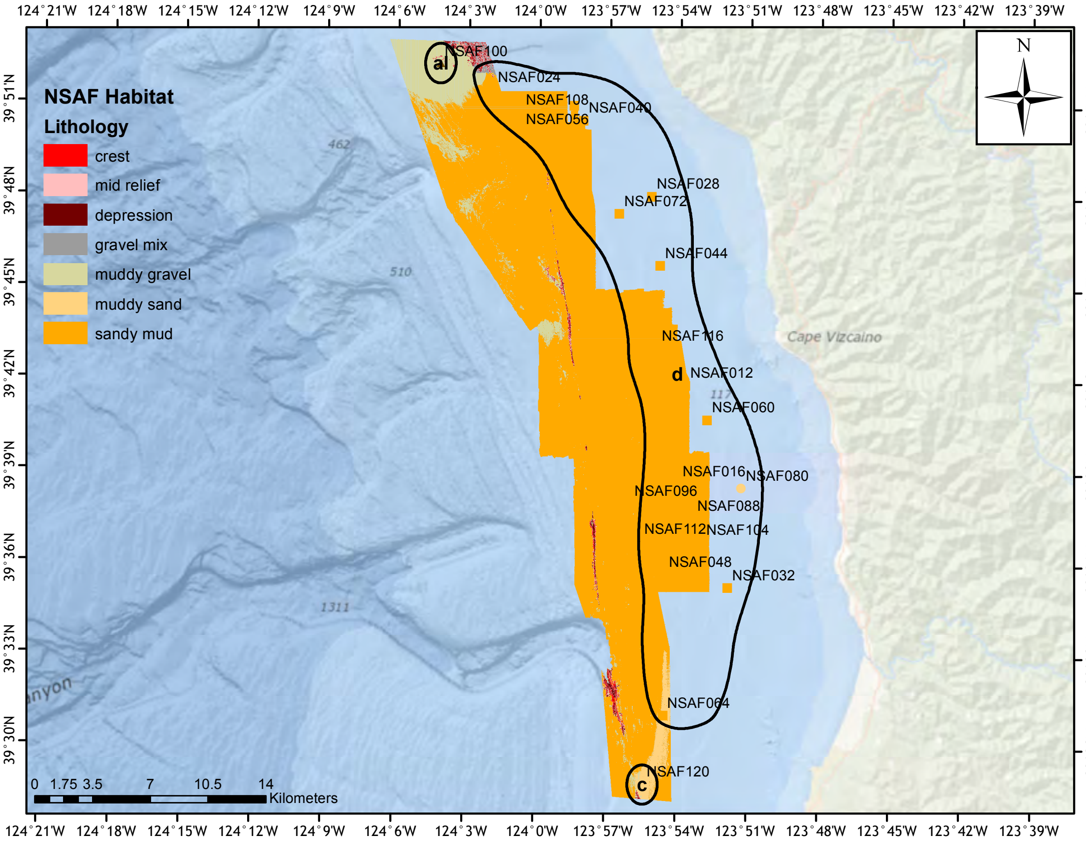


Figure 72. Macrofauna groups at the Northern San Andreas Fault site as determined by cluster and SIMPROF analyses
This site was very uniform in terms of depth and sediment type except for the gravel station in the north, which clustered with the gravel station at Bandon-Arago. Lithology classification in the legend is explained in Chapter 3.

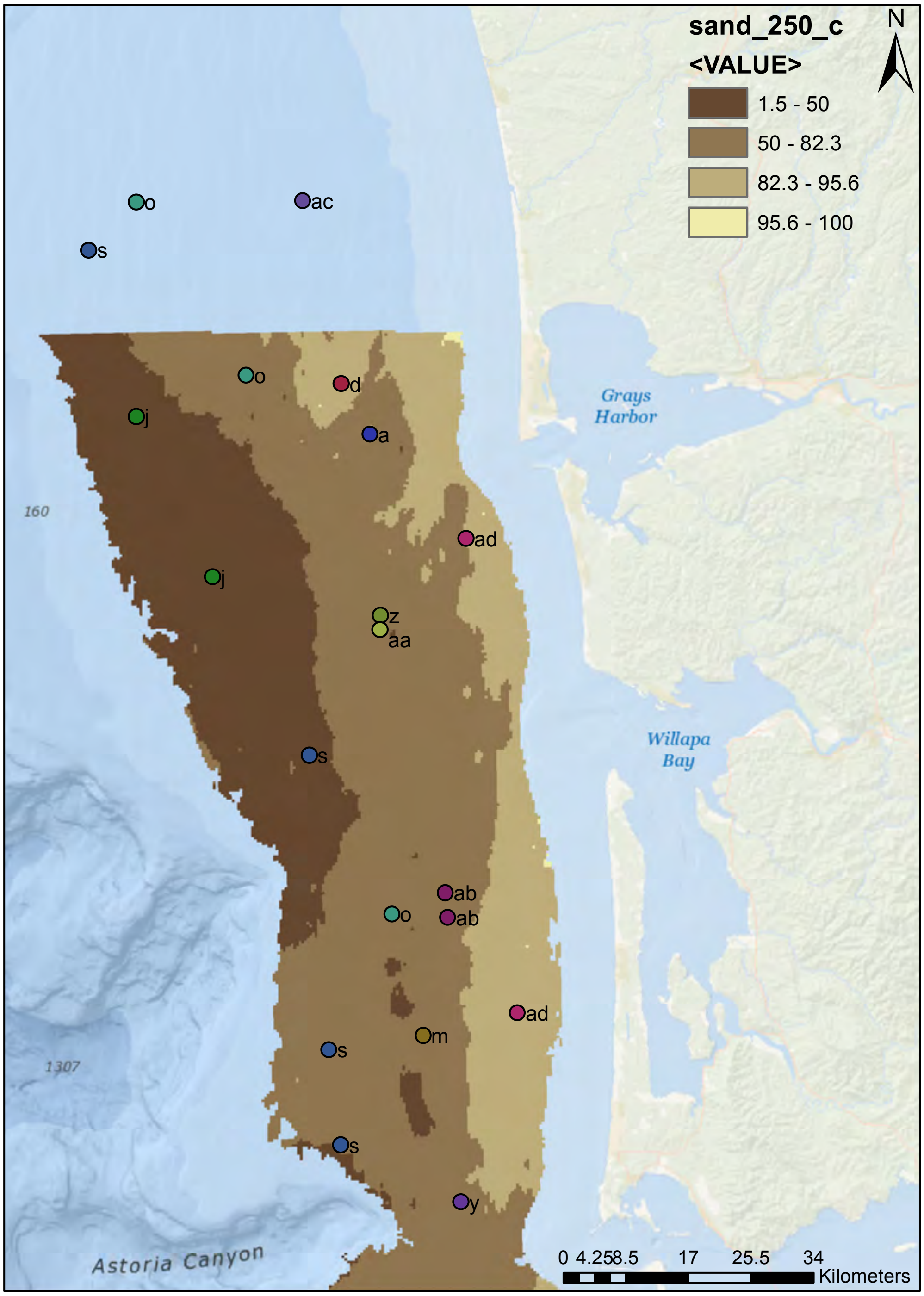


Figure 73. Macrofauna groups in Washington state as determined by cluster and SIMPROF analyses on the EPA dataset
Stations with the same color and letter code are statistically indistinguishable and significantly different from differently labeled stations. The ‘a’ station off Grays Harbor clustered with two stations in Oregon, and the ‘d’ station clustered with seven stations in Oregon. The four ‘s’ stations clustered with eight stations dispersed throughout Oregon. Map background is the percent sand raster dataset explained in Chapter 3 with the symbology modified to reflect the percent sand breaks determined by the LINKTREE analysis.

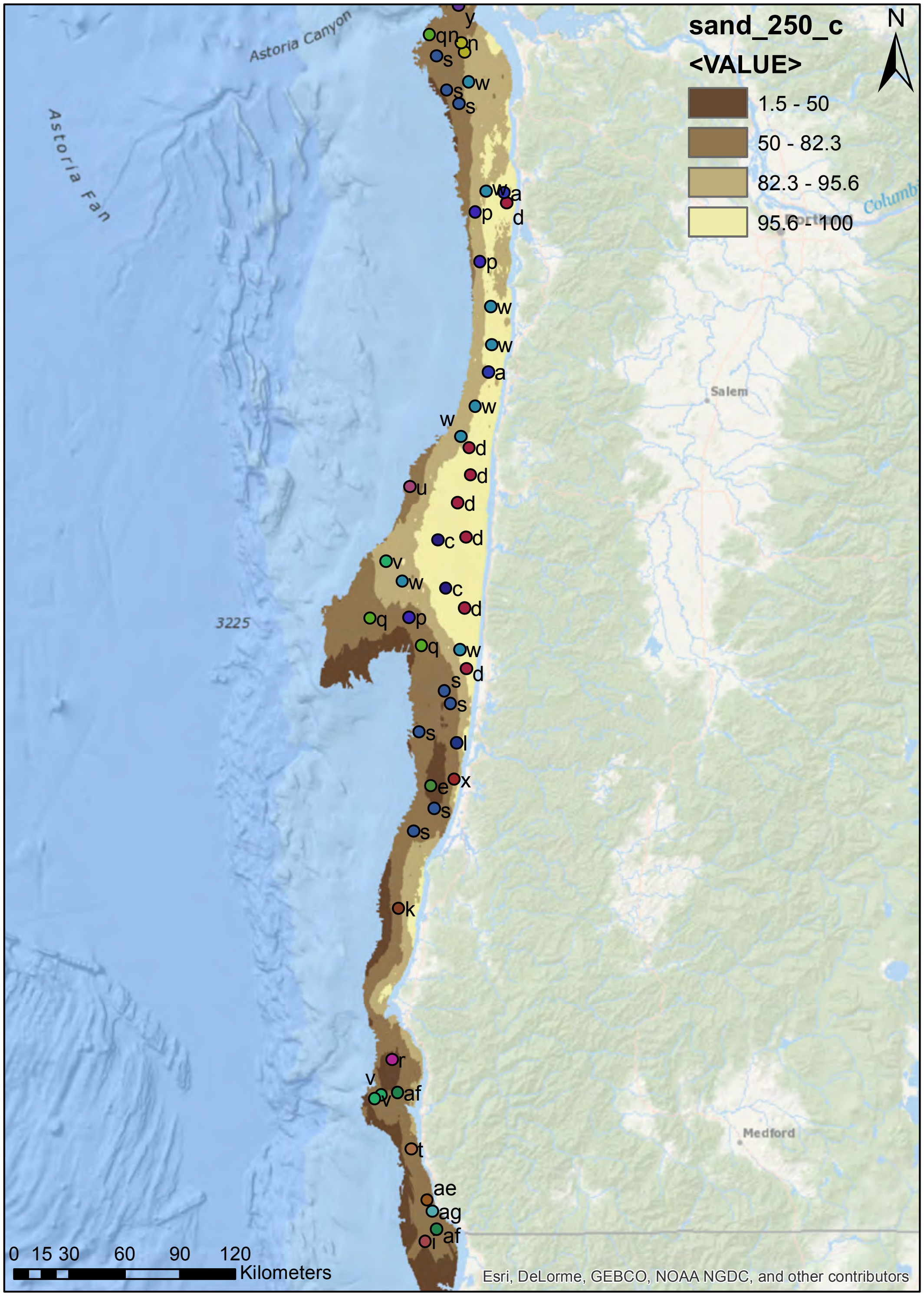


Figure 74. Macrofauna groups in Oregon as determined by cluster and SIMPROF analyses on the EPA dataset

Oregon stations that grouped with Washington stations are described above. Station ‘ag’ in southern Oregon grouped with one station in California. Map background is the percent sand raster dataset explained in Chapter 3 with the symbology modified to reflect the percent sand breaks determined by the LINKTREE analysis.

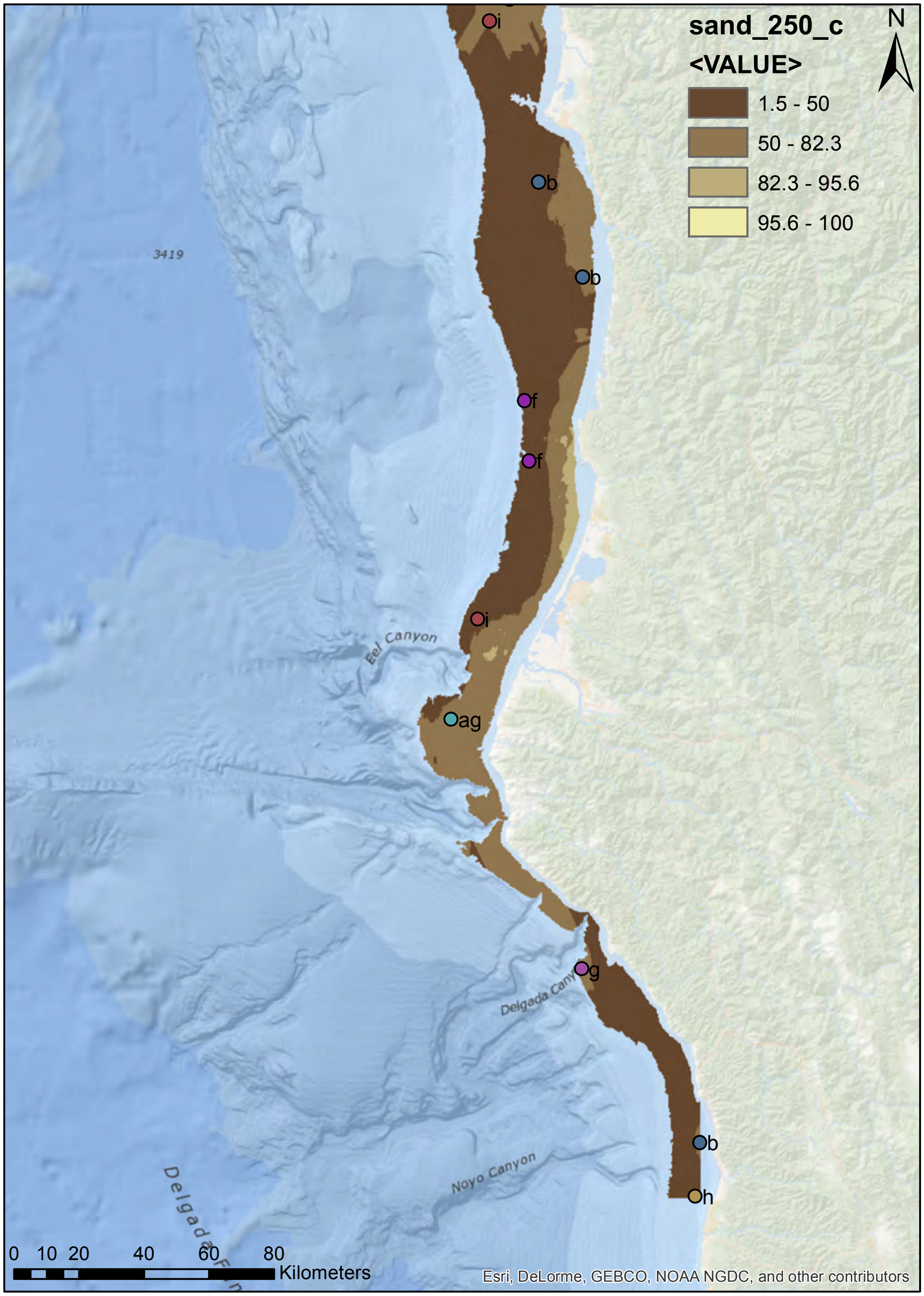


Figure 75. Macrofauna groups in northern California as determined by cluster and SIMPROF analyses on the EPA dataset
Station ‘ag’ in grouped with one station in southern Oregon. Map background is the percent sand raster dataset explained in Chapter 3 with the symbology modified to reflect the percent sand breaks determined by the LINKTREE analysis.

Table 30. Distinct groupings of BOEM sampling stations as determined by the Similarity of Profile (SIMPROF) test with characteristics species from the SIMPER test

The percentage of similarity (% sim) of species and abundances within a group is shown along with the species name that most defined the group and its abundance. Average depth and % of sand and gravel (top section) or median grain size (rest of the table) for those stations are also listed. The first 4 groups are listed in the top section with the average percent gravel of the stations in the group since those are the only groups with gravel. The remaining groups do not have any gravel, so the average median grain size of the stations in the group is presented. The station acronym indicates the site location. The letters at the end of the Characteristic Species name denotes major taxonomic grouping [(p) polychaete, (b) bivalve, (e) echinoderm, (g) gastropod] or is otherwise spelled out].

Group	% Sim	Stations		Depth (m)	Avg. % Sand	Avg. % Gravel	Characteristic Species	Avg. Abund.
a	11.2	GB103	GB122	71	99.91	74.08	*Prionospio steenstrupi* (p)	22.6
al	10.7	NSAF100		100	25	45.0	*Cyclocardia ventricosa* (b)	1.8
		BA568					Leptochitonidae (chiton)	1.5
							Terebellides reishi (p)	1.5
k	n/a	BA552		128	45.52	18.18	Single station not analyzed	
b	25.4	GH4	BA563	86.5	97.83	16.0	Exogone sp juv (p)	
		BA555	BA564				Capitellidae juv (p)	1.8
			BA572				*Scoloplos acmeceps* (p)	1.3

Group	% Sim	Stations	Depth (m)	Avg. % Sand	Avg. MGS	Characteristic Species	Avg. Abund.
ag	46.2	GB20	61.7	99.01	340.4	*Nutricola lordi* (b)	45.5
		GB76				*Spiophanes norrisi* (p)	15.3
		GB165				*Notomastus* sp. (p)	3.2
						Onuphis iridescens (p)	2.5
af	49.2	GB84	61.3	91.25	197.7	*Axinopsida serricata* (b)	108.9
		GB92				*Spiophanes norrisi* (p)	5.3
		GB221				*Macoma carlottensis* (b)	6.8
						Amphiodia urtica (e)	4.0
z	51.3	GB47	79.8	57.72	133.0	*Magelona berkeleyi* (p)	173.2
		GB63				*Macoma elimata* (b)	11.9
		GB111				*Galathowenia oculata* (p)	8.4
		GB119				*Axinopsida serricata* (b)	10.0
s	n/a	NEH7	87	98.52	217.2	Not analyzed	
t	n/a	NEH31	76	98.4	209.0	Not analyzed	
u	n/a	NEH71	76	98.66	206.6	Not analyzed	
v	57.0	NEH83	86.7	98.69	229.3	*Ennucula tenuis* (b)	13.6
		NEH91				*Axinopsida serricata* (b)	5.5
		NEH107				Pulsellidae (scaphopod)	4.0
						Euphilomedes carcharodonta	4.9

							(ostracod)	
w	49.1	NEH27	NEH75	71.8	98.62	211.5	*Axinopsida serricata* (b)	16.3
		NEH39	NEH79				*Polycirrus* sp. (p)	5.6
		NEH43	NEH87				*Rhepoxynius* spB (c)	4.1
							Nephtys sp. juv (p)	2.5
x	58.2	NEH11	NEH99	99.6	97.45	180.4	*Prionospio steenstrupi* (p)	15.4
		NEH23	NEH115				*Magelona berkeleyi* (p)	16.3
		NEH35					*Axinopsida serricata* (b)	11.2
							Pista estevanica (p)	7.3
								0.0
y	54.1	NEH51		94	98.45	254.3	*Ennucula tenuis* (b)	15.0
		NEH55					*Aphelochaeta sp* (p)	8.2
							Rhepoxynius variatus (c)	5.0
							Notomastus sp. (p)	4.0
aa	45.5	NEH15		62.5	98.7	252.38	*Ampelisca careyi* (c)	5.5
		NEH95					*Axinopsida serricata* (b)	8.5
							Polycirrus sp. (p)	4.5
							Magelona sacculata (p)	4.6
ad	57.2	NEH59	NPT58	68.8	100	239.8	*Axinopsida serricata* (b)	55.8
		NPT3	NPT62				*Nutricola lordi* (b)	42.4
		NPT10	NPT78				*Cylichna attonsa* (g)	4.9
		NPT13	NPT93				*Euphilomedes carcharodonta* (ostracod)	2.9
		NPT46	NPT110				*Magelona sacculata* (p)	2.7
			NPT118					
ac	57.1	NPT26		60.3	100	250.8	*Nutricola lordi* (b)	134.6
		NPT30					*Axinopsida serricata* (b)	42.4
		NPT42					*Cylichna attonsa* (g)	7.0
		NPT70					*Euphilomedes carcharodonta* (ostracod)	7.2
ae	49.6	NPT19		75.15	100	261.3	*Axinopsida serricata* (b)	10.9
		NPT67					*Nutricola lordi* (b)	12.1
							Magelona sacculata (p)	5.6
							Acteocina sp. (g)	1.5
ab	n/a	NPT86		48.5	100	335.5	Not analyzed	
ah	n/a	NPT57			100	398.7	Not analyzed	
ai	46.3	NPT14	CP553	63.7	99.76	426.6	*Nutricola lordi* (b)	31.1
		NPT85	CP557				*Ophelia assimilis* (p)	5.6
		NPT94	CP561				*Aphelochaeta* sp (p)	4.7
		NPT102	CP565				*Tellina nuculoides* (b)	3.6
		CP541	CP566					
		CP545	CP569					
		CP549	CP573					
			CP577					

ak	51.4	CP546	CP562	75.9	99.13	400.5	*Axinopsida serricata* (b)	29.6
		CP550	CP570				*Acila castrensis* (b)	8.2
		CP554	CP574				*Axiothella rubrocincta* (p)	2.1
		CP558	CP578				*Aphelochaeta sp* (p)	2.3
aj	n/a	CP542		73.6	91.12	351.3	Not analyzed	
e	48.6	SC5		129.5	52.98	70.2	*Macoma carlottensis* (b)	11.4
		SC21					*Axinopsida serricata* (b)	5.5
		SC33					*Rhabdus rectius* (scaphopod)	5.2
		SC134					*Adontorhina cyclica* (b)	3.4
f	57.0	SC1	SC65	104	47.06	59.4	*Axinopsida serricata* (b)	80.5
		SC17	SC77				*Macoma carlottensis* (b)	13.2
		SC37	SC105				*Acila castrensis* (b)	10.5
		SC41	SC136				*Ennucula tenuis* (b)	13.6
g	57.0	SC9		118.7	51.63	64.2	*Axinopsida serricata* (b)	45.1
		SC69					*Macoma carlottensis* (b)	11.6
		SC150					*Acila castrensis* (b)	7.6
							Sternaspis fossor (p)	3.5
h	47.8	SC29		120	41.32	49.9	*Macoma carlottensis* (b)	11.2
		SC73					*Axinopsida serricata* (b)	8.1
		SC97					*Amphioplus strongyloplax* (e)	3.4
		SC128					*Pista wui* (p)	2.6
i	52.1	BA556		79	81.2	161.1	*Axinopsida serricata* (b)	57.0
		BA580					*Macoma elimata* (b)	16.5
							Capitellidae juv (p)	10.8
							Macoma carlottensis (b)	9.0
j	48.6	BA548		95.5	46.9	58.2	*Axinopsida serricata* (b)	9.1
		BA579					*Eranno bicirrata* (p)	5.3
							Capitellidae juv (p)	2.5
							Macoma carlottensis (b)	2.0
l	61.8	BA543	BA551	116.6	52.47	55.3	*Axinopsida serricata* (b)	129.3
		BA544	BA560				*Acila castrensis* (b)	26.7
			BA576				*Macoma carlottensis* (b)	7.1
							Macoma elimata (b)	3.3
m	47.7	EUR2		54	48.5	59.5	*Axinopsida serricata* (b)	58.7
		EUR18					*Ampelisca careyi* (c)	6.5
		EUR22					*Lumbrineris luti* (p)	7.6
							Acteocina sp. (g)	4.6
n	52.8	EUR50		98	9.7	17.4	*Axinopsida serricata* (b)	9.2
		EUR54					*Sternaspis fossor* (p)	6.4
		EUR82					*Onuphis iridescens* (p)	3.1
		EUR98					*Ennucula* tenuis (b)	2.3
o	52.6	EUR6		59	26.3	31.6	*Axinopsida serricata* (b)	68.4
		EUR90					*Ennucula tenuis* (b)	31.8
							Ninoe gemmea (p)	10.7
							Acteocina sp. (g)	5.0

p	n/a	EUR106		79	11.5	18.1	Not analyzed	
q	59.0	EUR34	EUR74	70	10.5	21.1	*Axinopsida serricata* (b)	38.3
		EUR45	EUR101				*Ennucula tenuis* (b)	20.1
		EUR61	EUR109				*Sternaspis fossor* (p)	13.2
		EUR66	EUR117				*Ninoe gemmea* (p)	10.5
r	36.0	EUR38		120.5	9.6	15.0	*Onuphis iridescens* (p)	9.0
		EUR114					*Axinopsida serricata* (b)	3.9
							Nephtys punctate (p)	2.0
							Sternaspis fossor (p)	5.0
c	n/a	NSAF120		118	54.9	77.0	Not analyzed	
d	43.2	NSAF12	NSAF60	117.3	29.58	40.4	*Amphioplus strongyloplax* (e)	3.6
		NSAF16	NSAF64				*Axinopsida serricata* (b)	4.2
		NSAF24	NSAF72				*Acila castrensis* (b)	2.1
		NSAF28	NSAF80				*Chirimia similis* (p)	1.9
		NSAF32	NSAF88				*Onuphis iridescens* (p)	2.0
		NSAF40	NSAF96					
		NSAF44	NSAF104					
		NSAF48	NSAF108					
		NSAF56	NSAF112					
			NSAF116					

Table 31. Distinct groupings of EPA sampling stations and abundances of characteristic species as determined by the Similarity of Profile (SIMPROF) test along with characteristic species from the SIMPER test

The percentage of similarity (% sim) of species and abundances within a group is shown along with the species that most defined the group and its abundance. Average depth and percent sand for those stations are also listed. The station acronym indicates the site location. The letters at the end of the Characteristic Species name denotes major taxonomic grouping [(p) polychaete, (b) bivalve, (e) echinoderm, (g) gastropod] or is otherwise spelled out].

Group	% Sim	Stations	Depth (m)	% Sand	Characteristic Species	Avg. Abund.
l	60.6	CA03-0043	76.5	34.25	*Magelona longicornis (p)*	143.0
		CA03-0139			*Pionosyllis articulata (p)*	39.9
					Lumbrineris cruzensis (p)	13.4
					Paradiopatra parva (p)	19.1
b	19.4	CA03-0051	53.7	80.4	*Leitoscoloplos pugettensis (p)*	10.6
		CA03-0083			*Hemilamprops californicus (p)*	4.0
		CA03-0099			*Ampelisca careyi (c)*	4.1
					Rhepoxynius fatigans (c)	3.4
f	52.4	CA03-0147	112.5	1.55	*Sternaspis fossor (p)*	25.0
		CA03-0289			*Chloeia pinnata (p)*	15.0
					Lumbrineris luti (p)	15.0
					Microclymene caudata (p)	15.1
ag	31.1	CA03-0075	61.5	90.9	*Boccardia pugettensis (p)*	18.7
		OR03-0032			*Astyris gausapata (g)*	18.1
					Ampelisca careyi (c)	7.9
					Onuphis iridescens (p)	9.9
c	30.7	OR03-0014	70	98.7	*Chaetozone sp N2 (p)*	8.8
		OR03-0031			*Callianax baetica (g)*	2.0
					Mesochaetopterus sp. (p)	2.9
					Americhelidium rectipalmum (c)	1.0
n	65.2	OR03-0013	83	90.4	*Magelona longicornis (p)*	129.3
		OR03-0045			*Lumbrineris luti (p)*	37.9
					Prionospio jubata (p)	25.3
					Acila castrensis (b)	14.0
p	48.6	OR03-0003	107.7	89.3	*Magelona longicornis (p)*	52.5
		OR03-0016			*Prionospio jubata (p)*	21.6
		OR03-0037			*Axinopsida serricata (b)*	12.3
					Galathowenia oculata (p)	11.2
q	45.4	OR03-0034	114.7	80.57	*Huxleyia munita (b)*	15.9
		OR03-0036			*Magelona longicornis (p)*	12.9
		OR03-0040			*Prionospio jubata (p)*	9.2
					Lumbrineris luti (p)	5.1
v	47.2	OR03-0023	105.3	79	*Paradiopatra parva (p)*	32.8

		OR03-0035				*Aricidea simplex (p)*	13.7
		OR03-0044				*Clymenura gracilis (p)*	6.6
						Paraprionospio pinnata (p)	7.9
af	43.7	OR03-0001		51	96	*Amaeana occidentalis (p)*	10.9
		OR03-0005				*Axinopsida serricata (b)*	7.7
						Callianax pycna (g)	4.5
						Boccardia pugettensis (p)	3.0
w	36.9	OR03-0004	OR03-0026	80.6	96.89	*Acila castrensis (b)*	7.8
		OR03-0008	OR03-0038			*Galathowenia oculata (p)*	4.0
		OR03-0017	OR03-0039			*Spiophanes berkeleyorum (p)*	2.6
		OR03-0019	OR03-0042			*Pista estevanica (p)*	3.1
s	45.5	OR03-0002	OR03-0043	105.3	69.07	*Axinopsida serricata (b)*	28.4
		OR03-0007	OR03-0048			*Rhabdus rectius (scaphopod)*	11.7
		OR03-0012	WA03-0004			*Sternaspis fossor (p)*	8.1
		OR03-0021	WA03-0009			*Galathowenia oculata (p)*	9.9
		OR03-0024	WA03-0037				
		OR03-0027	WA03-0081				
d	33.7	OR03-0006	OR03-0030	59.4	98.65	*Spiophanes norrisi (p)*	16.1
		OR03-0009	OR03-0046			*Nutricola lordi (b)*	12.3
		OR03-0025	OR03-0047			*Axinopsida serricata (b)*	13.2
		OR03-0029	WA03-0070			*Spiophanes berkeleyorum (p)*	3.8
a	26.0	OR03-0015		60.7	98	*Callianax baetica (g)*	11.8
		OR03-0050				*Tellina nuculoides (b)*	6.3
		WA03-0042				*Nephtys californiensis (p)*	5.1
						Polygordius sp (p)	19.5
o	57.9	WA03-0002		78.3	79	*Magelona longicornis (p)*	164.7
		WA03-0034				*Prionospio jubata (p)*	19.9
		WA03-0086				*Mediomastus sp (p)*	11.9
						Aricidea ramosa (p)	13.3
ab	65.5	WA03-0018		55.5	76.75	*Euphilomedes carcharodonta (ostracod)*	85.5
		WA03-0031				*Euclymeninae* sp A (p)	46.0
						Rhepoxynius boreovariatus (c)	25.6
						Galathowenia oculata (p)	28.4
j	38.1	WA03-0023		103.5	44	*Axinopsida serricata (b)*	30.5
		WA03-0030				*Macoma carlottensis (b)*	22.6
						Sternaspis fossor (p)	5.5
						Rhabdus rectius (scaphopod)	2.9
ad	57.8	WA03-0025		34	92.65	*Axinopsida serricata (b)*	44.2
		WA03-0060				*Euphilomedes carcharodonta (ostracod)*	23.0
						Spiophanes norrisi (p)	36.3
						Ampelisca agassizi (c)	29.9

Table 32. LINKTREE analysis group letter code of BOEM stations

Includes description of the physical characteristics defining the group, within group similarity (Sim %) and abundances (avg. abund.) of top 50 % contributing characteristic species (cum. % contrib.)

Group	Sim%	Stations				Characteristic Species	Avg. Abund.	Cum.% Contrib.
A	10.15		GB103	GB122	NSAF100	*Prionospio steenstrupi*	1.0	68.34
>63 % gravel						*Galathowenia oculata*	0.8	85.67
B	15.76	GB4	BA552	BA563	BA568	Capitellidae juv	1.5	25.33
10 - 60 % gravel		GB47	BA555	BA564	BA572	Exogone sp juv	1.7	40.64
						Glycera nana	1.0	48.79
						Scoloplos acmeceps	0.7	55.6
C	30.35	GH63	EUR2	NSAF12	SC1	*Axinopsida serricata*	17.7	19.81
<86 % sand		GB111	EUR6	NSAF16	SC5			
		GB119	EUR18	NSAF24	SC9	*Acila castrensis*	2.6	26.93
			EUR22	NSAF28	SC17	*Amphioplus strongyloplax*	1.9	33.33
			EUR34	NSAF32	SC21			
		BA543	EUR38	NSAF40	SC29	*Macoma carlottensis*	2.5	39.66
		BA544	EUR45	NSAF44	SC33			
		BA548	EUR50	NSAF48	SC37	*Onuphis iridescens*	1.5	45.72
		BA551	EUR54	NSAF56	SC41	*Sternaspis fossor*	2.1	50.35
		BA560	EUR61	NSAF60	SC65			
		BA576	EUR66	NSAF64	SC69			
		BA579	EUR74	NSAF72	SC73			
		BA580	EUR82	NSAF80	SC77			
			EUR90	NSAF88	SC97			
			EUR98	NSAF96	SC105			
			EUR101	NSAF104	SC128			
			EUR106	NSAF108	SC134			
			EUR109	NSAF112	SC136			
			EUR114	NSAF116	SC150			
			EUR117	NSAF120				
H-L	43.08	GB76	NPT102	CP561	CP573	*Nutricola lordi*	26.1	24.55
>87 % sand		GB165	CP549	CP565	CP577	*Ophelia assimilis*	4.9	36.66
>351 um		NPT14	CP541	CP566		*Tellina nuculoides*	3.6	46.39
<72 m		NPT57	CP557	CP569		*Spiophanes norrisi*	3.3	55.79
H-R	43.44		CP542	CP554	CP570	*Acila castrensis*	5.9	31.8
>87 % sand			CP545	CP558	CP574	*Aphelochaeta sp*	2.5	40.1
>351 um			CP550	CP562	CP578	*Astyris gausapata*	2.4	46.54
73 - 81 m						*Axiothella rubrocincta*	1.6	52.01
F	41.67		GB84	NEH15	NEH71	*Axinopsida serricata*	21.4	15.59
>87 % sand			GB92	NEH27	NEH75	*Polycirrus* sp	3.5	21.94
< 81 m				NEH31	NEH79	*Nephtys* sp juv	1.9	27.06
<217 um				NEH39	NEH87	*Notomastus* sp	2.5	32.04

				NEH43		*Ampelisca careyi*	2.0	36.44
						Euphilomedes carcharodonta	1.8	40.4
						Cylichna attonsa	1.4	44.21
						Rhepoxynius spB	2.1	47.97
						Ennucula tenuis	1.6	51.51
G-L	33.06			GB20		*Axinopsida serricata*	22.3	19.89
<81 m				GB221		*Nutricola lordi*	13.0	33.29
<221 um				NEH95		*Spiophanes norrisi*	5.7	43.49
87 - 99.2 % sand				CP546		*Ampelisca careyi*	2.6	52.83
G-R	50.35	NEH59	NPT26	NPT62	NPT86	*Nutricola lordi*	52.5	23.15
<81 m		NPT3	NPT30	NPT67	NPT93	*Axinopsida serricata*	33.8	43.71
<221 um		NPT10	NPT42	NPT70	NPT94			
100 % sand		NPT13	NPT46	NPT78	NPT110	*Cylichna attonsa*	4.3	52.66
		NPT19	NPT58	NPT85	NPT118			
I-L	39.73			NEH7		*Ennucula tenuis*	8.9	11.5
>87 % sand				NEH83		*Axinopsida serricata*	9.4	22.2
86-91 m				NEH91		*Euphilomedes carcharodonta*	2.8	27.46
				NEH107		*Neotrypaea* sp.	1.6	32.23
				BAQ556		*Amphiodia urtica*	2.8	36.83
						Rhepoxynius spB	2.3	41.23
						Notomastus sp	1.8	45.3
						Pulsellidae	2.0	49.25
						Polycirrus sp	2.1	53.07
I-R	54.15			NEH11		*Prionospio steenstrupi*	10.9	7.05
>87 % sand				NEH23		*Ennucula tenuis*	9.6	13.62
>94 m				NEH35		*Magelona berkeleyi*	9.9	19.43
				NEH51		*Pista estevanica*	6.0	24.69
				NEH55		*Axinopsida serricata*	7.0	29.78
				NEH99		*Aphelochaeta* sp	4.8	34.78
				NEH115		*Huxleyia munita*	4.8	38.9
						Notomastus sp	3.5	42.94
						Amphiodia urtica	3.6	46.91
						Onuphis iridescens	2.8	50.46

Table 33. LINKTREE analysis group letter code of EPA stations

Includes description of the physical characteristics defining the group, within group similarity (Sim %) and abundances (avg. abund.) of top 50 % contributing characteristic species (cum. % contrib.).

