AN ABSTRACT OF THE THESIS OF

Curt E. Whitmire for the degree of Master of Science in Marine Resource Management presented on January 8, 2003.

Title: Using Remote Sensing, In situ Observations, and Geographic Information Systems to Map Benthic Habitats at Heceta Bank, Oregon

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Dawn J. Wright

Dramatic declines in many species of demersal fishes off the West Coast have resulted in the designation of nine commercially important species as being overfished. While the causes of those declines are not clearly understood, the fact remains that a paucity of life history and abundance data exists for many demersal species, also known as groundfish. Due to this uncertainty, only 21 of the 82 species of groundfish managed under the Groundfish Fishery Management Plan of the Pacific Fishery Management Council (PFMC) have been fully assessed. One challenge in designing a systematic survey of groundfish resources is that many species associate with heterogeneous substrate of varying relief. In many areas, the rugosity of the substrata precludes sampling by conventional techniques (e.g. bottom trawl gear). This has stimulated research that characterizes fish-habitat associations for use in design of new survey methodology.

Using a combination of remote sensing, in situ observations, and spatial analytical techniques, four benthic habitat classes were mapped for a large rocky bank off the central Oregon coast known as Heceta Bank. Observational data from human-occupied submersible and remotely operated vehicle dives in the late 1980s, 2000 and 2001 were used to establish habitat classes with specific substrate characteristics that have been statistically shown to correlate with demersal fish distributions. The observational habitat data was then extrapolated over the extent of a multibeam sonar survey conducted in 1998 using quantitative parameters derived from high-resolution bathymetric and backscatter imagery of the seafloor. The resultant map predicts the locations of four habitat classes: Ridge-Gully, High-Relief Rock (boulders, cobbles), Unconsolidated Sediment 1 (muds), and Unconsolidated Sediment 2 (sands).

The main utility of the habitat map developed as part of the current study is that it provides a context for analyses of a variety of spatial data. For instance, habitat data provides one additional spatial component besides depth and latitude that can be used to stratify catch per unit effort data from surveys and commercial logbooks. Also, essential fish habitat for many demersal species can now be identified in more detail. Finally, habitat data like those presented here can aid in the design of marine reserves and protected areas by providing a context for spatial analyses of data of ecological importance.

Using Remote Sensing, In situ Observations, and Geographic Information Systems to Map Benthic Habitats at Heceta Bank, Oregon

by

Curt E. Whitmire

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INTRODUCTION

Submarine banks are common physiographic seafloor features of the continental shelf off the coast of Oregon. Examples include Coquille, Stonewall, Daisy, and the largest - Heceta Bank. These banks support diverse assemblages of invertebrates and fishes and have consequently been target areas of fishery exploitation. Dramatic declines in several commercially important populations of demersal fishes known as groundfish have occurred along the U.S. West Coast during the last two to three decades (Ralston 1998; Bloeser 1999). While the reasons for these declines are not entirely clear, nine species of commercially important groundfish have declined sufficiently to be listed as “overfished”: Pacific Ocean perch, cowcod, bocaccio, canary rockfish, widow rockfish, darkblotched rockfish, lingcod, yelloweye rockfish, and Pacific whiting (PFMC 2001; Jim Hastie, pers. comm.). Because many of the commercially important West Coast groundfish show close association with often-rugged heterogeneous substrata, the fishery resources are difficult to assess using conventional survey techniques (e.g. trawling). Also, the broad spatial extent of these fisheries combined with the lack of habitat-specific estimates of abundance generally have precluded careful examination of the nature of the exploited habitats, the relationships among species and habitats, and the degree to which fishing activities have affected these habitats. Due to the paucity of data on relative abundance and life history characteristics for many species, only 21 of the 82 species (25.6%) managed under the Groundfish Fishery Management Plan (FMP) of the Pacific Fishery Management Council have been fully assessed (PFMC 2001).

Because of this uncertainty, scientists and managers have proposed that one way to increase the precision in fish stock assessments involves using the knowledge of important fish-habitat associations. In small specific geographic areas, the relationships between groundfish assemblages and their habitats have been delineated using in situ methodologies, and in some cases using geophysical mapping techniques (O'Connell and Carlile 1993; O'Connell et al. 2002; Fox et al. (1999, 2000); McRea et al. 1999; Yoklavich et al. 2000; Amend et al. 2001). Many of these studies were summarized by Reynolds et al. (2001) and Nasby-Lucas et al. (2002), and a few are highlighted here. Benthic habitat investigations combining observational data and sidescan sonar mapping in the U.S. began off the East Coast in the late 1970s (Able et al. 1987). Off the West Coast, habitat investigations using submersibles began in 1987 at Heceta Bank (Pearcy et al. 1989). Pearcy et al. examined fish distributions and habitat associations, and established six stations for future submersible operations. In the late 1980s, a group of investigators from Oregon State University and the Oregon Dept. of Fish & Wildlife used the *Delta* submersible to conduct transects on three banks off the Oregon coast including Heceta Bank (Hixon et al. 1991, Stein et al. 1992). They discovered clear correlations between fish abundance and seafloor habitat characteristics and established a 3-year time series of data on resident groundfish, invertebrates, and their habitat associations. However, there existed no high-resolution bathymetric map or detailed geologic map of any of the banks to extrapolate transect data and characterize habitat areas beyond the observational extent of the submersible. Although sidescan sonar has been used since the 1960s to interpret seafloor texture (Clay et al. 1964), acquisition of comparable resolution bathymetry had to await advances in computer processing and positioning systems that enabled the use of multibeam sonar for shallow water applications (Hughes-Clarke et al. 1996). With multibeam sonar, high-resolution bathymetric and backscatter data can be collected simultaneously; thus the ability to survey the seafloor more efficiently and at finer scales has greatly improved.

In order to spatially extrapolate the findings of historical *Delta* submersible dives at Heceta Bank (Hixon et al. 1991; Stein et al. 1992), an ongoing cooperative effort began in 1998 to conduct a more extensive habitat-based fisheries investigation of the area. The Heceta Bank Project was conceived as an interdisciplinary study of fish habitats involving experts in marine geology, fisheries biology and oceanography, and invertebrate ecology. The major research questions of this continuing project are:

1) At what scales are there quantifiable relationships between groundfish populations and seafloor morphology/texture?
2) What are the factors that control these relationships?
3) What changes may have occurred in the fish populations after a decade?
4) What are the characteristics and extent of natural refugia?

In order to answer these questions, the project was designed to integrate high-resolution seafloor imagery with historical and newly collected data from direct observations. For this reason, a high-resolution multibeam sonar survey was conducted at Heceta Bank in 1998 (Nasby-Lucas 2002, MBARI 2001). Using this newly acquired high-resolution seafloor imagery and the data set compiled from numerous *Delta* submersible dives in the late 1980s, species abundances were estimated in small selected homogeneous habitat areas adjacent to historical submersible transects (Nasby-Lucas et al. 2002). This new geographic information system (GIS) approach was an initial attempt at estimating groundfish abundance based on strong analytical evidence relating species to specific habitat characteristics. To differentiate from similar studies, the next logical progression for Heceta Bank is to efficiently relate small-scale observations and assessments of fish-habitat associations to even larger geographic areas. Large-scale seafloor habitat classification and mapping is critical to the accurate assessment of groundfish populations on a spatial scale pertinent to animal distributions, fisheries, and the physical, biological, and chemical processes that influence them.

This paper describes a GIS-based method for classifying and mapping habitats on Heceta Bank using a variety of geomorphologic parameters derived from high-resolution multibeam bathymetric and backscatter imagery. Using the fish-habitat associations determined from statistical analyses of both historical data and those collected in 2000 and 2001, a prediction map of demersal fish habitats was created for a large portion of Heceta Bank and the adjacent continental slope. The habitat map presented in this study provides the spatial context to estimate abundances of resident groundfish species over the entire multibeam survey area and analyze other data of ecological importance.

MATERIALS AND METHODS

Study Area

Heceta Bank is the most seaward portion of the continental shelf off Oregon, extending out to approximately 60 km off the central Oregon Coast (Figure 1). The geology of Heceta Bank was extensively described by Embley et al. (2002, in review) and is summarized here. Heceta Bank is a large rocky shoal off the central Oregon coast. Most of the Bank was eroded above sea level during low sea level stands. The wavecut platform is characterized by extensive outcroppings of Late Miocene and Early Pliocene mudstones, siltstones, and sandstones deposited in a forearc basin. The younger strata of those outcroppings have been differentially eroded to form distinct asymmetric 'hogback' ridges that are steeper on the updip end. Seismic reflection data (Muehlberg 1971) show that the younger sequences are well stratified and the older sequences exhibit little stratification due to massive bedding. The weathering of the jointed bedrock on top of the Bank resulted in extensive cobble and boulder pavements in some areas. These joint sets are most prominent within the outcroppings on the two topographic highs of the Bank and in areas on the southwest and northwest portions of the Bank. It is these boulder and cobble pavements that elicit the relatively high acoustic reflectivities visible in the Simrad EM 300 backscatter imagery (Figure 2, left panel). The outer edge of the Bank is marked by a sudden transition from higher to lower acoustic backscatter. Direct observational evidence from submersibles of wave-cut cliffs and intertidal boring clams has revealed that this transition is a probable paleo-shoreline of Late Wisconsin age (Goldfinger 1997; Embley and Valdés, pers. comm.).

Rocky habitats also occur seaward of the Bank, including deeper water outcrops of older rocks similar to those found on top of the Bank. Also seaward of the Bank, several well-defined pockmarks formed by methane

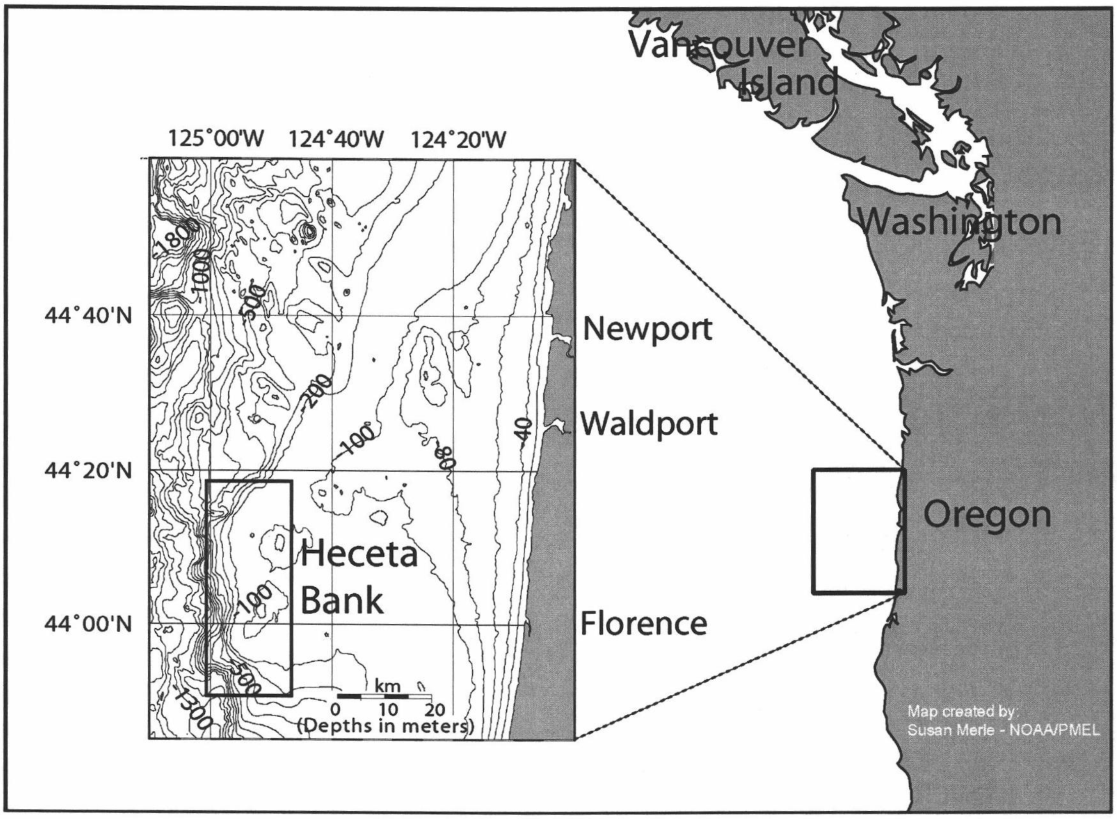


Figure 1: Heceta Bank.

Location of Heceta Bank and the adjacent continental margin in relation to the Oregon Coast. The Simrad EM 300 multibeam sonar survey area is highlighted by the bold rectangular box.

seeps are found in the mud zones between 200 and 450 meters water depth. These pockmarks contain carbonates and support or have in the past supported microbial mat and various mollusk and gastropod communities.