Group	*Sim%*	Stations		Characteristic Species	Avg. Abund.	Cum.% Contrib.
H-L	20.1	CA03-0083		*Amaeana occidentalis*	8.87	23.51
>95 % sand		CA03-0099		*Leitoscoloplos pugettensis*	6.10	38.86
<42 degrees		OR03-0005		*Ampelisca careyi*	4.26	52.61
H-R	21.99	OR03-0001	OR03-0029	*Axinopsida serricata*	4.70	8.09
>95 % sand		OR03-0004	OR03-0030	*Spiophanes norrisi*	3.66	15.3
>42.5 degrees		OR03-0006	OR03-0031	*Spiophanes berkeleyorum*	2.29	22.08
		OR03-0008	OR03-0038	*Cylichna attonsa*	1.80	27.62
		OR03-0009	OR03-0039	*Ampelisca careyi*	1.34	31.93
		OR03-0014	OR03-0046	*Callianax baetica*	1.44	35.6
		OR03-0015	OR03-0047	*Acila castrensis*	1.56	38.95
		OR03-0017	OR03-0050	*Leitoscoloplos pugettensis*	1.18	42.23
		OR03-0019	WA03-0007	*Galathowenia oculata*	1.03	44.63
		OR03-0025	WA03-0042	Chaetozone sp N2	1.12	47.02
		OR03-0026	WA03-0070	*Spiochaetotopterus pottsi*	0.67	49.35
C	22.99	CA03-0051		*Leitoscoloplos pugettensis*	18.30	14.37
<94.8 % sand		CA03-0075		*Astyris gausapata*	6.61	23.57
<69 m		OR03-0011		*Ampelisca careyi*	4.05	30.28
<42 degrees		OR03-0032		*Onuphis iridescens*	4.37	36.89
				Boccardia pugettensis	4.31	42.15
				Glycinde armigera	2.00	47.22
				Lumbrineris luti	3.18	52.27
D-L	48.44	WA03-0010		*Galathowenia oculata*	28.96	6.84
<80 % sand		WA03-0015		*Axinopsida serricata*	31.46	13.66
<69 m		WA03-0018		*Lumbrineris luti*	37.86	20.15
>46.3 degrees		WA03-0031		*Euphilomedes carcharodonta*	30.50	25.88
		WA03-0047		*Rhepoxynius boreovariatus*	15.95	31.09
				Amphiodia sp	17.54	36.12
				Leitoscoloplos pugettensis	10.94	40.76
				Euclymeninae sp A	15.28	45.31
				Chaetozone columbiana	5.75	48.81
				Euclymeninae juv	4.75	52.01
D-R	38.71	WA03-0020		*Axinopsida serricata*	53.05	14.32
82-94.8% sand		WA03-0025		*Euphilomedes carcharodonta*	31.14	26.93
<69 m		WA03-0060		*Ampelisca careyi*	10.36	34.69
>46.3 degrees				Amphiuridae	5.62	41.83
				Lyonsia californica	4.26	47.93
				Amphiodia sp	4.26	52.69
F-L	52.57	CA03-0035		*Lumbrineris cruzensis*	14.80	3.34

<94.8 % sand		CA03-0043		*Pionosyllis articulata*	26.11	6.61
71-81 m		CA03-0139		*Aricidea ramosa*	14.80	9.54
<42 degrees				Nemertea	11.06	12.44
				Lumbrineris luti	9.59	15.28
				Decamastus gracilis	17.92	18.12
				Lumbrineridae	9.91	20.95
				Axinopsida serricata	9.70	23.69
				Levinsenia gracilis	12.20	26.24
				Aphelochaeta tigrina	10.94	28.74
				Apistobranchus tullbergi	10.47	31.23
				Mediomastus sp	14.49	33.69
				Sternaspis fossor	13.73	36.09
				Prionospio jubata	10.02	38.46
				Glycera nana	5.30	40.7
				Spiophanes berkeleyorum	9.38	42.91
				Magelona longicornis	26.39	45.07
				Cossura pygodactylata	5.89	47.16
				Nephtys cornuta	5.23	49.25
				Amphiodia urtica	8.12	51.27
F-R	42.45	CA03-0019		*Chloeia pinnata*	13.59	6.21
<94.8 % sand		CA03-0147		*Microclymene caudata*	14.03	11.77
>102 m		CA03-0289		Euclymeninae juv	4.64	15.76
<42 degrees				*Lumbrineris cruzensis*	6.03	19.08
				Pholoe glabra	3.31	22.41
				Spiophanes berkeleyorum	4.00	25.53
				Heterophoxus affinis	3.22	28.56
				Dougaloplus amphacanthus	3.71	31.55
				Nemertea	4.47	34.54
				Aphelochaeta monilaris	4.64	37.38
				Sternaspis fossor	7.85	40.05
				Adontorhina cyclica	3.18	42.68
				Lumbrineris luti	5.36	45.14
				Aricidea simplex	3.57	47.58
				Onuphis iridescens	2.42	49.87
				Orchomene decipiens	2.42	52.16
G-L	36.14	OR03-0002	OR03-0035	*Galathowenia oculata*	10.47	6.12
<94.8 % sand		OR03-0003	OR03-0036	*Axinopsida serricata*	10.02	11.67
>71 m		OR03-0007	OR03-0037	*Magelona longicornis*	13.44	16.9
>42.3 degrees		OR03-0012	OR03-0040	*Prionospio jubata*	7.08	21.64
<1.30 % TOC		OR03-0013	OR03-0041	*Lumbrineris luti*	6.10	26.21
		OR03-0016	OR03-0042	*Paraprionospio pinnata*	4.26	30.65
		OR03-0018	OR03-0043	*Glycera nana*	2.42	33.38
		OR03-0020	OR03-0044	*Euclymeninae juv*	2.42	36.1
		OR03-0021	OR03-0045	*Sternaspis fossor*	2.90	38.62
		OR03-0022	OR03-0048	*Maldane sarsi*	2.53	41.08

		OR03-0023	OR03-0049	*Spiophanes berkeleyorum*	3.01	43.43
		OR03-0024	WA03-0002	*Macoma carlottensis*	2.82	45.74
		OR03-0027	WA03-0004	*Adontorhina cyclica*	2.35	47.85
		OR03-0028	WA03-0009	*Decamastus gracilis*	2.46	49.94
		OR03-0034	WA03-0034	*Rhabdus rectius*	2.35	51.92
			WA03-0037			
			WA03-0081			
			WA03-0086			
G-R	27.28	OR03-0033		*Sternaspis fossor*	6.24	17.96
<94.8 % sand		WA03-0023		*Galathowenia oculata*	6.85	31.15
>71 m		WA03-0030		*Axinopsida serricata*	8.97	42.65
>42.3 degrees				*Lumbrineris luti*	3.18	53.38
>1.32 % TOC						

Table 34. Total abundances of all identified worm taxa at each site
The number of 0.1 m^2 box cores taken at each site are available in Table 14 in Chapter 5.

Taxa	GB	Neh	Npt	CP	SC	BA	Eur	NSAF
ANNELIDA								
Polychaeta								
Amaeana occidentalis	0	0	0	3	0	0	27	0
Ampharete acutifrons	0	0	0	0	0	0	0	1
Ampharete finmarchica	0	1	0	1	0	1	3	0
Ampharete sp.	0	5	3	1	0	3	1	0
Amphicteis sp.	0	1	0	0	3	0	0	2
Anobothrus gracilis	0	0	0	0	0	1	1	0
Aphelochaeta sp.	4	58	0	139	1	7	0	2
Aphrodita sp.	0	0	0	0	0	4	1	0
Apistobranchus tullbergi	4	2	0	0	0	0	1	0
Apoprionospio pygmaea	0	0	0	1	0	2	0	0
Aricidea antennata	0	0	0	0	0	2	0	0
Aricidea catherinae	0	0	0	0	0	2	1	0
Aricidea cerrutii	2	0	0	0	1	0	0	1
Aricidea pacifica	4	11	0	0	0	0	2	0
Aricidea sp.	3	21	3	0	1	0	2	0
Artacama coniferi	0	1	0	0	1	0	10	1
Asabellides lineata	0	0	0	0	0	0	0	3
Axiothella rubrocincta	11	7	5	37	0	4	0	0
Barantolla nr. americana	0	0	0	0	0	0	1	0
Bispira sp.	0	0	0	0	0	0	0	1
Boccardia sp.	0	0	0	1	0	0	2	0
Brada sachalina	0	0	0	0	4	0	2	0
Bylgides macrolepidus	0	1	0	0	4	0	0	0
Capitellidae juv.	1	0	0	48	0	43	0	0
Chaetopteridae	0	0	0	2	0	0	0	0
Chaetopterus variopedatus cmplx	0	1	0	0	0	0	0	0
Chaetozone bansei	6	22	12	0	0	0	0	0
Chaetozone nr setosa	1	2	0	0	0	0	0	0
Chaetozone sp.	1	0	0	0	0	6	0	0
Cheilonereis cyclurus	0	0	0	1	0	0	0	0
Chirimia similis	0	1	0	0	8	0	1	46
Cirratulidae [ant. frag]	0	0	0	0	0	2	3	0
Clymenura sp.	0	0	0	0	0	0	0	8
Cossura candida	0	1	0	0	0	0	0	1
Decamastus gracilis	0	0	0	0	0	0	6	1
Dialychone nr albocincta	1	3	0	0	0	0	4	0
Dialychone veleronis	0	1	0	0	0	0	1	0
Diopatra ornata	0	0	0	0	0	34	5	0

Dipolydora brachycephala	1	0	0	0	1	0	0	0
Dipolydora cardalia	0	4	0	0	1	0	0	0
Dorvillea (Schistomeringos) annulata	0	0	0	0	6	0	0	1
Drilonereis longa	1	1	0	0	1	1	1	1
Enipo canadensis	0	0	0	0	0	0	4	1
Eranno bicirrata	2	4	0	0	0	29	7	0
Eranno lagunae	2	2	0	0	0	2	0	0
Eteone sp.	2	3	0	0	2	0	4	0
Euclymeninae	0	15	0	0	0	0	31	7
Euclymeninae sp. A	19	27	8	0	29	0	2	0
Eunoe sp.	0	0	0	5	0	0	0	0
Exogone lourei	0	0	0	0	1	0	0	15
Galathowenia oculata	53	13	0	30	8	3	6	34
Geminosyllis ohma	1	0	0	0	0	0	0	0
Glycera americana	1	0	0	0	0	1	1	0
Glycera nana	14	9	0	0	0	11	12	0
Glycera oxycephala	0	0	5	1	22	1	2	3
Glycinde armigera	16	10	21	20	21	21	4	3
Glycinde picta	0	0	0	1	1	0	0	0
Glycinde sp. juv	0	0	3	0	0	0	1	0
Goniada brunnea	1	0	0	0	6	4	5	2
Goniada maculata	4	6	0	0	1	1	4	0
Harmothoe extenuata	2	0	0	0	0	0	0	0
Hermandura fauveli	4	7	5	0	1	0	0	0
Hesperonoe complanata	0	1	1	0	1	0	0	0
Heteromastus filobranchus	0	0	0	0	0	0	2	0
Lanassa venusta	1	1	0	0	0	1	0	0
Laonice cirrata	5	0	0	1	8	0	8	1
Leitoscoloplos pugettensis	0	3	1	15	1	7	3	2
Lepidasthenia berkeleyae	0	7	0	0	0	0	1	0
Lepidonotus spiculus	1	0	0	0	0	0	0	0
Levinsenia gracilis	0	0	0	0	0	0	3	0
Lumbrineris latreilli	0	0	0	0	0	0	15	0
Lumbrineris sp.	2	1	0	0	20	29	4	6
Lysippe labiata	0	0	0	0	1	0	1	0
Magelona berkeleyi	749	108	2	0	3	6	6	0
Magelona hartmanae	0	0	0	0	0	0	8	0
Magelona longicornis	0	0	0	0	0	0	35	0
Magelona sacculata	8	25	69	4	0	0	0	0
Maldane sarsi	2	1	0	0	16	0	68	2
Malmgreniella bansei	0	1	0	0	0	0	1	0
Malmgreniella cf sanpedroensis	0	0	0	0	14	0	11	0

Malmgreniella liei	0	0	0	0	0	0	1	0
Malmgreniella scriptoria	0	0	0	0	27	0	0	4
Malmgreniella sp.	0	0	0	1	3	3	0	0
Mediomastus californiensis	12	9	5	33	0	7	0	0
Melinna heterodonta	1	0	0	0	1	0	1	6
Melinna oculata	0	0	0	0	1	0	1	0
Mesochaetopterus taylori	2	8	4	0	0	0	0	0
Metasychis disparidentatus	0	0	0	0	0	5	5	0
Microspio pigmentata	14	4	13	0	0	0	0	0
Monticellina cryptica	0	0	0	0	0	0	5	0
Monticellina serratiseta	1	0	0	0	0	0	1	0
Monticellina sp.	1	0	0	0	1	0	0	1
Monticellina tesselata	0	0	0	0	26	0	24	7
Myriochele gracilis	0	0	0	0	3	0	0	1
Myriochele sp.	0	0	0	0	0	0	1	0
Myxicola infundibulum	0	0	0	0	0	0	0	1
Naineris uncinata	0	1	0	0	0	0	0	0
Nephtys caeca	0	0	0	0	0	0	2	0
Nephtys caecoides	11	14	0	16	11	2	7	2
Nephtys ferruginea	4	13	0	0	11	0	12	10
Nephtys glabra	0	0	0	0	0	0	3	2
Nephtys punctata	0	1	0	0	0	7	9	12
Nephtys sp. juv.	8	38	35	0	0	0	8	14
Nereis sp. juv.	0	0	4	0	0	0	0	0
Nereis procera	0	0	0	9	0	3	0	0
Nereis zonata	3	9	0	0	3	0	12	1
Nicomache lumbricalis	4	0	0	0	0	0	0	0
Nicomache personata	6	0	0	0	0	0	0	0
Ninoe gemmea	2	0	0	0	27	0	137	12
Notocirrus californiensis	0	1	0	0	0	0	1	0
Notomastus hemipodus	16	26	0	0	7	0	2	2
Notomastus latericeus	2	13	7	1	0	0	0	0
Notomastus lineatus	0	4	0	0	0	0	0	0
Notomastus sp. juv.	27	70	0	7	4	0	0	0
Notomastus tenuis	0	0	2	2	0	3	0	0
Onuphis iridescens	28	38	23	22	34	36	45	55
Onuphis sp. juv.	4	1	0	0	0	0	0	0
Ophelia assimilis	5	0	32	108	0	0	0	0
Ophelina acuminata	1	1	0	1	4	10	3	5
Ophiodromus pugettensis	0	0	0	0	2	0	0	0
Paradiopatra parva	1	0	0	0	35	0	13	14
Paranaitis polynoides	0	1	2	0	0	0	0	0
Parandalia occularis	0	0	0	9	0	0	0	0

Paraprionospio alata	1	17	1	0	15	0	33	44
Pectinaria californiensis	1	4	0	1	15	0	1	0
Pherusa plumosa	0	3	0	0	0	0	0	0
Pholoe sp.	1	5	1	0	7	1	1	1
Pholoides asperus	17	0	0	0	0	0	0	0
Phyllodoce cuspidata	2	5	1	0	3	0	1	1
Phyllodoce groenlandica	0	0	0	0	0	0	2	0
Phyllodoce hartmanae	0	3	1	21	0	0	0	0
Phyllodoce longipes	0	0	1	0	0	0	0	0
Phyllodoce sp. 1	0	0	0	0	0	0	1	0
Phylo felix	1	0	0	0	0	0	2	0
Pilargis maculata	2	0	0	0	1	0	14	0
Pista agassizi	0	3	0	0	0	0	0	0
Pista brevibranchiata	0	0	0	0	0	0	4	2
Pista estevanica	5	65	0	0	1	0	2	1
Pista moorei	0	1	0	0	1	0	2	1
Pista wui	0	5	0	1	21	17	12	1
Polycirrus sp.	0	0	0	0	0	6	0	0
Polycirrus sp. complex	4	91	0	0	0	0	1	1
Praxillella gracilis	0	1	0	0	1	0	29	10
Praxillella sp.	0	0	4	0	1	3	7	13
Prionospio lighti	2	1	0	2	1	1	0	0
Prionospio steenstrupi	20	97	1	0	14	4	4	17
Proclea graffi	7	2	0	0	0	0	0	0
Rhodine bitorquata	4	10	0	0	2	0	35	0
Sabellidae juv.	3	0	0	0	0	0	0	0
Scalibregma californicum	0	0	0	3	0	0	0	1
Scionella japonica	0	0	0	0	0	0	1	0
Scolelepis squamata	0	0	2	4	0	2	0	0
Scoletoma luti	18	29	0	1	9	3	51	1
Scoletoma zonata	0	0	0	0	0	4	0	0
Scoloplos acmeceps	2	13	23	2	0	7	0	0
Scoloplos armiger	0	0	0	0	0	3	0	0
Sigalion spinosus	0	3	8	0	0	0	0	0
Sigambra bassi	0	0	0	0	1	0	1	0
Spio cf thulini (was *S. filicornis*)	1	9	3	37	0	5	1	0
Spiochaetopterus pottsi	5	12	5	0	3	0	2	1
Spionidae juv. (post-larval)	3	0	0	0	0	2	0	0
Spiophanes berkeleyorum	37	19	13	34	8	4	7	2
Spiophanes norrisi	64	6	38	58	0	0	0	4
Sternaspis fossor	5	0	0	0	71	25	186	6
Sthenelais verruculosa	1	6	1	0	0	0	2	0
Streblosoma bairdi	0	19	0	0	0	0	0	0

Tenonia priops	2	1	0	2	0	0	0	0
Terebellides californica	0	0	0	0	2	0	3	4
Terebellides reishi	1	0	0	0	3	4	6	2
Terebellides sp.	0	3	0	0	0	2	0	0
Terebellides sp. 1	0	0	0	0	0	0	1	0
Travisia brevis	0	9	0	0	1	0	0	0
Travisia japonica	0	0	1	0	2	0	1	1
Travisia pupa	0	0	0	0	0	1	0	0
Trichobranchus glacialis	0	0	0	0	0	0	3	0
Typosyllis cornuta	2	2	0	0	0	0	6	0
Typosyllis heterochaeta	0	2	0	0	0	0	0	0
Typosyllis pigmentata	0	1	0	0	0	0	0	0
Typosyllis sp.	0	6	0	2	1	0	0	0
Unknown Polychaete	0	0	0	0	0	33	0	0
Oligochaeta								
Oligochaeta	0	0	0	0	1	0	0	0
NEMERTEA								
Anopla								
Carinoma mutabilis	1	4	25	0	0	0	0	0
Cerebratulus sp.	1	0	0	0	0	1	2	0
Lineidae	1	0	0	0	0	0	2	0
Micrura sp.	3	2	1	0	10	0	0	0
Tubulanus polymorphus	1	6	2	0	0	0	1	2
Tubulanus sp.	0	1	0	3	0	2	0	0
Enopla								
Paranemertes californica	1	0	0	0	0	0	1	0
Amphiporus sp.	0	1	0	0	0	0	0	0
Hoplonemertea	0	0	0	0	1	0	0	0
NEMOTODA	0	0	0	0	0	71	0	0

Table 35. Total abundance of all identified molluscan taxa at each site
The number of 0.1 m^2 box cores taken at each site are available in Table 14 in Chapter 5

Taxa	GB	Neh	Npt	CP	SC	BA	Eur	NSAF
MOLLUSCA								
Scaphapoda								
Gadila aberrans	0	2	3	0	135	13	17	0
Pulsellidae	9	58	0	1	6	4	0	0
Rhabdus rectius	5	49	0	0	2	0	0	0
Caudofoveata								
Chaetoderma sp.	5	1	0	0	9	1	8	0
Gastropoda								
Acteocina sp.	3	21	24	8	19	3	39	0
Admete gracilior	0	0	0	0	0	0	2	0
Alvania compacta	4	0	0	0	4	2	0	0
Amphissa columbiana	2	0	0	0	0	0	0	0
Antiplanes sp.	0	0	0	0	0	2	1	0
Astyris gausapata	2	38	50	48	36	18	5	6
Boonea oregensis	0	16	0	0	2	0	0	0
Caesia fossata	0	0	0	0	0	0	3	0
Callianax (Olivella) baetica	0	40	75	23	0	0	0	0
Callianax (Olivella) pycna	0	0	0	2	0	0	0	0
Cylichna attonsa	10	45	98	23	6	0	3	0
Diaphana californica	0	0	0	1	0	0	0	0
Epitonium indianorum	1	0	0	0	1	0	0	0
Epitonium sp.	0	0	0	0	0	0	15	0
Exilioidea rectirostris	0	0	0	0	0	0	0	0
Gastropteron pacificum	2	0	0	0	0	0	0	0
Haminoea vesicula	0	0	0	1	0	0	0	0
Hima mendica	0	1	0	0	0	0	0	0
Homalopoma radiatum	0	9	0	0	0	0	0	0
Lacuna vincta	0	0	0	0	0	0	0	1
Lirobittium sp.	0	0	0	0	0	0	4	0
Nactica clausa	0	0	0	0	7	1	0	0
Odostomia sp.	11	15	18	5	19	14	17	0
Oenopota fidicula	3	2	3	1	1	1	0	0
Oenopota sp.	0	0	0	2	0	1	0	0
Polygireulima rutile	0	0	0	0	1	0	0	0
Rectiplanes santarosana	0	1	0	0	0	0	0	0
Rictaxis punctcaelatus	0	0	0	0	0	0	4	0
Turbonilla sp.	2	16	10	3	1	1	21	0
Turridae	0	0	0	0	3	0	0	1
Gastropoda sp juvenile	0	0	0	0	0	0	1	1
Unknown Gastropod	0	0	0	0	2	0	0	0

Bivalvia								
Acila castrensis	7	37	8	105	206	188	24	65
Adontorhina cyclica	0	0	0	0	48	28	56	14
Axinopsida serricata	451	258	876	335	895	833	780	155
Cardiomya pectinata	0	0	0	0	0	0	3	1
Cariidae	0	0	0	0	0	0	0	0
Compsomyax subdiaphana	4	2	0	0	25	10	14	6
Cuspidariidae	0	0	0	0	3	0	0	0
Cyclocardia ventricosa	5	9	0	0	32	2	20	8
Ennucula tenuis	18	150	2	0	108	19	291	9
Hiatella arctica	2	0	0	0	2	0	0	0
Huxleyia munita	0	45	0	0	0	0	0	0
Kurtiella (Rochefortia) tumida	2	0	4	1	4	0	20	1
Laternula marilina	0	0	0	0	27	0	0	1
Lucinoma annulatum	3	7	0	0	0	0	0	0
Macoma carlottensis	60	22	28	2	267	65	1	37
Macoma elimata	57	12	0	9	29	56	11	0
Macoma sp. juvenile	0	0	0	0	0	1	55	6
Megayoldia thraciaeformis	0	0	0	0	2	0	0	0
Modiolus rectus	0	1	0	0	0	0	0	0
Mytilidae sp. juvenile	0	0	0	0	0	0	3	0
Nemocardium centrifilosum	1	0	0	0	0	0	0	0
Nuculana cellulita	2	0	0	0	0	0	0	0
Nuculana hamate	0	0	0	0	0	8	3	1
Nutricola lordi	153	42	1598	724	0	1	0	5
Pandora bilirata	2	1	0	0	5	0	0	0
Pandora filose	0	0	0	0	0	0	2	0
Pharidae	0	0	0	0	0	0	0	0
Saxicavella pacifica	5	3	4	2	0	0	0	0
Siliqua alta	1	1	2	1	0	0	0	0
Siliqua sp. juvenile	0	0	0	0	0	0	4	0
Solamen columbianum	3	4	0	0	1	5	8	2
Tellina bodegensis	0	0	0	1	0	0	0	0
Tellina carpenter	0	3	0	0	0	0	0	2
Tellina modesta	0	0	0	1	0	1	0	0
Tellina nuculoides	1	0	28	61	0	2	0	0
Terebratalia transversa	1	0	0	0	0	0	0	0
Terebratulina unguiculata	1	0	0	0	0	0	0	0
Thyasira flexuosa	6	14	0	0	2	0	0	0
Yoldia seminuda	7	2	1	1	13	0	14	0
Yoldiiae sp. 2	0	0	0	0	3	0	0	0
Zirfaea pilsbryi	1	0	0	0	0	0	0	0
Bivalvia sp. juvenile	0	0	0	0	0	0	6	2

Polyplacophora								
Leptochitonidae	0	0	0	0	0	2	0	1

Table 36. Total abundance of all identified arthropod taxa at each site
The number of 0.1 m^2 box cores taken at each site are available in Table 14 in Chapter 5

Taxa	GB	Neh	Npt	CP	SC	BA	Eur	NSAF
ARTHROPODA								
Ostracoda								
Cylindroleberididae	0	1	12	0	0	0	0	0
Euphilomedes carcharodonta	2	46	71	0	0	0	0	0
Euphilomedes producta	0	0	0	0	0	0	5	0
Copepoda								
Calanus sp.	1	0	0	0	1	0	0	3
Maxillopoda								
Balanus sp.	0	0	0	0	0	0	1	0
Malacostraca								
Acanthaxius spinulicauda	0	0	0	0	1	0	0	0
Achelia sp.	1	0	0	0	0	0	0	0
Acidostoma sp.	0	0	0	0	0	0	2	0
Americhelidium shoemakeri	1	5	3	0	0	0	0	0
Ampelisca agassizi	1	5	15	0	0	1	0	0
Ampelisca careyi	30	43	34	20	13	4	68	3
Ampelisca hancocki	2	0	0	0	0	0	2	0
Aoroides inermis	0	1	0	0	1	0	0	0
Aoroides sp.	1	4	0	3	1	1	0	0
Argissa hamatipes	1	1	0	0	0	0	2	0
Byblis sp.	2	0	0	0	0	1	1	0
Calocarides spinulicauda	0	0	0	0	1	1	0	0
Cancer jordani	1	0	0	0	0	0	1	0
Caprella mendax	0	0	0	0	4	0	2	0
Caprella sp.	0	0	0	6	0	0	0	0
Cheirimedeia cf. macrodactyla	0	2	3	0	0	0	0	0
Cheirimedeia zotea	3	1	0	6	0	0	12	0
Crangon alaskensis	1	2	3	2	0	0	1	0
Crangon sp.	0	1	1	3	0	0	1	0
Desdimelita desdichada	2	1	0	0	0	0	3	0
Diastylis cf. bidentata	0	2	0	0	1	0	0	0
Diastylis paraspinulosa	0	0	0	0	0	1	2	0
Diastylis quadriplicata	0	0	0	0	2	0	0	0
Diastylis santamariensis	1	1	0	0	1	0	8	0
Diastylis sp.	0	0	0	0	0	2	0	1
Diastylopsis dawsoni	5	2	1	0	0	0	20	0
Eohaustorius sawyeri	0	4	7	0	0	0	0	0
Eualus berkeleyorum	0	0	0	0	0	0	1	0
Eualus pusiolus	1	0	0	0	0	0	0	0
Eudorella pacifica	0	0	0	0	9	0	0	1

Eudorellopsis longirostris	0	1	0	0	0	0	0	0
Foxiphalus similis	1	0	0	0	1	0	11	0
Foxiphalus golfensis	0	0	0	0	0	2	0	0
Gammaropsis ellisi	1	0	0	0	0	0	0	0
Gibberosus myseri	0	0	1	0	0	0	0	0
Gammaropsis sp.	0	0	0	5	0	0	0	0
Grandifoxus longirostris	0	4	13	0	0	3	0	0
Haliophasma geminatum	0	2	0	0	0	0	0	0
Harpiniopsis fulgens	0	0	0	0	3	0	0	0
Hemilamprops californica	0	1	0	6	3	0	0	0
Heterophoxus affinis	0	0	0	0	18	7	11	6
Heterophoxus ellisi	0	0	0	0	5	4	0	2
Heterophoxus frequens	0	0	0	0	0	1	0	0
Heterophoxus oculatus	0	0	0	0	0	1	0	0
Heterophoxus sp.	0	0	0	0	0	3	0	0
Hippolytidae	1	0	0	0	0	0	0	0
Hippomedon coecus	0	2	0	0	0	0	0	0
Hippomedon columbianus	0	1	0	0	0	0	0	0
Ischyrocerus sp.	3	0	0	0	0	0	0	0
Isaeidae	0	0	0	74	0	2	0	0
Lissocrangon stylirostris	1	0	0	0	0	0	0	0
Lysianassidae sp.1	0	0	0	0	0	0	0	1
Maera loveni	0	0	0	0	0	0	1	0
Majoxiphalus major	1	0	0	0	0	0	0	0
Metaphoxus frequens	0	1	0	0	2	0	0	0
Metridia pacifica	0	0	0	0	0	0	0	1
Mysidacea	0	0	1	0	1	0	0	0
Nebalia sp.	0	0	3	1	0	0	0	0
Neocrangon communis	0	0	0	0	3	0	0	1
Neotrypaea sp.	4	20	2	0	3	5	0	5
Nicippe tumida	0	0	0	0	2	0	0	0
Opisa tridentata	0	1	0	0	0	0	0	0
Orchomene pacifica	1	3	2	0	0	0	0	0
Orchomene pinguis	0	2	112	0	0	0	0	0
Pacifacanthomysis nephrophthalma	0	1	0	1	0	0	0	0
Pacifoculodes spinipes	0	0	1	0	0	0	0	0
Pagarus sp.	0	0	0	6	0	0	0	0
Pandalus jordani	0	0	0	0	0	0	0	3
Paraphoxus sp.	0	0	0	0	0	0	2	0
Pardaliscella symmetrica	0	0	0	0	2	0	0	0
Photis bifurcata	6	0	0	0	0	0	0	0
Photis brevipes	2	10	8	26	0	2	4	0

Photis macinerneyi	0	0	0	1	0	0	0	1
Photis sp.	0	0	0	1	0	4	1	2
Pinnixa occidentalis complex	4	6	14	9	2	1	0	35
Pinnotheridae	0	0	0	1	0	2	1	0
Pleusymtes sp.	2	1	0	0	0	0	0	0
Prachynella lodo	0	0	0	0	1	0	1	0
Protomedeia articulata	0	0	0	0	4	0	5	4
Protomedeia prudens	5	1	0	0	2	0	3	0
Rhachotropis sp.	0	1	0	0	0	0	0	0
Rhepoxynius abronius	1	7	20	0	0	0	0	1
Rhepoxynius bicuspidatus	0	0	0	0	6	1	0	2
Rhepoxynius boreovariatus	24	0	0	0	0	0	20	0
Rhepoxynius dabouis	0	64	1	0	0	0	0	0
Rhepoxynius sp.	0	0	1	0	0	0	0	0
Rhepoxynius sp. 1	7	0	1	0	0	0	0	0
Rhepoxynius variatus	0	17	0	1	0	0	0	0
Rhepoxynius vigitegus	0	0	1	0	0	0	0	0
Rocinela angustata	0	0	0	0	0	0	2	0
Rutiderma lomae	0	0	0	0	0	0	2	0
Scleroconcha trituberculata	0	0	0	0	0	0	0	2
Scoloura phillipsi	0	3	0	0	0	0	0	0
Spirontocaris sp.	0	0	0	0	2	0	0	0
Stenothoidae	2	0	0	0	0	0	0	0
Synidotea sp.	2	0	2	15	0	0	1	0
Thysanoessa sp.	0	0	0	0	1	0	0	0
Trachypleustes sp.	1	0	0	0	0	0	0	0
Tritella pilimana	0	0	0	0	1	0	0	0
Wecomedon wecomus	0	5	4	0	0	0	0	0
Westwoodilla tone	0	5	0	0	1	0	2	0

Table 37. Total abundance of all ‘other’ taxa at each site
The number of 0.1 m^2 box cores taken at each site are available in Table 14 in Chapter 5

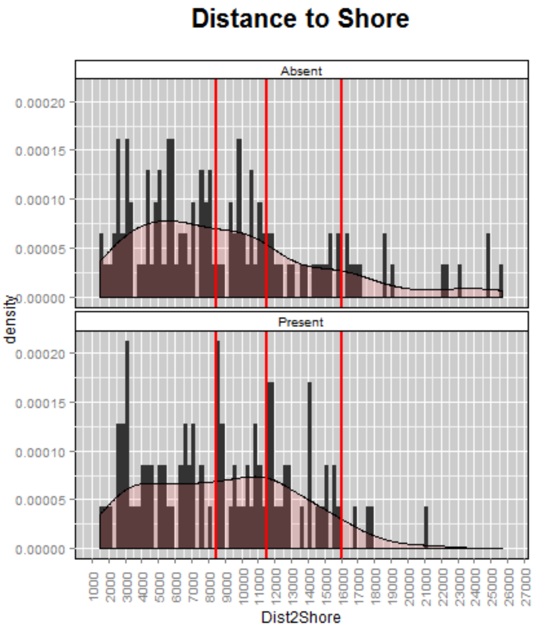
Taxa	GB	Neh	Npt	CP	SC	BA	Eur	NSAF
CNIDARIA								
Anthozoa								
Athenaria	1	1	0	0	0	0	0	0
Edwardsia juliae	0	1	0	0	0	0	0	2
Halcampa decemtentaculata	0	0	0	0	0	1	0	1
Halcampidae	3	5	0	0	0	0	0	0
Halcampoides purpurea	0	0	0	0	0	0	2	0
Pachycerianthus sp.	1	0	0	0	2	0	6	1

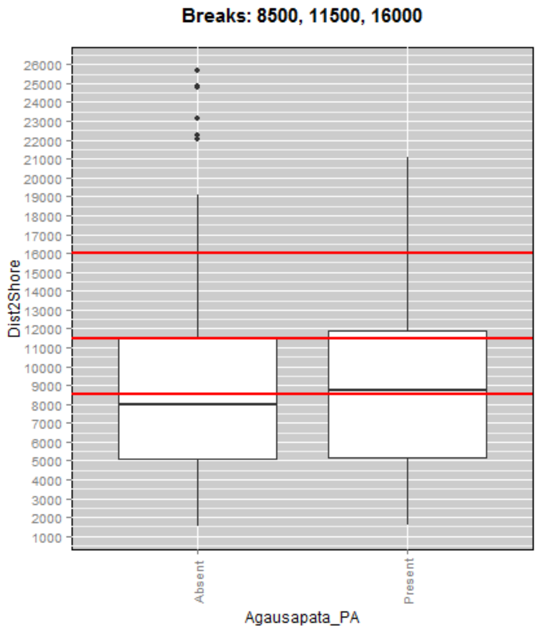
Peachia quinquecapitata	0	0	1	1	0	0	2	0
Ptilosarcus gurneyi	0	0	1	0	0	0	0	0
Stylatula elongata	1	0	0	0	0	0	0	0
ECHINODERMATA								
Echinoidea								
Brisaster latifrons	0	0	0	0	40	4	1	15
Dendraster excentricus	5	0	9	1	0	0	0	0
Holothuroidea								
Cucumariidae	1	0	0	0	0	0	0	0
Pentamera sp.	0	0	0	0	1	2	7	3
Paracaudina chilensis	0	0	0	0	2	0	0	0
Ophiuroidea								
Amphiodia occidentalis	2	11	0	0	1	1	0	2
Amphiodia urtica	26	60	9	3	3	3	19	2
Amphioplus strongyloplax	0	0	0	0	106	5	16	82
Amphipholis squamata	6	0	0	0	0	0	0	0
Amphiuridae sp. 1	0	0	0	0	2	0	0	2
Amphiuridae sp. 2	0	0	0	0	0	0	0	11
Amphiuridae sp. 3	0	0	0	0	1	0	0	4
Ophiopholis aculeata	6	0	0	0	0	0	0	0
Ophiura lutkeni	1	2	0	0	13	1	1	0
Unknown brittle star	0	0	0	0	0	0	4	5
ECHIURA								
Echiura								
Echiuridae	2	8	2	0	0	0	5	1
Arhynchite pugettensis	0	0	1	0	0	0	0	0
Boniella sp.	0	0	0	19	0	3	0	0
SIPUNCULA								
Sipunculidea								
Thysanocardia nigra	1	3	0	0	0	0	12	2
Nephasoma diaphanes	0	0	0	0	0	0	0	50
CHAETOGNATHA								
Sagittoidea								
Saggita sp.	0	0	0	2	0	0	0	0
PHORONIDA								
Phoronis								
Phoronis sp.	0	0	2	20	0	0	0	0
HEMICHORDATA								
Entropneusta								
Glossobalanus sp.	1	0	0	0	0	0	0	0

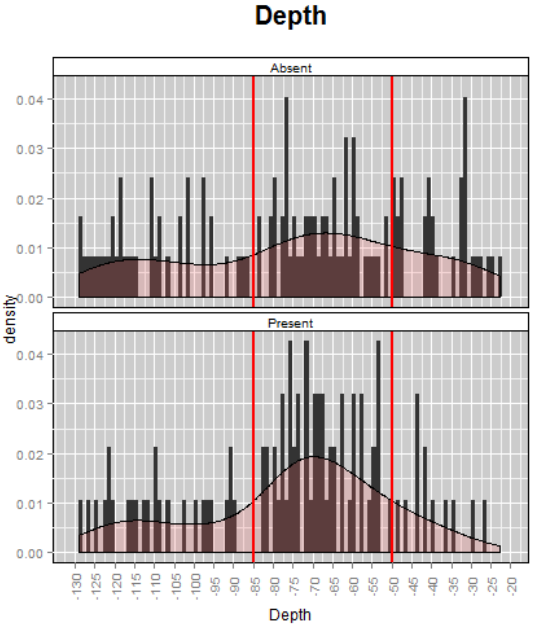
Appendix 6. Benthic Macrofauna Models: Species Response Histograms, Bayesian Belief Networks, and Model Update and New Species Application Instructions

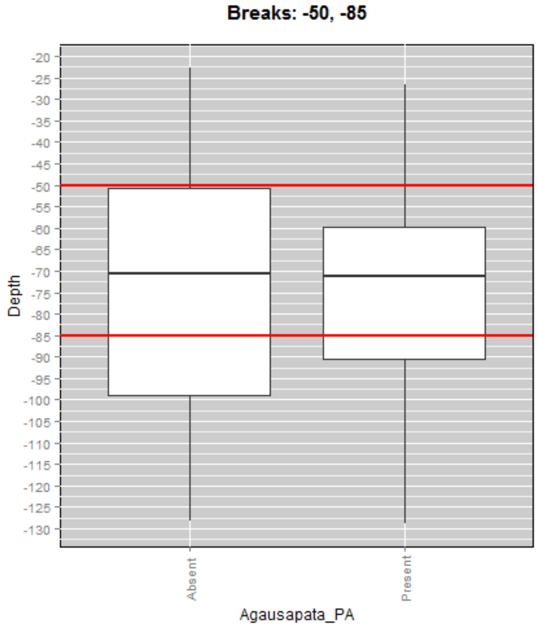
Appendix 6.1 Species Response Histograms

Appendix 6.1.1 *Alia gausapata*

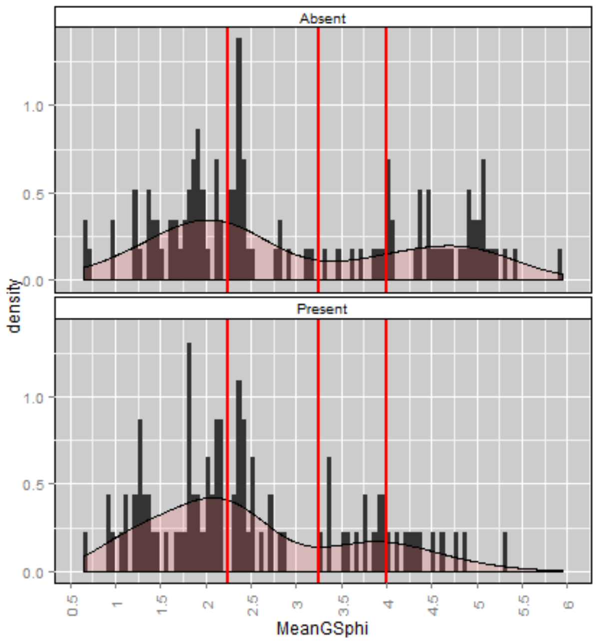




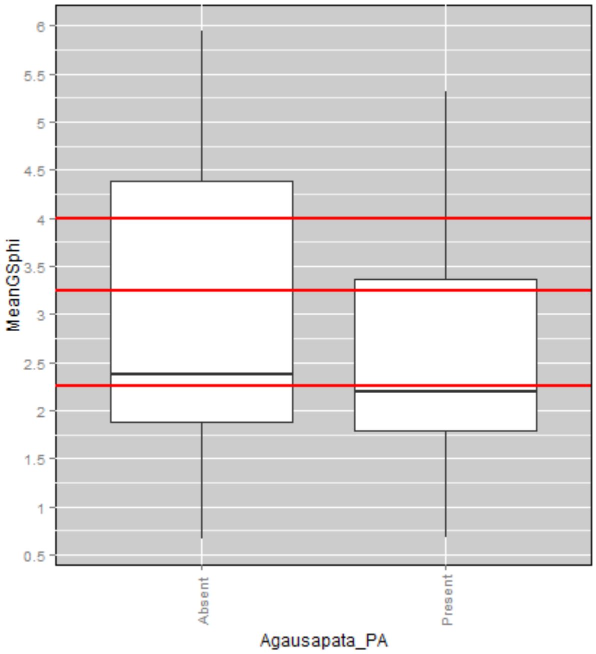




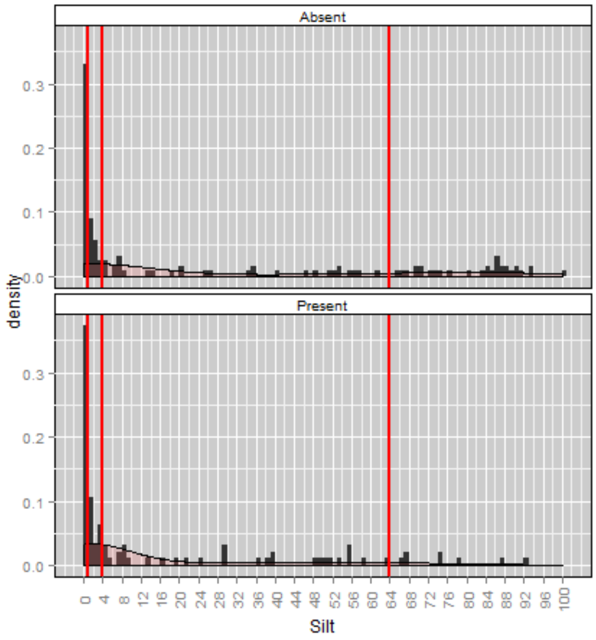
Grain Size



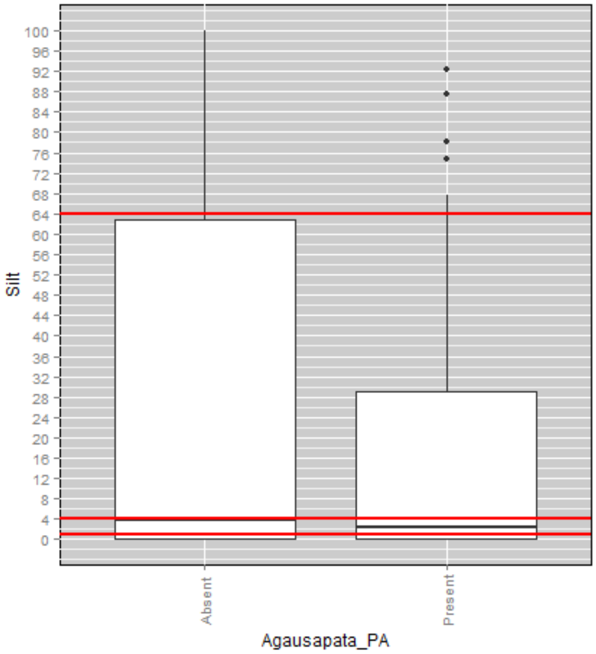
Breaks: 2.25, 3.25, 4

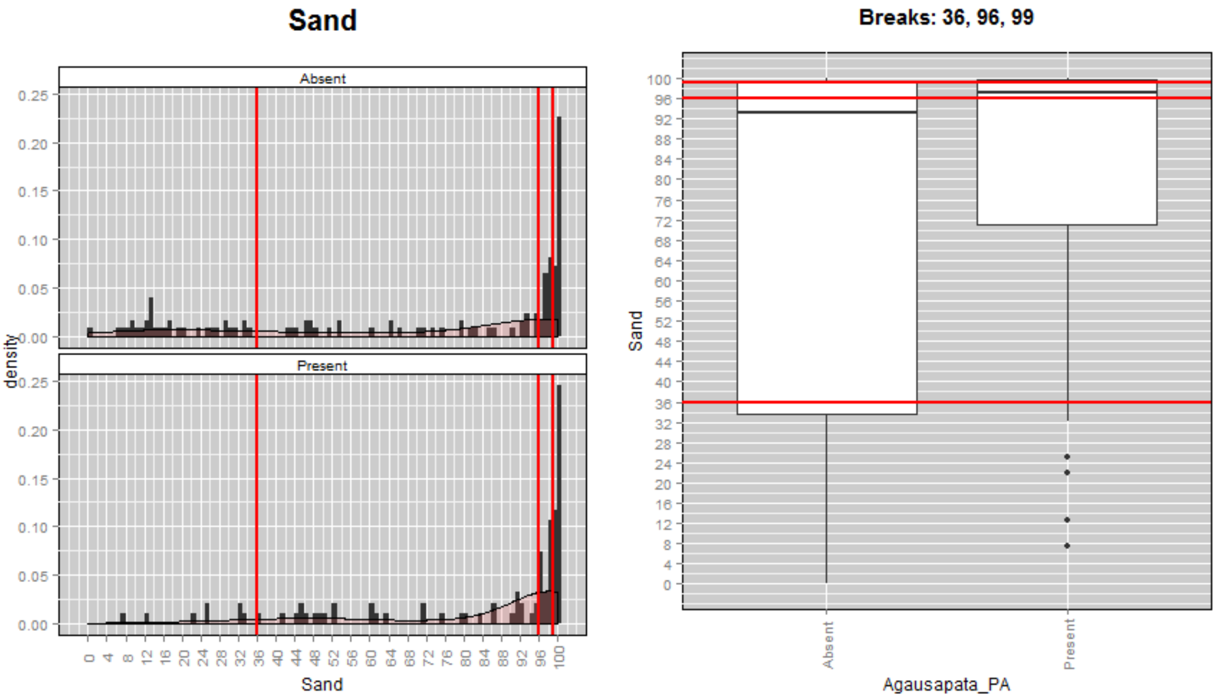


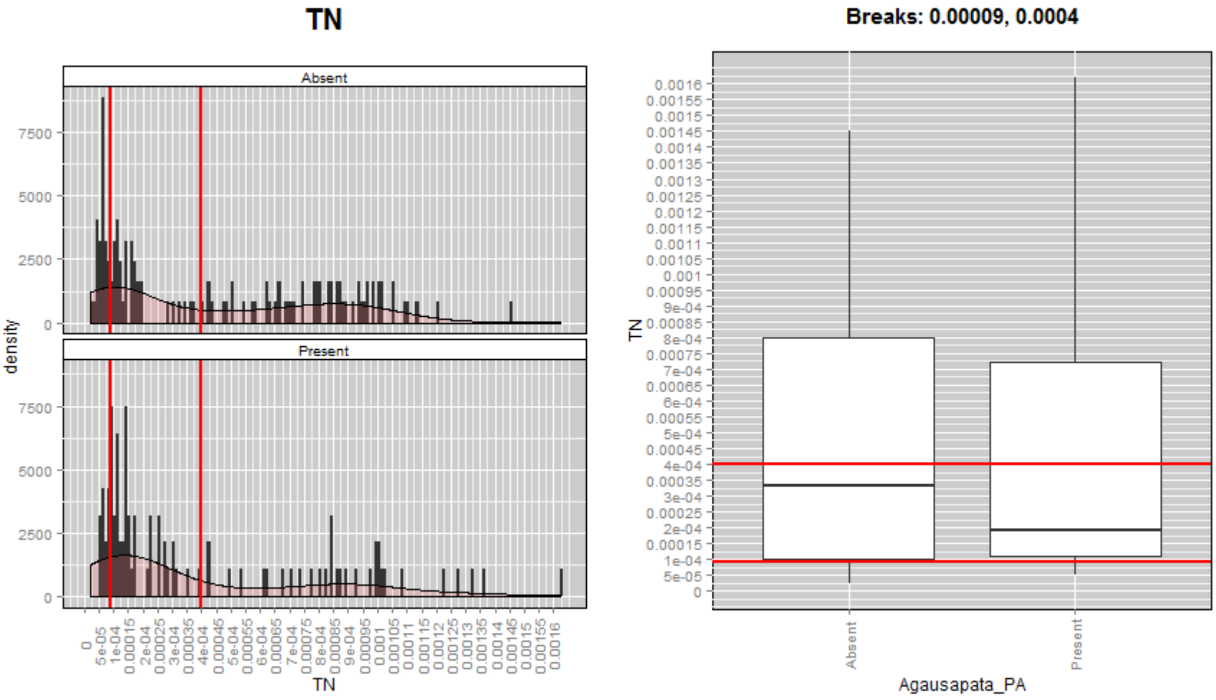
Silt

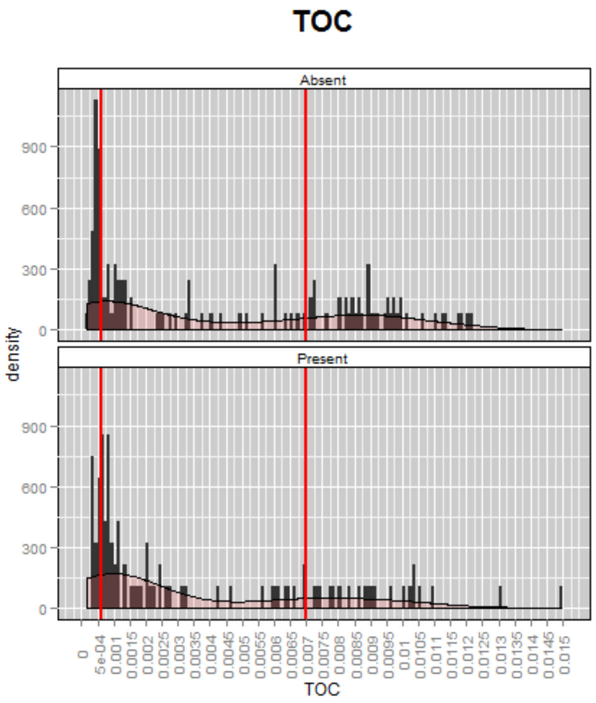


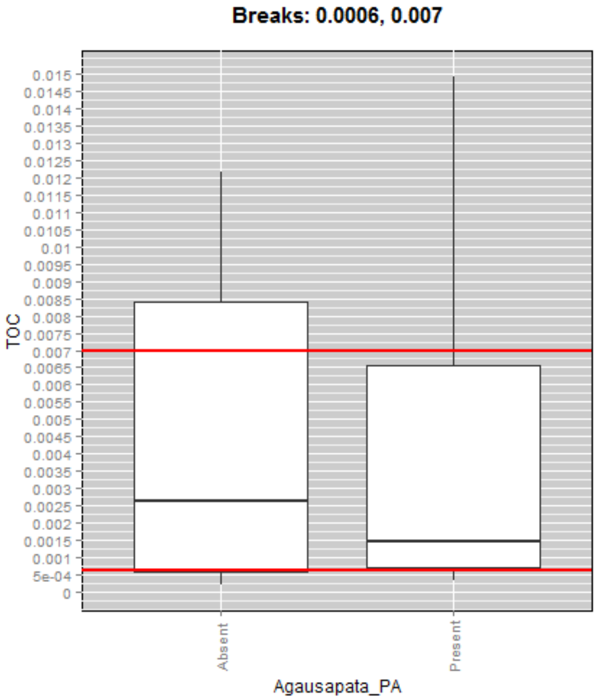
Breaks: 1, 4, 64



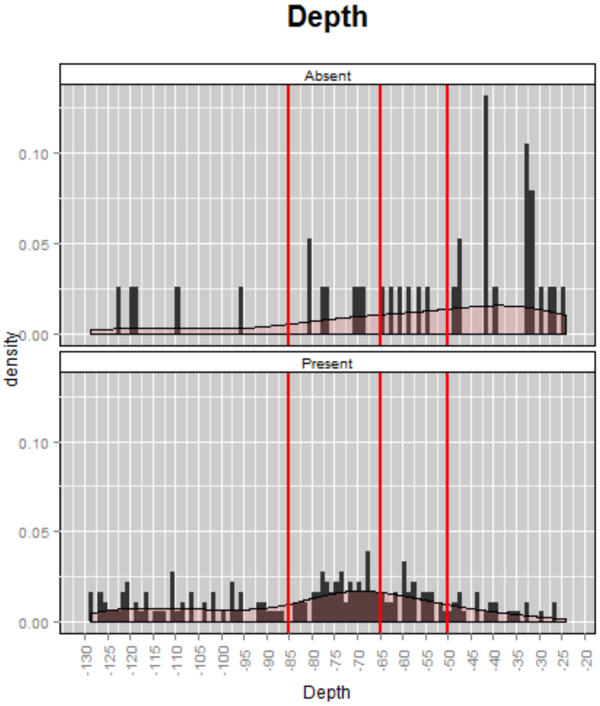

Sand
Breaks: 36, 96, 99
Absent
Present
density
0.00
0.05
0.10
0.15
0.20
0.25
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60 64 68 72 76 80 84 88 92 96 100
Sand
Sand
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60 64 68 72 76 80 84 88 92 96 100
Absent
Present
Agausapata_PA

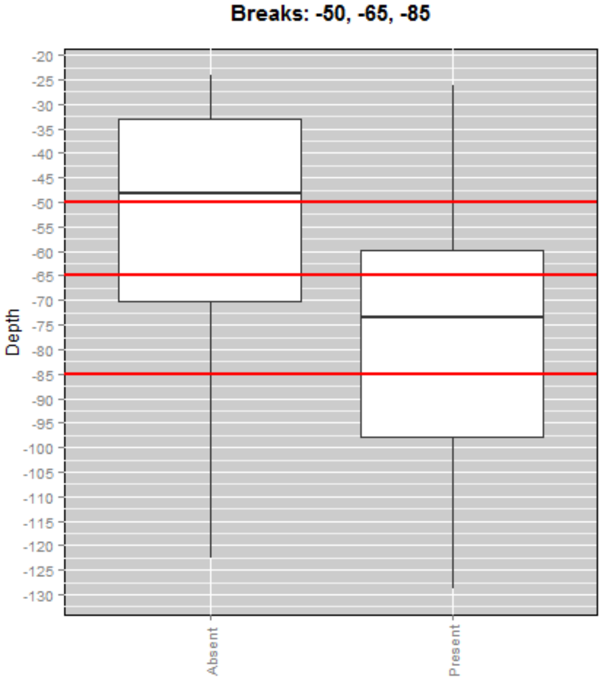

TN
Breaks: 0.00009, 0.0004
Absent
Present
density
0
2500
5000
7500
0 5e-05 1e-04 0.00015 2e-04 0.00025 3e-04 0.00035 4e-04 0.00045 5e-04 0.00055 6e-04 0.00065 7e-04 0.00075 8e-04 0.00085 9e-04 0.00095 0.001 0.00105 0.0011 0.00115 0.0012 0.00125 0.0013 0.00135 0.0014 0.00145 0.0015 0.00155 0.0016
TN
TN
0 5e-05 1e-04 0.00015 2e-04 0.00025 3e-04 0.00035 4e-04 0.00045 5e-04 0.00055 6e-04 0.00065 7e-04 0.00075 8e-04 0.00085 9e-04 0.00095 0.001 0.00105 0.0011 0.00115 0.0012 0.00125 0.0013 0.00135 0.0014 0.00145 0.0015 0.00155 0.0016
Absent
Present
Agausapata_PA

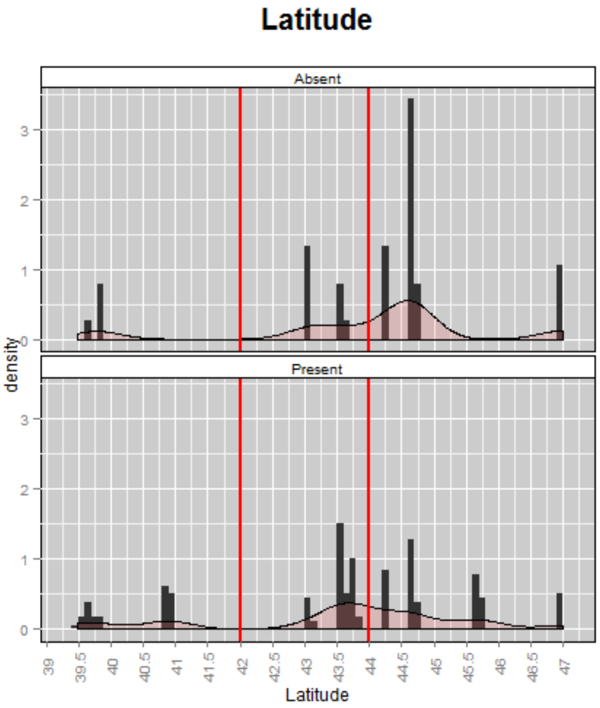

TOC
Absent
Present
density
900
600
300
0
0
5e-04
0.001
0.0015
0.002
0.0025
0.003
0.0035
0.004
0.0045
0.005
0.0055
0.006
0.0065
0.007
0.0075
0.008
0.0085
0.009
0.0095
0.01
0.0105
0.011
0.0115
0.012
0.0125
0.013
0.0135
0.014
0.0145
0.015
TOC

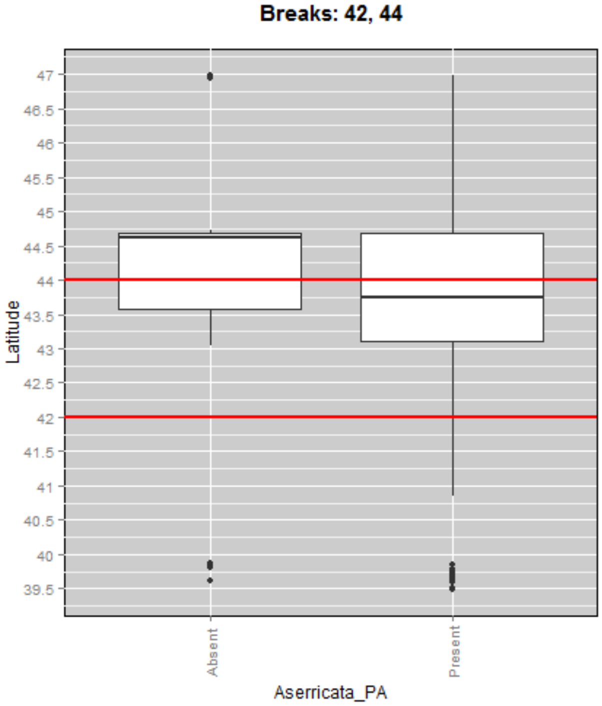

Breaks: 0.0006, 0.007
TOC
0.015
0.0145
0.014
0.0135
0.013
0.0125
0.012
0.0115
0.011
0.0105
0.01
0.0095
0.009
0.0085
0.008
0.0075
0.007
0.0065
0.006
0.0055
0.005
0.0045
0.004
0.0035
0.003
0.0025
0.002
0.0015
0.001
5e-04
0
Absent
Present
Agausapata_PA

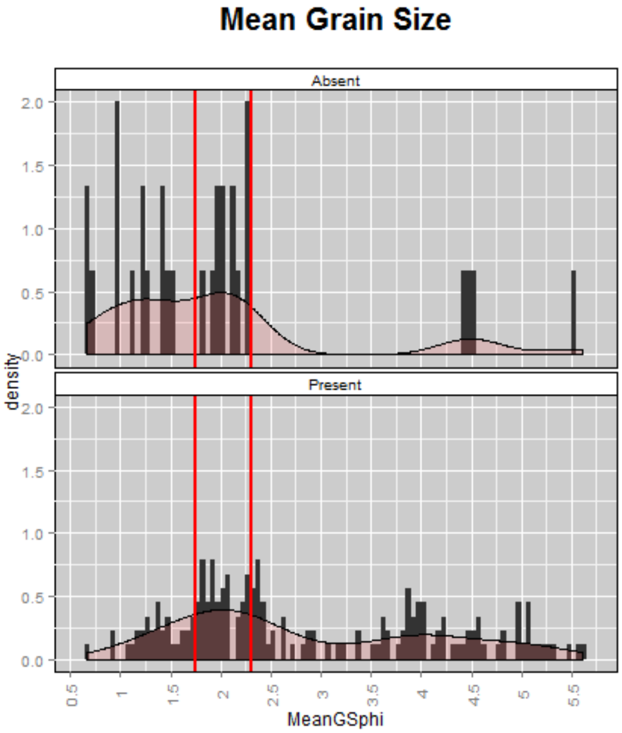
Appendix 6.1.2 *Axinopsida serricata*



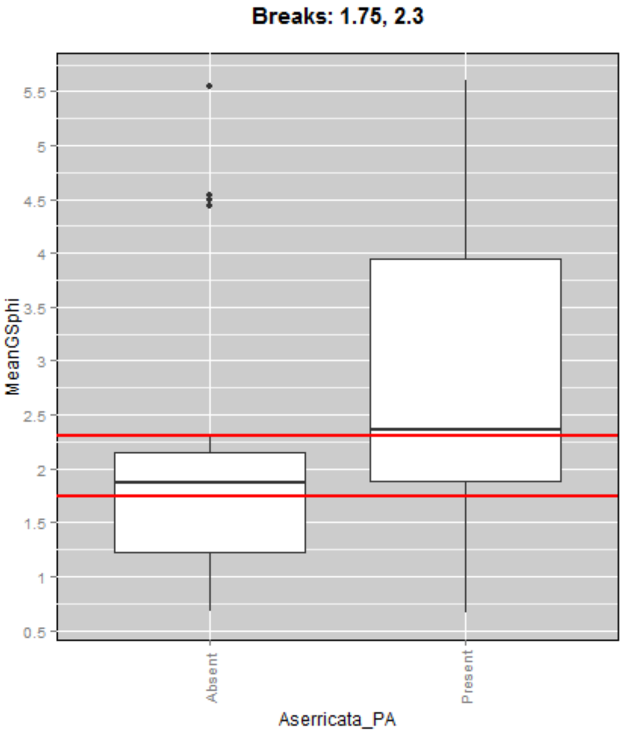






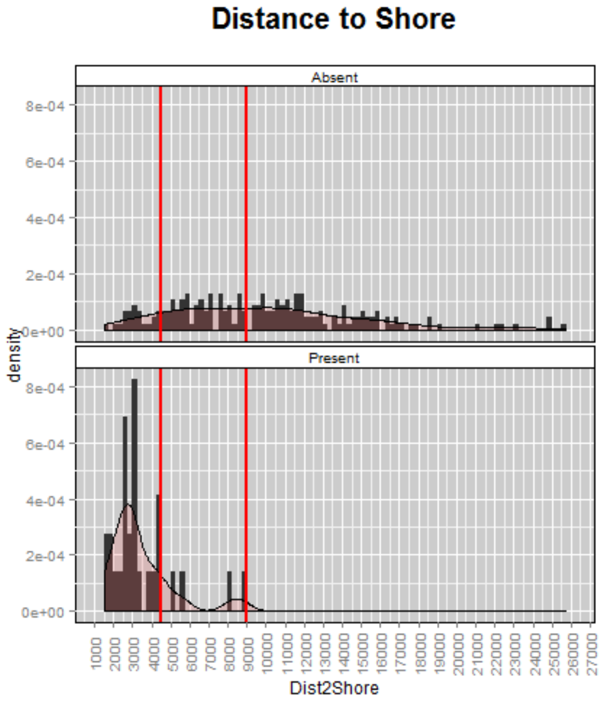


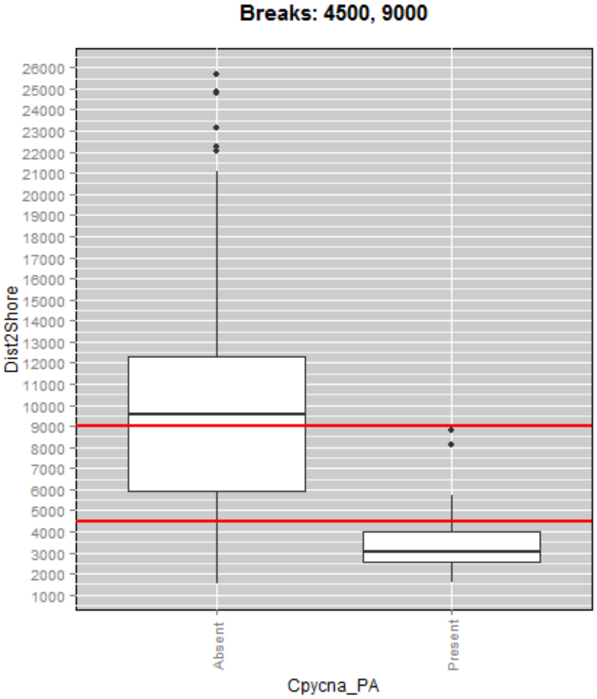
Mean Grain Size

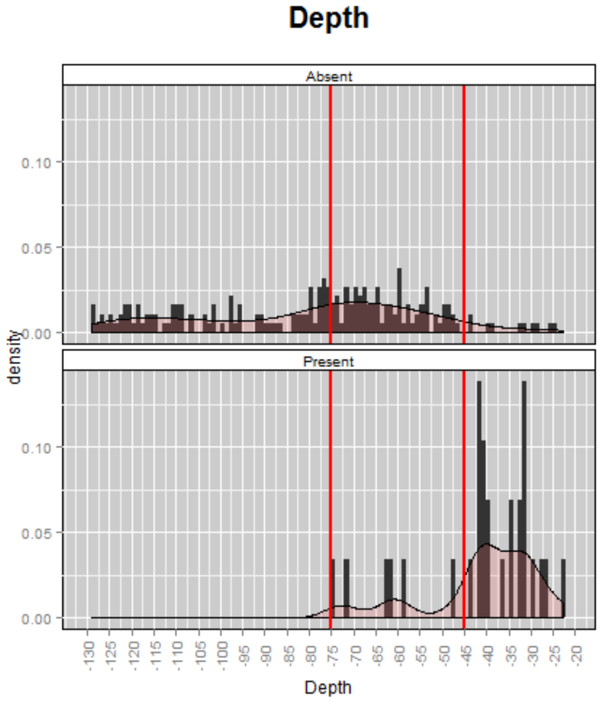


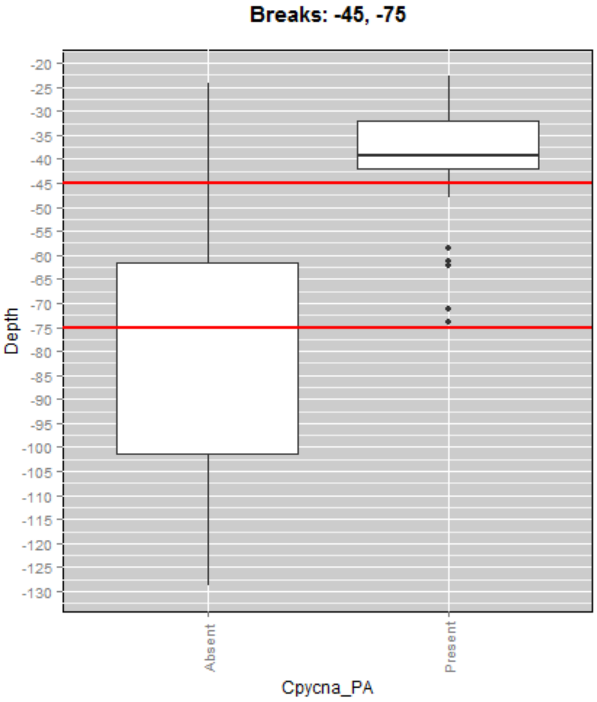
Breaks: 1.75, 2.3

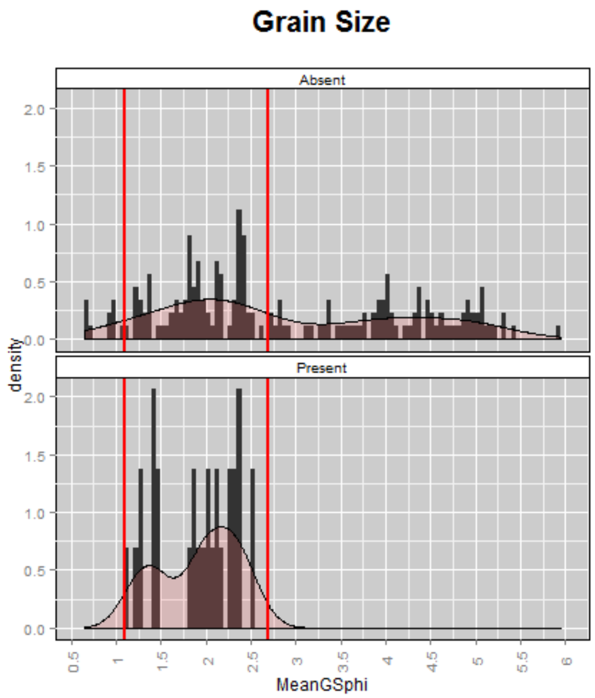
Appendix 6.1.3 *Callianax pycna*

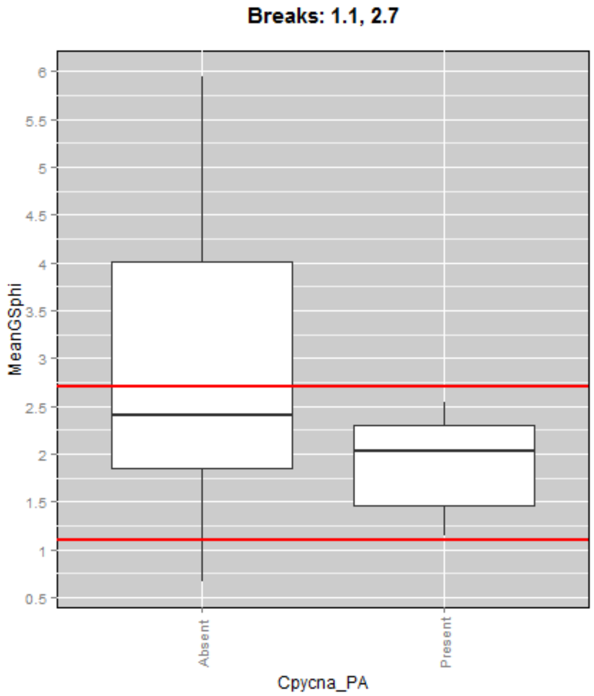

Distance to Shore

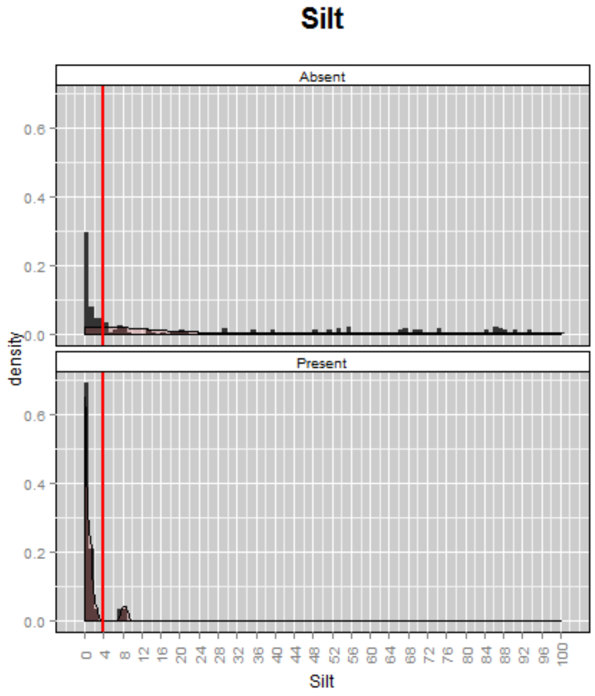

Breaks: 4500, 9000

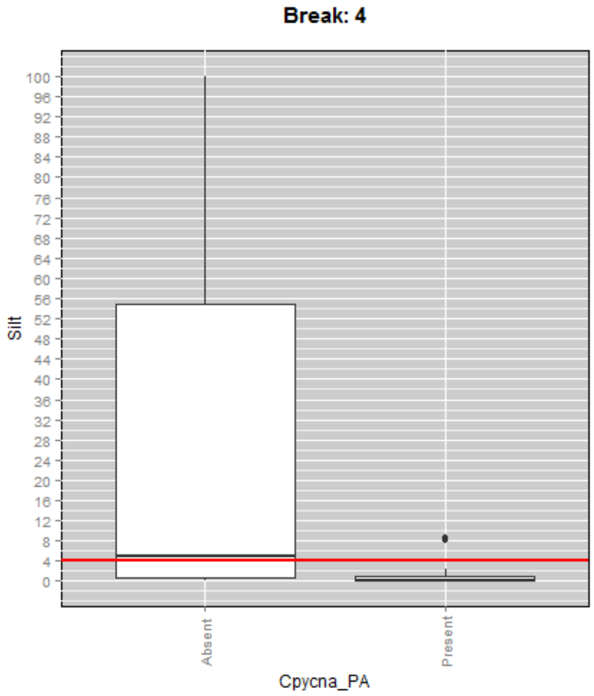

Depth

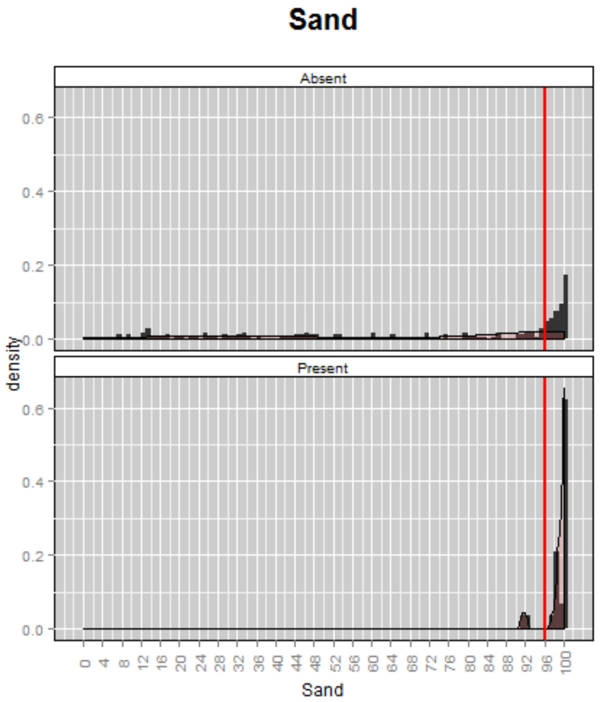

Breaks: -45, -75


Grain Size
Absent
Present
density
2.0
1.5
1.0
0.5
0.0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
MeanGSphi