Due to its gross physiography, Heceta Bank greatly influences shelf transport, both in the alongshore and across-shelf directions. Contours of temperature, salinity, sigma-t, chlorophyll, and nutrients (nitrate and silicate) tend to align roughly with local isobaths (Huyer 1983); suggesting the principal axis of alongshore velocity is nearly parallel to local isobaths (Kundu and Allen 1976). Furthermore, southward flow along the shelf appears to be diverted seaward by Stonewall and Heceta Banks; and eventually results in meandering circulation immediately south of Heceta Bank. These eddies cause retention, and patches of high chlorophyll concentrations (up to 15 mg/m^3) at the surface have been detected in the vicinity of Heceta Bank (Barth, pers. comm.).

One important aspect of Heceta Bank and the immediate vicinity is that it includes both areas disturbed by intense and repeated bottom trawling and areas of possible natural refugia for groundfish. The shallow portions of the Bank are characterized by hogback ridges of varying relief and expansive fields of boulders and cobbles. The Bank's rugosity appears to provide refuge for many species of demersal fishes including numerous rockfishes and lingcod, as well as large schools of unidentified juvenile rockfishes (Hixon et al. 1991). On the other hand, mud and sand dominate the slopes of the Bank where many flatfish and some rockfish species reside and these plains show extensive disturbance from bottom trawl gear. The diversity in habitats makes Heceta Bank an ideal location for studying groundfish distributions, characterizing natural refugia, and assessing the effects of fishing impacts.

Multibeam Sonar

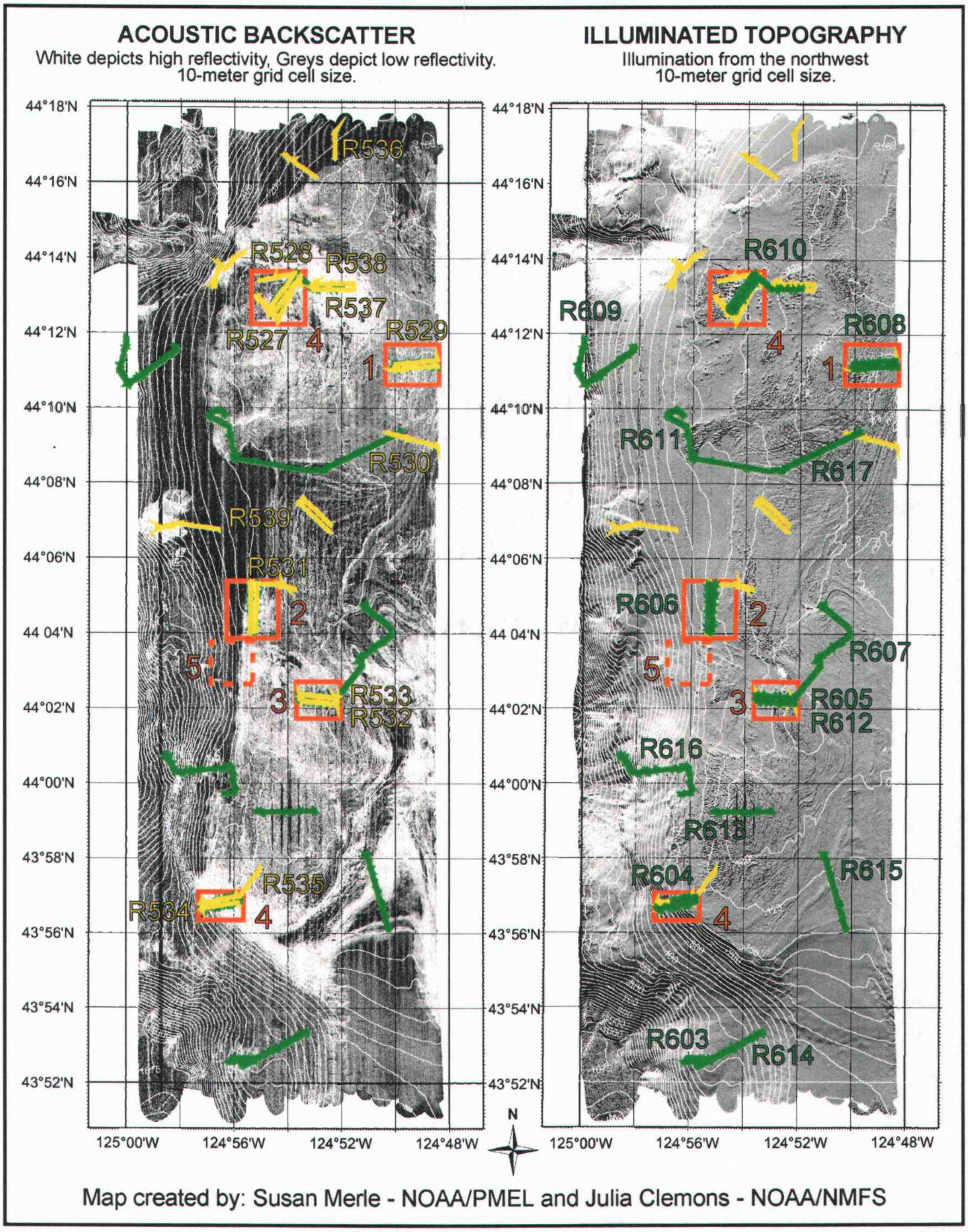
In May of 1998, a multibeam sonar survey of the Heceta Bank area was conducted using a hull-mounted Simrad EM 300 multibeam echo sounder (Nasby-Lucas 2002; MBARI 2001). The EM 300 is a medium-range, high-resolution multibeam system engineered to conduct surveys in depth ranges from 10-5,000 meters but is particularly effective in continental shelf and slope applications (Table 1; Kongsberg Simrad 2001-2003). Its intermediate frequency (30 kHz) makes it a good compromise between resolution and survey efficiency in areas such as the continental margin where depths change rapidly between the shelf (<100 m) and lower slope (<2,000 m). Using the chartered vessel M/V *Ocean Alert*, 47 overlapping north-south swaths of up to 45 km long were made over a period of 80 hours, and resulted in approximately 725 km^2 coverage of the seafloor (Nasby-Lucas et al. 2002). The raw multibeam data were processed with SWATHED software (Ocean Mapping Group, Univ. of New Brunswick Fredericton) – the processing steps are described in Nasby-Lucas et al. (2002). This processing produced high-resolution maps (Figure 2) of bathymetry and acoustic backscatter.

Table 1: Simrad EM 300 multibeam echo sounder specifications.

System	Frequency	# of beams	Min/Max Depths	Coverage	Max Swath Width
EM 300	30 kHz	135	10/5000 meters	Up to 150º	>5000 meters

Figure 2: Simrad EM 300 multibeam sonar imagery.

The acoustic signal amplitude (backscatter) image of the left panel depicts the relative acoustic reflectivities of the seafloor substrata. The lighter the shading the higher the reflectivity values. ROPOS remotely-operated vehicle dives are represented with line segments (2000 dives are yellow; 2001 dives are green) and the locations of historical dive stations (Pearcy et. al. 1989, Hixon et. al. 1991, Stein et. al. 1992) are represented with orange boxes. The topography image of the right panel is artificially illuminated from the northwest, which creates shadows to the southeast of relief. Depth contours are represented in white at 25-meter intervals.



Map created by: Susan Merle - NOAA/PMEL and Julia Clemons - NOAA/NMFS

Figure 2: Simrad EM 300 multibeam sonar imagery.

Bathymetric Principles

Echo sounders determine depth by measuring the two-way travel time of a transmitted acoustic wave – time it takes the acoustic wave to travel from the transducer transmit array to the seafloor and back to the transducer receive array. The basic principle behind multibeam echo sounders as compared to single beam echo sounders is that larger swath coverage can be achieved using a transducer array of multiple beams (Figure 3). In echo sounders, acoustic beams are formed via the excitation of quartz crystals on the transducer array. The propagation of multiple acoustic waves from the transducer creates a linear series of elliptical areas of ensonification (i.e. footprints) on the seafloor (Figure 3, right image). The return signal from each beam is used to measure the average depth of its corresponding footprint.

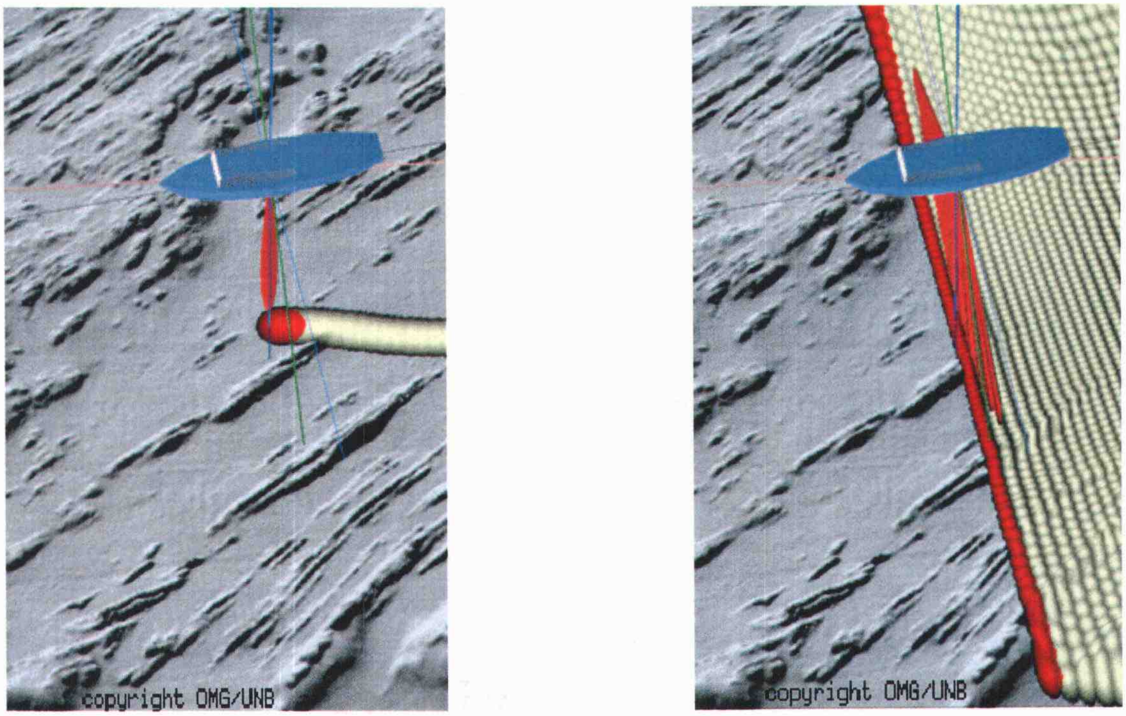


Figure 3: Single-beam vs. multibeam sonar.

Schematic describing single beam (left panel) and multibeam (right panel) sonar modes of operation (modified from Hughes Clarke, Ocean Mapping Group, Univ. of New Brunswich Fredericton).

The spatial resolution of multibeam sonar is dependent on the beam-forming capabilities of the particular system. In high-resolution systems, beams are narrowly focused, and can thus produce smaller footprints. Since depths are averaged over a single footprint, the resolution of the system is inversely proportional to the size of the footprint. In other words, the smaller the footprint, the higher the spatial resolution of the multibeam system. As the size of the footprint changes with changing depth, the multibeam system electronically adjusts the beam angles to optimize the spatial coverage over the entire swath width of the beams. Also, the period of each ping changes with depth – increasing as depth increases and vice versa. Therefore, resolution is indirectly a function of depth since the footprint size of each beam is electronically controlled by the multibeam system.

For this study, the multibeam data for the deeper areas (>500 m) along the western flanks of Heceta Bank were gridded to 10 meters while the data for the shallower portions (70-150 m) were gridded to approximately 5 meters. Fortunately, it is in these shallow regions where it is thought the largest diversity in habitats occurs.

One of the challenges of seafloor mapping in the past has been the geo-referencing of the depth soundings collected by sonar systems. Over the last two decades, civilian maritime navigation has become very accurate and precise due to the utilization of the global positioning system (GPS), which has a maximum positional accuracy of 1-2 meters (Hughes Clarke et al. 1996). Navigation on the M/V *Ocean Alert* consisted of a differential GPS system using a local reference station. Since vessel attitude constantly changes, corrections for roll, pitch, and heave of the vessel were also applied using a shipboard attitude sensor; and local tidal variations were incorporated into the depth calculations.

Acoustic Backscatter Principles

Acoustic backscattering is defined as the total amount of acoustic energy (signal amplitude) reflected from the seafloor and received by the echo sounder transducer array. Two physical processes affect the interaction of acoustic waves with the seafloor: acoustic scattering and specular reflection. Acoustic scattering is a "functional relationship between the intensity of the scattered energy with the angle of ensonification, the angle of the returning acoustic wave, the roughness of the seafloor, and the material properties of the seafloor" (Nishimura 1997). The highest acoustic amplitude returns are caused by the densest substrate or areas of high topographic variation while softer unconsolidated sediments and flat areas produce the lowest amplitude returns. It is the knowledge of how various lithologic materials scatter acoustic waves that facilitates many seabed textural classifications. Specular reflection is dominant at near incident angles and results in a relatively strong amplitude return from the water-sediment interface (Nishimura 1997). Unfortunately, it is this strong amplitude return that causes a sonar image artifact known as nadir noise (Blondel 1997), which appears in backscatter imagery as relatively high reflective linear striping along the sonar swath and directly under the vessel path (Figure 2, left panel).

Submersible Dives

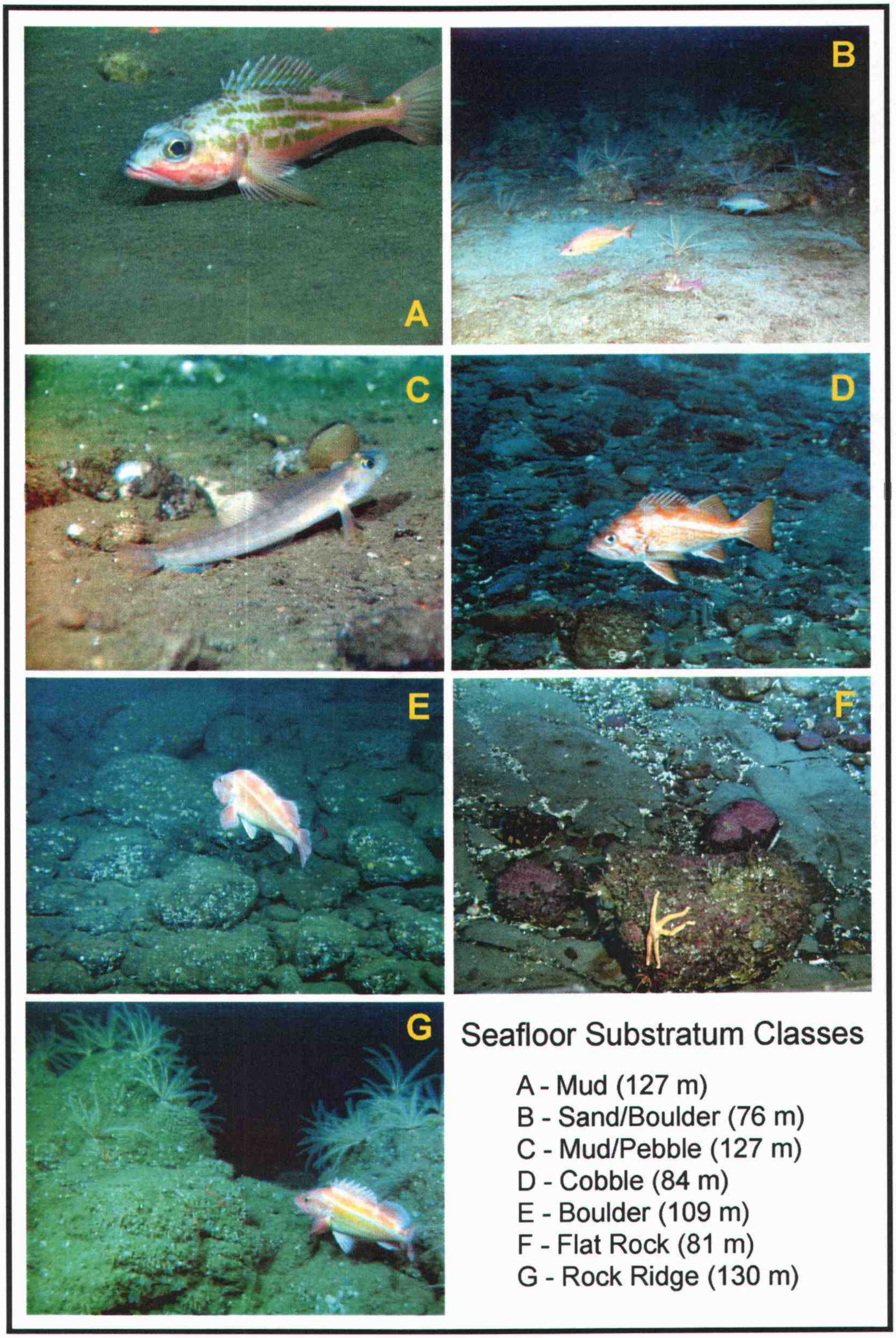
Submersible dives using the remotely operated vehicle (*ROPOS*) and human occupied vehicle (*Delta*) were conducted in summers of 2000 and 2001 to groundtruth the imagery and collect information about benthic substrata and fauna. A total of 5 *Delta* (in 2000 only) and 28 *ROPOS* dives (Figure 2) were completed, including transects at six historical stations established during the 1988-1990 programs at Heceta Bank (Pearcy et al. 1989; Hixon et al. 1991; Stein et al. 1992), as well as across boundaries defined on the sonar imagery and across zones of particular biologic and/or geologic interest (e.g. pockmarks). The resulting geographic coverage better represents the diversity in habitats on the Bank than did those of the 1988-1990 programs. The purpose of the dives was to either conduct quantitative fish transects or to explore areas of interest. The design of the fish transects simulates those conducted during the 1988-1990 program and was described by Hixon et al. (1991); Stein et al. (1992); and Nasby-Lucas et al. (2002); and a brief description follows. Each fish dive included two 30-minute linear transects with a 10-minute quiet period between transects to assess the effects of submersible lighting and noise on fish behavior. Parallel lasers mounted on the submersibles were used to approximate fish size and transect width. Daytime fish transects were repeated during the night with *ROPOS* to evaluate diel patterns of behavior. Exploratory dives with *ROPOS* were also used to study new areas and collect biological and lithological samples.

Observational data were interpreted from high-resolution digital video to detail information about benthic substrata, demersal fish species and abundances, and benthic invertebrate fauna. The seabed was characterized by the same 7-class system used during the 1988-1990 program and represented the diversity in texture and topographic relief observed in the submersible videos. Those seven substratum classes (Figure 6) listed in order of increasing texture and relief were mud (M), sand (S), pebble (P, diameter <6.5 cm), cobble (C, diameter >6.5 cm and <25.5 cm), boulder (B, >25.5 cm), flat rock (F, low vertical relief), and diagonal rock ridge (R, high vertical relief). The seabed was classified using a 2-letter code – the first letter denoting primary substratum (>50% of field of view) and the second letter denoting secondary substratum (>20% of field of view). If only one substratum was visible or the secondary substratum covered less than 20% of the field of view, the primary substratum was recorded twice (e.g. MM). Changes in substrata were recorded only when the duration of the substratum patch was ≥ 10 seconds on the videos. Fish densities were calculated using the length of the substratum patch and transect width.

Since the number of dives and bottom time by *ROPOS* far exceeded that of *Delta*, only the ROV observational data were used in this classification. Furthermore, compilation of substrate data was concurrently performed by two individuals so as to minimize any subjectivity associated with video interpretations.

Figure 4: Observed substrata on Heceta Bank.

Seven classified substratum types observed from submersibles at Heceta Bank. Water depths are listed in parentheses.



Seafloor Substratum Classes

A - Mud (127 m)
B - Sand/Boulder (76 m)
C - Mud/Pebble (127 m)
D - Cobble (84 m)
E - Boulder (109 m)
F - Flat Rock (81 m)
G - Rock Ridge (130 m)

Figure 4: Observed substrata on Heceta Bank.

Classification Approach

A variety of methods exist for classifying seafloor habitats, ranging from very qualitative to entirely quantitative. One relatively qualitative approach involves the visual interpretation of sidescan or backscatter imagery produced by sidescan and multibeam sonars, respectively (e.g. Wakefield et al. 1998). This approach is strongly dependent on the expertise of the interpreter and his/her experience in pattern recognition, and thus is not very repeatable. At the other end of the spectrum, published algorithms are used in a neural network to quantitatively classify seafloor substrata. This can be achieved either by characterizing returned acoustic signal amplitudes (e.g. Questar-Tangent QTC View) or analyzing patterns in sidescan or multibeam backscatter imagery (e.g. Triton-Elics SeaClass). This type of approach is often applied in situations were little groundtruthing is available, and should yield similar results regardless of the user. Yet another approach involves using a combination of quantitative topographic and textural parameters derived from bathymetric and acoustic backscatter data, respectively (e.g. Dartnell 2000).

Before choosing a particular approach, it was necessary to evaluate the objectives of the classification and potential limitations of available data. The major objective of this study was to produce a map of seafloor habitats that will provide a context for improved abundance estimates of resident groundfish species. The ability to map habitats at a particular scale is dependent on the resolution of the available seafloor imagery; which in this case corresponds to a macroscale level of classification (on order of 1-10 m; Greene et al. 1999) that includes seafloor features such as ridges and boulders. That is not to say that smaller features cannot be identified using the multibeam data; smaller scale substrata such as muds, sands, and cobbles exhibit discernable textural patterns in acoustic backscatter imagery. However, differentiating between all seven substrata classes (mud, sand, pebble, cobble, boulder, flat rock, and rock ridge) proved to be problematic. For instance, it was difficult to distinguish boulders from cobbles because they exhibit similar patterns in acoustic backscatter imagery and are not individually resolved by the available bathymetric imagery. Consequently, it was necessary to group various closely associated substrata in order to map them efficiently. From statistical analyses conducted during the 1988-1990 program, it is known that boulders and cobbles were strongly correlated as were ridges and sands; and these substrata combinations showed correlations to various species of resident groundfish (Hixon et al. 1991; Stein et al. 1992). According to these findings and foreseeable limitations of the imagery, closely associated substratum classes were grouped into four target habitat classes:

- Ridge-Gully
- High-Relief Rock (boulders, cobbles)
- Unconsolidated Sediment 1 (muds)
- Unconsolidated Sediment 2 (sands)

Considering the objectives of this study, the amount of available observational data, and scale issues, a more quantitative approach to classifying seafloor habitats was chosen. The approach used in this study is similar to one described in Dartnell 2000, and will be described next.

Data Analyses

The basic method for this classification involved a hierarchical decision tree with parameters derived from high-resolution multibeam bathymetric and backscatter imagery. Before assigning parameter values in the decision tree, it was necessary to determine which parameters were strongly correlated with the seven substratum classes (and related target habitat classes). Therefore, a multivariate analysis was performed on the seven substratum classes and the image parameters. Once these strong correlations were known, it was necessary to identify the ranges of values for each parameter that was specific to a particular target habitat class (e.g. High-Relief Rock). For that reason, the observational data had to be compared to the relevant geomorphologic parameters for that target habitat class. Once these steps were completed for all four target habitat classes, the finished decision tree was applied to all the gridded parameters to create a habitat prediction map for the Heceta Bank survey area (Figure 17).

Dynamic Segmentation

To exploit the multitude of data available from direct observations, it was necessary to translate it into a format favorable to spatial analysis. The optimal format chosen was the dynamic segmentation data structure developed by Environmental Systems Research Institute, Inc. (ESRI) because it is ideal for modeling and analyzing linear features such as those representing submersible dive transects. Dynamic segmentation was previously applied to the substrata dataset interpreted from video data collected during the three historical studies at Heceta Bank (Nasby-Lucas et al. 2002). This facilitated an analysis of small homogeneous habitat patches and subsequent estimation of fish abundance within those patches.

Dynamic segmentation allows for the representation of changing ‘events’ along a linear feature; the ‘events’ in this case being the seven seafloor substratum classes (Figure 4) used in historical studies at Heceta Bank. To be consistent with the historical methods and substratum classification, videos were interpreted by noting time and change in substratum with the same 2-letter codes used during the 1988-1990 program. A translation of substrate data into this data structure was necessary for relating groundtruthed data to the multibeam imagery (Figure 5).