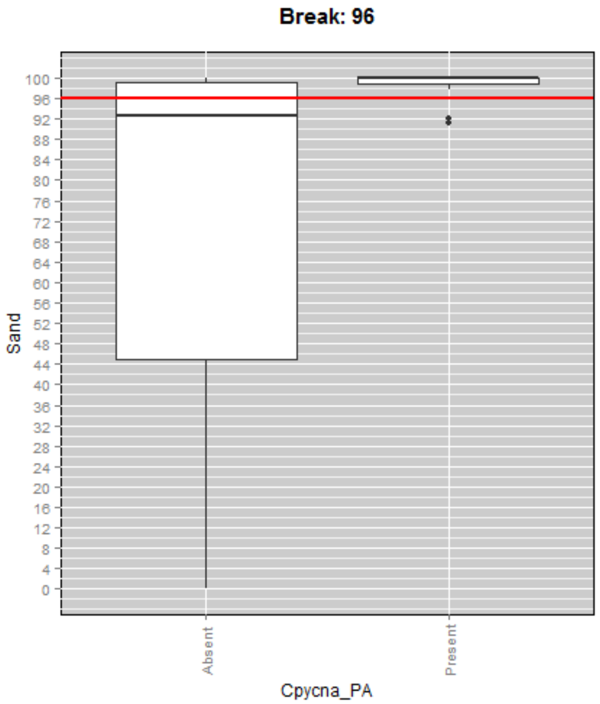

Breaks: 1.1, 2.7
MeanGSphi
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
Absent
Present
Cpycna_PA


Silt
Absent
Present
density
0.6
0.4
0.2
0.0
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
84
88
92
96
100
Silt

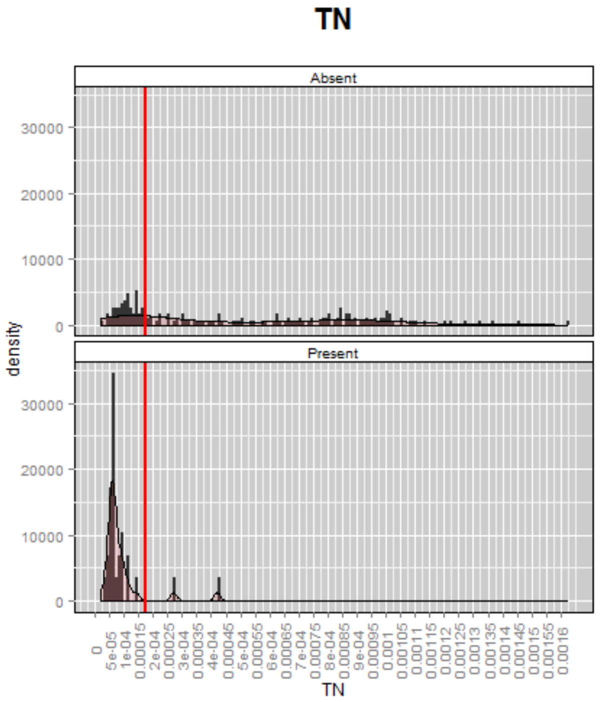

Break: 4
Silt
100
96
92
88
84
80
76
72
68
64
60
56
52
48
44
40
36
32
28
24
20
16
12
8
4
0
Absent
Present
Cpycna_PA



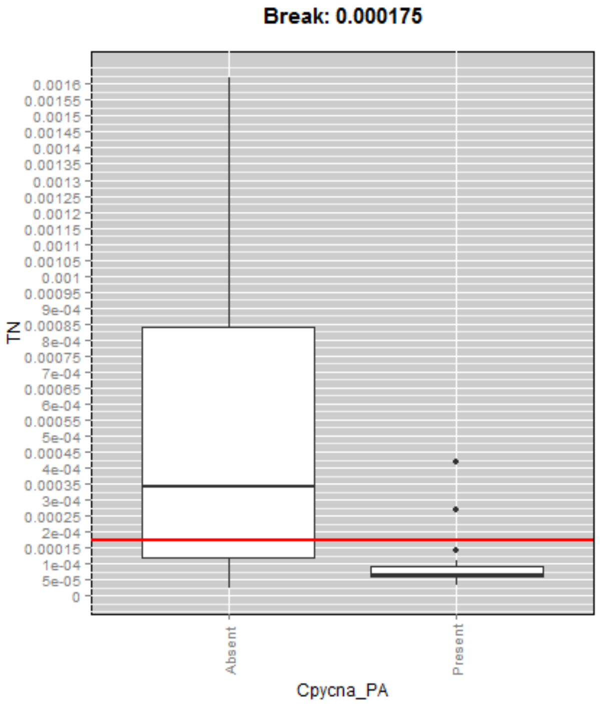
Sand
Absent
Present
density
0.0
0.2
0.4
0.6
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60 64 68 72 76 80 84 88 92 96 100
Sand



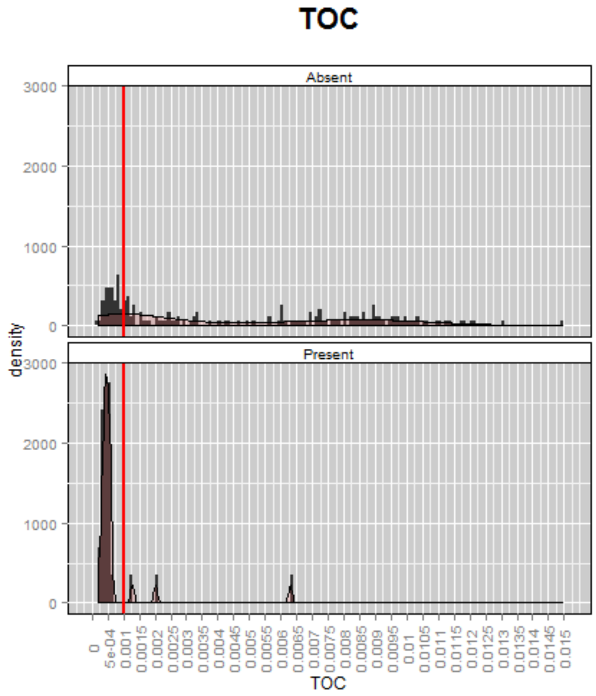
Break: 96
Sand
100 96 92 88 84 80 76 72 68 64 60 56 52 48 44 40 36 32 28 24 20 16 12 8 4 0
Absent
Present
Cpycna_PA

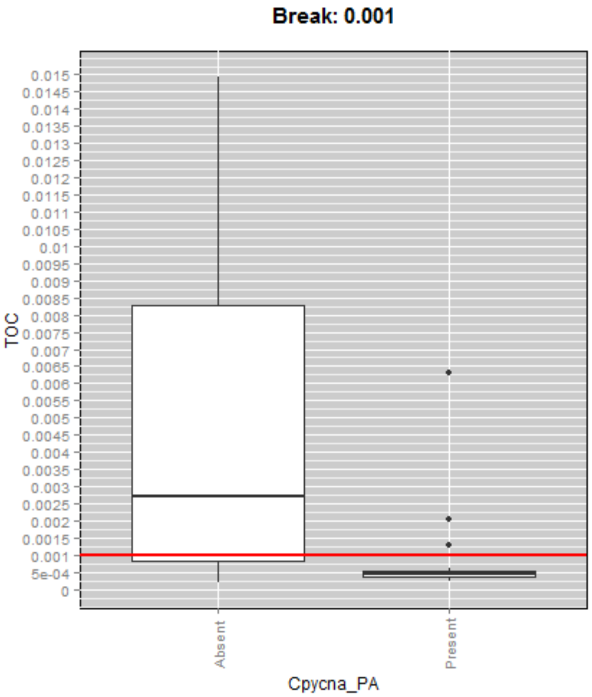


TN
Absent
Present
density
0
10000
20000
30000
0 5e-05 1e-04 0.00015 2e-04 0.00025 3e-04 0.00035 4e-04 0.00045 5e-04 0.00055 6e-04 0.00065 7e-04 0.00075 8e-04 0.00085 9e-04 0.00095 0.001 0.00105 0.0011 0.00115 0.0012 0.00125 0.0013 0.00135 0.0014 0.00145 0.0015 0.00155 0.0016
TN

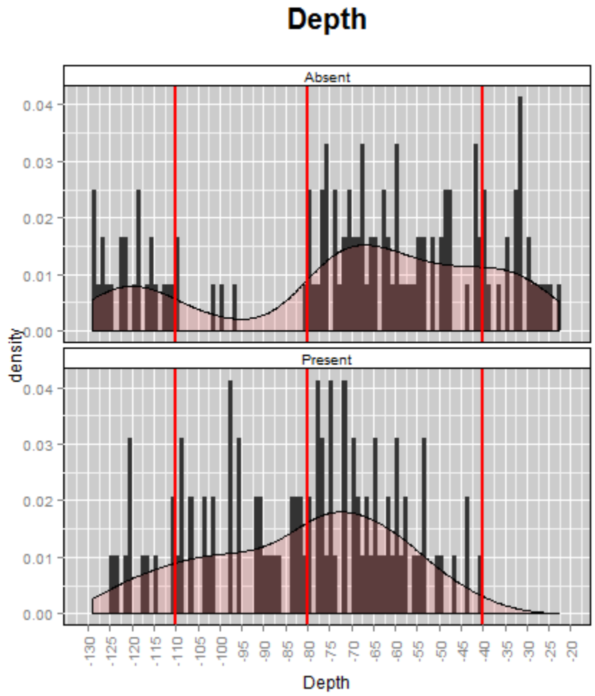


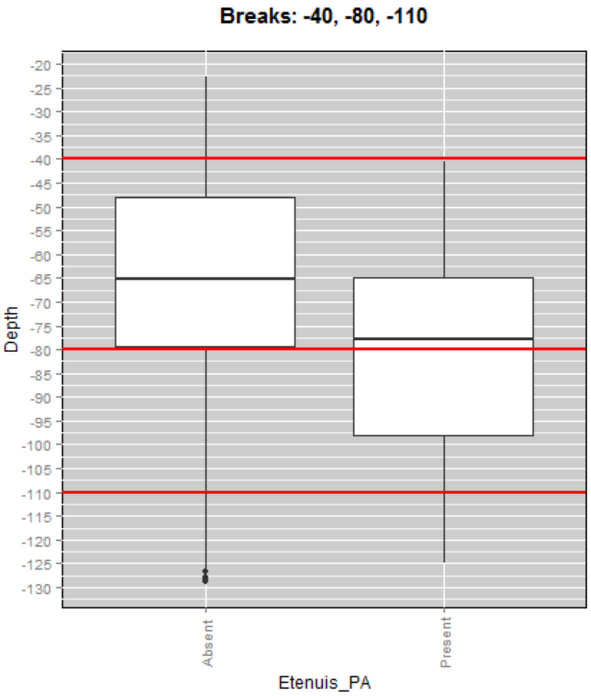
Break: 0.000175
TN
0.0016 0.00155 0.0015 0.00145 0.0014 0.00135 0.0013 0.00125 0.0012 0.00115 0.0011 0.00105 0.001 0.00095 9e-04 0.00085 8e-04 0.00075 7e-04 0.00065 6e-04 0.00055 5e-04 0.00045 4e-04 0.00035 3e-04 0.00025 2e-04 0.00015 1e-04 5e-05 0
Absent
Present
Cpycna_PA

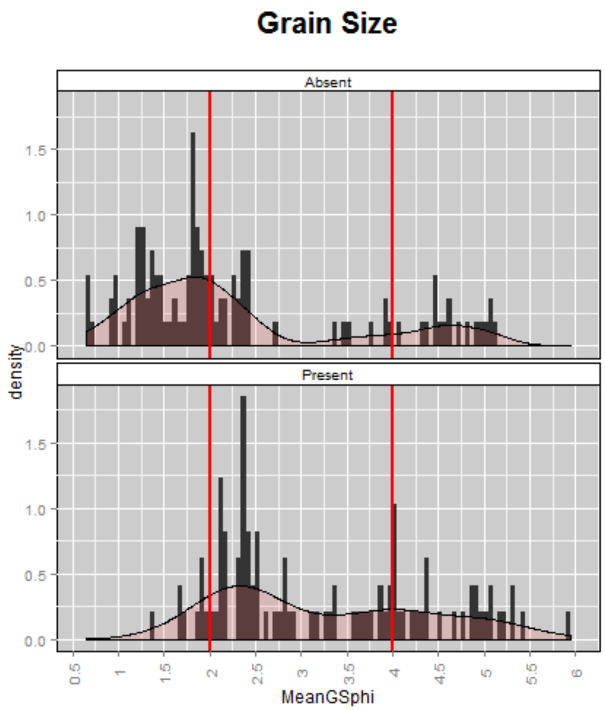


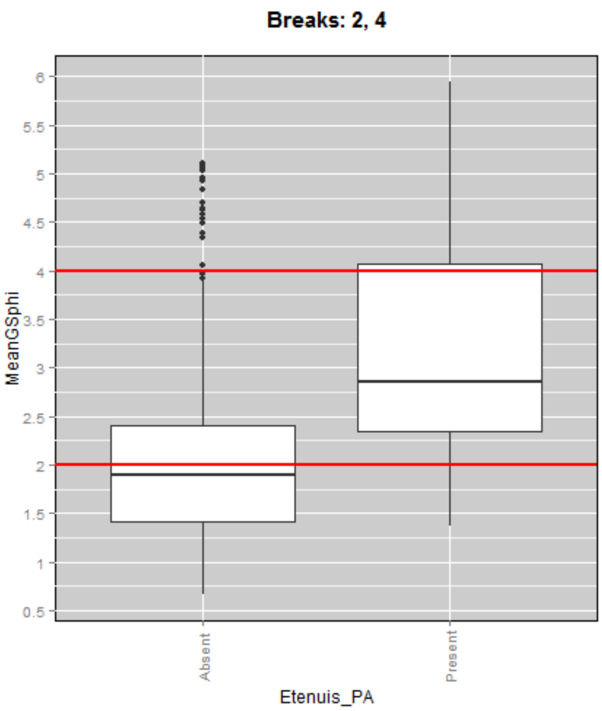


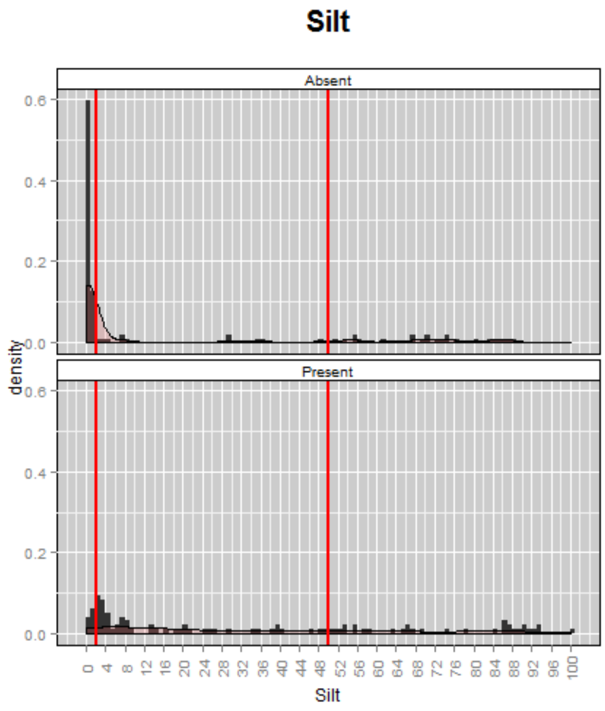
Appendix 6.1.4 *Ennucula tenuis*

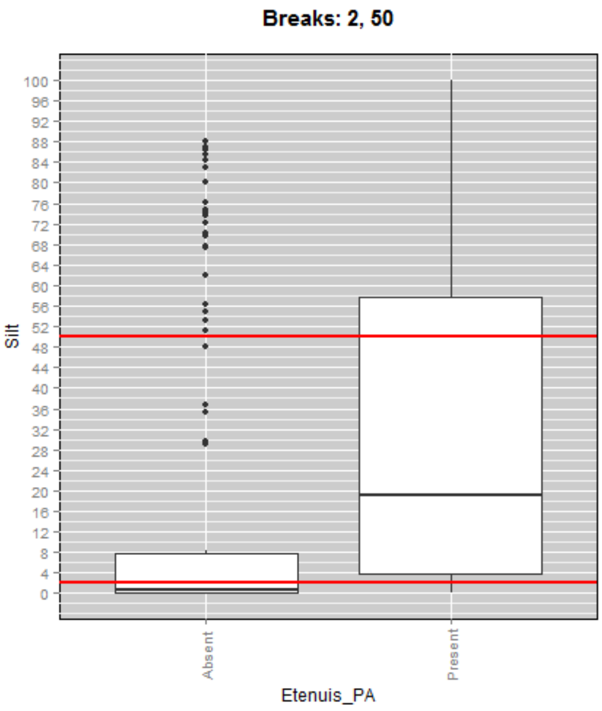


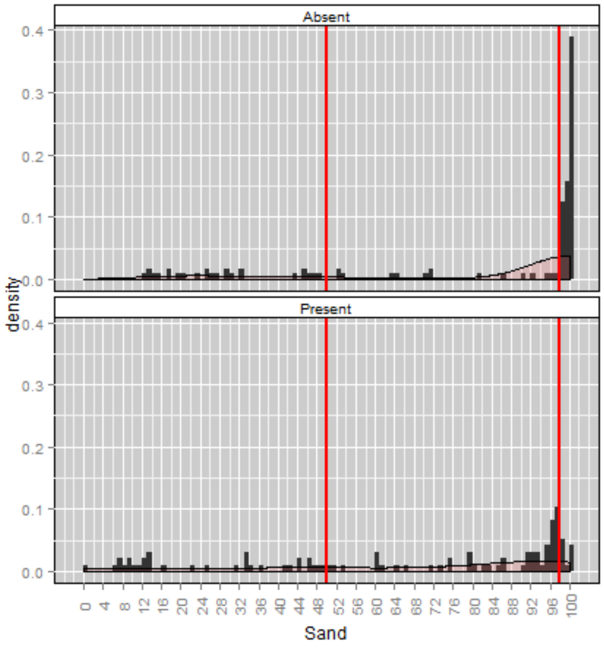



Grain Size

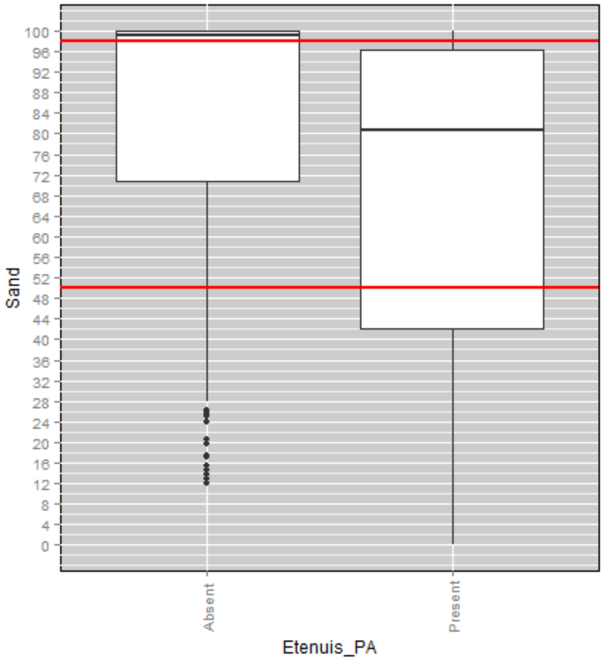

Breaks: 2, 4


Silt

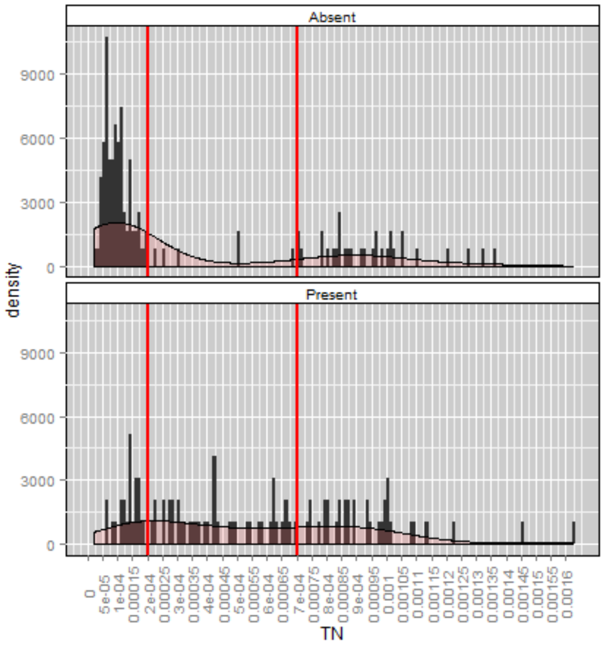

Breaks: 2, 50



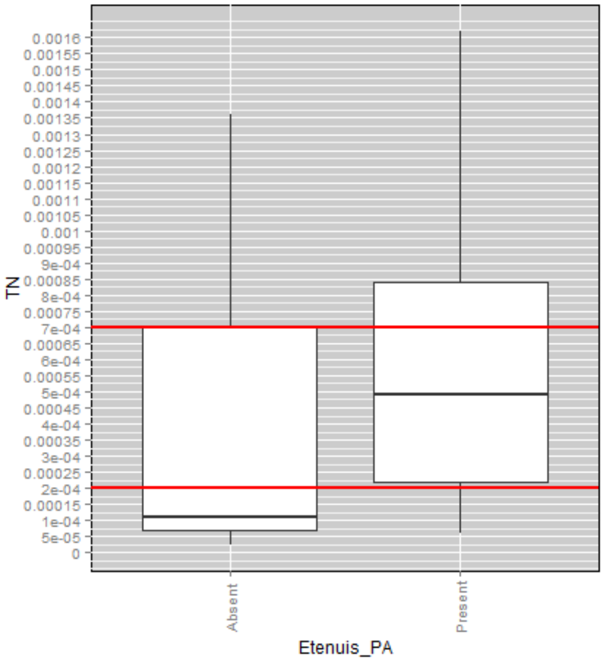
Sand



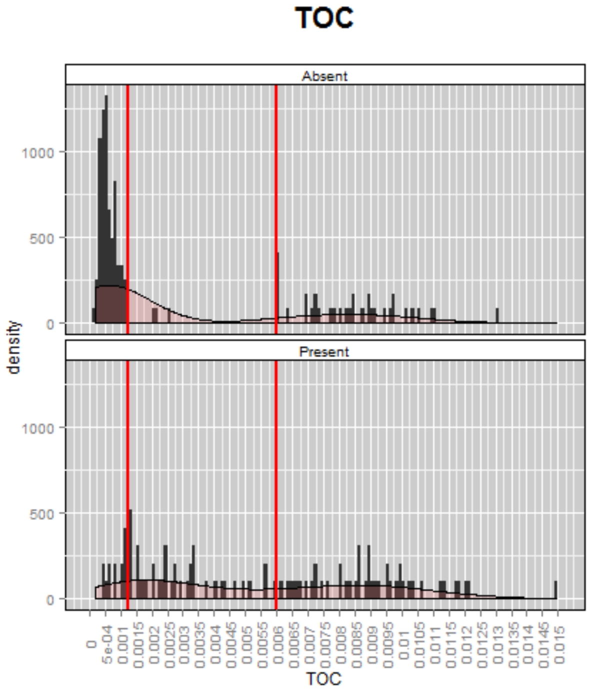
Breaks: 50, 98

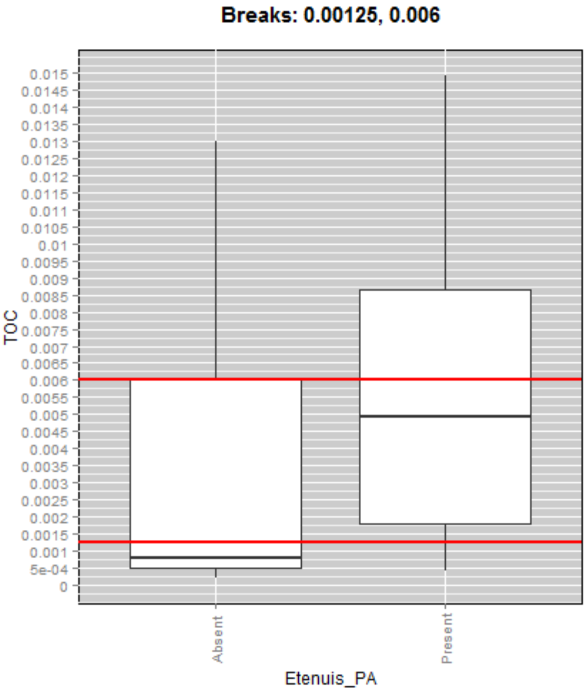


TN

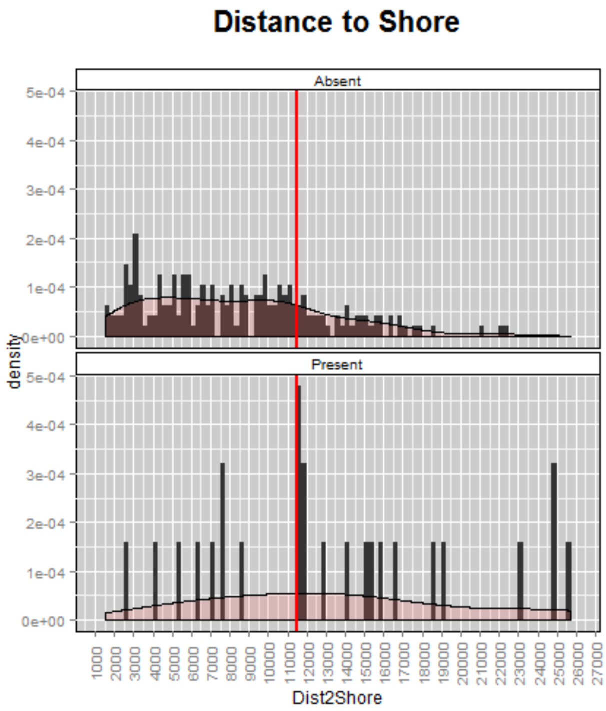


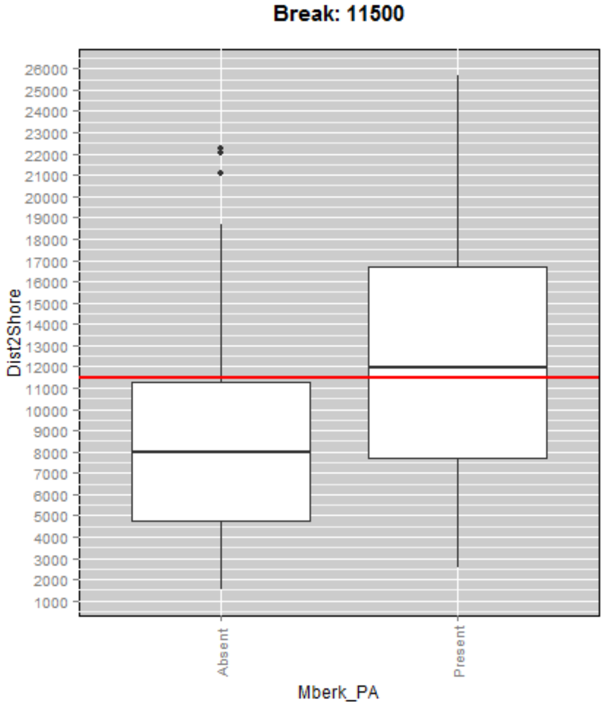
Breaks: 0.0002, 0.0007

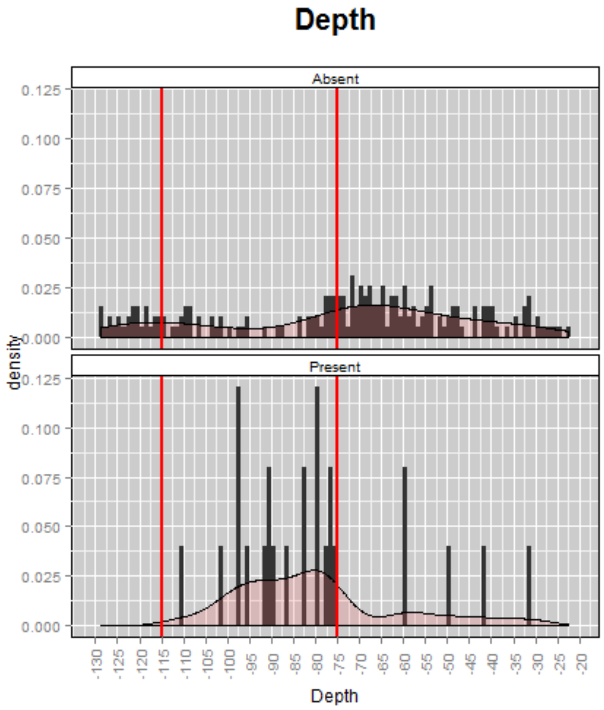

TOC
Absent
Present
density
1000
500
0
0
5e-04
0.001
0.0015
0.002
0.0025
0.003
0.0035
0.004
0.0045
0.005
0.0055
0.006
0.0065
0.007
0.0075
0.008
0.0085
0.009
0.0095
0.01
0.0105
0.011
0.0115
0.012
0.0125
0.013
0.0135
0.014
0.0145
0.015
TOC

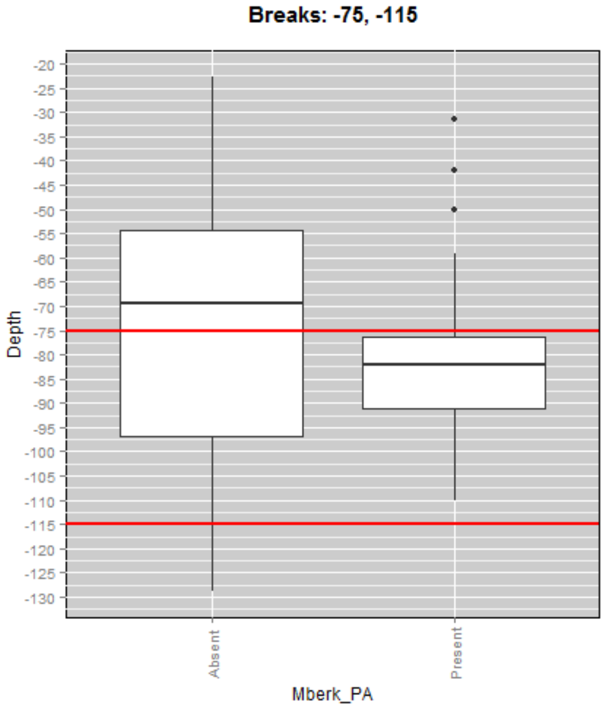

Breaks: 0.00125, 0.006
TOC
0.015
0.0145
0.014
0.0135
0.013
0.0125
0.012
0.0115
0.011
0.0105
0.01
0.0095
0.009
0.0085
0.008
0.0075
0.007
0.0065
0.006
0.0055
0.005
0.0045
0.004
0.0035
0.003
0.0025
0.002
0.0015
0.001
5e-04
0
Absent
Present
Etenuis_PA

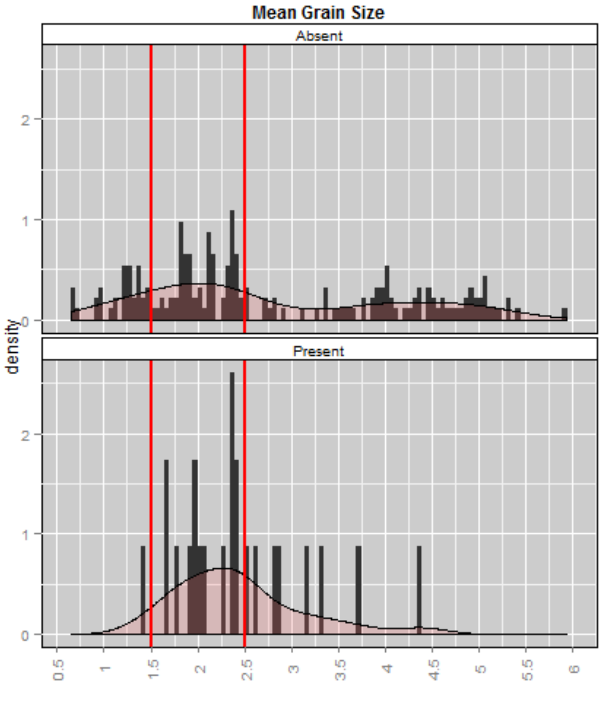
Appendix 6.1.5 *Magelona berkeleyi*

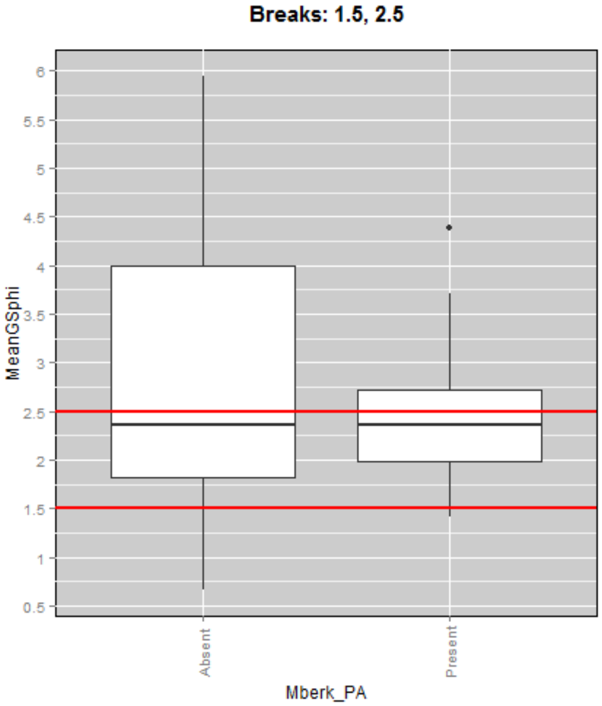


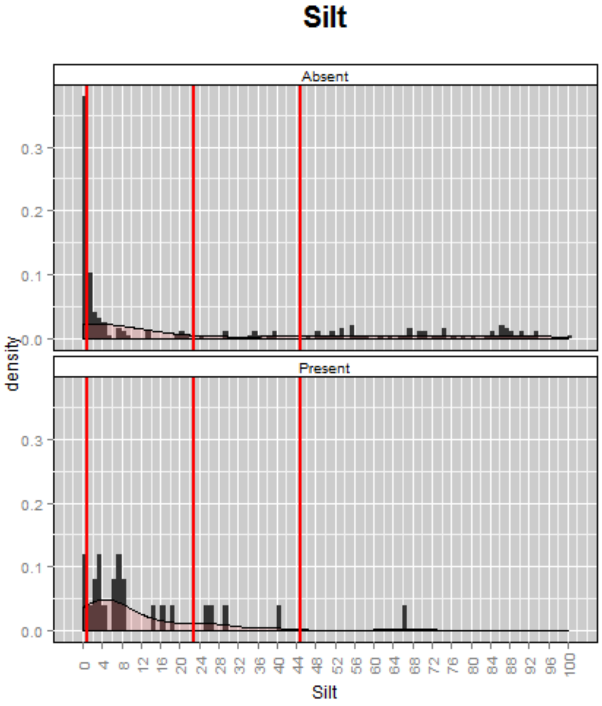


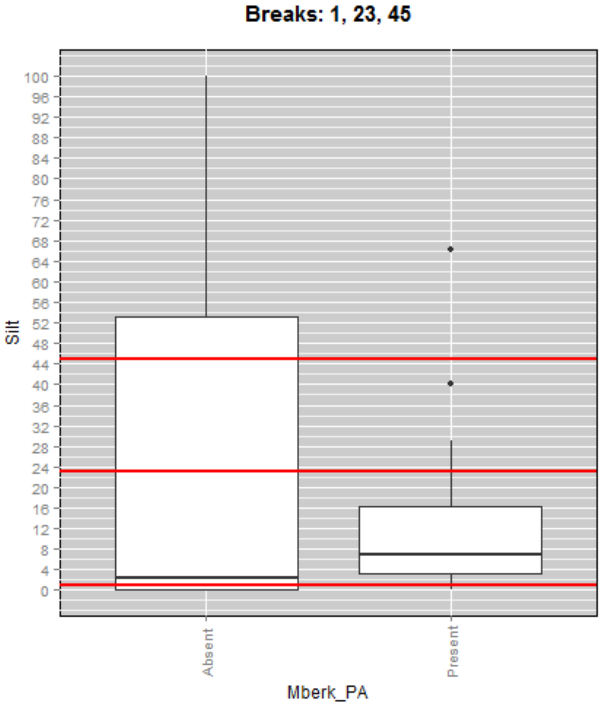


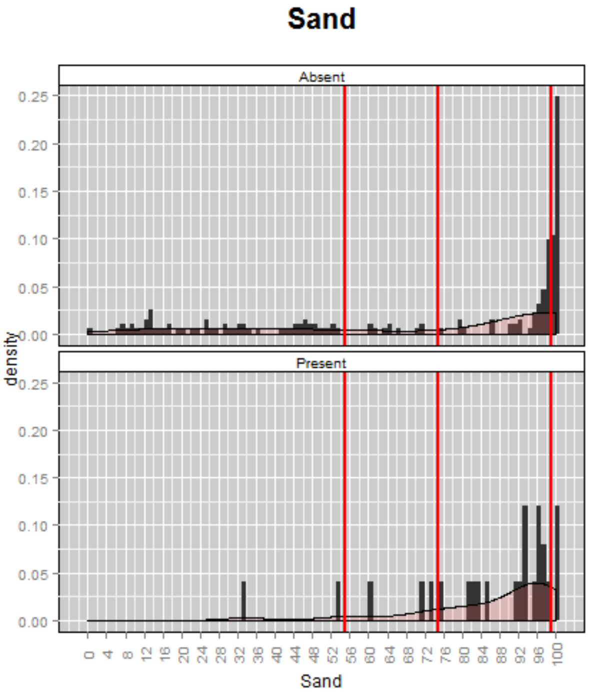


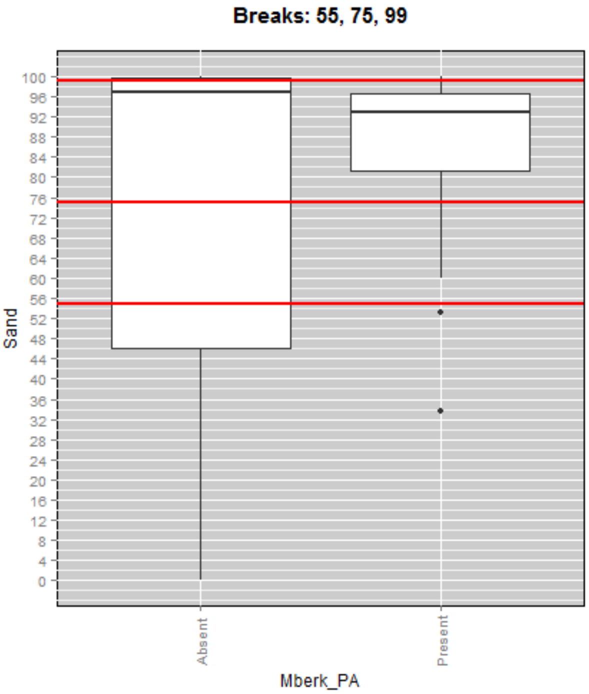

Mean Grain Size
Absent
Present
density
0
1
2
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6

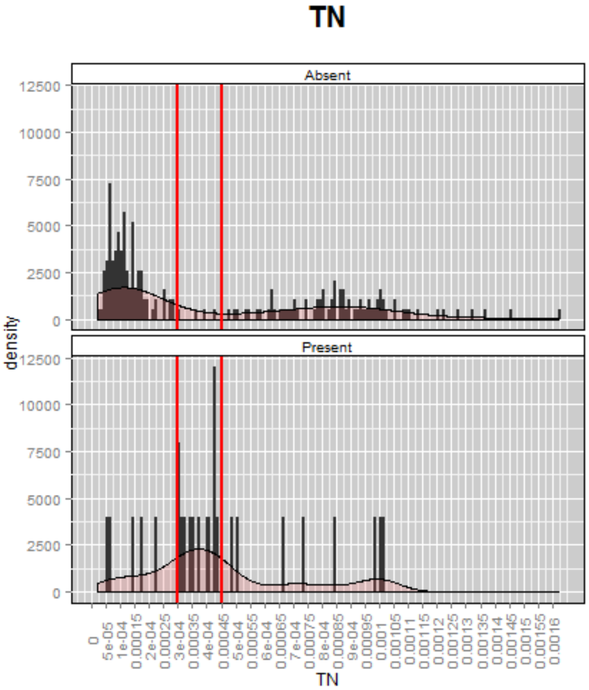

Breaks: 1.5, 2.5
MeanGSphi
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
Absent
Present
Mberk_PA

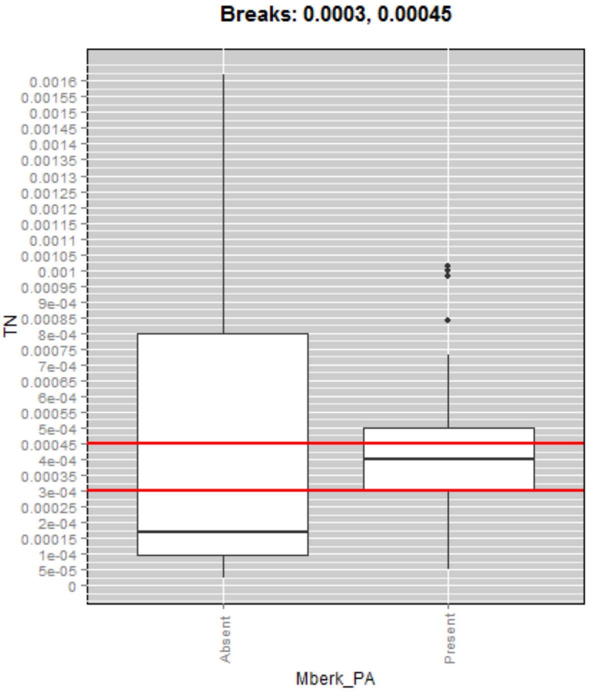

Silt
Absent
Present
density
0.0
0.1
0.2
0.3
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
84
88
92
96
100
Silt

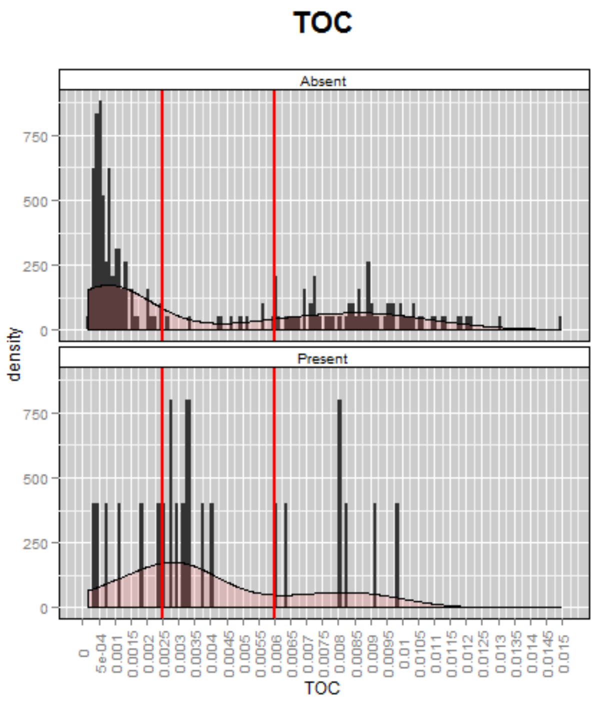

Breaks: 1, 23, 45
Silt
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
84
88
92
96
100
Absent
Present
Mberk_PA

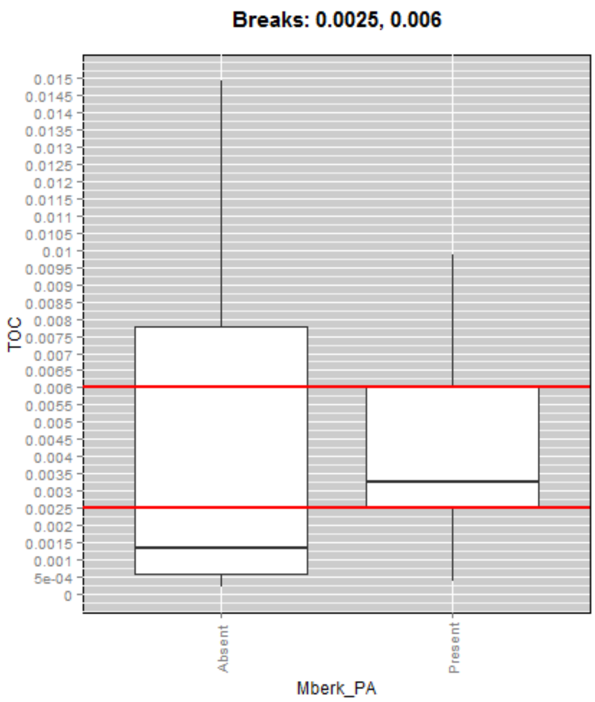

Sand
Absent
Present
density
0.25
0.20
0.15
0.10
0.05
0.00
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
84
88
92
96
100
Sand


Breaks: 55, 75, 99
Sand
100
96
92
88
84
80
76
72
68
64
60
56
52
48
44
40
36
32
28
24
20
16
12
8
4
0
Absent
Present
Mberk_PA

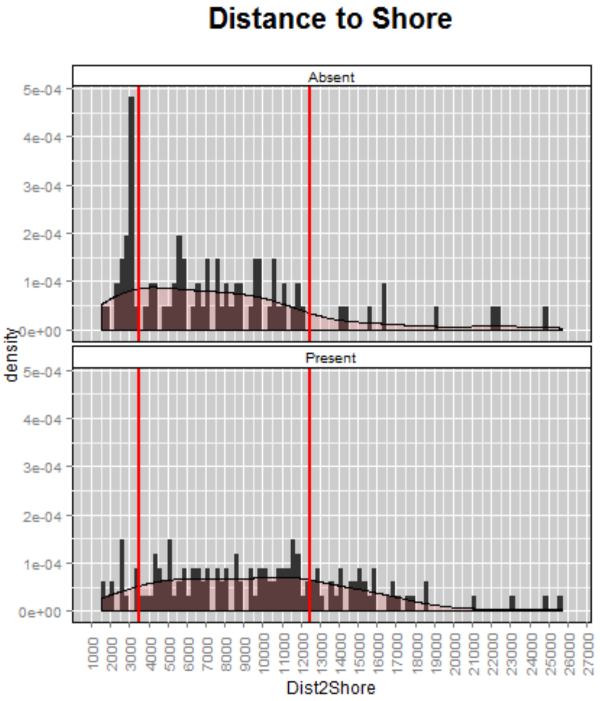

TN
Absent
Present
density
12500
10000
7500
5000
2500
0
0
5e-05
1e-04
0.00015
2e-04
0.00025
3e-04
0.00035
4e-04
0.00045
5e-04
0.00055
6e-04
0.00065
7e-04
0.00075
8e-04
0.00085
9e-04
0.00095
0.001
0.00105
0.0011
0.00115
0.0012
0.00125
0.0013
0.00135
0.0014
0.00145
0.0015
0.00155
0.0016
TN

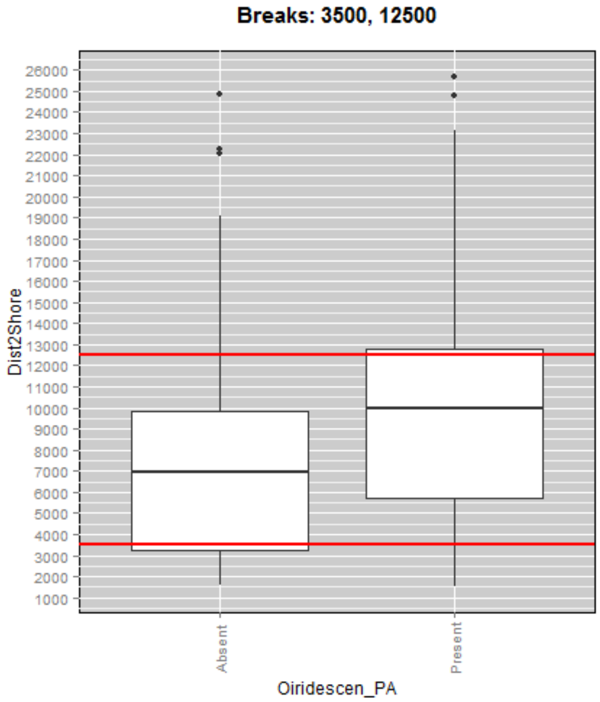

Breaks: 0.0003, 0.00045
TN
0.0016
0.00155
0.0015
0.00145
0.0014
0.00135
0.0013
0.00125
0.0012
0.00115
0.0011
0.00105
0.001
0.00095
9e-04
0.00085
8e-04
0.00075
7e-04
0.00065
6e-04
0.00055
5e-04
0.00045
4e-04
0.00035
3e-04
0.00025
2e-04
0.00015
1e-04
5e-05
0
Absent
Present
Mberk_PA

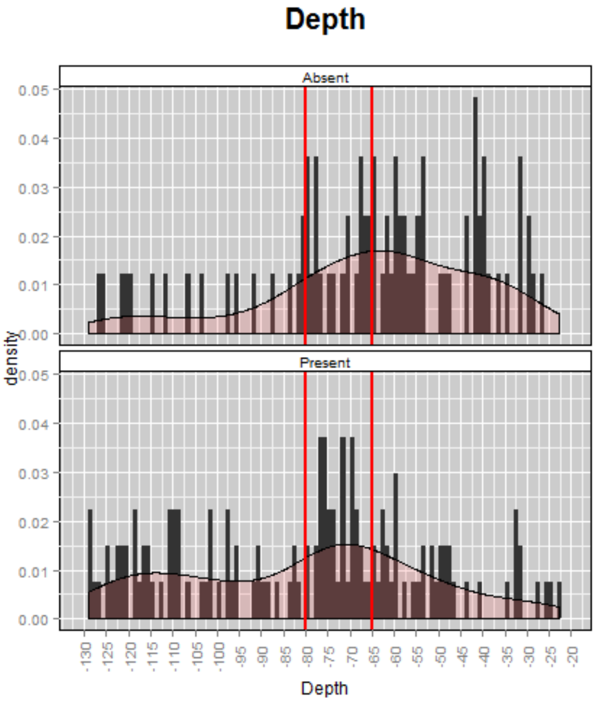

TOC
Absent
Present
density
750
500
250
0
TOC
0
5e-04
0.001
0.0015
0.002
0.0025
0.003
0.0035
0.004
0.0045
0.005
0.0055
0.006
0.0065
0.007
0.0075
0.008
0.0085
0.009
0.0095
0.01
0.0105
0.011
0.0115
0.012
0.0125
0.013
0.0135
0.014
0.0145
0.015

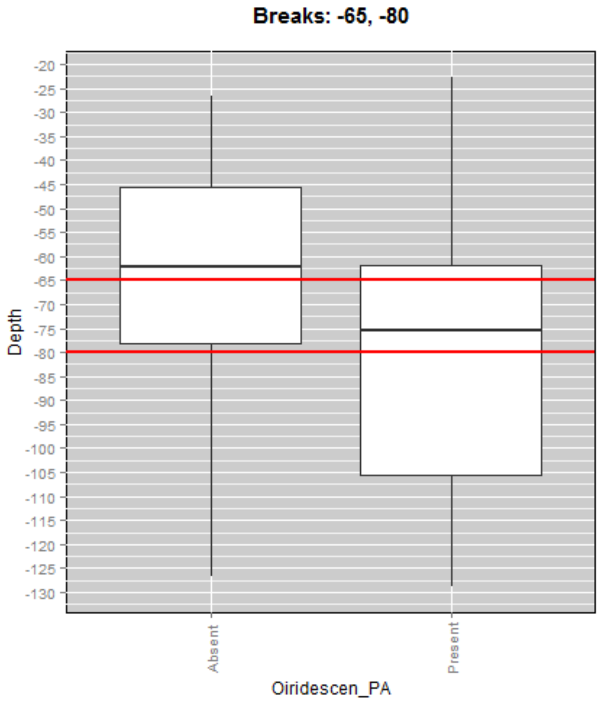

Breaks: 0.0025, 0.006
TOC
0.015
0.0145
0.014
0.0135
0.013
0.0125
0.012
0.0115
0.011
0.0105
0.01
0.0095
0.009
0.0085
0.008
0.0075
0.007
0.0065
0.006
0.0055
0.005
0.0045
0.004
0.0035
0.003
0.0025
0.002
0.0015
0.001
5e-04
0
Absent
Present
Mberk_PA

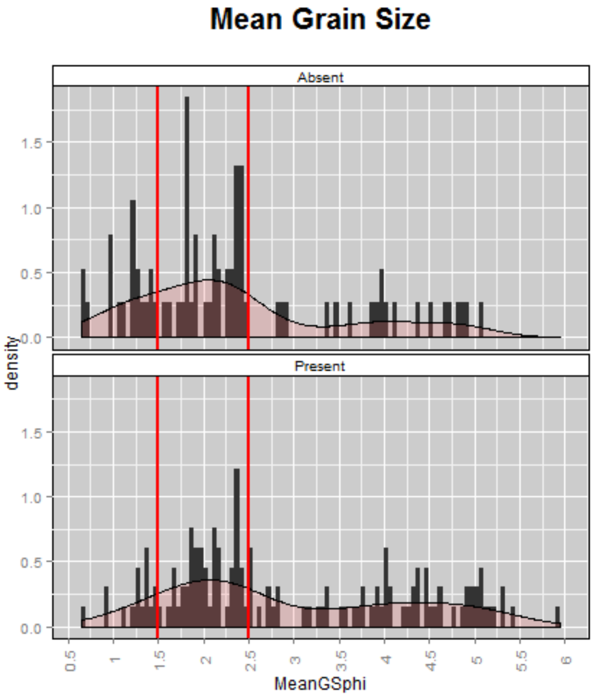
Appendix 6.1.6 *Onuphis iridescens*

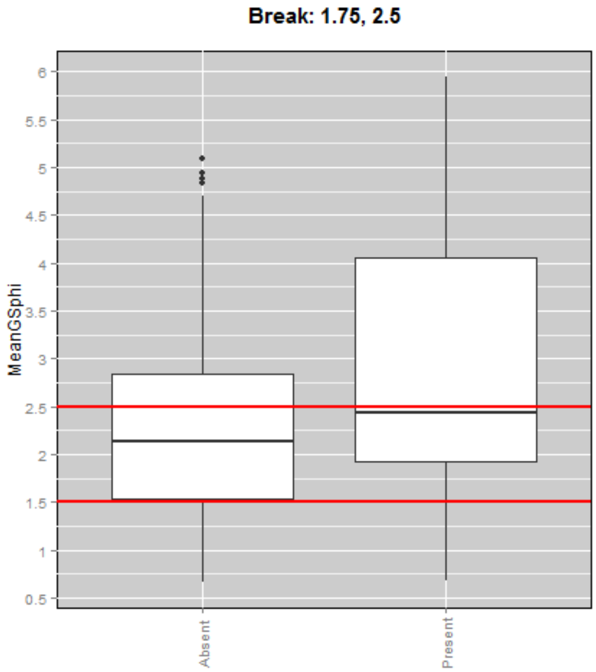


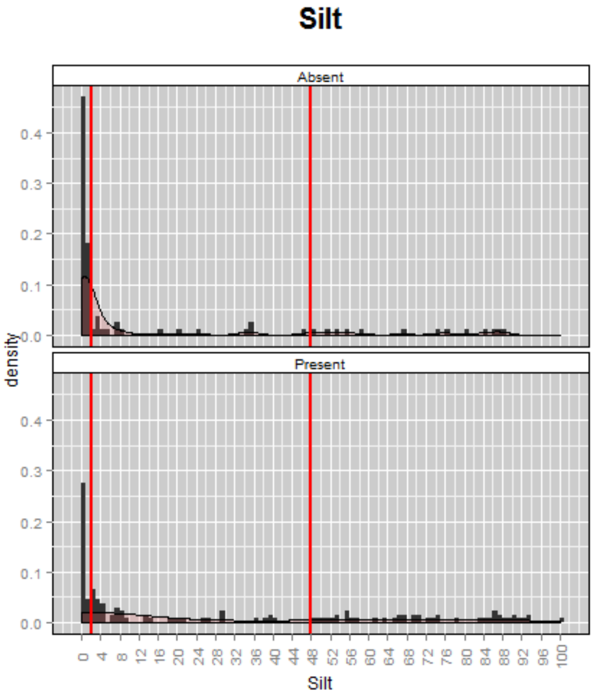


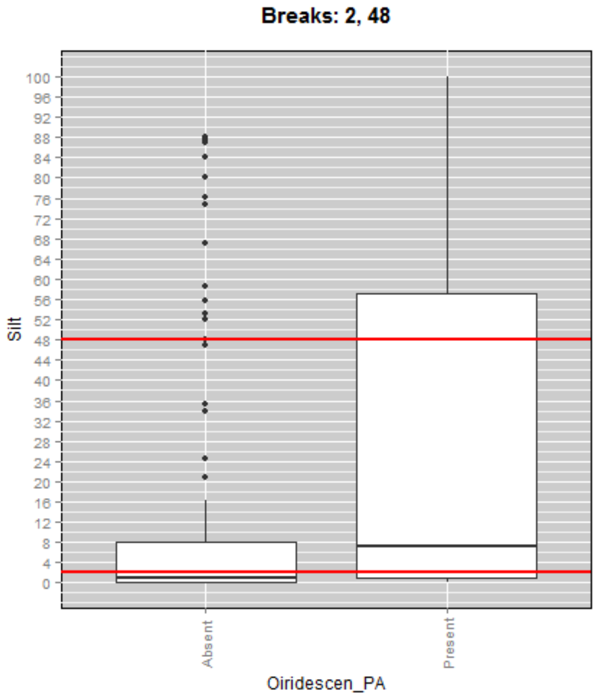


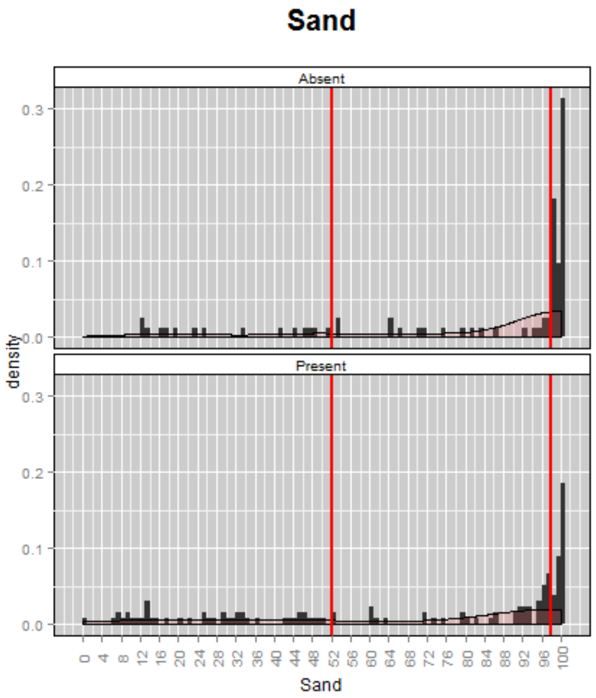


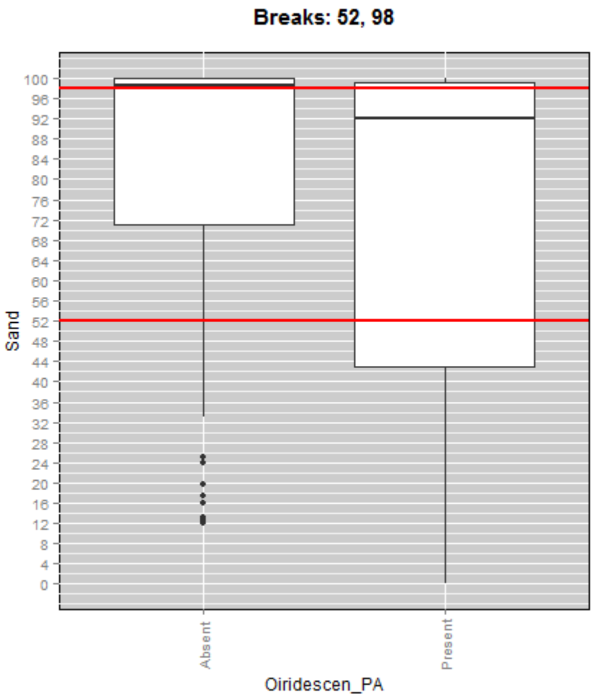

Mean Grain Size
Absent
Present
density
0.0
0.5
1.0
1.5
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
MeanGSphi

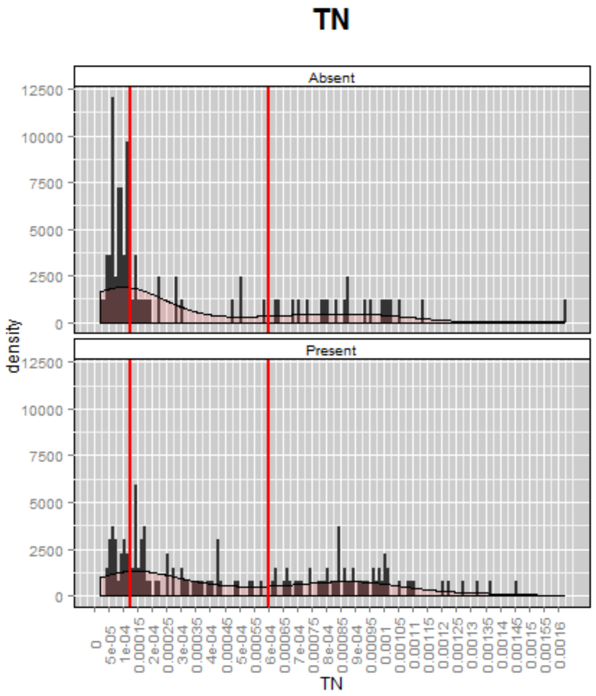

Break: 1.75, 2.5
MeanGSphi
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
Absent
Present
Oiridescen_PA

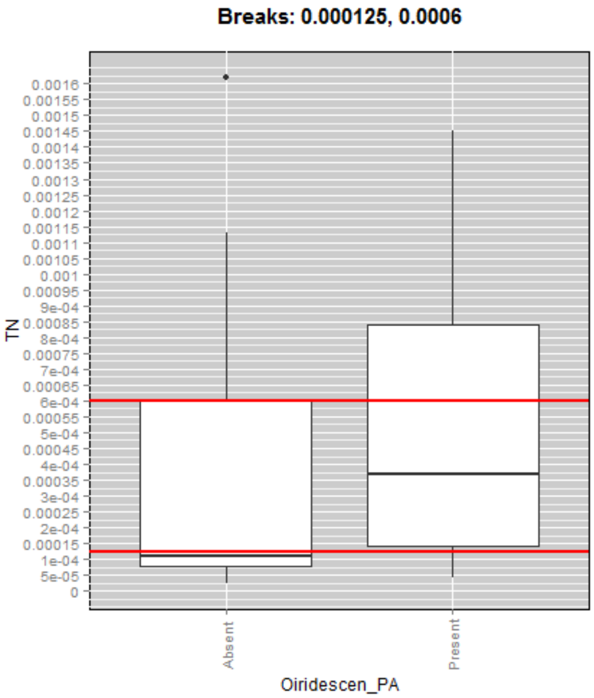

Silt
Absent
Present
density
0.0
0.1
0.2
0.3
0.4
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
84
88
92
96
100
Silt

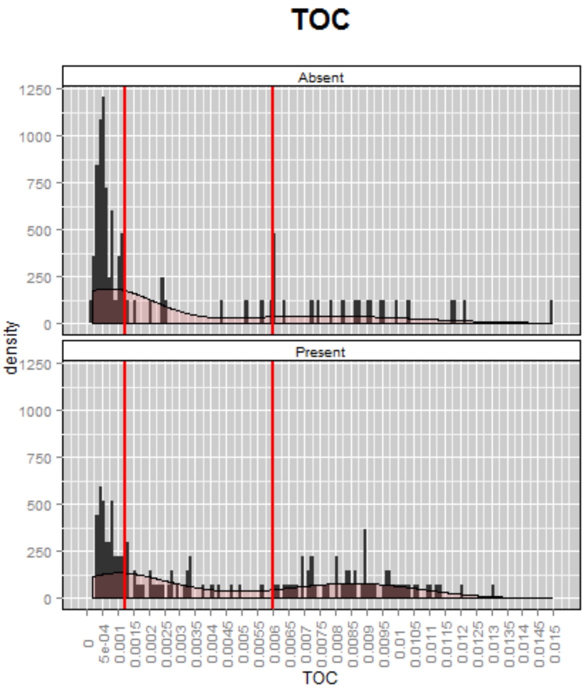

Breaks: 2, 48
Silt
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
84
88
92
96
100
Absent
Present
Oiridescen_PA

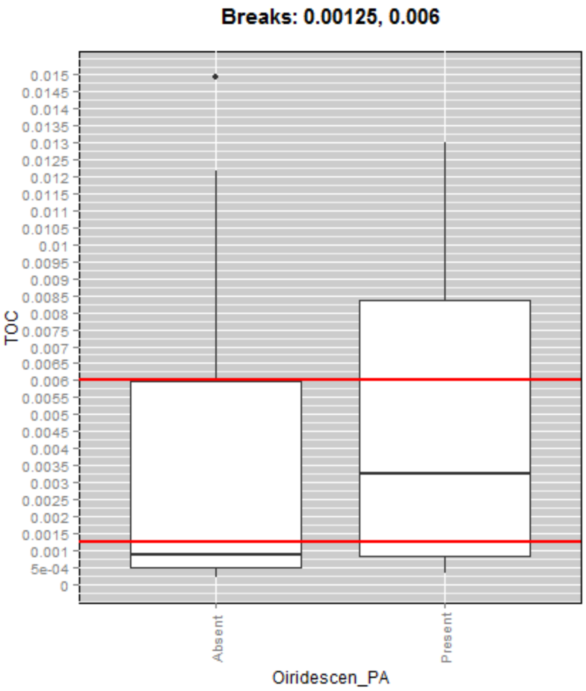

Sand
Absent
Present
density
0.0
0.1
0.2
0.3
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60 64 68 72 76 80 84 88 92 96 100
Sand


Breaks: 52, 98
Sand
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60 64 68 72 76 80 84 88 92 96 100
Absent
Present
Oiridescen_PA

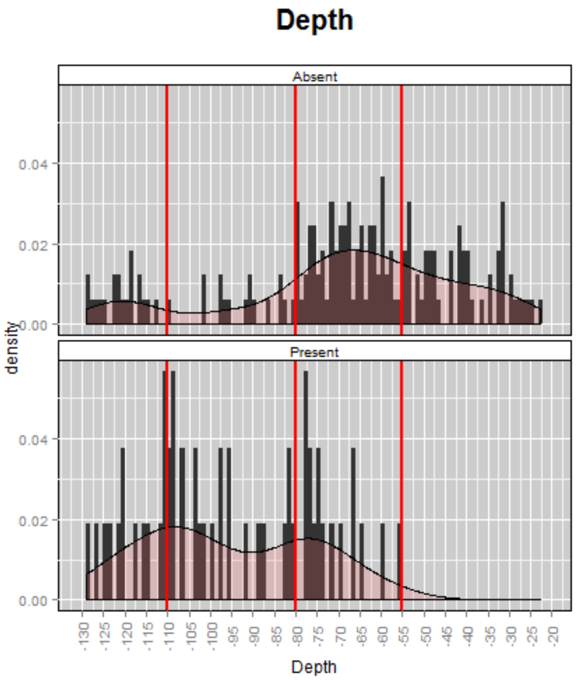

TN
Absent
Present
density
0
2500
5000
7500
10000
12500
0 5e-05 1e-04 0.00015 2e-04 0.00025 3e-04 0.00035 4e-04 0.00045 5e-04 0.00055 6e-04 0.00065 7e-04 0.00075 8e-04 0.00085 9e-04 0.00095 0.001 0.00105 0.0011 0.00115 0.0012 0.00125 0.0013 0.00135 0.0014 0.00145 0.0015 0.00155 0.0016
TN

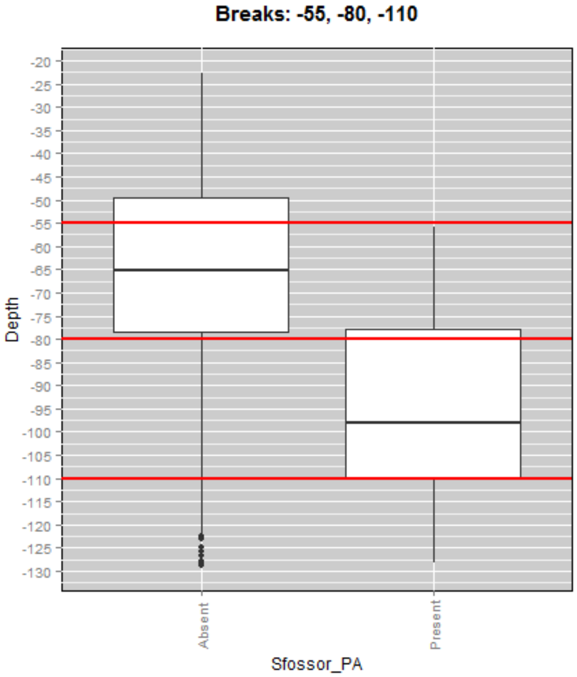

Breaks: 0.000125, 0.0006
TN
0 5e-05 1e-04 0.00015 2e-04 0.00025 3e-04 0.00035 4e-04 0.00045 5e-04 0.00055 6e-04 0.00065 7e-04 0.00075 8e-04 0.00085 9e-04 0.00095 0.001 0.00105 0.0011 0.00115 0.0012 0.00125 0.0013 0.00135 0.0014 0.00145 0.0015 0.00155 0.0016
Absent
Present
Oiridescen_PA

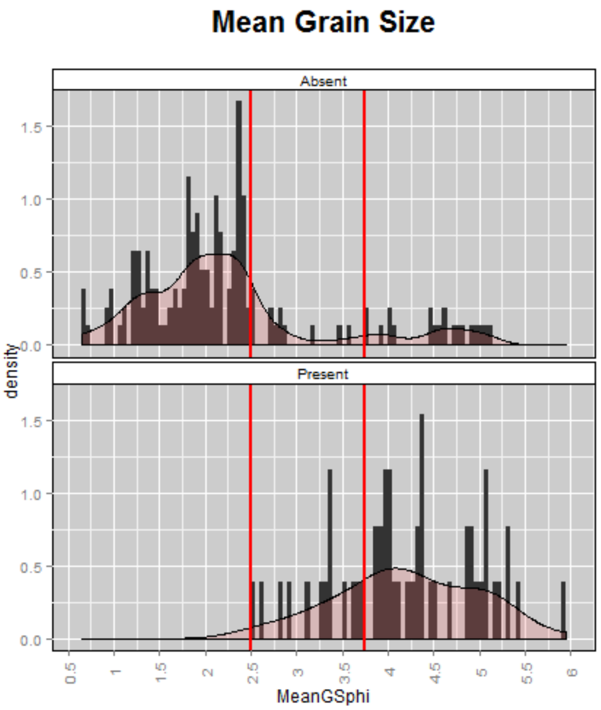

TOC
Absent
Present
density
1250
1000
750
500
250
0
TOC
0
5e-04
0.001
0.0015
0.002
0.0025
0.003
0.0035
0.004
0.0045
0.005
0.0055
0.006
0.0065
0.007
0.0075
0.008
0.0085
0.009
0.0095
0.01
0.0105
0.011
0.0115
0.012
0.0125
0.013
0.0135
0.014
0.0145
0.015