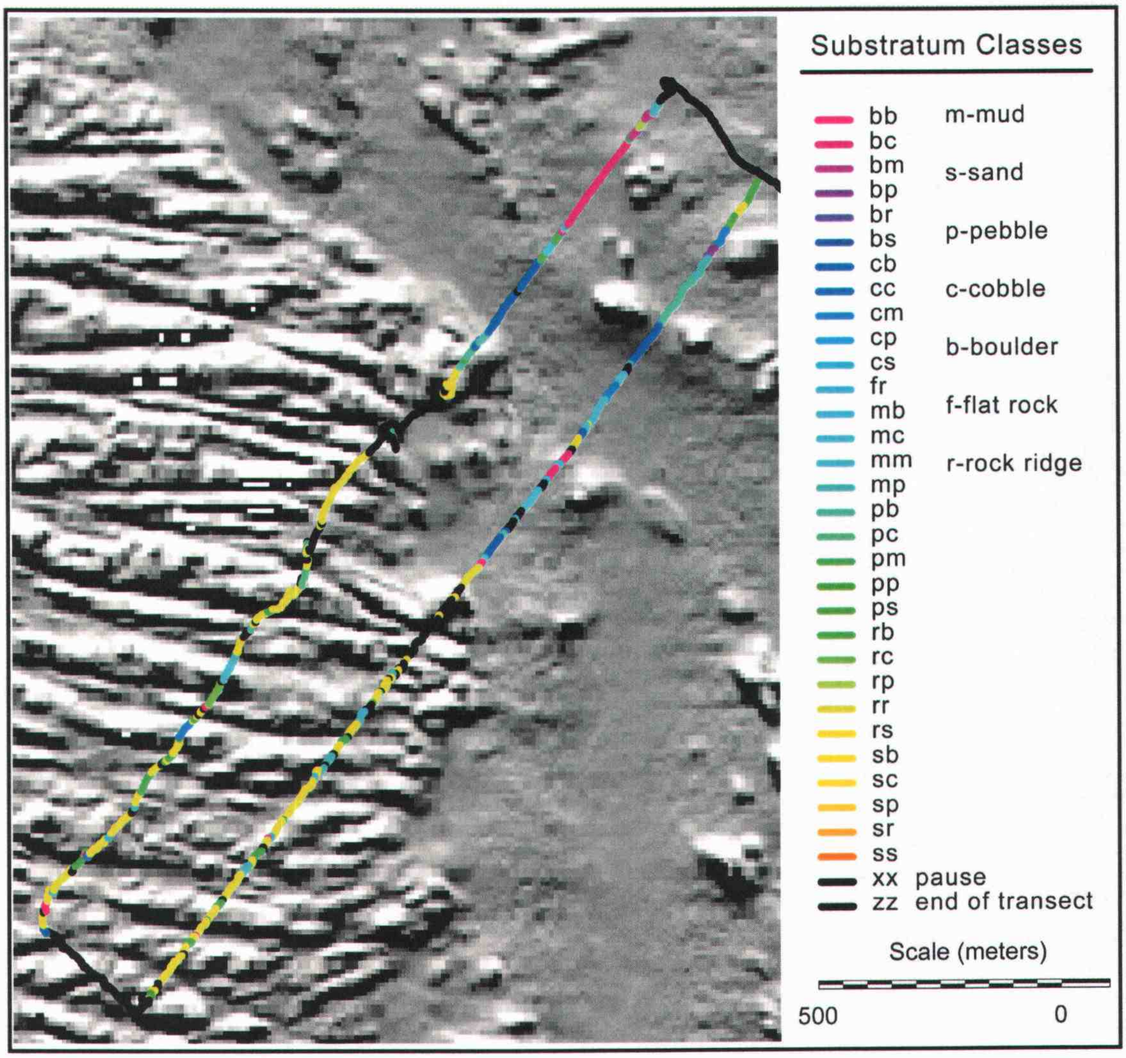


Figure 5: ESRI's dynamic segmentation data structure.

ROPOS dive R610 is formatted into the dynamic segmentation data structure and overlain onto an inset of the EM 300 multibeam sonar illuminated topography imagery. Seafloor substratum classes are color-coded according to the above key.

Map Parameters Derived from Multibeam Data

Once target habitats were established and the observational data were translated into a format favorable to spatial analysis, it was necessary to derive parameters from the multibeam imagery that would facilitate the creation of distinct signatures for each target habitat. The classification used in this study is essentially a two-fold approach – a topographic component comprised of parameters derived from the bathymetric data and a textural component comprised of the parameters derived from the backscatter data (Figure 8). Using a combination of parameters derived from these two main data sets, conditions specific to each target habitat class were defined.

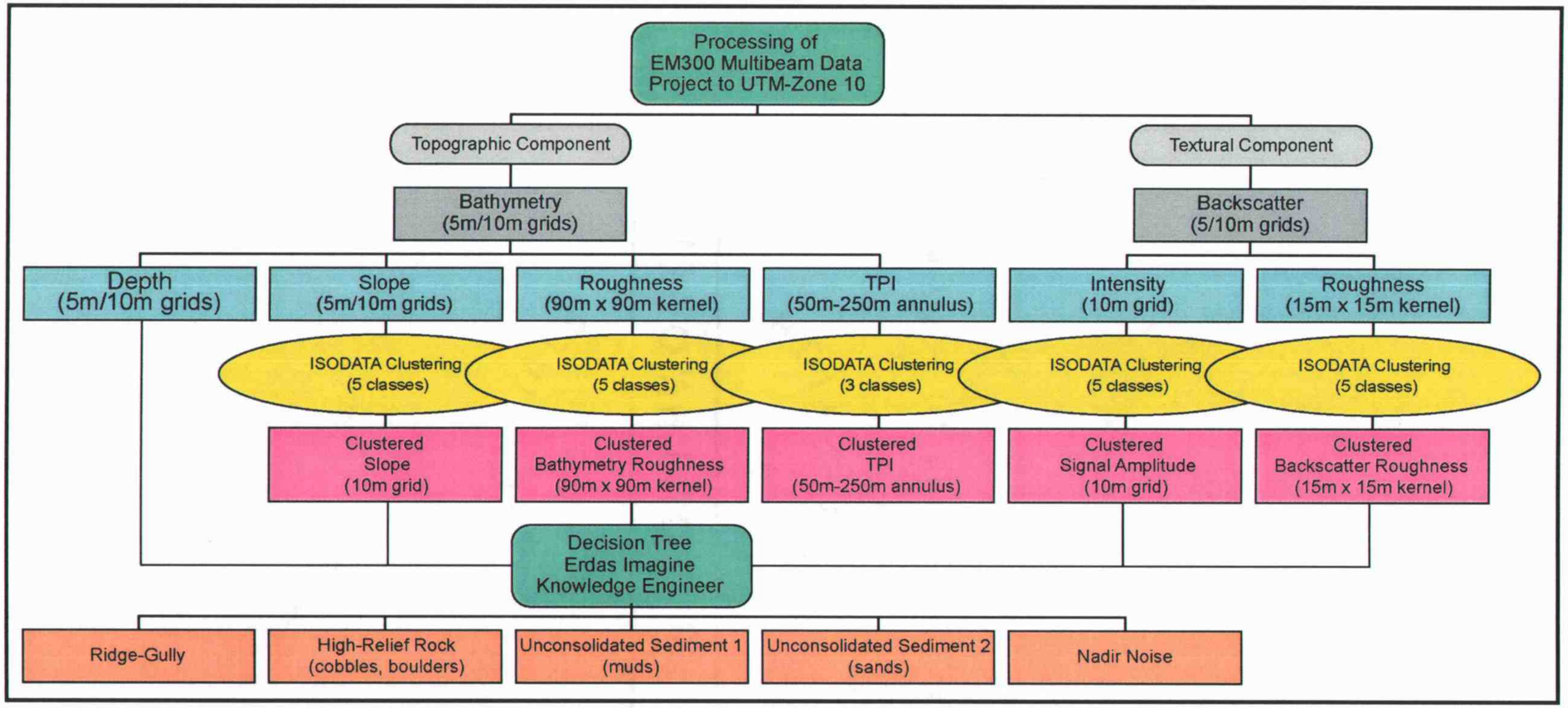


Figure 6: Flow chart of habitat classification process.

Ovals represent processes; rectangles represent intermediate raster images. Adopted from Dartnell (2000).

Signal Amplitude

The first parameter used to define specific seafloor habitats was acoustic signal amplitude (backscatter). On one end of the backscatter spectrum, mud is easily distinguished because it exhibits the lowest local acoustic reflectivities in the backscatter imagery. On the other end, boulders and cobbles exhibit the highest acoustic reflectivities (Embley et al. 2002, in review) and are easily mapped using backscatter data alone. However, in areas where the coverage of boulders or cobbles is less and mud pervades the interstices, the backscattered acoustic energy might be less than in areas with complete coverage of boulders and/or cobbles. Surprisingly, rocky ridges on Heceta Bank yield only moderate backscatter values, because they are composed primarily of semi-consolidated mudstones with a primary porosity that is further enhanced by the boring of benthic organisms. In the acoustic backscatter imagery, linear features of higher backscatter values are evident in areas of ridges. These higher backscatter values are not caused by the ridges themselves, but correspond to patches of boulders or cobbles that have eroded from larger outcroppings and have settled between ridge features. These and other phenomena preclude using backscatter alone as a means to differentiate all target habitats.

Backscatter Roughness

In order to differentiate between homogeneous and heterogeneous backscatter provinces, backscatter roughness was derived from the signal amplitude data. Backscatter roughness is a measure of the total variance in acoustic amplitude (backscatter) between all pixel values within a specified neighborhood (e.g. rectangular kernel, circle, annulus). The function of this roughness derivation is scale dependent. For instance, a roughness value for a pixel within an area of 1 kilometer^2 might be very different than the roughness value for the same pixel in an area of 30 meter^2. Low backscatter roughness values represent neighborhoods where there is little variance among the incorporated pixels, whereas high backscatter roughness values represent neighborhoods with larger variance. High backscatter roughness might correspond to areas where softer substrata (i.e. mud) are interlaced with harder substrata (i.e. boulders or cobbles) within a single neighborhood. On the other hand, areas of low backscatter roughness correspond to neighborhoods with homogeneous substrata – either all mud or all boulder/cobble for instance. For this classification, backscatter roughness was calculated for a 15-meter^2 rectangular kernel.

Bathymetric Data

The primary data source for the topographic component of the classification was the bathymetric data. Depth itself is a useful parameter in seafloor classifications. However, out of the four target habitat classes only the *Ridge-Gully* class is known to occur within a discrete depth stratum (67 to 205 meters water depth). Boulder, cobbles, and unconsolidated sediments occur throughout the entire depth range of the multibeam survey. In order to differentiate between the other three target habitat classes, three additional parameters were derived from the bathymetric data: slope, roughness, and topographic position index (TPI).

Slope

The first parameter derived from the bathymetric data was local slope (first derivative of depth). Slope is defined as the variance of depth in the neighborhood of a target pixel. In this paper, it is termed local slope because it is limited to the spatial resolution of the data, and in this study was calculated from both the 5-meter and 10-meter bathymetric grid. Slope is used to identify specific topographic features in bathymetric imagery. For instance, ridges on Heceta Bank elicit medium slope values (4-30°) while areas of boulders or cobbles or flat surfaces of unconsolidated sediments elicit low slope values (<4°).

Bathymetry Roughness

The second image derived from the bathymetric data was bathymetry roughness. In the same way that backscatter roughness depicts the variance in backscatter within a neighborhood, bathymetry roughness is a measure of the total variance in depth. As with any 'roughness' derivation, bathymetry roughness is scale dependent, and different values for a particular pixel may result from varying neighborhood sizes. For instance, roughness calculated for a 90-meter^2 neighborhood revealed larger ridge features while roughness calculated for a 30-meter^2 neighborhood revealed smaller outcroppings. As with slope, bathymetry roughness is useful in identifying topographic features in the bathymetric grid, but is best at depicting specific size-class features. For this classification, bathymetry roughness was calculated for 30-meter^2 and 90 meter^2 rectangular kernels.