Breaks: 0.00125, 0.006
TOC
0.015
0.0145
0.014
0.0135
0.013
0.0125
0.012
0.0115
0.011
0.0105
0.01
0.0095
0.009
0.0085
0.008
0.0075
0.007
0.0065
0.006
0.0055
0.005
0.0045
0.004
0.0035
0.003
0.0025
0.002
0.0015
0.001
5e-04
0
Absent
Present
Oiridescen_PA

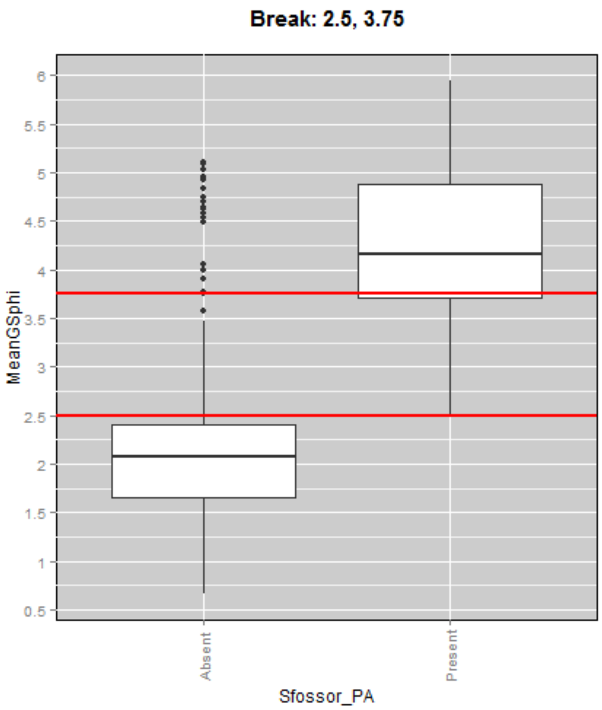
Appendix 6.1.7 *Sternaspis fossor*


Depth

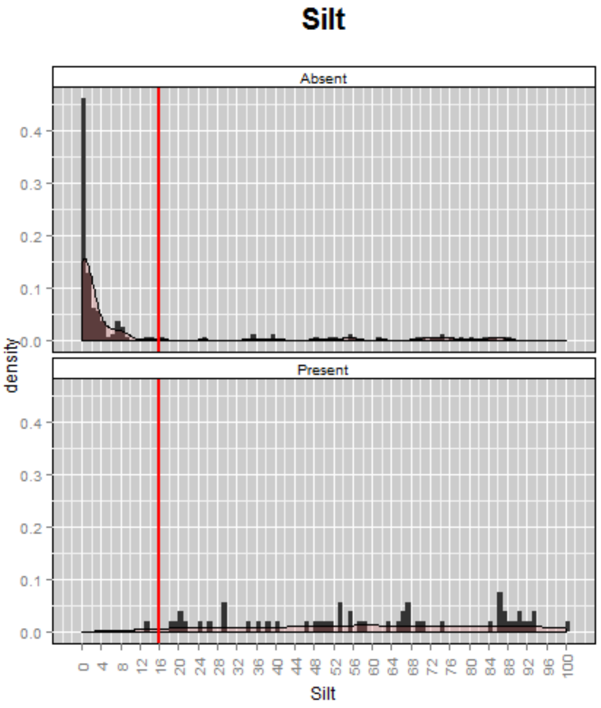

Breaks: -55, -80, -110



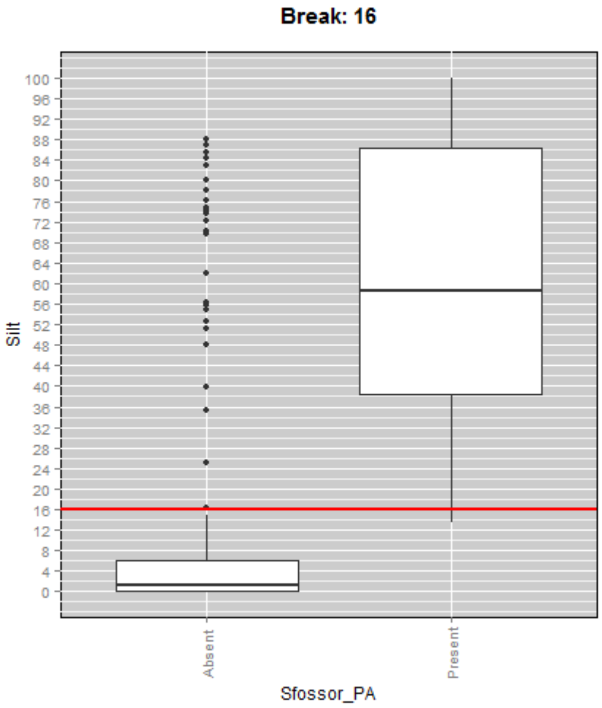
Mean Grain Size



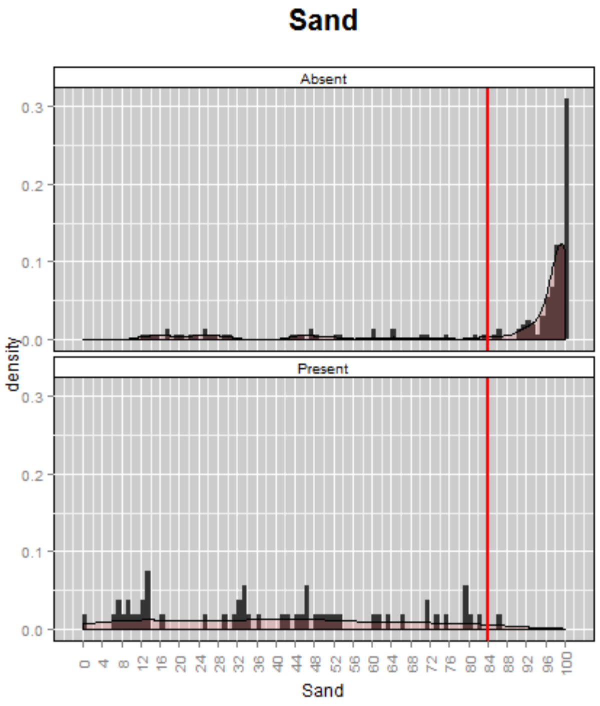
Break: 2.5, 3.75

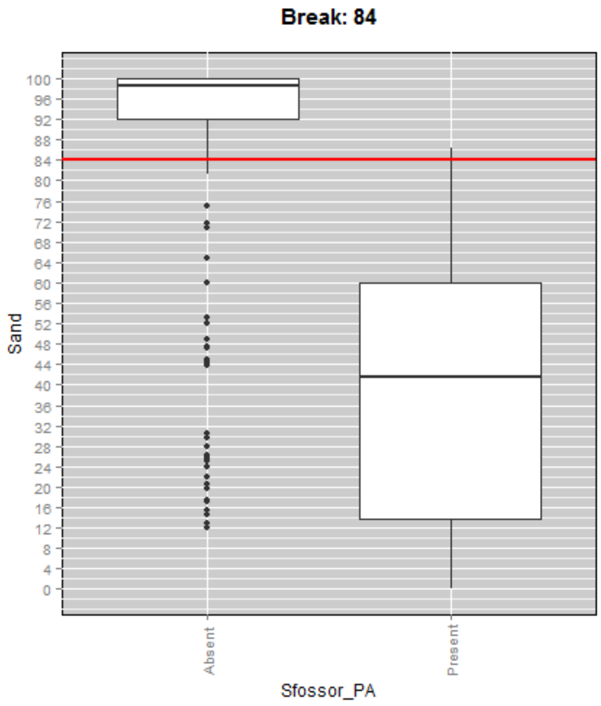


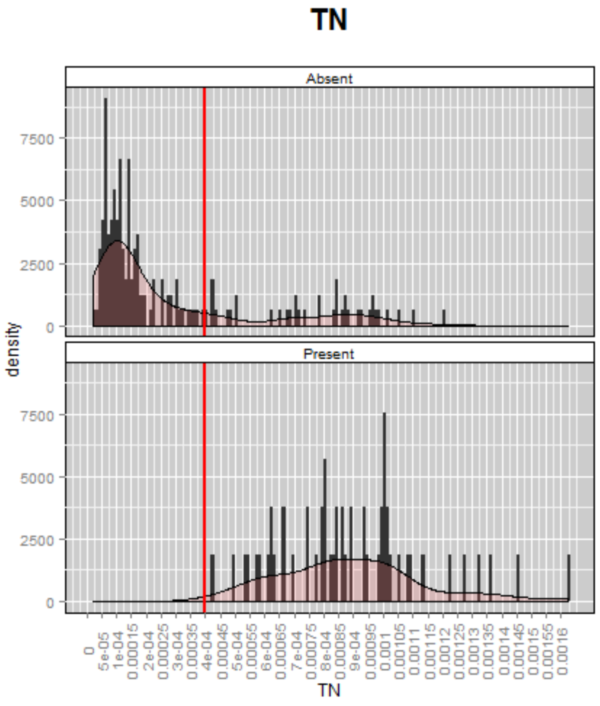
Silt

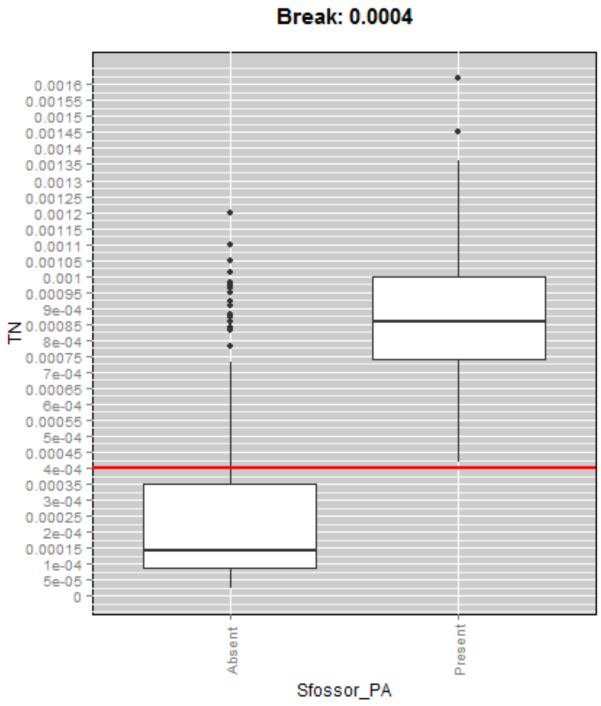


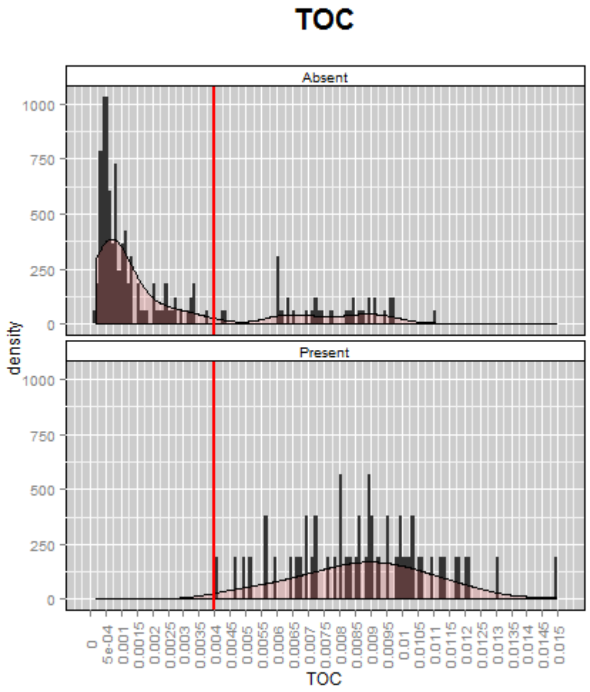
Break: 16

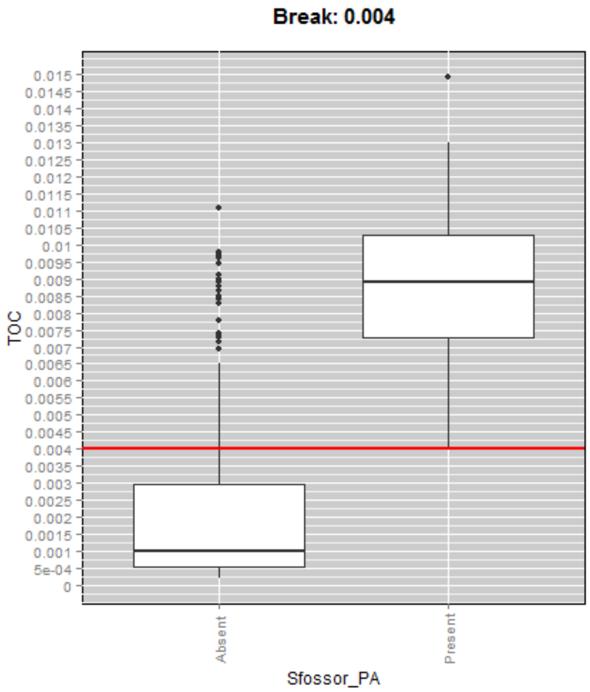

Sand
Absent
Present
density
0.0
0.1
0.2
0.3
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60 64 68 72 76 80 84 88 92 96 100
Sand


Break: 84
Sand
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60 64 68 72 76 80 84 88 92 96 100
Absent
Present
Sfossor_PA


TN
Absent
Present
density
0
2500
5000
7500
0 5e-05 1e-04 0.00015 2e-04 0.00025 3e-04 0.00035 4e-04 0.00045 5e-04 0.00055 6e-04 0.00065 7e-04 0.00075 8e-04 0.00085 9e-04 0.00095 0.001 0.00105 0.0011 0.00115 0.0012 0.00125 0.0013 0.00135 0.0014 0.00145 0.0015 0.00155 0.0016
TN

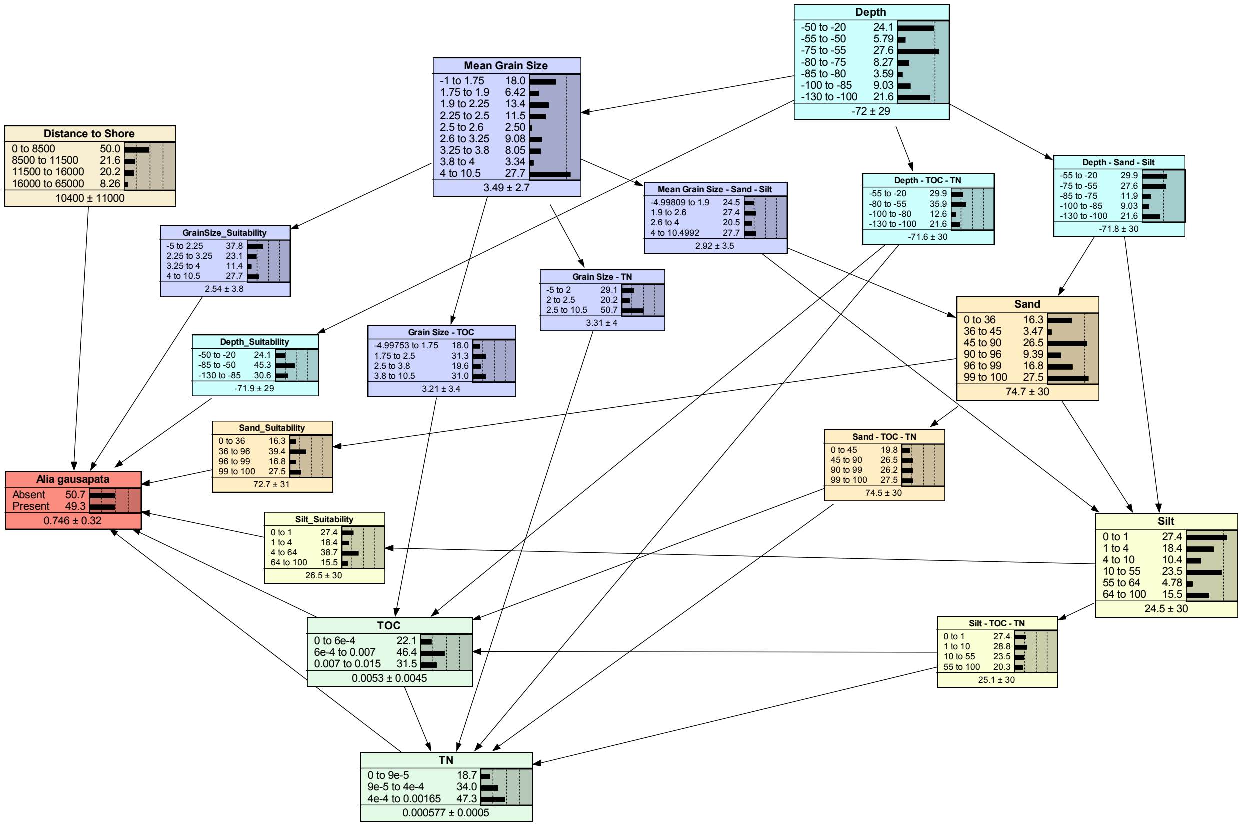

Break: 0.0004
TN
0 5e-05 1e-04 0.00015 2e-04 0.00025 3e-04 0.00035 4e-04 0.00045 5e-04 0.00055 6e-04 0.00065 7e-04 0.00075 8e-04 0.00085 9e-04 0.00095 0.001 0.00105 0.0011 0.00115 0.0012 0.00125 0.0013 0.00135 0.0014 0.00145 0.0015 0.00155 0.0016
Absent
Present
Sfossor_PA


TOC
Absent
Present
density
1000
750
500
250
0
TOC
0
5e-04
0.001
0.0015
0.002
0.0025
0.003
0.0035
0.004
0.0045
0.005
0.0055
0.006
0.0065
0.007
0.0075
0.008
0.0085
0.009
0.0095
0.01
0.0105
0.011
0.0115
0.012
0.0125
0.013
0.0135
0.014
0.0145
0.015

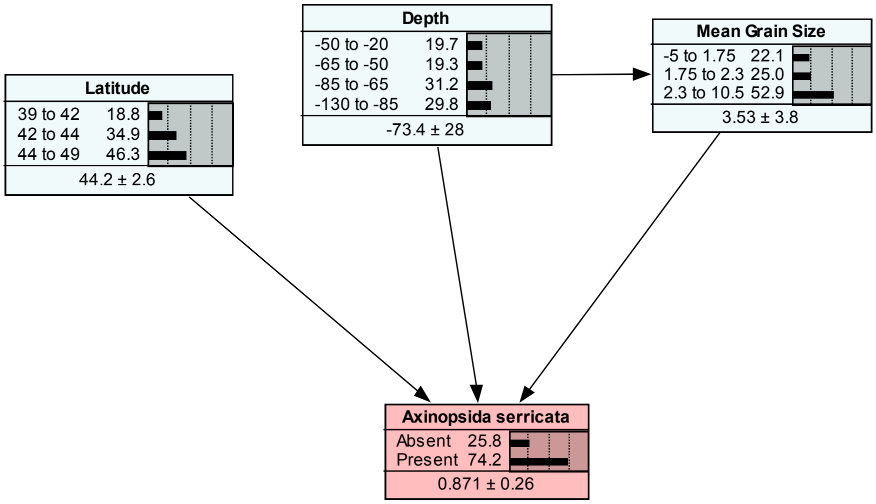

Break: 0.004
TOC
0.015
0.0145
0.014
0.0135
0.013
0.0125
0.012
0.0115
0.011
0.0105
0.01
0.0095
0.009
0.0085
0.008
0.0075
0.007
0.0065
0.006
0.0055
0.005
0.0045
0.004
0.0035
0.003
0.0025
0.002
0.0015
0.001
5e-04
0
Absent
Present
Sfossor_PA

Appendix 6.2 Bayesian Belief Networks

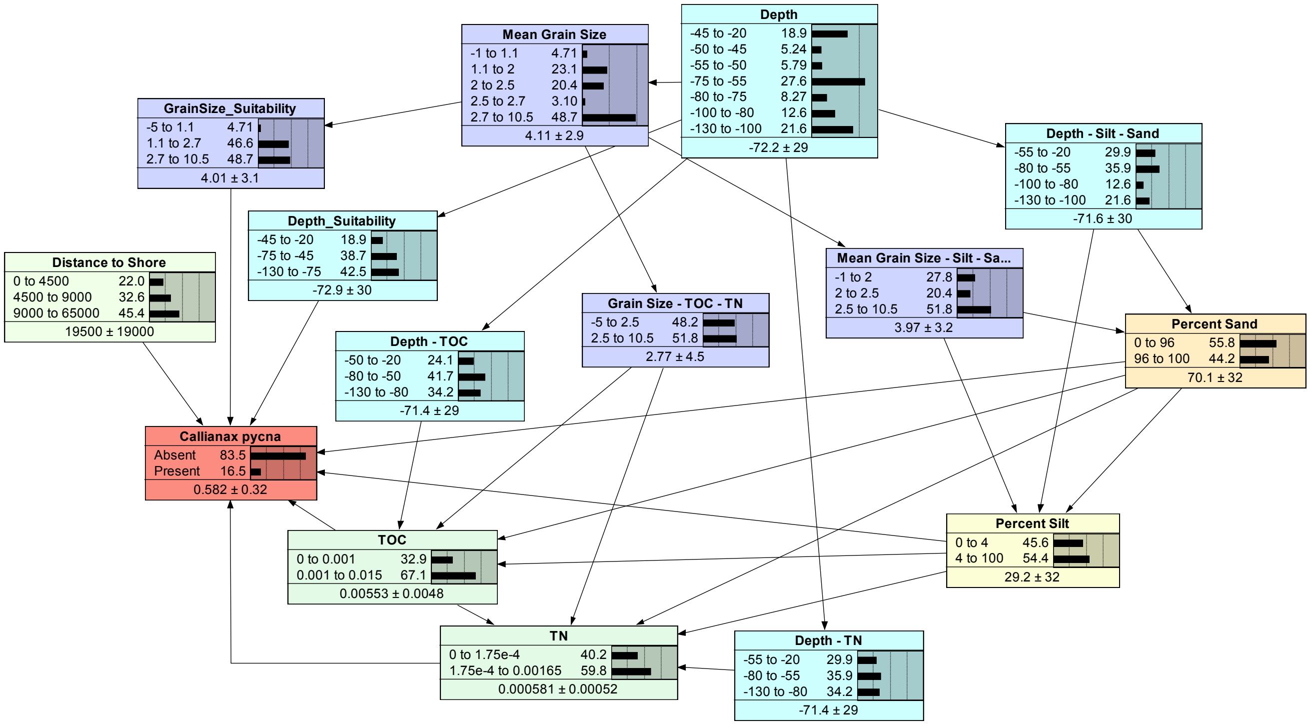
Appendix 6.2.1 *Alia gausapata*



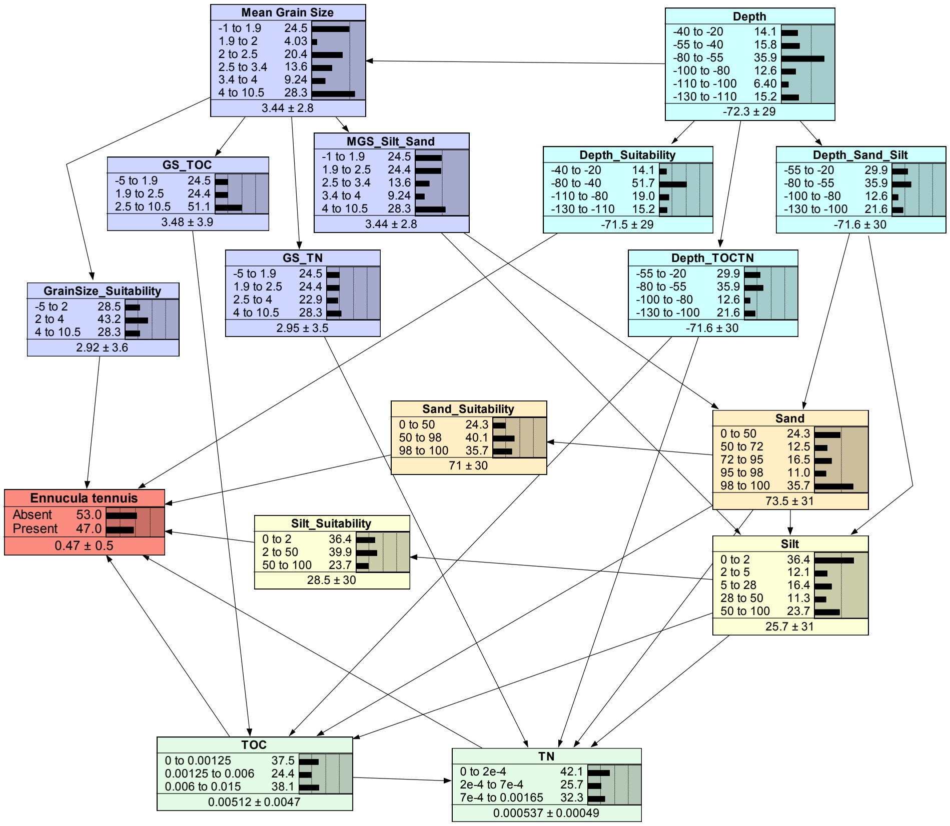
Appendix 6.2.2 *Axinopsida serricata*



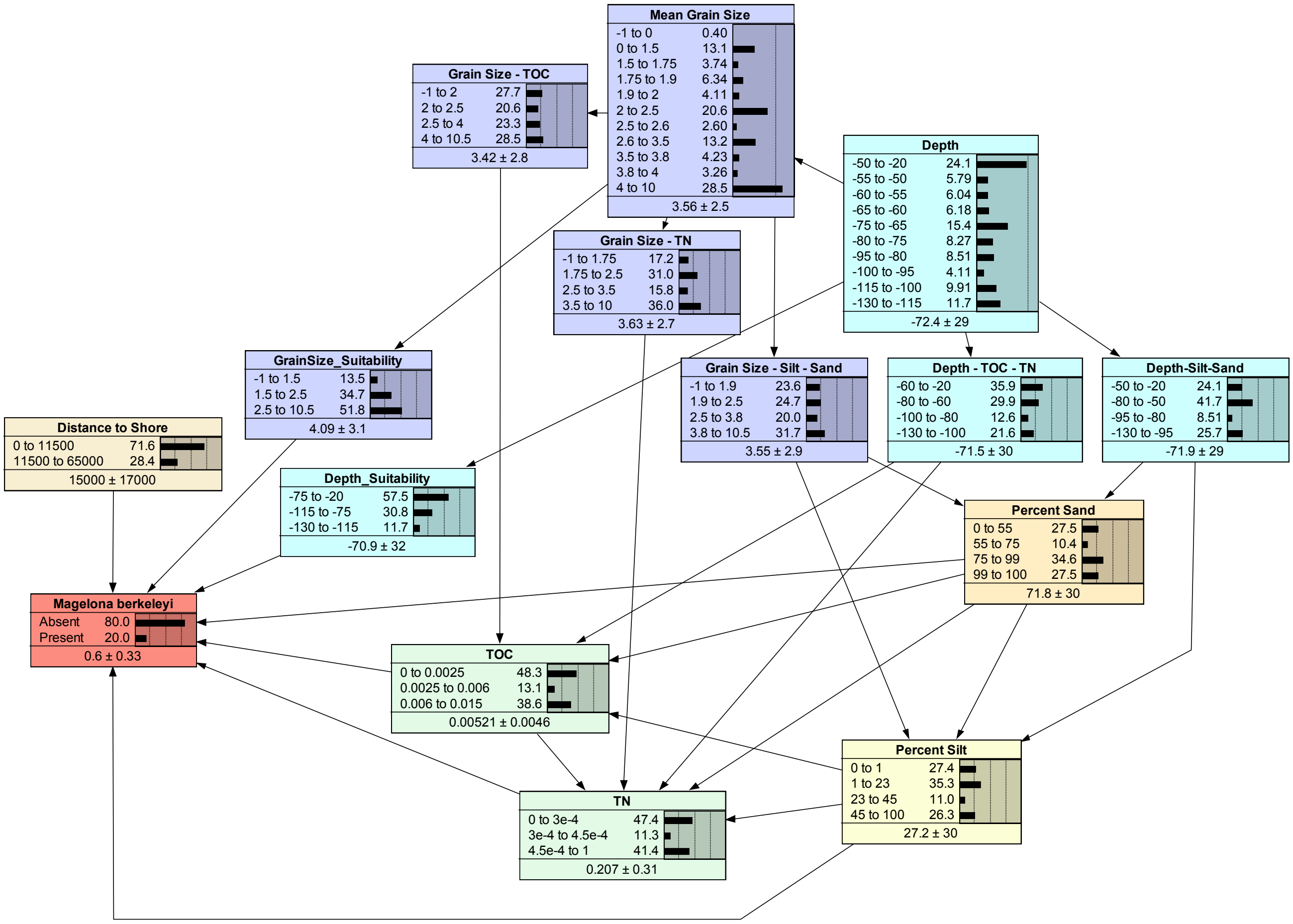
Appendix 6.2.3 *Callianax pycna*



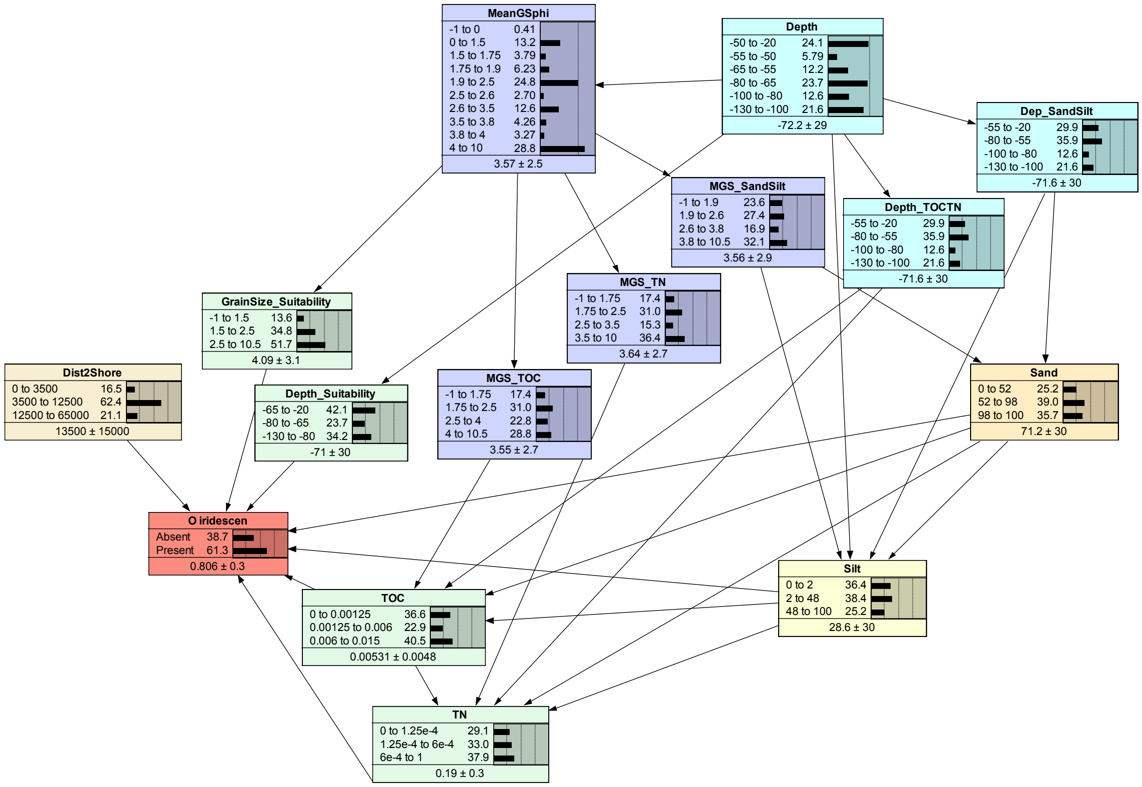
Appendix 6.2.4 *Ennucula tennuis*



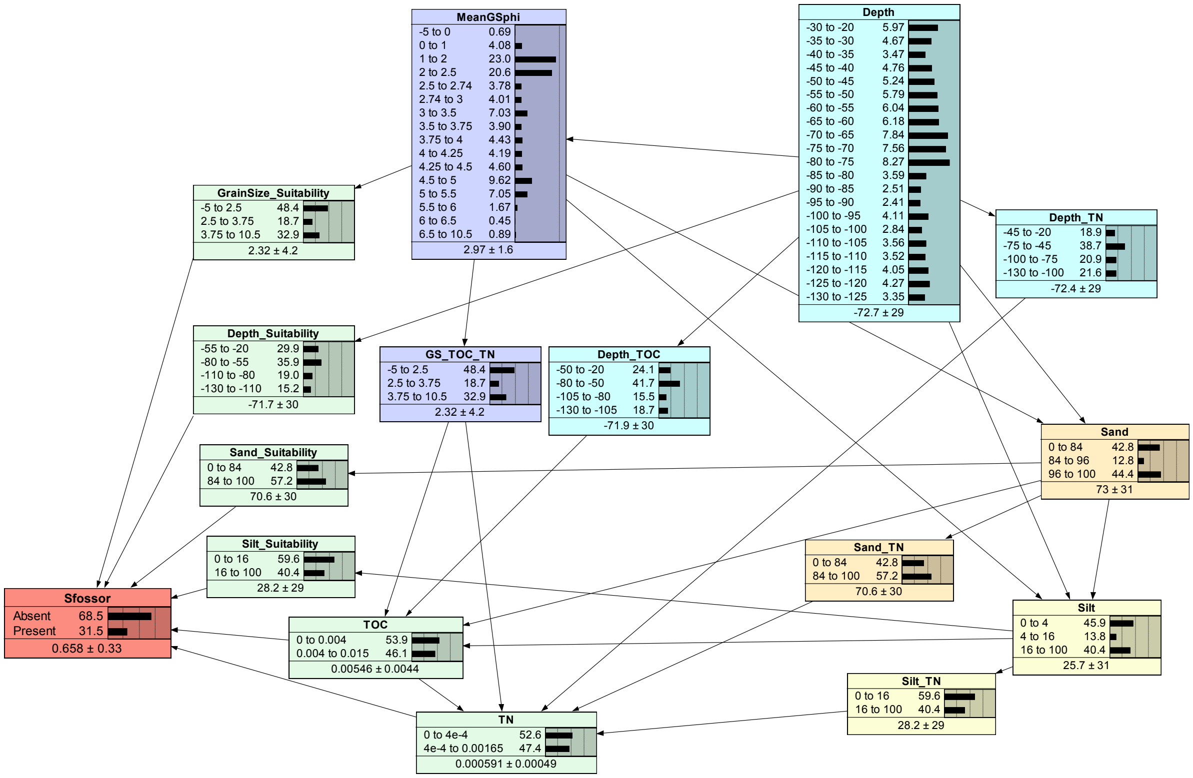
Appendix 6.2.5 *Magelona berkeleyi*



Appendix 6.2.6 *Onuphis iridescens*



Appendix 6.2.7 *Sternaspis fossor*



Appendix 6.3 Instructions to Update with New Information and Apply Net to New Species

Appendix 6.3.1 Update with New Information

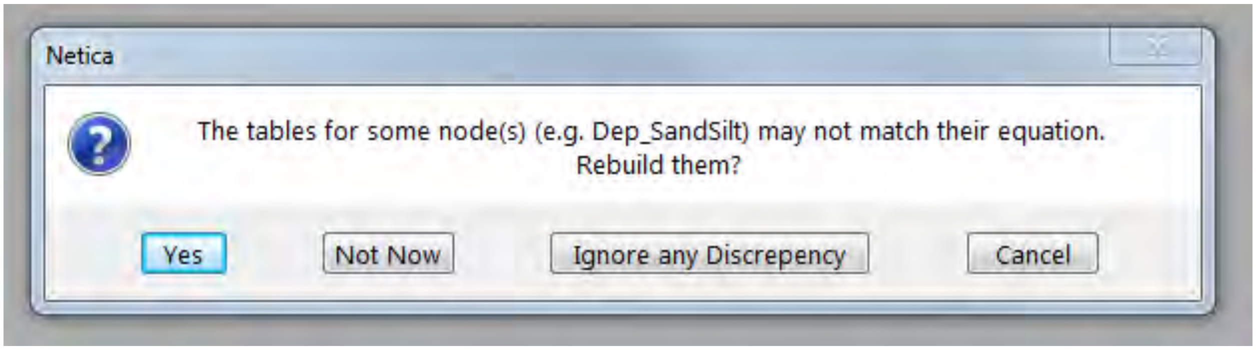
Step 1 – Set up case file

The case file is a.txt, .csv, or .xls (.xlsx will not work) with new species-environment data. Headings in case file must match the name of each corresponding node in the net. This will be verified in step 4.

Step 2 –Open Bayesian Belief Network (xxx.neta) in Netica® program.

Step 3 – If BBN has intermediate nodes with equations, the tables may need to be rebuilt upon opening the file. Follow the outlined steps to rebuild tables if prompted.

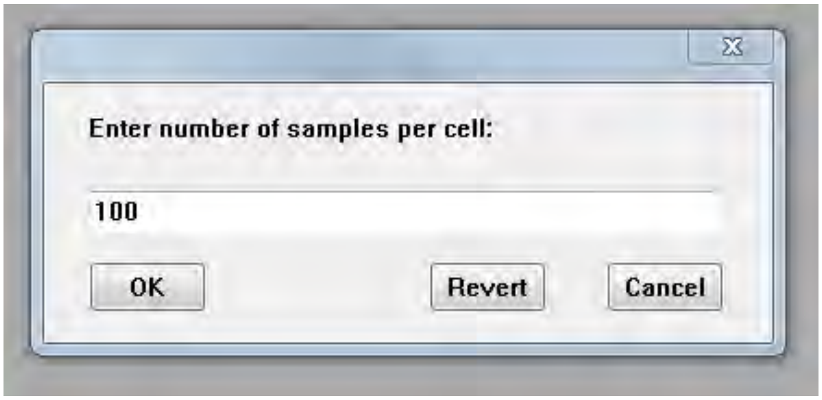
Select **YES** to rebuild tables.



Netica

The tables for some node(s) (e.g. Dep_SandSilt) may not match their equation. Rebuild them?

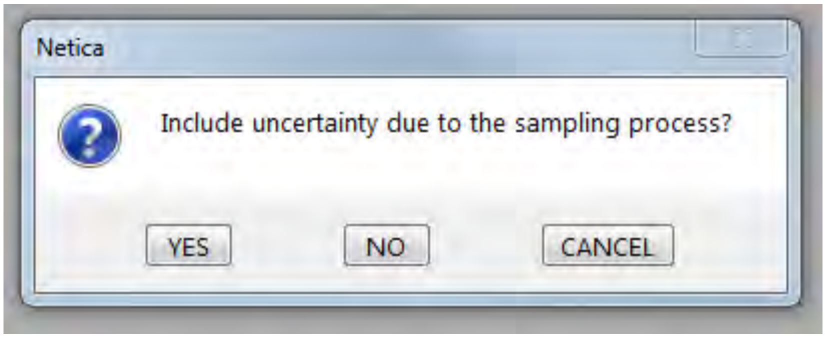
Set samples per cell to **100**.



Enter number of samples per cell:

100

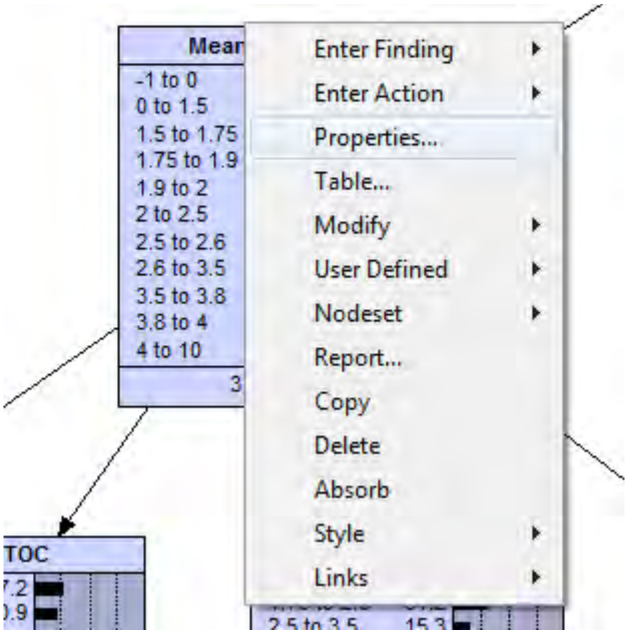
When asked to include uncertainty, select **NO**. This is because intermediate nodes redefine their parents with 100% certainty.



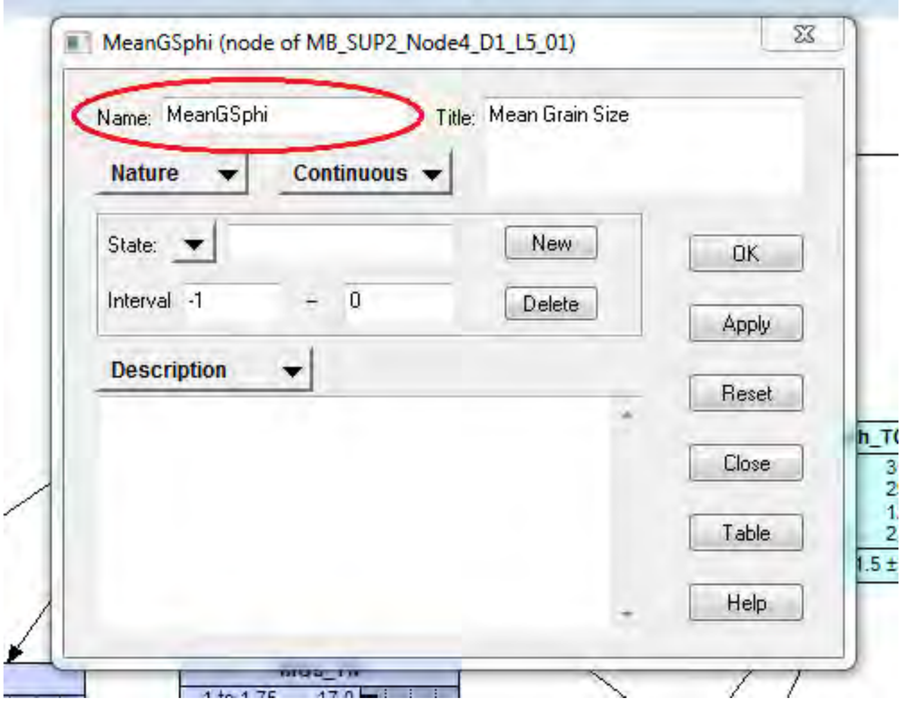
Include uncertainty due to the sampling process?

Step 4 – Verify that case file headers (column names) match node names. Netica® is case sensitive, so names must match exactly. Column headers and node names may not contain spaces.

Right click on a node and select **Properties**



The node name field must match the column header in the case file. Change case file names if they do not match. Note that this name differs from the node's title, which is what is displayed in the final net.


MeanGSphi (node of MB_SUP2_Node4_D1_L5_01)

Name: MeanGSphi

Title: Mean Grain Size

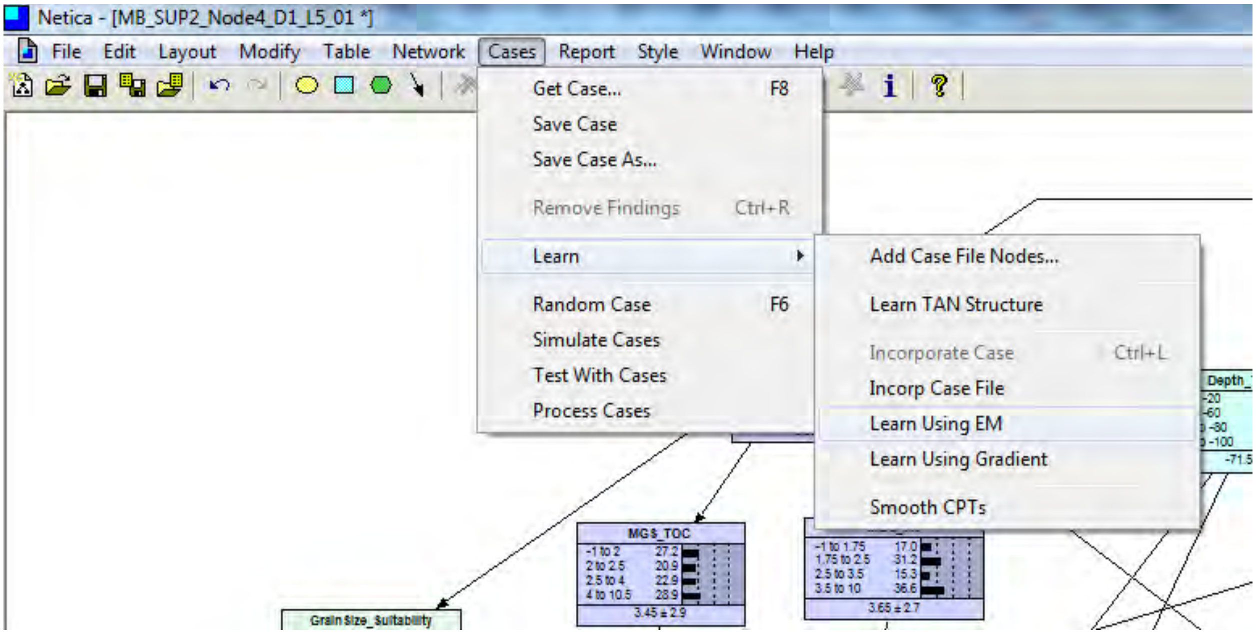
Nature: Continuous

Interval -1 – 0

After verifying the node names, close the node properties box and repeat for all the nodes that match a column in the case file.

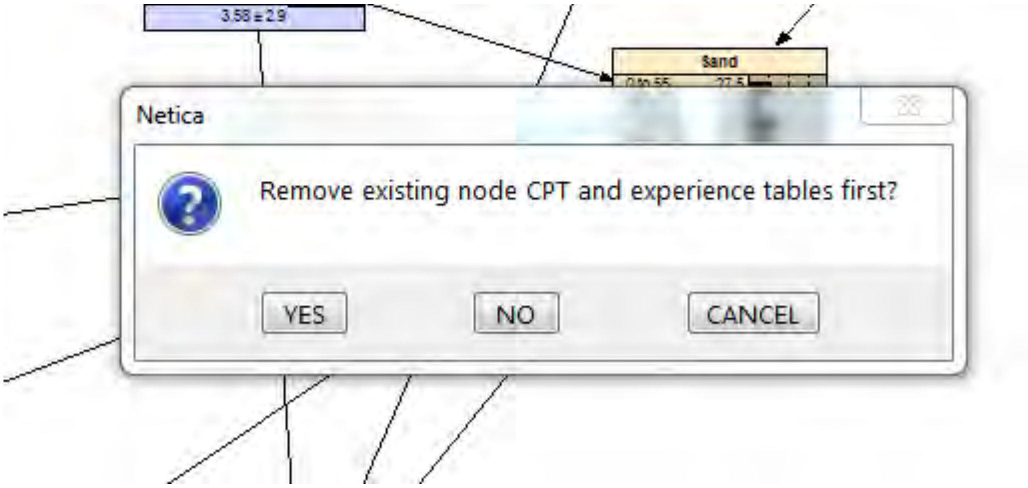
Step 5 – Train net with new data

Under **Cases** in Netica® Menu, Select **Learn** > **Learn using EM**


Netica - [MB_SUP2_Node4_D1_L5_01 *]

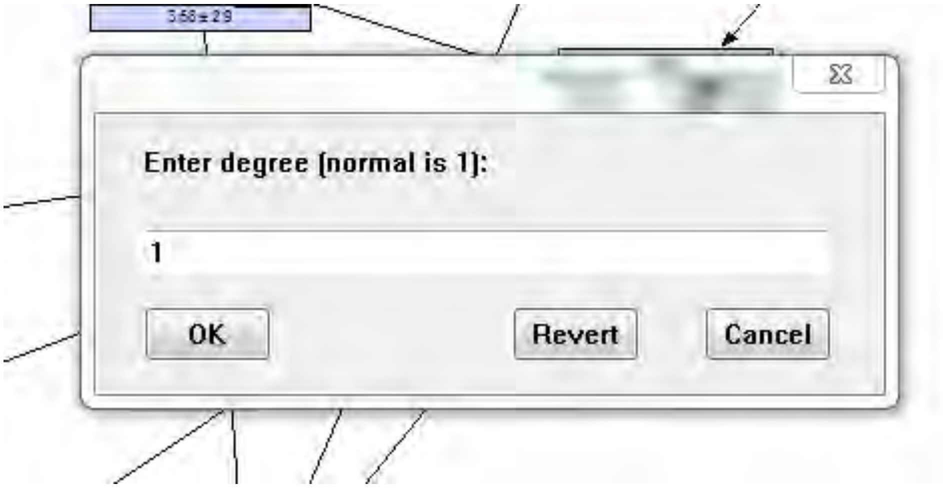
Navigate to and select case file

Remove existing node and experience tables? – **NO**



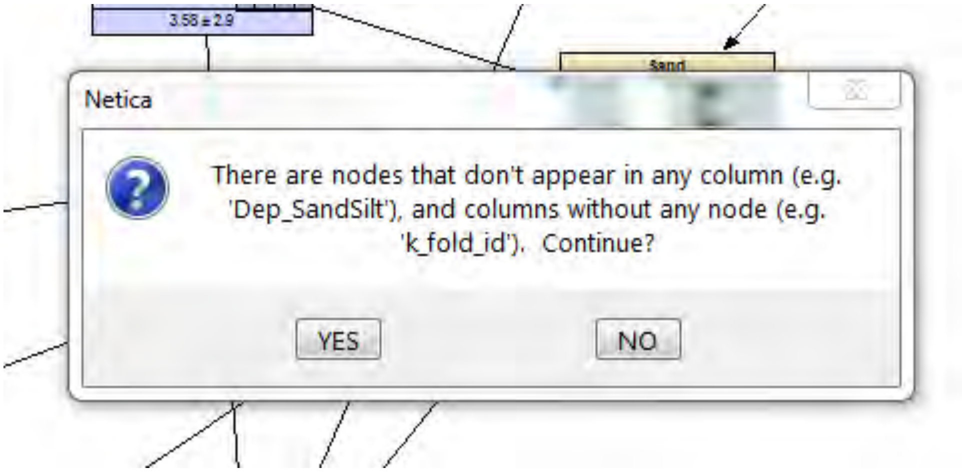
Remove existing node CPT and experience tables first?

Enter **1** for degree


Enter degree (normal is 1):

1

Error Message: It is important to verify that the error message is only warning about 1) intermediate nodes in the net that do not have a representative column in the case file, or 2) columns in the case file that are not represented as nodes in the net. This error message will also appear if there is a mismatch between column names of the case file versus names of nodes in the net (ex: depth vs Depth). If certain that all case file column names are correct, proceed by selecting **YES**.


Netica

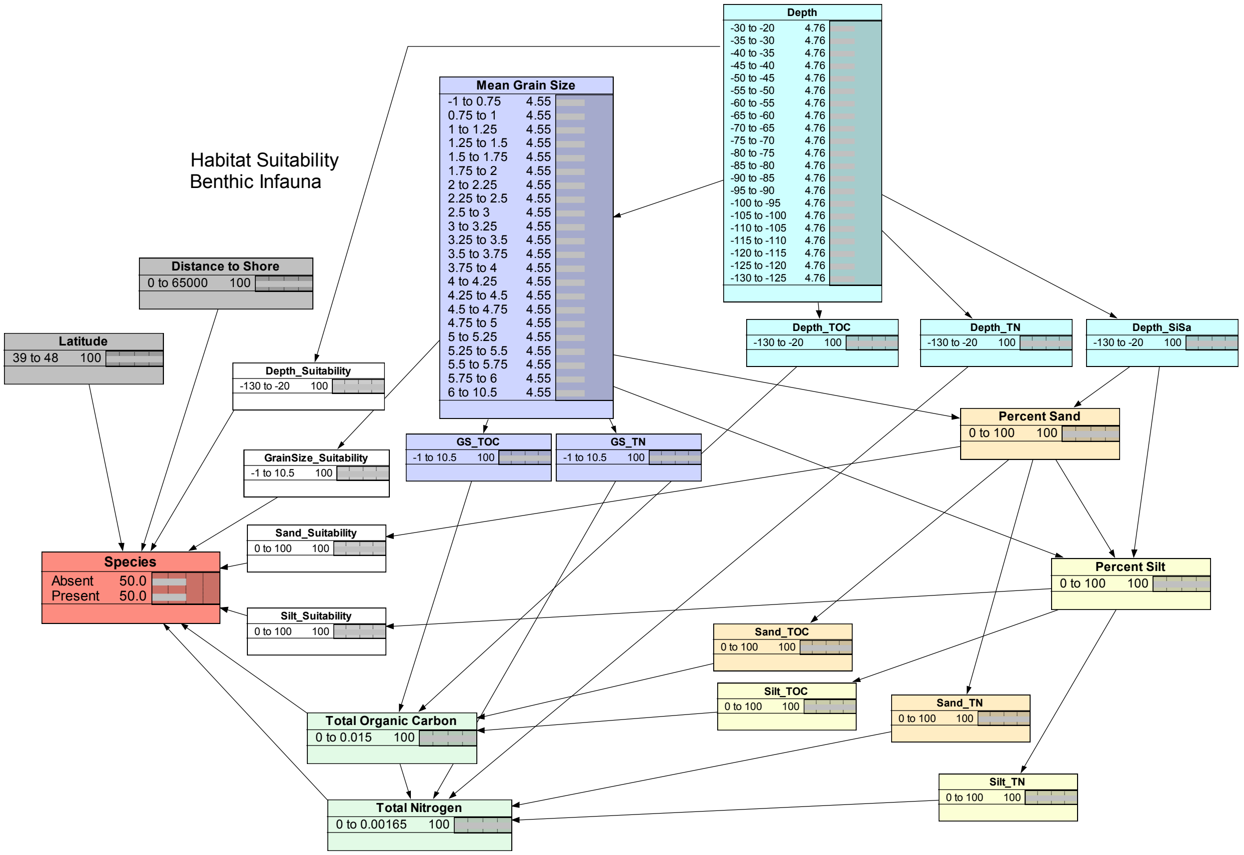
There are nodes that don't appear in any column (e.g. 'Dep_SandSilt'), and columns without any node (e.g. 'k_fold_id'). Continue?

The Bayesian Belief Network is now updated.

Appendix 6.3.2 Instruction to Apply Net to New Species

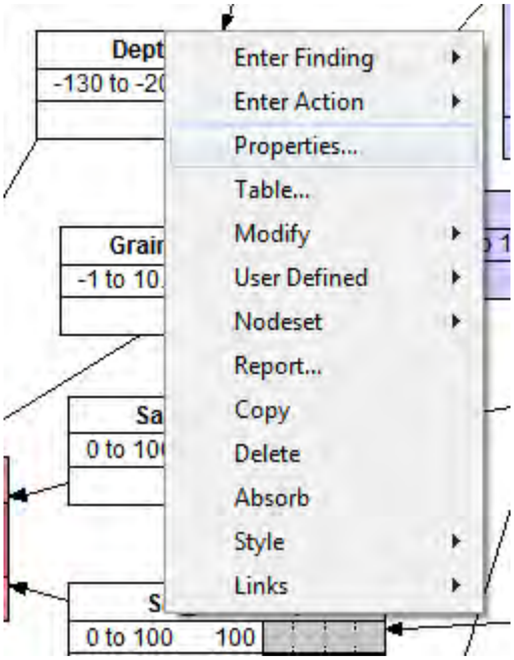
This tutorial covers the mechanics of applying the base macrofaunal net to a new species and does not detail the statistical techniques used to develop discretization breakpoints, variable selection, or model validation, as these techniques rely on advanced statistical knowledge.

Step 1. Open base macrofauna net

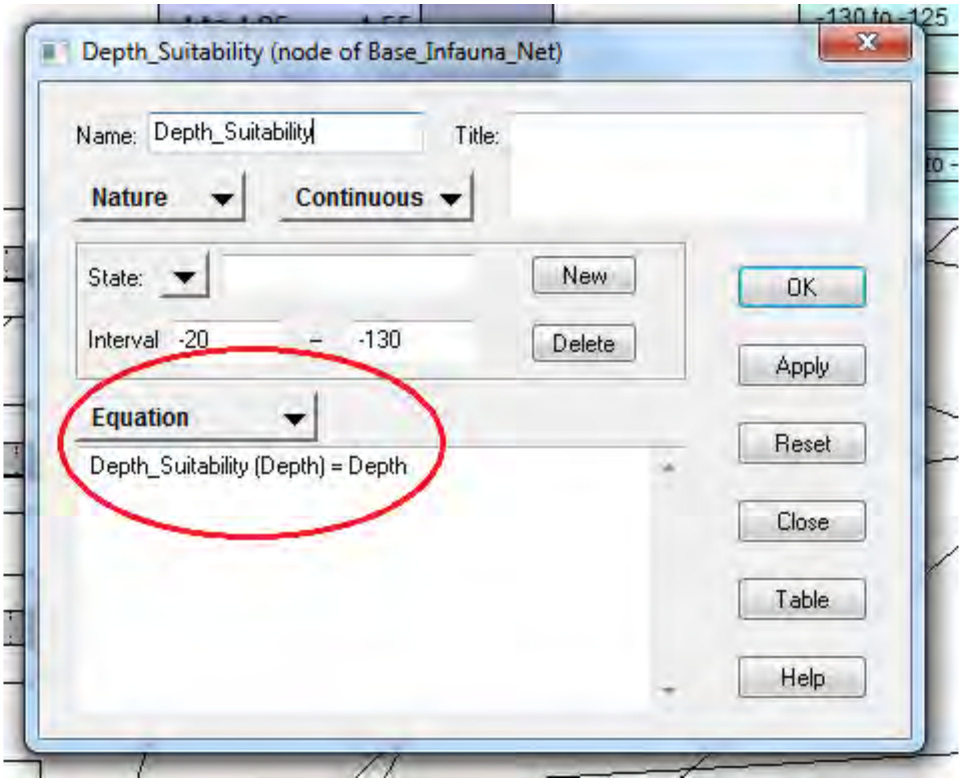


Step 2. Discretize Nodes

Right click on a node and select properties



Intermediate Nodes will have equations in the dialog box, signifying that it equals its parent node. Do not change the equation. Select the arrow to the right of the Equation dialog box.



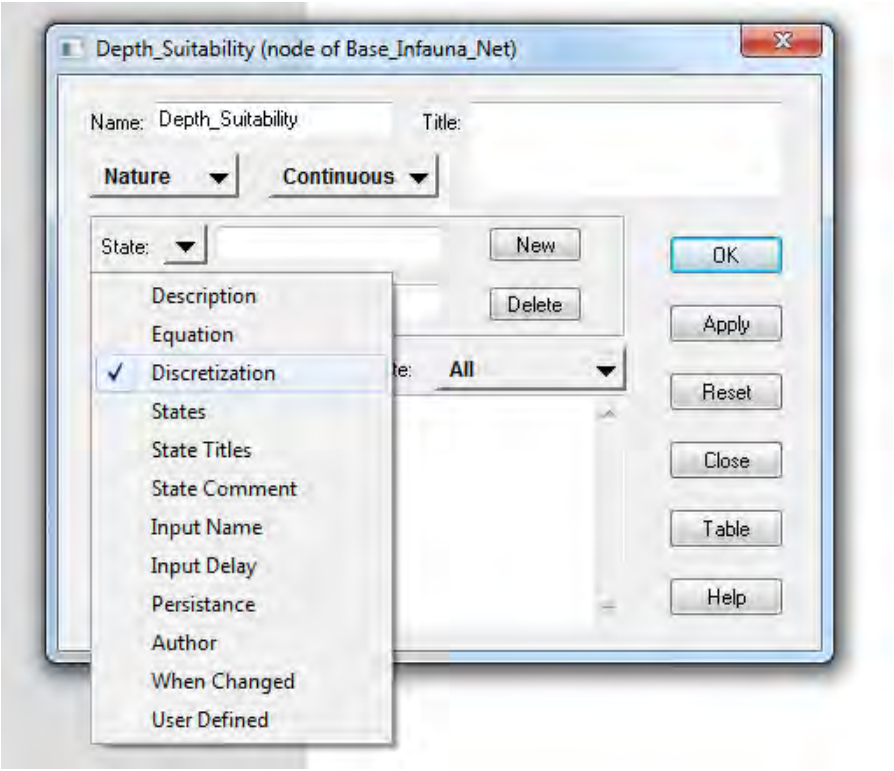
Depth_Suitability (node of Base_Infauna_Net)

Name: Depth_Suitability

Interval -20 – -130

Depth_Suitability (Depth) = Depth

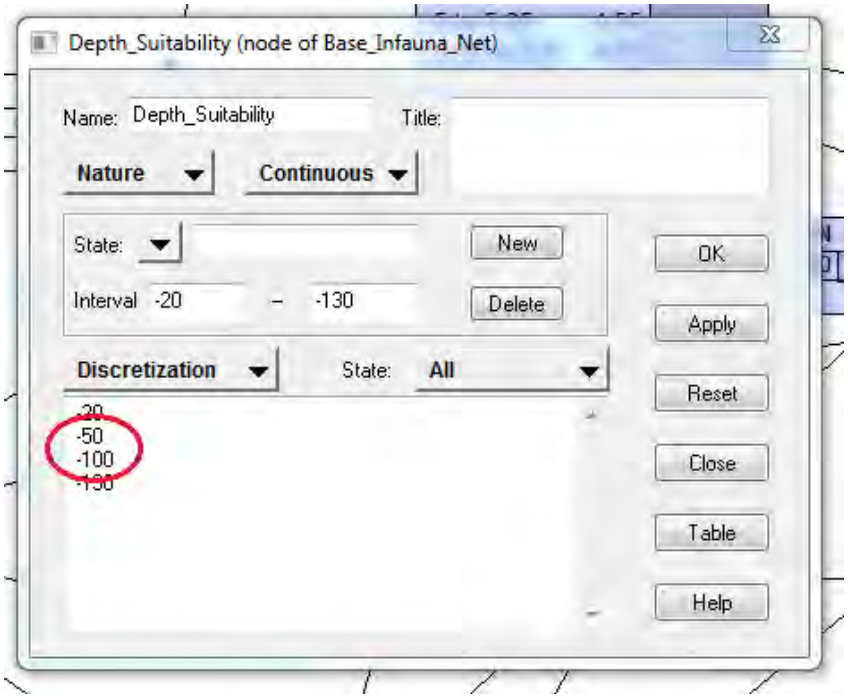
In the drop down menu, select **Discretization**



Depth_Suitability (node of Base_Infauna_Net)

Name: Depth_Suitability

Enter breakpoint values in dialog box between absolute minimum and maximum values.


Depth_Suitability (node of Base_Infauna_Net)

Name: Depth_Suitability

Title:

Interval -20 – -130

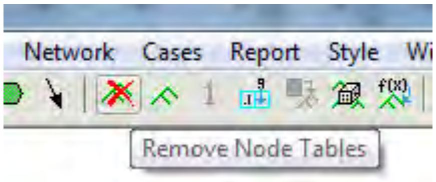
State: All

-20
-50
-100
-130

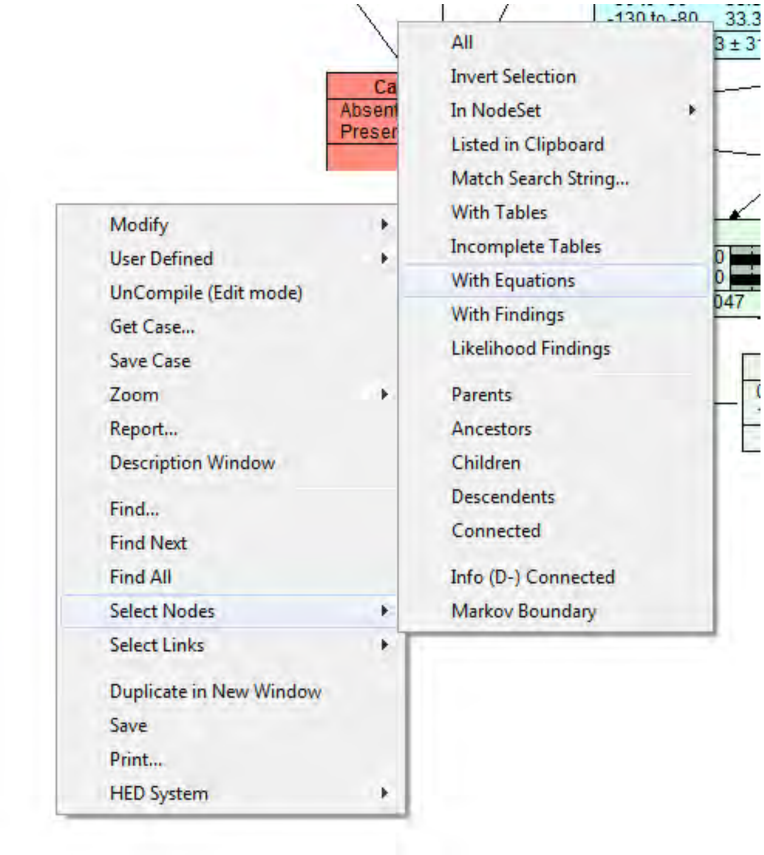
After entering breakpoint values, select **OK** to close out of properties. Repeat for all Nodes.

Step 3 – Learn CPT Tables

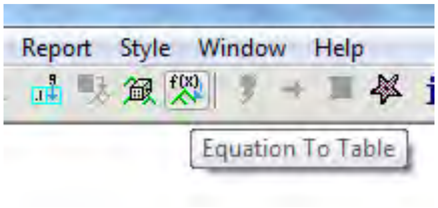
Fist select all nodes (ctrl a) and click on the Remove Node Tables icon (red x) in Netica®'s menu.



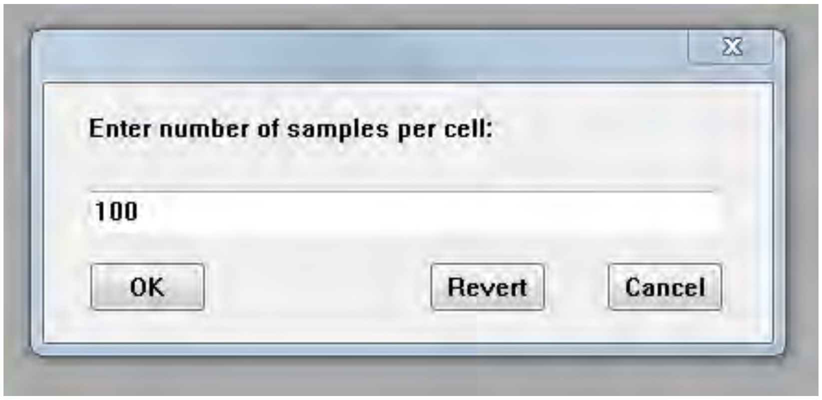
Clicks anywhere in the net to unselect all the nodes. Right click on an empty space in the net and choose **Select Nodes < With Equations**



Select the Equation to Table (f(x)) icon in Netica®'s menu.

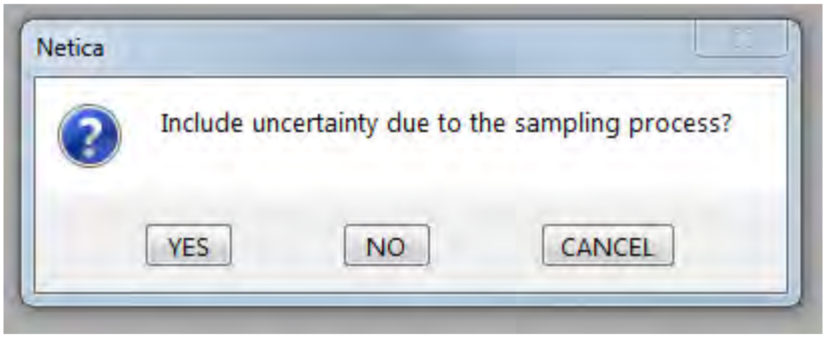


Set samples per cell to **100**.


Enter number of samples per cell:

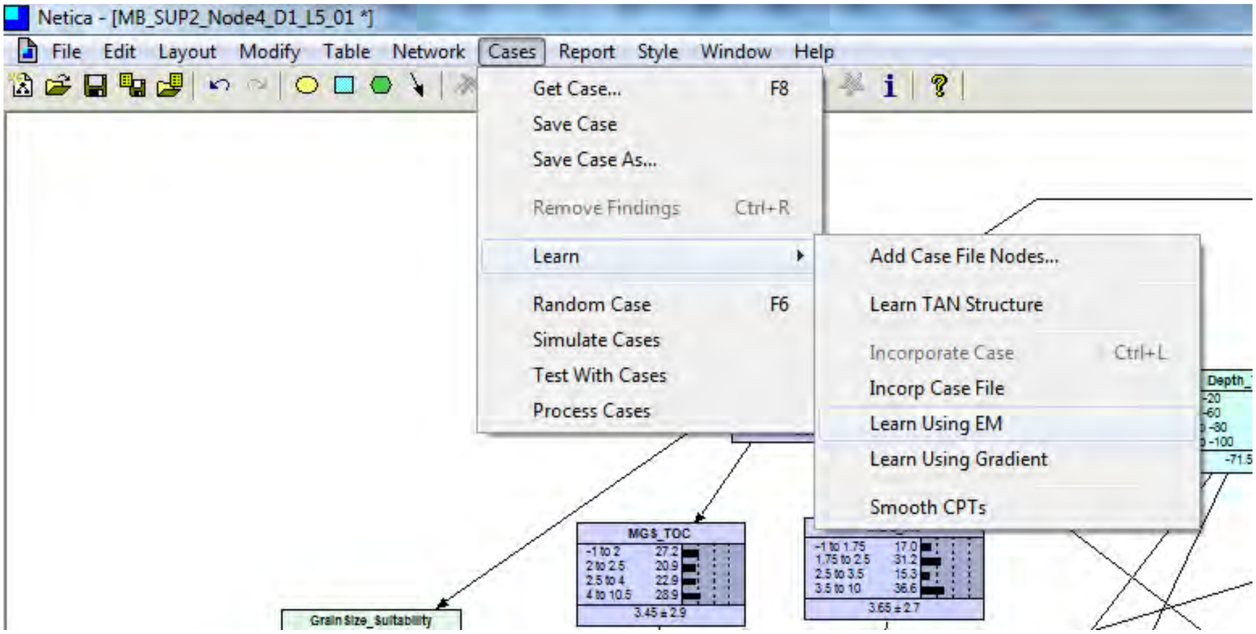
100

When asked to include uncertainty, select **NO**. This is because intermediate nodes redefine their parents with 100% certainty.



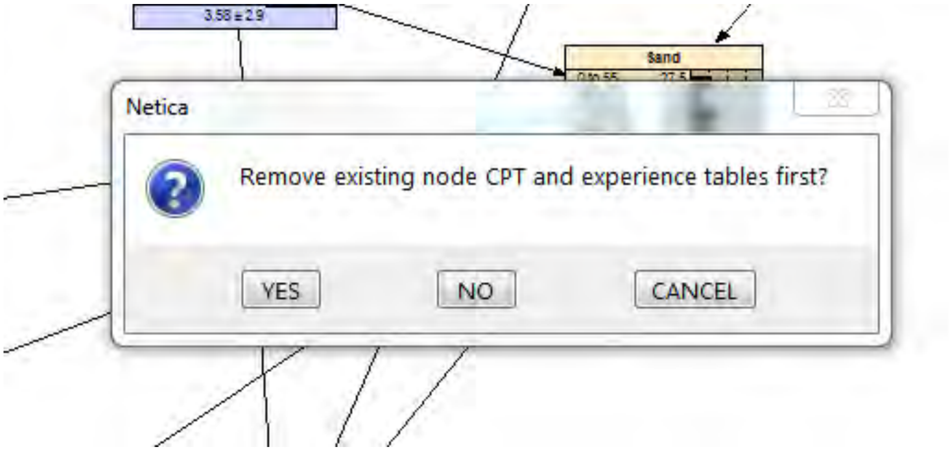
Include uncertainty due to the sampling process?

Under **Cases** in Netica® Menu, Select **Learn** > **Learn using EM**



Navigate to and select usSeabed file

Remove existing node and experience tables? – **NO**



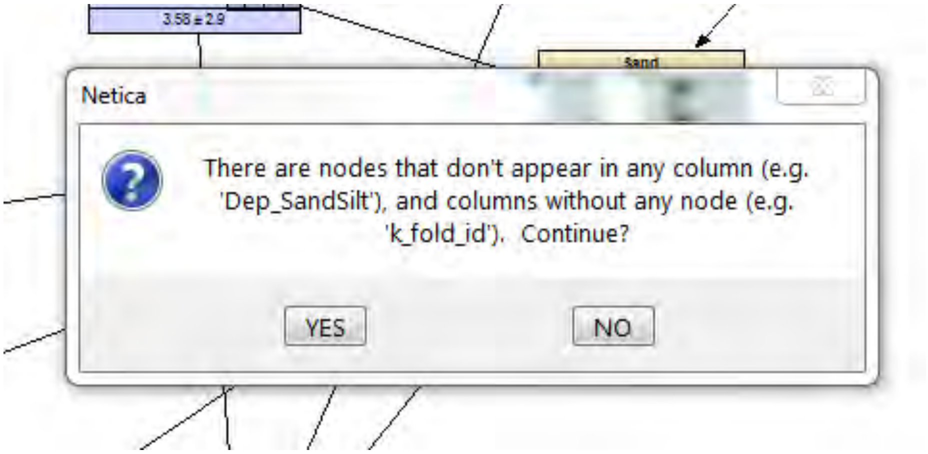
Remove existing node CPT and experience tables first?