Topographic Position Index

The third parameter derived from the bathymetric data was topographic position index (TPI). As with roughness, TPI is another neighborhood statistical algorithm. The TPI algorithm compares the elevation of each pixel to that of the mean elevation value within a specified neighborhood. The algorithm is defined as:

TPI<scale factor> = int((dem – focalmean(dem, annulus, irad, orad)) + 0.5)

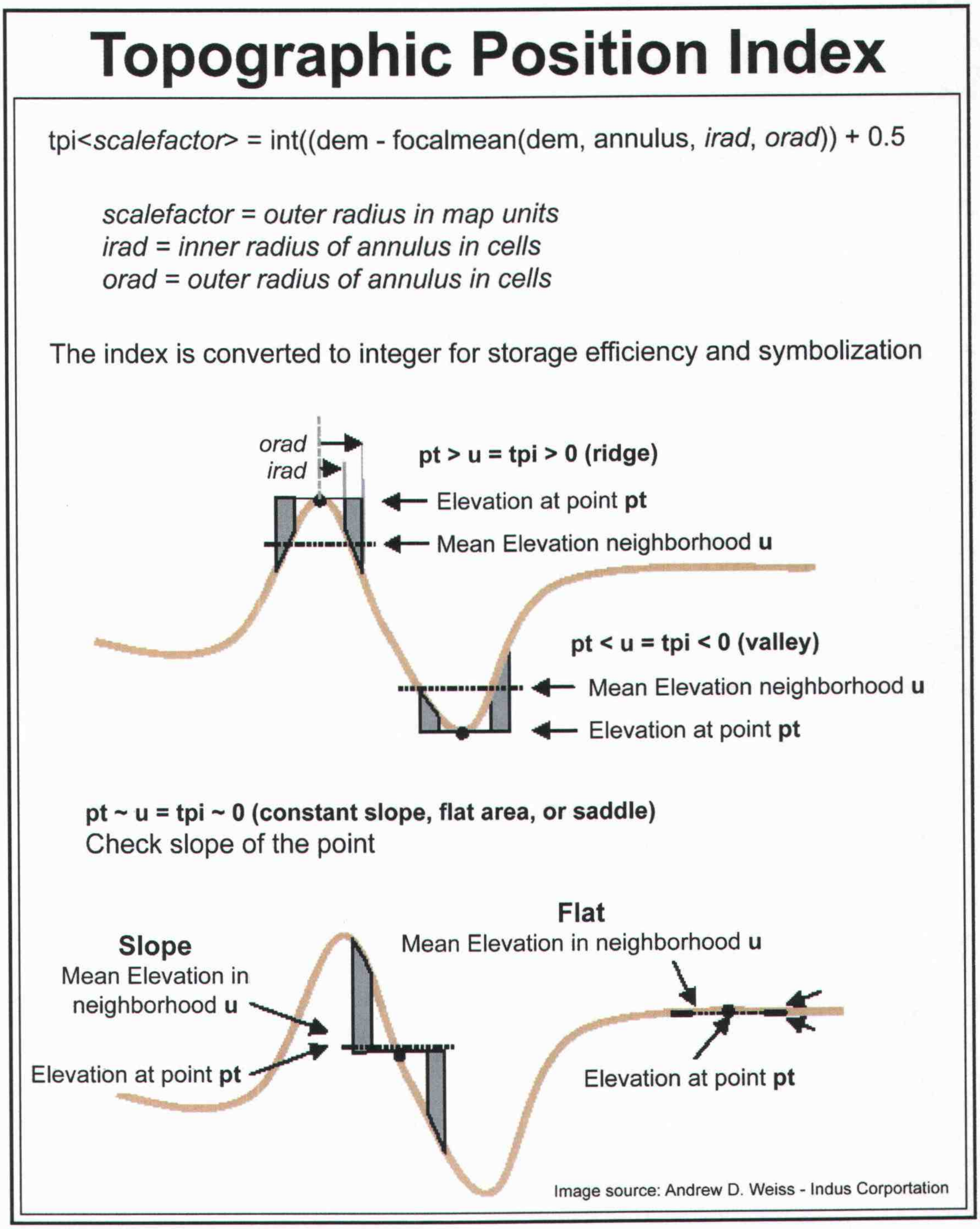
Where:

scale factor = outer radius in map units
irad = inner radius in cells
orad = outer radius in cells

The algorithm first calculates the mean value of all the pixels within a specified neighborhood (e.g. rectangular kernel, circular ring, annulus) and then calculates the variance from that mean. These variance values are rounded to the nearest integer value for ease of storage.

Positive TPI values represent topographic positions that are higher than the mean elevation within the specified neighborhood, while negative values denote positions lower than the mean elevation (Figure 7). As with the roughness algorithm, TPI is scale-dependent. To determine which scale factor might be appropriate for identifying macroscale ridge features in our study area, numerous vertical dive profiles from the *ROPOS* transects were consulted. After some simple calculations, it appeared evident that many ridges on Heceta Bank occur at a 20-30 meter frequency. Consequently, TPI at numerous annuli sizes was calculated, each being large enough to encompass features of 20-30 meters in size.

For this classification, TPI<50>, TPI<75>, TPI<125>, TPI<150>, and TPI<250> were calculated. Classification of TPI into positive, negative, and zero variance classes provided an automated method of depicting ridge and gully features. Since ridges are resolved by both the 5-meter and 10-meter bathymetric grids and are therefore visible on the illuminated topography imagery, they served as a means to visually assess which scale factor of TPI represented the most ridges and outcroppings. After repeated examination, it was evident that TPI<125> was the optimal scale factor for this application.



Topographic Position Index

tpi<*scalefactor*> = int((dem - focalmean(dem, annulus, *irad*, *orad*)) + 0.5

scalefactor = outer radius in map units
irad = inner radius of annulus in cells
orad = outer radius of annulus in cells

The index is converted to integer for storage efficiency and symbolization

Image source: Andrew D. Weiss - Indus Corportation

Figure 7: TPI algorithm.

Algorithm and schematic describing topographic position index (Adopted from Weiss 2000).

Multivariate Statistics

Multivariate associations among groundtruthed substrata and various scales of the six geomorphologic parameters (i.e. backscatter intensity, backscatter roughness, slope, bathymetry roughness, TPI, and depth) were examined using principal components analysis (PCA). PCA "reduces the dimensions of a single group of data by producing a smaller number of abstract variables (linear combinations of the original variables, principal components)" (James and Mulloch 1990). The primary goal of the PCA was to extract strong correlations between observed seafloor substratum classes and the derived geomorphologic parameters, in order to establish a rules-based decision tree. Strong correlations revealed in the first three principal component scores helped determine which geomorphologic parameters could be used to define each target habitat class in a decision tree.

Also, PCA of 2000-2001 *ROPOS* transect data and canonical correlation analysis (CCA) of historical *Delta* transect data were used to group related substratum classes. For instance, CCA of historical data revealed that 'hard' substratum classes were strongly correlated as well as were 'soft' substratum classes. In other words, 'hard' substrata like boulders and cobbles could be grouped, as well as 'soft' substrata like muds and sands. PCA of *ROPOS* data collected in 2000 and 2001 also revealed similar correlations, and will be described in the **Results** section. These two statistical tools helped define the four target habitat classes for a decision tree: *Ridge-Gully*, *High-Relief Rock (boulders, cobbles)*, *Unconsolidated Sediment 1 (muds), and Unconsolidated Sediment 2 (sands).*

ISODATA Clustering

To simplify their large 8-bit datasets, each gridded geomorphologic parameter was statistically clustered using the Unsupervised Classification utility in Erdas Imagine. Unsupervised classification, also know as ISODATA clustering, groups pixels based on their natural arrangement in the image data. Specifically, this method uses minimum spectral distances to assign a cluster to each pixel. The mean and covariance matrix of each cluster is calculated and the program iteratively groups subsequent pixels based on shifting means of each cluster. For all parameters, the gridded data were clustered into five classes based on 1.0 standard deviation units; the exception being TPI<125> which was clustered into three classes to represent positive, negative, and zero variance values.

Once correlations between observed substratum classes and geomorphologic parameters were known, it was next necessary to determine the values for each rule in the decision tree. For this reason, the distributions of the clustered parameter pixel values were examined for each substratum class.

Rules-Based Decision Tree

Using the results from the PCA and comparisons of clustered geomorphologic parameter data with groundtruthed substratum classes, a rules-based decision tree was established using the Knowledge Engineer utility in Erdas Imagine (Figure 8). For this application, hypotheses represented the target habitat classes; rules represented the substratum classes specific to each target habitat class; and variables were the geomorphologic parameters used in the rules to define the hypotheses. For example, High-Relief Rock is the hypothesis; Boulder and Cobble are the substratum classes; and acoustic signal amplitude (backscatter intensity) and backscatter roughness are the variables used to define High-Relief Rock (Figure 8). The decision tree was applied to the clustered backscatter intensity data and the four clustered derivative parameters (i.e. backscatter roughness, slope, bathymetry roughness (90m^2), TPI<125>) to create the output prediction map using Imagine's Expert Classifier utility. In addition, depth was used as a rule for the

"Ridge-Gully" target habitat because ridges (as defined for this study) are known to locally occur only on the Bank (<205 m water depth).

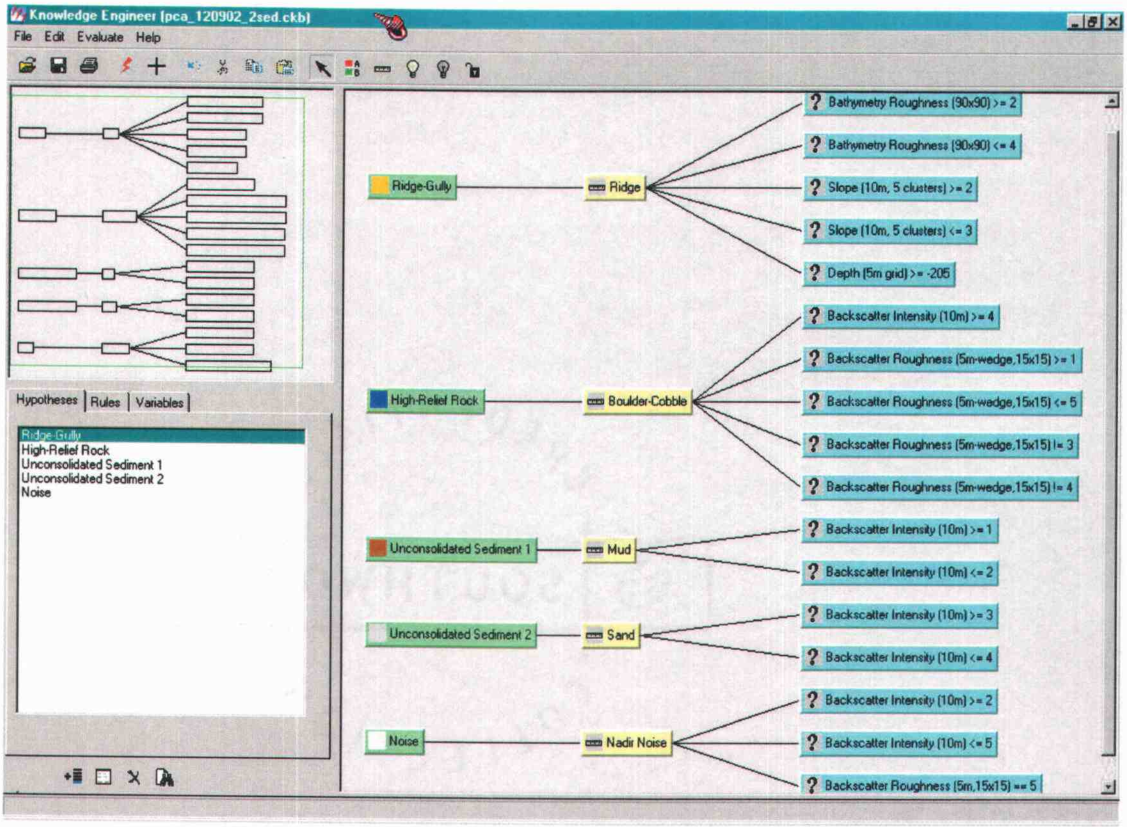


Figure 8: Decision tree.

Rules-based decision tree created in Erdas Imagine Knowledge Engineer. Hypotheses (left column of right window) represent the target habitat classes; rules (middle column of right window) represent the classified substratum classes observed from the submersibles; variables (right column of right window) represent the parameters derived from the gridded multibeam bathymetry and backscatter data.

Noise Removal

Nadir noise caused by specular reflection is common with multibeam sonar systems, and shows up as a linear feature of higher backscatter along the sonar swath directly under the vessel. This nadir noise is prevalent in Heceta Bank backscatter imagery and appears as white lines traversing a north-south axis in the center of each sonar swath. The nadir noise also appears in all images derived from the acoustic backscatter data and therefore is evident in the final habitat map (Figure 17).

One noise removal technique was employed prior to the initiation of the classification process. In Erdas Imagine, Fourier analysis was used in an attempt to remove periodic noise, namely nadir noise, in acoustic backscatter imagery. The premise behind Imagine's application of Fourier transformations is to convert gridded imagery from the spatial domain into a frequency domain by converting the image data into a series of two-dimensional sine waves of various frequencies (Erdas 1997A). The resulting Fourier image is not easily viewed but the magnitude of the image data can be displayed in Imagine, where periodic noise caused by banding, spotting, or striping appears as artifacts. Once identified, Fourier editing techniques can be used to filter out periodic noise, and the cleaned frequency data can be inversely transformed back into spatial image data.

Fourier transformations were performed for the acoustic backscatter imagery, but only some minor artifacts were discovered. These frequency artifacts were removed using a wedge filter, but the method did not significantly remove the nadir noise and rather appeared to undesirably "smooth" the image data. Furthermore, the original and Fourier-edited backscatter grids were not strongly correlated in the PCA analysis (Table 2), which was expected since the two should represent very similar data. Therefore, the Fourier-edited backscatter grid was only used to compute backscatter roughness since nadir noise significantly affects this calculation.

After the decision tree was applied to all the image grids, a second noise removal process described by Dartnell (2000) was used to filter out nadir noise, and is detailed here. In ArcINFO's GRID utility, a running filter –

FOCALMAJORITY – reclassifies the center pixel of a specified neighborhood as the same value of the majority pixels within the neighborhood. In other words, if a pixel classified as noise was surrounded by a majority of pixels classified as *Unconsolidated Sediment* within a specified neighborhood, the noise pixel would be reclassified as *Unconsolidated Sediment*.

RESULTS

Principal Components Analysis

The first three principal components described 48.5% of the total variance among all 19 factors (Table 2). From PC1, ridges were highly correlated to many topographic parameters including bathymetry roughness (all scales), slope (both 5-m and 10-m), TPI<125>, and depth. Similar parameters are strongly correlated to each other because they represent similar data, only at varying scales. For example, all four bathymetry roughness parameters have almost equal PC scores, as do the two slope grids (5-m and 10-m). PC1 also suggested that ridges are strongly correlated to one of the backscatter roughness grids (15-m^2 kernel, wedge). This particular roughness grid was derived from a backscatter grid that was smoothed using a Fourier noise removal utility (Erdas 1997B). PC2 and PC3 revealed that the 'harder' substratum classes – boulders and cobbles – are highly correlated; and are in turn strongly correlated to depth and the two backscatter grids (5-m and 10-m) and backscatter roughness (15-m^2 kernel, wedge; PC2 only). Therefore, backscatter amplitude and roughness were used as rules for defining the *High-Relief Rock* habitat. PC3 showed strong correlations between ridges, boulders, and cobbles. During submersible dives, boulders and cobbles were often observed at the bases of many ridges and outcrops; so it is believed they may have formed either in place or due to erosion of the ridges and outcrops. PC3 also suggested that mud and pebbles are strongly correlated to depth. However, muds (and sands) are known to occur over the entire depth strata of the multibeam survey, so depth is not a useful factor for the two *Unconsolidated Sediment* target habitat classes.

Table 2: Principal Components Analysis results.

Variables listed in italics are the observed substratum classes; variables listed in bold are the map parameters derived from the bathymetric and backscatter data.

VARIABLE	**PC1**	**PC2**	**PC3**
Eigenvalue	*4.4994*	*2.7965*	*1.9144*
Proportion	*0.237*	*0.147*	*0.101*
Ridge	-0.120	-0.458	-0.189
Boulder	0.056	0.351	-0.294
Cobble	0.037	0.248	-0.208
Pebble	-0.016	0.018	0.251
Sand	-0.006	-0.055	-0.043
Mud	0.095	0.110	0.605
Flat Rock	0.007	-0.070	0.044
Backscatter Amplitude (5 meter grid)	0.025	0.408	-0.279
Backscatter Amplitude (10 meter grid)	0.034	0.351	-0.321
Bathymetry Roughness (30 m^2 kernel)	-0.411	0.005	-0.019
Bathymetry Roughness (90 m^2 kernel)	-0.425	0.146	0.057
Bathymetry Roughness (35 m^2 kernel)	-0.428	-0.062	-0.049
Bathymetry Roughness (95 m^2 kernel)	-0.430	0.114	0.036
Backscatter Roughness (15 m^2 kernel, no wedge)	0.007	-0.180	-0.024
Backscatter Roughness (15 m^2 kernel, wedge)	-0.171	0.228	0.098
Slope (5 meter)	-0.325	-0.089	-0.087
Slope (10 meter)	-0.305	-0.018	0.062
TPI<125>	-0.130	-0.074	-0.144
Depth	-0.084	0.399	0.414

Comparison of Map Parameters with Observational Data

Rule determination for the *Ridge-Gully* hypothesis was a deviation from the rule determination for the other target habitat classes. Since macroscale ridges are resolved in the EM 300 topography imagery, aligning classification runs with the imagery superseded using the cluster values that intersected a majority of groundtruthed pixels. For example, comparison of groundtruthed data with the clustered 10-meter slope data revealed that slope clusters 1 and 2 intersected the most groundtruthed RR pixels (Figure 9). However, upon overlaying the clustered slope image onto the topography imagery, it appeared that clusters 2 and 3 best represented the locations of ridges. Therefore, slope cluster 2 and 3 were used as values in the decision tree. Also for the *Ridge-Gully* hypothesis, bathymetry roughness (90-m^2 kernel) clusters 2, 3, and 4 were shown to intersect many of the groundtruthed RR pixels (Figure 10), and also effectively represented macroscale ridges in the topography imagery. Therefore, they were used as values in the decision tree. Although TPI<125> was shown to correlate strongly with groundtruthed ridge pixels in the PCA, classification runs using TPI did not result in contiguous areas of pixels classified as *Ridge-Gully*. Furthermore, slope and bathymetry roughness were sufficient to represent the locations of macroscale ridges on the Bank, so TPI was determined to be a superfluous factor and was therefore not used as a rule for the *Ridge-Gully* habitat class. Since slope clusters 2 and 3 and bathymetry roughness clusters 2, 3, and 4 also represent non-ridge areas off the Bank, a maximum water depth value of 205 meters was used to define the *Ridge-Gully* hypothesis because macroscale ridges (as defined in this study) are know to only occur on top of the Bank (<205 m water depth).

For the *High-Relief Rock* hypothesis, strong correlations between textural parameters and boulder and cobble substratum classes were evident in the PCA (Table 2) and therefore were used for rules. Comparison of boulder (BB) and cobble (CC) groundtruthed pixels with those of the clustered acoustic signal amplitude data (10-m) revealed that clusters 4 and 5 had the most pixel intersections (Figures 11 and 12, respectively). Clustered backscatter roughness (15 m^2 kernel, wedge) was also used as a rule and clusters 1, 2, and 5 had the most pixel intersections with boulders (BB) and cobbles (CC) (Figures 13 and 14, respectively).

Clustered acoustic signal amplitude (backscatter) was the only parameter used as a rule to define both *Unconsolidated Sediment* target habitat classes. Comparison of groundtruthed pixel values with the clustered backscatter data (10-m) revealed that SS pixels intersect with higher backscatter clusters

(clusters 3 and 4; Figure 15) than do MM pixels (clusters 1 and 2; Figure 16). For this reason, the predictions are that *Unconsolidated Sediment 1* represents higher concentrations of mud while *Unconsolidated Sediment 2* represents higher concentrations of sand.

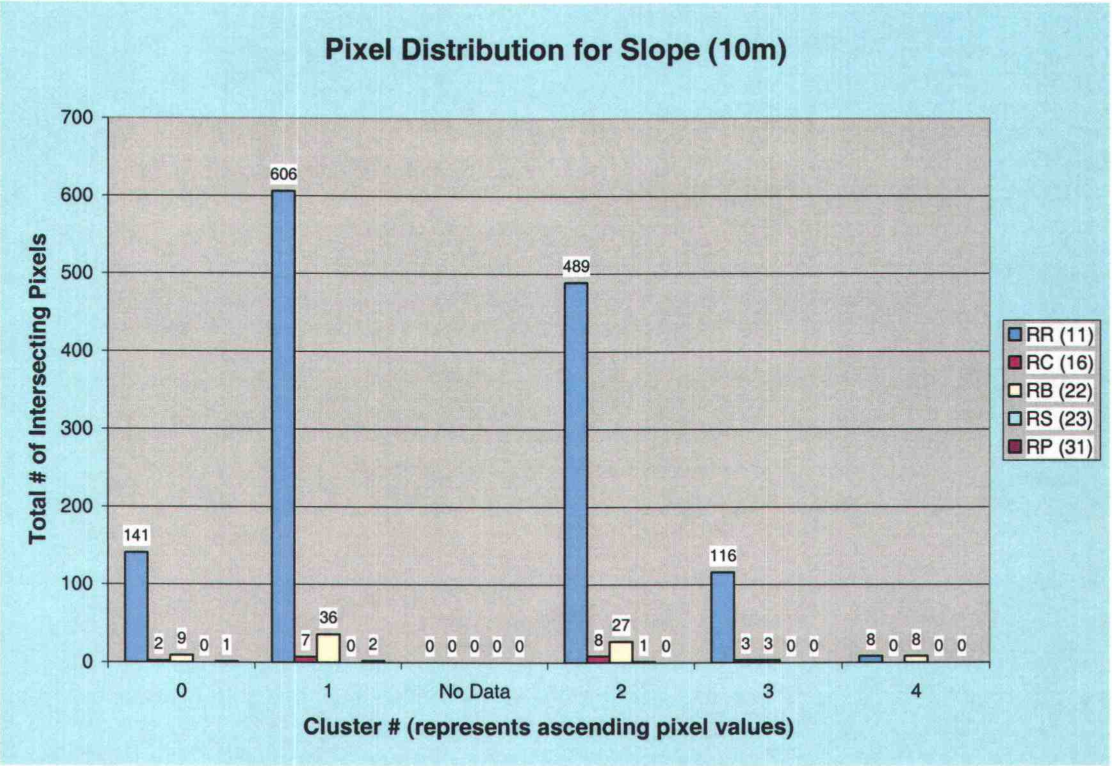


Figure 9: Pixel distribution for clustered slope data.

Graph detailing pixel intersections of groundtruthed M- substratum types with the clustered slope data.

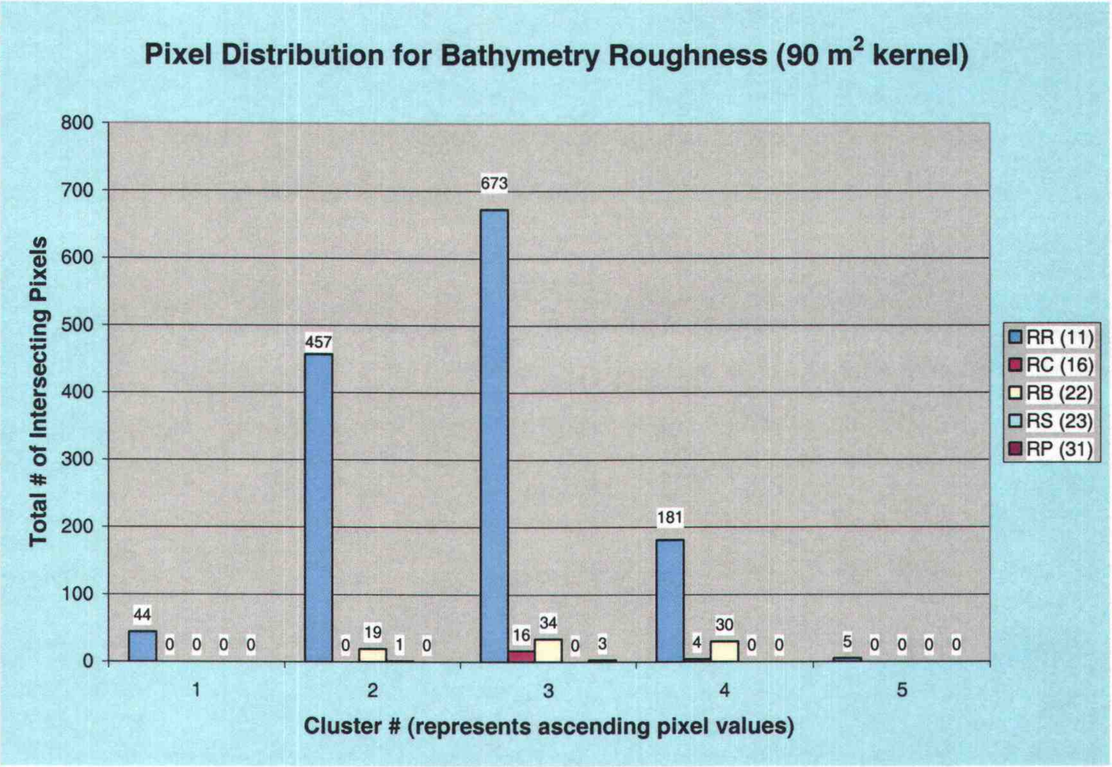


Figure 10: Pixel distribution for clustered bathymetry roughness data.

Graph detailing pixel intersections of groundtruthed R- substratum types with the clustered bathymetry roughness data.