Degree is **0.05**

Enter degree (normal is 1):

0.05

Error Message: It is important to verify that the error message is only warning about 1) intermediate nodes in the net that do not have a representative column in the case file, or 2) columns in the case file that are not represented as nodes in the net. This error message will also appear if there is a mismatch between column names of the case file versus names of nodes in the net (ex: depth vs Depth). If certain that all case file column names are correct, proceed by selecting **YES**.



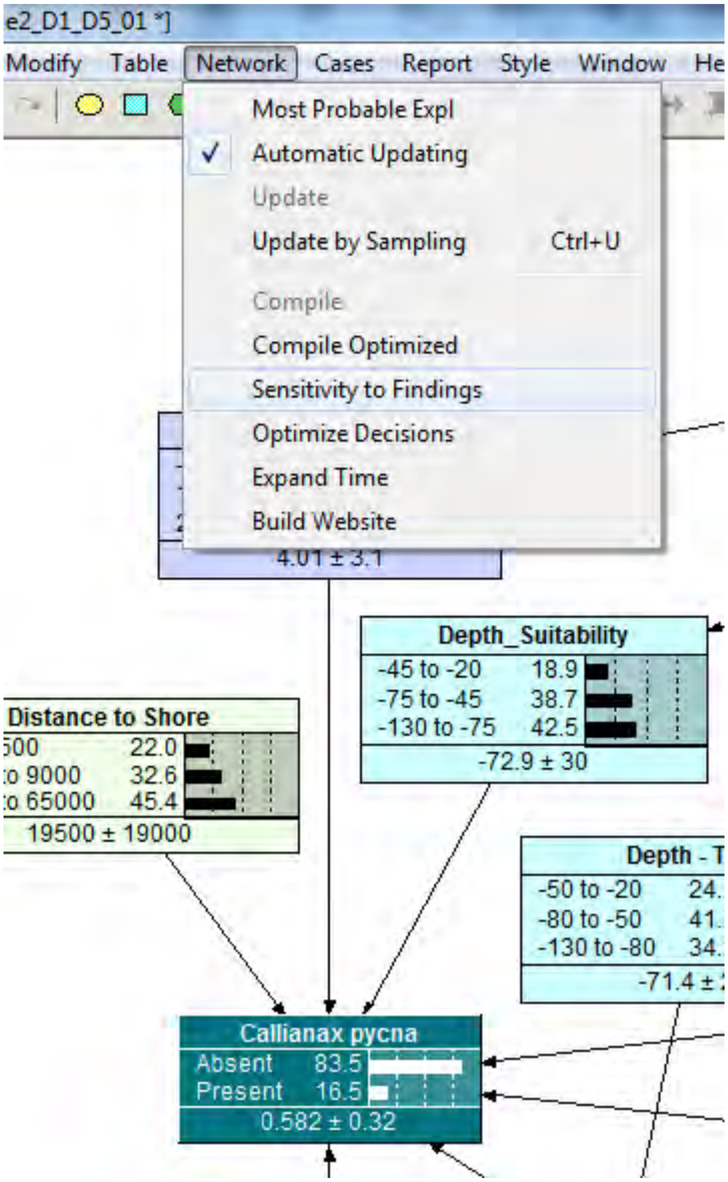
There are nodes that don't appear in any column (e.g. 'Dep_SandSilt'), and columns without any node (e.g. 'k_fold_id'). Continue?

Repeat EM Learning steps using case file. Degree for case file should be 1.

The new species net has been created.

Step 4 – Sensitivity to Findings

Highlight Species node by clicking on title. Select **Network > Sensitivity to Findings** from Netica®'s menu. This will report variables in order of influence on species.



Step 5 – Test cases

Highlight Species node by clicking on title. Select **Cases > Test with Cases** from Netica®'s menu. This will report a summary of the confusion matrix table and different performance metrics.

Appendix 7. Data Products and Distribution

A hardcopy digital archive of all spatial data has been produced through this study. The archive is an ESRI File Geodatabase of feature (vector) and raster data as well as FGDC metadata for all datasets included. The outline below details the datasets included in the "BOEM.gdb" ArcGIS File Geodatabase (Compatible with ArcGIS Versions 10.0 and greater)

1) Raster Datasets (Imagery)
    a) Bathymetry (depth in meters, all BOEM study sites and backlog sites)
    b) Shaded Relief Bathymetry (all BOEM study sites and backlog sites)
    c) Backscatter (all BOEM study sites and backlog sites)
    d) Sediment grain size and composition (mean phi, % sand, regional coverage)
    e) Data Density & Quality Maps (individual data types and aggregate quality)
    f) Regionally Predictive Map of Rock Outcrop
    g) Outcrop Model
    h) Regional Slope Map
2) Feature Datasets (Vector point, polyline, and polygons)
    a) Contour (5 m bathymetry contour interval polylines)
        i) CapeFalconContours
        ii) CoquilleBankContours
        iii) EurekaContours
        iv) GraysBankContours
        v) H12130Contours
        vi) H12131Contours
        vii) MeanGrainsizeContours (1 phi unit contour interval)
        viii) NehalemContours
        ix) NewportContours
        x) NSAFContours
        xi) PercentSandContours (10% contour interval)
        xii) SiltCoosContours
        xiii) SpongeReefContours
        xiv) StonewallBankContours
        xv) WAInshoreContours
    b) DataOutlines (polygons depiciting study sites or regions)
        i) BOEM Sites
        ii) EFH_SubRegion_Strata
        iii) ExistingSites
        iv) NonBOEMSites
    c) IsopachOutcropStability (polyline and polygons)
        i) IsopachMap
        ii) SiesmicLinesForIsopach
        iii) SeismicPredictedRock
        iv) SlopeStability
        v) SlopeStabiltiyPolygons
    d) SeabedClassification
        i) CapeFalconFaultHabitat
        ii) CoquilleBankHabitat

        iii) EurekaHabitat
        iv) GraysBankHabitat
        v) H12130Habitat
        vi) H12131Habitat
        vii) NehalemHabitat
        viii) NewportHabitat
        ix) NSAFHabitat
        x) SiltCoosHabitat
        xi) SpongeReefHabitat
        xii) StonewallBankHabitat
        xiii) WA_OR_NCA_V4_0_SGH_FINAL
        xiv) WAInshoreHabitat
    e) SeabedSamples (points)
        i) BOEM_Shipek_Grab_Samples
        ii) OSU_Box_Cores
        iii) OSU_Shipek_Grab_Samples
        iv) XYBOEMAttrib
        v) XYEPAAttrib
    f) Submersible
        i) NOAA_Sled_Transects_2010
        ii) OSUWE2011_HabSegments
        iii) OSUWE2011_Trackline
        iv) OSUWE2011_TracklinePoints
        v) OSUWE2012_Trackline

In addition to the archive geodatabase online map services for each feature or imagery dataset have been developed and are available via the Active Tectonics and Seafloor Mapping Lab's ArcGIS Server. Explore the map service catalog at:

http://bhc.coas.oregonstate.edu/arcgis/rest/services/BENTHIC

2014_BOEM_GeoDataService

Data_Quality

Grainsize

Local_Scale_Habitat_Maps

Predicted Outcrop

V4_Physiographic_Habitat_WA_OR_NCA

V4_Primary_Lithology_WA_OR_NCA

V4_Seafloor_Induration_WA_OR_NCA

Finally, we also publish metadata records for all datasets through the Active Tectonics and Seafloor Mapping Lab's Metadata Catalog, a searchable and harvestable catalog service for the web provided by ESRI Geoportal technology. Search for datasets at: http://bhc.coas.oregonstate.edu/geoportal

Technical Summary

STUDY TITLE: SURVEY OF BENTHIC COMMUNITIES NEAR POTENTIAL RENEWABLE ENERGY SITES OFFSHORE THE PACIFIC NORTHWEST

REPORT TITLE: BENTHIC HABITAT CHARACTERIZATION OFFSHORE THE PACIFIC NORTHWEST

VOLUME 1: Evaluation of Continental Shelf Geology
VOLUME 2: Evaluation of Continental Shelf Benthic Communities

CONTRACT NUMBER: M10AC20002

SPONSORING OCS REGION: PACIFIC

APPLICABLE PLANNING AREAS: WASHINGTON-OREGON, NORTHERN CALIFORNIA

FISCAL YEARS OF PROJECT FUNDING: 2010 – 2015

COMPLETION DATE OF REPORT: NOVEMBER 24, 2014

COSTS: FY 2010 $1,598,846
FY 2011 $0
FY 2012 $0
FY 2013 $0
FY 2014 $0
FY 2015 $0

CUMULATIVE PROJECT COST: $1,598,846

PROJECT MANAGER: SARAH K. HENKEL

AFFILIATION (OF PROJECT MANAGER): HATFIELD MARINE SCIENCE CENTER, OREGON STATE UNIVERSITY

ADDRESS: 2030 S.E. MARINE SCIENCE DR., NEWPORT, OR, 97365

PRINCIPAL INVESTIGATORS*: SARAH K. HENKEL AND CHRIS GOLDFINGER

KEY WORDS: Bayesian, benthic, box core, grain size, habitat suitability, macro-invertebrate, mega-invertebrate, multibeam, northern California, Oregon, ROV, seafloor, surficial geologic habitat, Washington

BACKGROUND: While the oceans of western North America hold great potential for the development of both marine hydrokinetic and floating wind renewable energy technologies, concerns have been raised about effects on seafloor-associated (benthic) organisms by the installation of devices and mooring systems. To assess potential effects of development on benthic resources, it is necessary to gather a baseline understanding of the distributions of benthic organisms and how they relate to the physical environment (habitat). However, little is known about species-habitat relationships and community processes on the outer continental shelf. The first step in evaluating benthic species-habitat associations is to understand the benthic habitat, which for this project is defined as the depth and surficial substrate (or lithology). Historically, there have been few surveys in the Pacific Northwest. In 1995-1998, the

STRATAFORM project, initiated by the Office of Naval Research, resulted in maps and sediment analysis of the continental slope and shelf between Trinidad Head and Cape Mendocino, California, and other efforts by Oregon State University (OSU) scientists have mapped a number of the rocky banks offshore Oregon and Washington. More recently, Oregon and California have undertaken a large effort to map considerable proportions of their state waters. Similar to historical mapping efforts, invertebrate surveys have been patchy. While there has been some documentation of invertebrate bycatch from the trawl fishery, little is known about mega-invertebrate assemblages on this part of the continental shelf, with a few surveys conducted over the past two decades. Sedimentary (soft bottom) seafloor is the predominant habitat on the continental shelf and it is likely to be the habitat targeted for offshore renewable energy development; however, only one extensive study of benthic macrofauna has been conducted on the shelf in the region: a 2003 US Environmental Protection Agency (EPA) National Coastal Assessment.

OBJECTIVES: The purpose of this project is to provide a regional understanding of the physical properties of the seafloor and the distribution and location of invertebrates for Federal waters in the Pacific Northwest. The first objective was to build upon existing mapping datasets by collecting new data from key locations and integrating these results into a suite of data products designed to improve our understanding of seabed habitats at both local and regional scales. The second major objective was to survey benthic invertebrates in the region and distinguish communities associated with particular habitat characteristics. We focused on two main groups of invertebrates: mega-invertebrates (surveyed using a Remotely Operated Vehicle (ROV)) and macro-invertebrates (larger than 1 mm, collected using a box-corer). Finally, we aimed to develop models to predict habitat suitability for individual invertebrate species. By assembling this information for the first time in this region, this project provides predictive capabilities of where benthic habitats and invertebrate species/communities of interest may occur to inform decision-making regarding siting of facilities.

DESCRIPTION: The Active Tectonics and Seafloor Mapping Lab at OSU mapped the seafloor at five sites located 4.8 to 19 km (3 to 12 mi) offshore during the summers of 2010 and 2011. Bathymetry was mapped using high-resolution multibeam sonar, accurate to within a few centimeters resolution, and seabed hardness and texture were interpreted from multibeam backscatter data. Seabed grab samples were acquired from soft-bottom areas and analyzed using a laser diffraction particle size analyzer to identify relationships between grain size, bathymetry and backscatter data. Mapping products include local-scale habitat maps, an updated and extended regional Surficial Geologic Habitat map, data density and quality maps and a predictive rock outcrop map. The Benthic Ecology Lab at OSU visited three sites with rocky reef habitat using an ROV: Grays Bank, Washington, and Siltcoos and Bandon-Arago, Oregon, during the summers of 2011 and 2012. Substrate type (on and off the reefs) was quantified and observed invertebrates living on or attached to the sediments (mega-invertebrates) were identified from the resulting footage. To sample macrofauna living in soft-bottoms, during summer 2010, 118 macrofaunal and sediment samples were collected at the six originally proposed sites using a 0.1 m^2 box-corer. Two additional sites were sampled during the summer of 2012 to fill in latitudinal and habitat gaps. Sediment samples were sieved using 1 mm mesh and all macrofaunal organisms were identified and counted after a sub-sample of sediment was removed for particle size analysis. Bayesian networks were developed to statistically infer suitable habitat for seven species of soft-sediment-associated benthic macrofauna along on the continental shelf of the Pacific Northwest. Models were learned from benthic macrofauna sampling data collected from the eight sites along the Pacific Northwest continental shelf. Netica® software was implemented for the design and analysis of statistical models. The final products are static Habitat Suitability Probability maps communicating areas along the shelf that are likely good habitat for species of interest. We also developed maps communicating error or uncertainty associated with each Habitat Suitability Probability map.

SIGNIFICANT CONCLUSIONS: The multi-faceted approach to narrowing the information gap undertaken by this project yielded measureable gains in baseline data coverage in the study area. We added value to the new mapping data by developing seabed classifications at project survey sites as well as incorporating data from external sources into the classification. A key accomplishment of the project has been carrying the new mapping through to the regional synthesis data sets, the Version 4.0 Surficial Geologic Habitat Map for Washington, Oregon, and northern California and the probability of outcrop model ensuring that the most up-to-date seabed habitat information is available for marine renewable energy planning. While these integrations were not intended as comprehensive region-wide data collection and mapping efforts, they have provided key datasets that can be used to assess data distribution, thematic habitat map quality, likelihood of rock outcrop, and surficial sedimentary character. In terms of mega-faunal invertebrates, we identified at least four habitat types based on associated observed invertebrates (outlined in results below). These are somewhat different than geological classifications and should be considered in future surveys as distinct seafloor habitats. All four main habitat types were associated with mega-invertebrates that provided structure and complexity to the seafloor environment. Some taxa groups, such as gorgonians and sponges, which are long-lived and slow growing, were found not just on rocky reefs but also were characteristic of the areas with smaller rocks around the reef. Likewise, distinctions between macrofaunal invertebrate assemblages did not fully align with traditional sediment classifications. Areas comprised of very high percentages of sand (> 87%) contained multiple significantly different assemblages, differentiated based on particle size. Conversely, areas comprised of greater than 15% mud (regardless of whether it was 20% or 75% mud) were quite similar with no further differentiation associated with grain size. Within sediment types, depth-related changes were observed, with distinctions in assemblages occurring at approximately 10 m depth intervals. A benthic macrofauna model framework for invertebrates living within marine sediment that is both adaptable to new species and updateable was developed. Evaluation of many different model parameters and structure found a common suite of explanatory variables: regional variables (Distance to Shore, Depth, Latitude and Mean Grain Size) that are used to then predict *in situ* variables (Percent Silt, Percent Sand, TOC and TN). Experience maps are a novel product that communicate the percentage of data informing probabilities in the model. These maps help to communicate regional confidence in predictions arising from sampling effort.

STUDY RESULTS: The individual mapping components each provide an important update for the regional knowledge base. Multibeam bathymetry and backscatter data collection funded under this project at local-scale study sites corresponds to an approximately 5% increase in mapping coverage over the continental shelf study region (8 – 130 m depth from southern Washington to northern California). When including and accounting for the coverage that was made possible by leveraging external projects such as the OOI sites survey and the NOAA Ocean Explorer NSAF study, the new data coverage estimate is closer to 7%. Seabed imagery was classified for seabed habitat type for each of the six project study sites and seven additional backlog sites to create 13 new local seabed habitat maps. The completion of 13 site-specific habitat maps as well as the consolidation of 37 new externally developed sources of mapping data, largely collected through the Oregon and California State Waters Mapping Programs and identified in the EFH review, laid the groundwork for making significant updates to continental shelf habitats of the regional Surficial Geologic Habitat (SGH) map for Oregon and Washington, resulting in the new Version 4.0 habitat map. In addition to newly mapped areas of continental shelf and slope, the Version 4.0 SGH map also underwent significant modifications/updates to its underlying attributes. The "mixed" seabed induration modifier (second character of SGH Prefix) usage was corrected and the SGH primary and secondary lithology codes were redefined to clear up ambiguities making the distinction between homogeneous sediment mixtures and heterogeneous habitat patches more clearly defined. We adopt the recommended definition of SGH_Pref1 and SGH_Pref2 presented in the review and have incorporated the two newly identified map sources for Oregon. The Version 3.0 data quality maps for the SGH were updated resulting in a complete set of Version 4 data quality map products. The update extended the bathymetry density and sediment sample layers south into California waters in order to reflect the usage of new regional bathymetry and sample data for regional SGH mapping in this region where physiographic canyon and channel systems were modified and sediment type was added. To evaluate the overall probability of rock outcrop, we incorporated six mapping components into an expert Bayesian model constructed using Netica®. The environmental data was sampled at a 200 m x 200 m spaced grid interval and predictions were made for over 2.5 million prediction points. A final Probability of Rock Outcrop map was assembled from the model output. Inverse Distance Weighted modeling was used to develop maps of grain size and percent sand composition on the continental shelf from 20 m to 130 m.

For the mega-invertebrate surveys, a total of 28 different substratum patch types were identified across the ROV stations. The fewest different substratum patch types were observed and analyzed at Siltcoos Reef, intermediate patch type diversity was observed and analyzed at Grays Bank, and the greatest numbers of substratum patch types were observed and analyzed at Bandon-Arago. A total of 91 taxa representing eight phyla were identified. We identified at least four habitat types for mega-invertebrate assemblages: (1) Pure Mud dominated by sea whips and burrowing brittle stars; (2) Mixed Mud-Rock (which may be further divided based on size of mixed-in rocks) characterized by various species in low density; (3) Consolidated Rocks characterized by high diversity and density of sessile and motile mega-invertebrates (at deeper depths there may be some distinction between flat and ridge rocks); and (4) Rubble Rocks showing less diversity and density than the consolidated rocks, probably due to the disturbance generated by the unconsolidated rocks. The two rocky habitats might not be as distinct at deeper depths where reefs might have their own local assemblages due to the predominance of locally induced conditions and deep species recruiting. Future studies should be designed to obtain thorough video coverage of transition areas between consolidated rock and mud habitats to discern whether different sizes of rocks mixed in with mud support distinct mega-invertebrate assemblages.

In the macrofauna collections polychaetes (Annelida) and bivalves (Mollusca) dominated the assemblages at each site. The site with the highest average Shannon-Weiner diversity was Nehalem and the lowest average diversity was found at the Newport site. The greatest ranges in number of species among stations as well as in H' diversity among stations were found at Grays Bank and Bandon-Arago; this was expected as these sites encompassed the greatest variety of sediment types (including gravel). Based on invertebrate species abundances, gravelly stations clustered together, regardless of site, and some sandy stations clustered across sites. Overall the subset of measured environmental variables that correlated best with the distribution of stations based on the macrofaunal invertebrate assemblages included depth, % sand, % gravel and median grain size with a correlation of 0.709. Further analysis indicated high gravel and moderate gravel assemblages very distinct from the rest of the groupings. Next, all stations (n = 70 across 5 sites) that were less than 84% sand (> 16% silt) formed a significantly similar group, which was not further subdivided, indicating that silty habitats support similar macrofaunal assemblages regardless of latitude or depth. Within stations that had > 87% sand, stations were further split on the basis of depth, median grain size, and finally a differentiation between 99.2 and 100% sand.

We developed Habitat Suitability Probability models for seven species of interest in the next chapter: *Axinopsida serricata, Ennucula tenuis, Astyris gausapata, Callianax pycna, Magelona berkeleyi, Onuphis iridescens,* and *Sternaspis fossor*. Some of these species were chosen because they represent ones that might be expected to change distributions based on sediment changes due to wave energy converter (WEC) installations. Others were chosen because of other characteristics about their distributions in order to demonstrate the utility of the tool across a spectrum of species. Model outputs for these seven species were then 'field validated' using data collected in the region later in the course of the study. Regions of rock, cobble and gravel were masked from the final predictive maps as the model was developed only for soft sediment habitats. However, preliminary models for the hard bottom glass sponge dictyonine species group are under development using the Probability of Outcrop map along with "Ridges" identified from the Version 4 Surficial Geologic Habitat map.

STUDY PRODUCT(S):

Report S.K. Henkel, C. Goldfinger, C. Romsos, K. Politano, L.G. Hemery, A. Havron and B. Black. 2014. Benthic Habitat Characterization offshore the Pacific Northwest. Bureau of Ocean Energy Management, OCS Study BOEM 2014-662.

Theses

Lockett	A Bayesian approach to habitat suitability prediction (http://ir.library.oregonstate.edu/xmlui/handle/1957/28788)
Lee	Patterns of benthic macroinvertebrate communities and habitat associations in temperate continental shelf waters of the Pacific Northwest (http://ir.library.oregonstate.edu/xmlui/handle/1957/29185)
Labou	Physical factors affecting the spatial distribution of infaunal bivalve assemblages and species along the continental shelf of the Pacific Northwest (http://ir.library.oregonstate.edu/xmlui/handle/1957/42751)
Havron	The application of Bayesian networks towards benthic fauna habitat suitability modeling along the US west coast (In Prep.)

Websites

Web Data Viewer:	http://bhc.coas.oregonstate.edu/benthic
Web Map Services:	http://bhc.coas.oregonstate.edu/arcgis/rest/services/BENTHIC http://bhc.coas.oregonstate.edu/arcgis/rest/services/habitat
Geoportal:	http://bhc.coas.oregonstate.edu:8080/geoportal

Databases

Arc GIS Personal Geodatabase of all GIS Data Products (DVD distribution)
MS Access Database of ROV video observations (substrata and organisms)
.csv files of all physical data and invertebrate counts from box core collections
(All invertebrate and associated data have been submitted to the NODC under accession number 0122659; http://data.nodc.noaa.gov/accession/0122659.)

Listing of raster imagery filenames in the BOEM.gdb by site (row) and imagery type (column)

BOEM.gdb (ESRI File Geodatabase)				
Bathymetry and Derivative Raster Datasets				
SITE	Backscatter	Bathymetry	Color Shaded-Relief	Grey Shaded-Relief
Grays Bank, WA	graysbank_8m_bs	graysbank_8m_bthy	graysbank_8m_colorshd	graysbank_8m_hllshd
Nehalem, OR	Nehalem_50cm_bs	Nehalem_8m_bthy	Nehalem_8m_colorshd	Nehalem_8m_hllshd
Newport, OR	Newport_1m_bs	Newport_8m_bthy	Newport_8m_colorshd	Newport_8m_hllshd
Silt Coos, OR	siltcoos_1m_bs	siltcoos_4m_bthy	siltcoos_4m_colorshd	siltcoos_4m_hllshd
Eureka, CA	eureka_18m_bs	eureka_18m_bthy	eureka_18m_hllshd	NA
NSAF, CA	nsaf_4m_bs	nsaf_8m_bthy	nsaf_8m_colorshd	nsaf_8m_hllshd
WA Inshore	wa_inshore_1m_bs	wa_inshore_2m_bthy	wa_inshore_2m_colorshd	wa_inshore_2m_hllshd
WA Sponge Reef	wa_sponge_2m_bs	wa_sponge_8m_bthy	wa_sponge_8m_colorshd	wa_sponge_8m_hllshd
Cape Falcon	capefalcon_1m_bs	capefalcon_4m_bthy	capefalcon_4m_colorshd	capefalcon_4m_hllshd
Stonewall Bank	Stonewall_2m_bs	Stonewall_2m_bthy	Stonewall_2m_colorshd	Stonewall_2m_hllshd
Coquille Bank	coquille_10m_bs	coquille_15m_bthy	coquille_15m_colorshd	coquille_15m_hllshd
H12130	NA	h12130_4m_bthy	h12130_4m_colorshd	h12130_4m_hllshd
H12131	NA	h12131_4m_bthy	h12131_4m_colorshd	h12131_4m_hllshd

Listing and description of all vector format features in the BOEM.gdb ESRI file geodatabase.

BOEM.gdb (ESRI File Geodatabase)		
FeatureClass	Feature Dataset	Description
Contour	CapeFalconContours	5 meter interval bathymetry countour
	CoquilleBankContours	5 meter interval bathymetry countour
	EurekaContours	5 meter interval bathymetry countour
	GraysBankContours	5 meter interval bathymetry countour
	H12130Contours	5 meter interval bathymetry countour
	H12131Contours	5 meter interval bathymetry countour
	NehalemContours	5 meter interval bathymetry countour
	NewportContours	5 meter interval bathymetry countour
	NSAFContours	5 meter interval bathymetry countour
	SiltCoosContours	5 meter interval bathymetry countour
	SpongeReefContours	5 meter interval bathymetry countour
	WAInshoreContrours	5 meter interval bathymetry countour
	PercentSandContours	10% interval contour
	MeanGrainsizeContours	1 phi unit interval contour
DataOutlines	BOEMSites	Site outlines for study sites
	EFH_SubRegion_Strata	Regional strata from 2012 EFH Review Synthesis
	ExistingSites	Site outlines for habitat maps developed through other work
	NonBOEMSites	Site outlines for "backlog" sites
IsocoreOutcropStability	Isocore	Map of minimum isocore sediment thickness
	SeismicLinesForIsopach	Tracklines used to develop Isocore map
	SeismicPredictedRock	Map of areas where rock may occur along seismic survey lines
	SlopeStabiltityPredictedRock	Map of areas where unstable slopes may cause rock outcrop
SeabedClassification	CapeFalconFaultHabitat	Local-scale habitat map
	CoquilleBankHabitat	Local-scale habitat map
	EurekaHabitat	Local-scale habitat map
	GraysBankHabitat	Local-scale habitat map
	H12130Habitat	Local-scale habitat map
	H12131Habitat	Local-scale habitat map
	NehalemHabitat	Local-scale habitat map
	NewportHabitat	Local-scale habitat map
	NSAFHabitat	Local-scale habitat map
	SiltCoosHabitat	Local-scale habitat map
	SpongeReefHabitat	Local-scale habitat map
	StonewallBankHabitat	Local-scale habitat map
	WA_OR_NCA_V4_0_SGH	Regional -scale habitat map
	WA_InshoreHabitat	Local-scale habitat map
SeabedSamples	BOEM_Shipek_Grab_Samples	Shipek Grab Samples (and textural data) for BOEM sites
	ORSWMP_Shipek_Grab_Samples	Shipek Grab Samples (and textural data) from the ORSWMP
	BOEM_Box_Cores_Sed	Box Core Samples (with textural data) for BOEM sites
	BOEM_Box_Cores_Bio	Box Core Samples (infauna and sed. data) for BOEM sites
	EPA_Box_CORES	Box Core Samples (infauna and sed. data) for EPA sites
Submersible	NOAA_Sled_Transects_2010	Tracklines for NOAA Sled deployments
	OSUWE2011_HabSegments	Habitat segments for 2011 ROV depolyments
	OSUWE2011_Trackline	Tracklines for ROV deployments 2011
	OSUWE2012_HabSegments	Habitat segments for 2012 ROV depolyments
	OSUWE2012_Trackline	Tracklines for ROV deployments 2012

Listing and descriptions of regional raster datasets in the BOEM.gdb

BOEM.gdb (ESRI File Geodatabase)	
Regional Raster Datasets	Description
MeanGrainsize	Modeled mean grainsize
PercentSand	Modeled % Sand composition
OutcropModel	Modeled rocky outcrop liklihood
V3_SGH_Map_Quality	Previous Regional Data Quality Map
V4_SGH_Map_Quality	Version 4.0 Data Quality map
V4_Data_Quality_Updates	Mapping quaity overlay
V4bathydensity	Ranked bathymetry data density
V4sampdensity	Ranked sample data density
V4ssdensity	Ranked sidescan data density
V4seisdensity	Ranked seismic data density
waornca_100m_colorshd	Color shaded-relief image of the region
WestCoastSlope100m	bathymetric slope map of the region

Publications

Hemery, LG and Henkel, SK. (*Revised version submitted*) Patterns of benthic mega-invertebrate communities and habitat associations in Pacific Northwest continental shelf waters. Biodiversity and Conservation.

Labou, SG and Henkel, SK. (*In revision*) Factors related to distinct infaunal bivalve assemblages differ in sand versus silt shelf habitats. Marine Environmental Research.

Presentations

Goldfinger:

1. Ocean Sciences Meeting: Hawaii – Predicting Benthic Invertebrate Distribution: GIS-Linked Bayesian Belief Networks for Marine Spatial Planning. February 2014

Henkel:

1. Environmental Interactions of Marine Renewables: Stornoway, Scotland – Estimating distribution of sedimentary benthic habitats and species on the eastern Pacific shelf and detecting effects of device deployment. May 1, 2014
2. Benthic Ecology Meeting: Jacksonville, FL – Classifying Benthic Habitats is Complex: but that’s Not what Epifaunal Invertebrates Like about It. March 2014
3. Western Society of Naturalists Meeting: Oxnard, CA – Identifying Invertebrate Assemblages on the PNW Shelf for Habitat Mapping and Environmental Assessment. (Poster) November 2013
4. Oregon Marine Renewable Energy Environmental Science Conference: Corvallis, Oregon – Linking Habitat and Benthic Invertebrate Species Distributions in Areas of Potential Renewable Energy Development. November 2012
5. Oregon Institute of Marine Biology Fall Seminar Series: Charleston, OR – Diversity and Dynamics of Benthic Invertebrates on the Oregon and Washington Shelf. November 2012
6. Benthic Ecology Meeting: Norfolk, Virginia – Spatial Heterogeneity of Pacific Northwest Infauna Increases with Grain Size. March 2012

7. Western Society of Naturalists: Vancouver, Washington – Spatial and Temporal Patterns in the Distribution of Infaunal Invertebrates. November 2011
8. Heceta Head Coastal Conference: Florence, Oregon – Assessment of Benthic Habitats and Communities in Areas Targeted for Offshore Wave Energy Development. October 2011
9. American Fisheries Society: Seattle, Washington – Assessment of Benthic Habitats and Communities in Areas Targeted for Offshore Wave Energy Development. September 2011
10. Benthic Ecology Meeting: Mobile, Alabama – Benthic Assemblages at Sites Proposed for Wave Energy Testing. March 2011

Gilbane

1. Western Society of Naturalists Meeting: Oxnard, CA – The Role of Collaboration in Conducting a Regional Benthic Assessment. November 2013
2. Oregon Marine Renewable Energy Environmental Science Conference: Corvallis, Oregon – Gorgonians as a potential indicator for assessing sea floor condition in marine spatial planning. November 2012

Havron

1. International Marine Conservation Congress: Glasgow, Scotland – Bayesian Inference of Benthic Infauna Habitat Suitability along the U.S. West Coast. August 2014

Hemery:

1. North American Echinoderm Conference: FL – Ecological niche and species distribution modeling of sea stars along the Pacific Northwest coast. June 2014

Labou:

1. Western Society of Naturalists Meeting: Oxnard, CA – Physical Factors Affecting the Distribution of Infaunal Bivalve Assemblages along the Continental Shelf of the Pacific Northwest November 2013
2. Heceta Head Coastal Conference: Florence, OR – Mapping spatial and temporal variation of bivalves. (Poster) October 2012.

Lee:

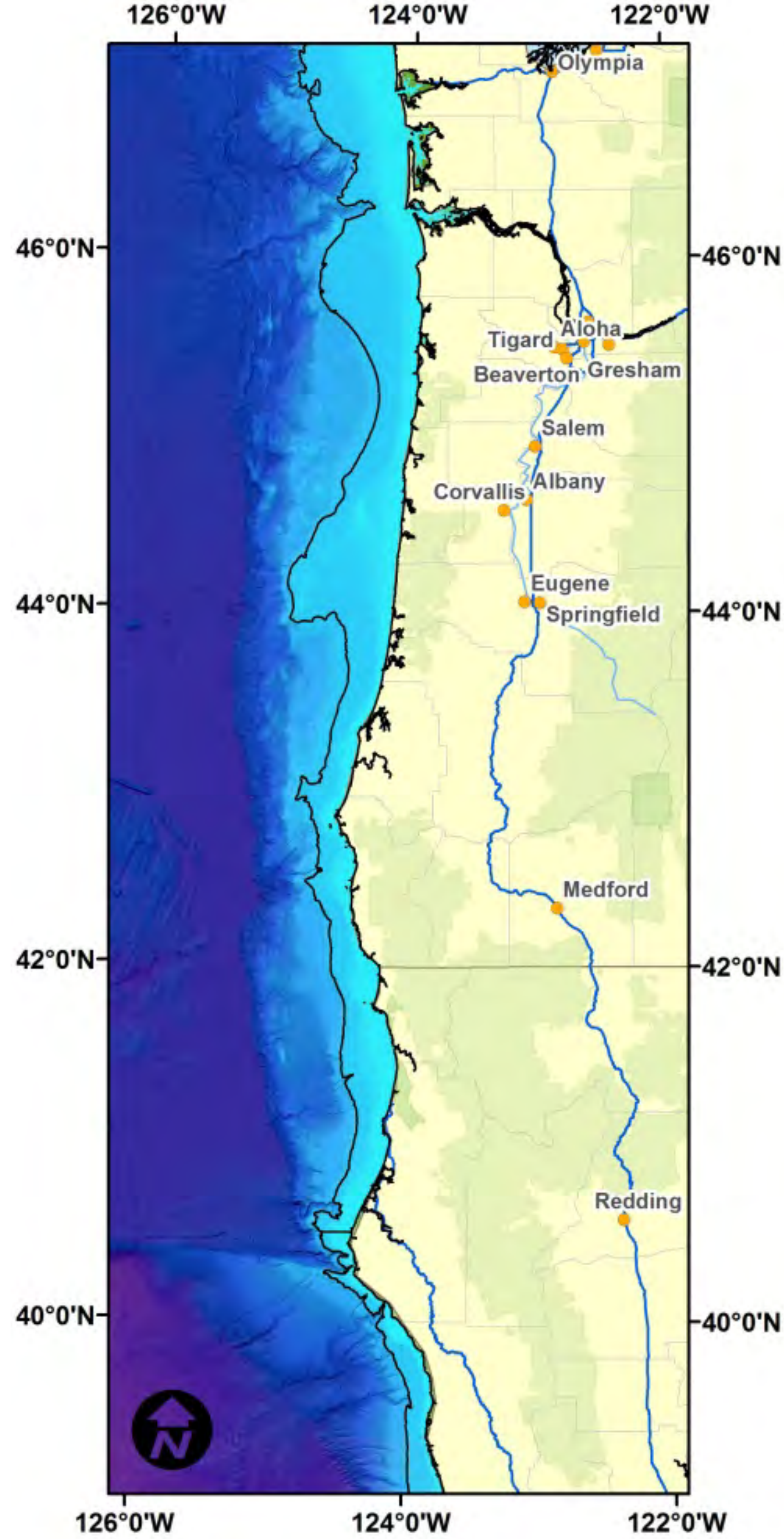
1. Ocean Sciences Meeting, Salt Lake City, Utah – Finding Appropriate Abiotic Parameters to Evaluate Benthic Macroinvertebrate Assemblages in Temperate Continental Shelf Waters. (Poster) February 2012
2. Western Society of Naturalists: Vancouver, Washington – Variances of Asteroid Echinoderms Densities across Substrata, Depth, and Temperature. November 2011

Lockett:

1. Western Groundfish Conference: Seattle, WA – Predicting Benthic Invertebrate Distribution: GIS-linked Bayesian Belief Networks for Marine Spatial Planning. (Poster) February 2012

Media

Beaver Nation Video: http://sites.oregonstate.edu/beaver-nation/everywhere/coast/#henkel


126°0'W
124°0'W
122°0'W
46°0'N
44°0'N
42°0'N
40°0'N
Olympia
Aloha
Tigard
Gresham
Beaverton
Salem
Albany
Corvallis
Eugene
Springfield
Medford
Redding
N

The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under US administration.

The Bureau of Ocean Energy Management

As a bureau of the Department of the Interior, the Bureau of Ocean Energy (BOEM) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS) in an environmentally sound and safe manner.

The BOEM Environmental Studies Program

The mission of the Environmental Studies Program (ESP) is to provide the information needed to predict, assess, and manage impacts from offshore energy and marine mineral exploration, development, and production activities on human, marine, and coastal environments.