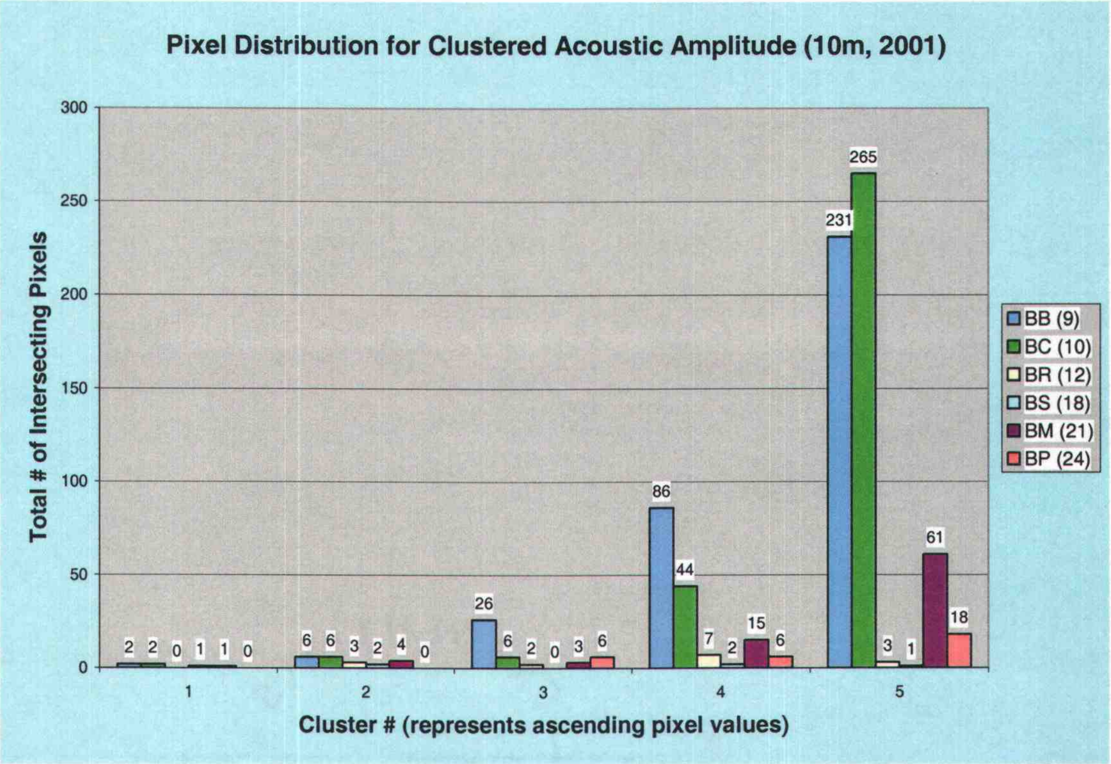


Figure 11: Pixel distribution for clustered backscatter data (1).

Graph detailing pixel intersections of groundtruthed B- substratum types with the clustered acoustic signal amplitude data.

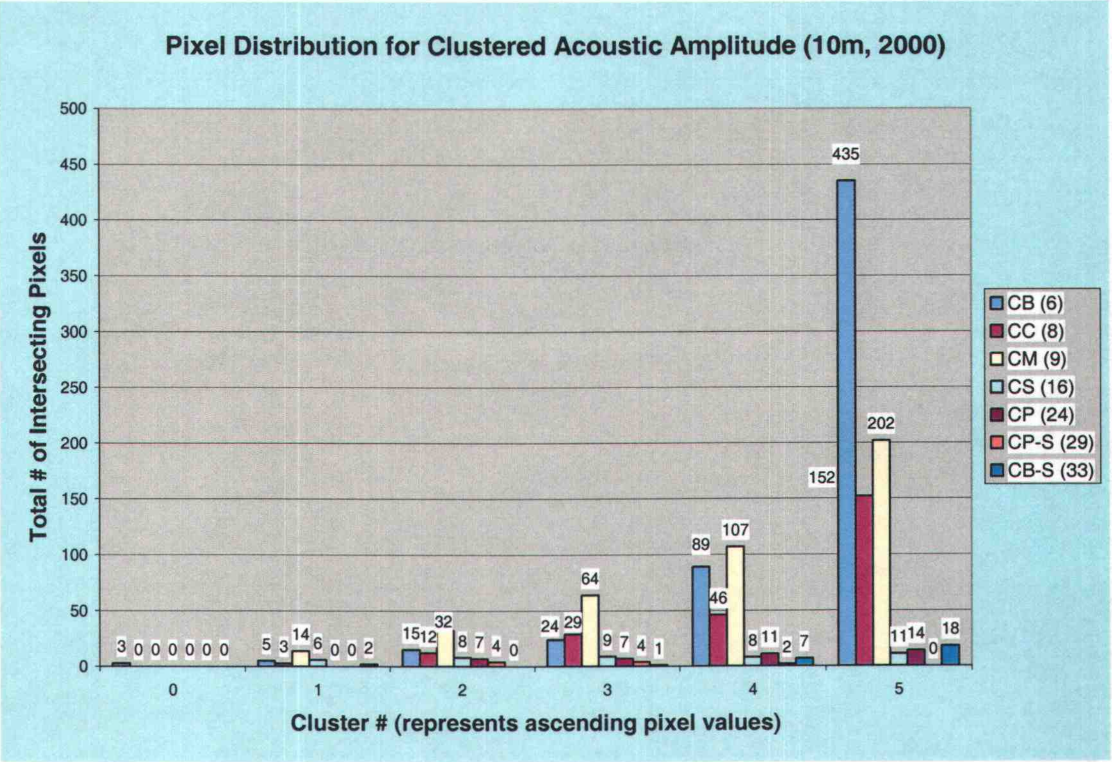


Figure 12: Pixel distribution for clustered backscatter data (2).

Graph detailing pixel intersections of groundtruthed C- substratum types with the clustered acoustic signal amplitude data.

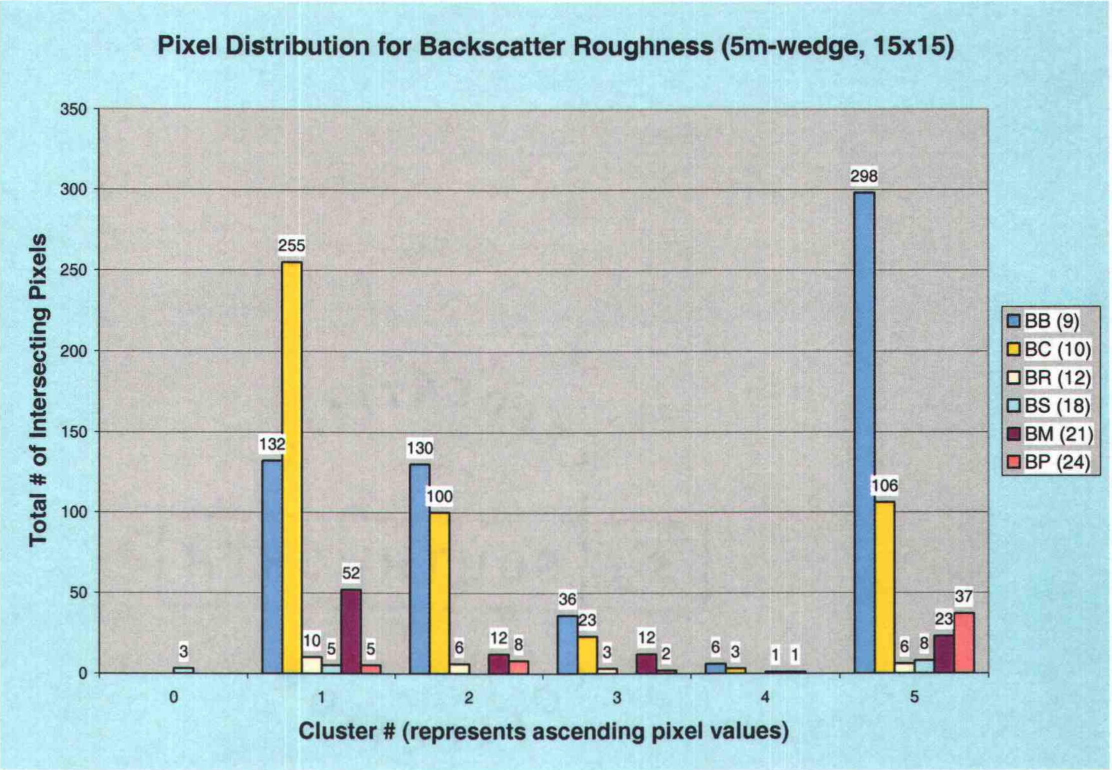


Figure 13: Pixel distribution for clustered backscatter roughness data (1).

Graph detailing pixel intersections of groundtruthed B- substratum types with the clustered backscatter roughness data.

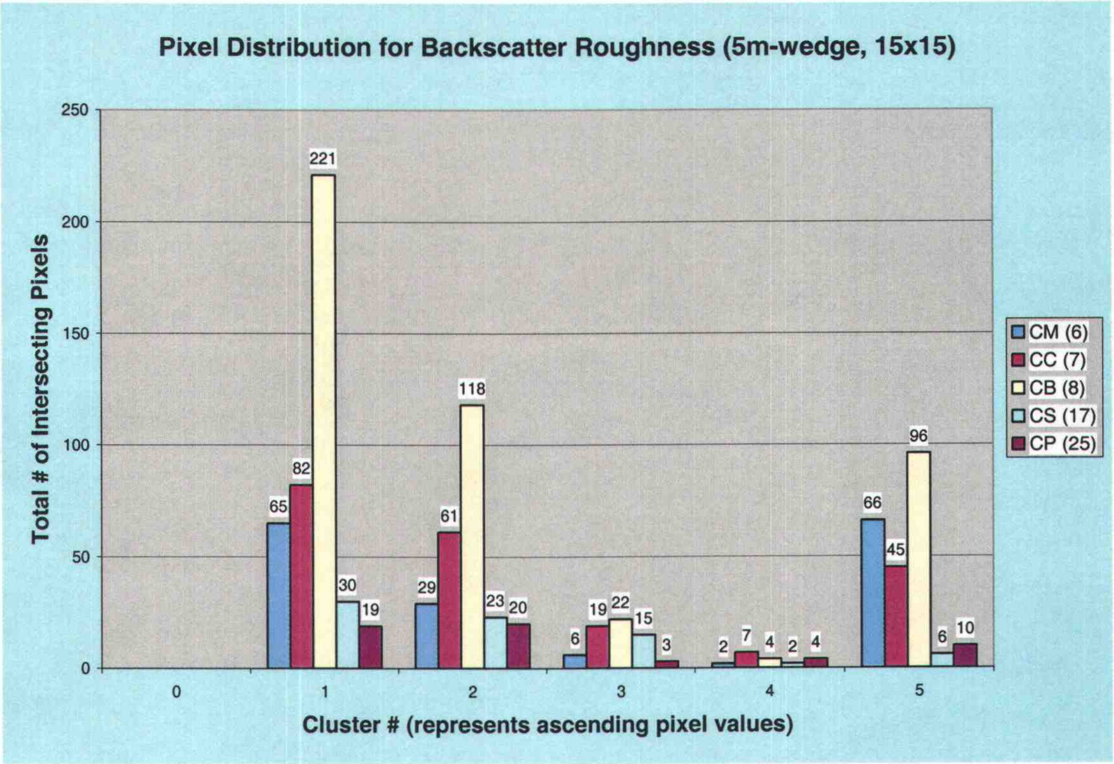


Figure 14: Pixel distribution for clustered backscatter roughness data (2).

Graph detailing pixel intersections of groundtruthed C- substratum types with the clustered backscatter roughness data.

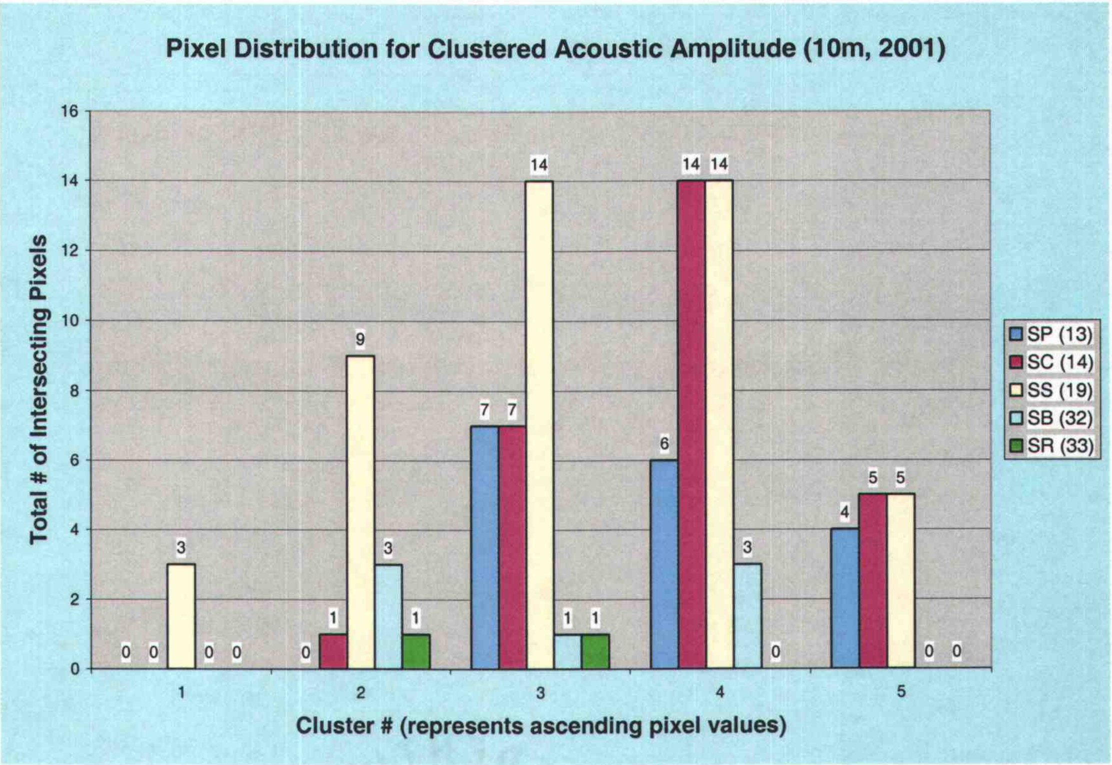


Figure 15: Pixel distribution for clustered backscatter data (3).

Graph detailing pixel intersections of groundtruthed S- substratum types with the clustered acoustic signal amplitude data.

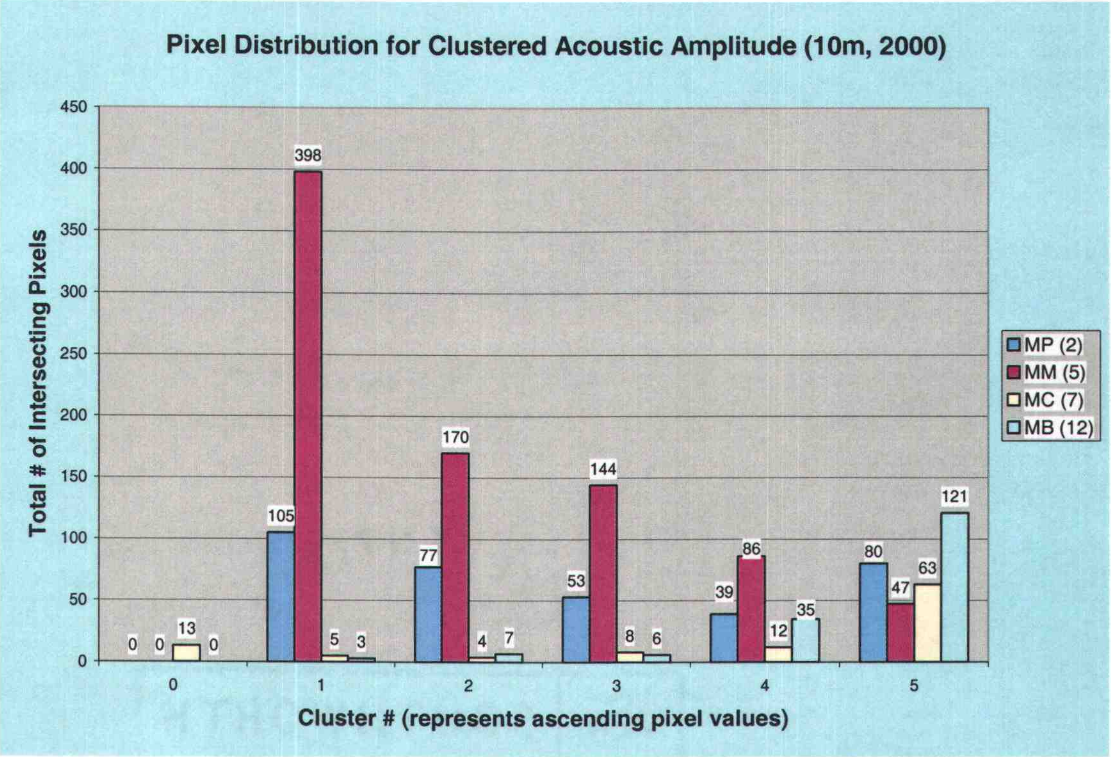


Figure 16: Pixel distribution for clustered backscatter data (4).

Graph detailing pixel intersections of groundtruthed M- substratum types with the clustered acoustic signal amplitude data.

Seafloor Habitat Characteristics

Target habitat classes (i.e. hypotheses) were defined by the values of the clustered map parameter data (i.e. variables). The values of the variables in turn define the substratum types (Figure 4) used to characterize the bottom during the 1988-1990 program and 2000-2001 *ROPOS* dives at Heceta Bank. Hypotheses, rules, and variables (Table 3) were combined in the rules-based decision tree (Figure 8) to output seafloor habitat predictions. The cluster #'s and associated pixel values for each variable are shown in Table 3 while the resulting output classification results are shown in Figure 17.

Table 3: Target habitat class characteristics.

Hypotheses, rules, variables, cluster #'s, and corresponding values for the rules-based decision tree.

Hypothesis	Rule	Variable	Cluster(s)	Cluster Values
Ridge-Gully	Ridge	Bathymetry Roughness (90x90m kernel)	2,3,4	Variance = 3-16
Ridge-Gully	Ridge	Slope (10m)	2,3	3-8 degrees
Ridge-Gully	Ridge	Depth	N/A	> -205m
High-Relief Rock	Boulder-Cobble	Backscatter Intensity (10m)	4,5	189-237
High-Relief Rock	Boulder-Cobble	Backscatter Roughness (15x15m kernel, wedge)	1,2,5	Variance = 1-12,30-64
Unconsolidated Sediment 1	Mud	Backscatter Intensity (10m)	1,2	44-182
Unconsolidated Sediment 2	Sand	Backscatter Intensity (10m)	3,4	183-195
Noise	Nadir Noise	Backscatter Intensity (10m)	2,3,4,5	176-237
Noise	Nadir Noise	Backscatter Roughness (15x15m kernel, no wedge)	5	Variance = 11-63

Noise Removal Results

The FOCALMAJORITY noise removal technique was fairly effective in removing nadir noise, but some is still evident in the final habitat prediction map (Figure 17). The number of pixels classified as *Nadir Noise* was reduced by ~76% (from 378,430 to 91,855) using a rectangular kernel size of 7x7 pixels.

Also, because the FOCALMAJORITY technique does not remove all noise, some pixels were misclassified. For example, misclassified pixels in the *Unconsolidated Sediment 1* areas of the flanks of the Bank show up as linear striping of pixels classified as either *High-Relief Rock* or *Unconsolidated Sediment 2* (Figure 17).

Figure 17: Heceta Bank habitat predictions.

The left panel map is the raw output of the decision tree created in Erdas Imagine Knowledge Engineer. The right panel map is the result of a noise removal algorithm employed on the left panel image data.

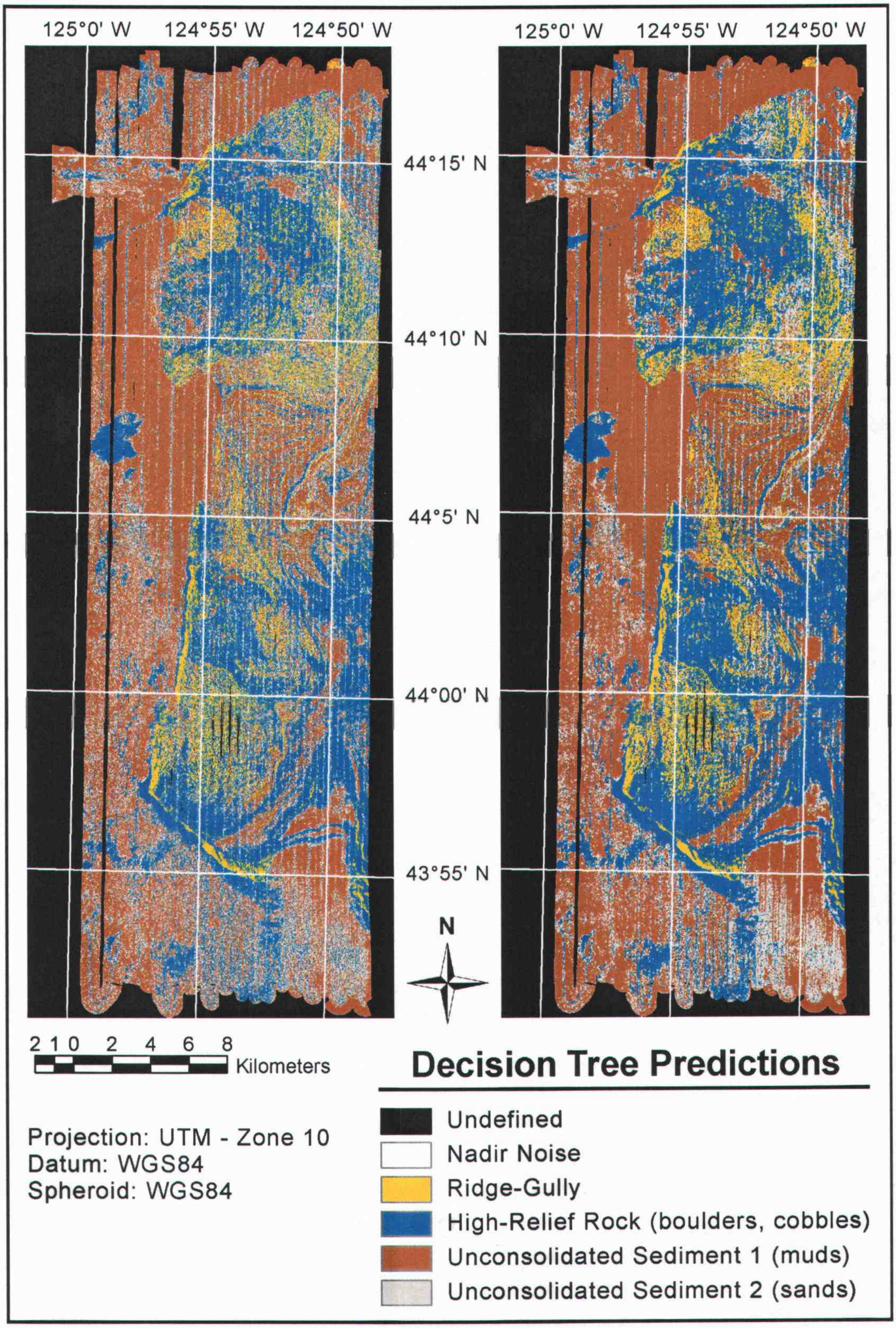


Figure 17: Heceta Bank habitat predictions.

DISCUSSION

Specific Findings

A primary finding of this study is that seafloor habitats for groundfish can be delineated by identifying specific seafloor characteristics observed from submersibles and extrapolating them using parameters derived from high-resolution seafloor imagery. Numerous studies have identified correlations between demersal fish and seafloor substrata (O'Connell et al. 2002; Amend et al. 2001; Fox et al. (1999, 2000); McRea et al. 1999; Yoklavich et al. 2000), and others have even extrapolated their findings to small homogeneous habitat areas (O'Connell and Carlile 1993; Nasby-Lucas et al. 2002). However, this study is one of the first to characterize seafloor habitats over a large area of varying topographic relief and seafloor texture (see also Dartnell 2000). Furthermore, these habitat maps afford a context for spatial analyses of other data of ecological importance, which will be discussed later.

The confidence associated with any classification is dependent on the quality of the available seafloor imagery and the extent of groundtruthing; and this study was fortunate to have both precisely positioned bathymetric and backscatter imagery and direct in situ observations along transects that covered a large diversity of habitats. Both bathymetry and backscatter data were necessary for a comprehensive topographic and textural classification of seafloor habitats. Bathymetry alone resolves seafloor features at the spatial resolution of the bathymetric imagery, but textural patterns observed in backscatter imagery are indicative of smaller-scale structural variations. These variations have been found to be influential to the composition of benthic macroinvertebrates and the distribution of demersal fish species (Nasby-Lucas et al. 2002). For example, boulders and cobbles offer vastly different structures for benthic fauna than do muds and sands; and distinct assemblages have been correlated to unique structures (Hixon et al. 1991).

While topography and geology provide primary structure, many benthic macroinvertebrates provide secondary biogenic substrate for many species of groundfish and therefore influence their distributions.

The ability to classify and map habitats is scale-dependent, and therefore dependent on the resolution of the available imagery. Acoustic waves from a 30 kHz sonar system penetrate softer sediments on the order of centimeters and are accurate to approximately 10 meters at 500 meters water depth (Kongsberg Simrad 2001-2003). Higher frequency sonar can yield higher resolution but the attenuation of acoustic energy generally increases with increasing depth. Since the multibeam survey in this study covered both the shelf and adjacent slope, using a higher frequency in deeper areas may have compromised data quality. On the other hand, lower frequency signals would penetrate further into softer sediments, giving a better indication of the underlying geologic structure, but at the cost of resolution. Besides, available seismic reflection data (Muehlberg 1971) already provided insight on the Bank's subsurface geology (see **Study Area** section). Regardless of the optimum multibeam system, the acquisition of the sonar data for this study was opportunistic, and future studies might benefit from a more comprehensive survey design.

The method presented in this paper is a first attempt at efficiently classifying and mapping demersal fish habitats at Heceta Bank. Despite the wealth of transect data used in this classification, additional video surveys are necessary to confirm habitat boundary predictions. Furthermore, there is potential to classify and map additional macrohabitats and some habitats apparently significant to groundfish distributions have since been discovered. For example, on a recent submersible survey of Heceta Bank in September 2002, investigators observed large diverse schools of rockfish over isolated pinnacles (Wakefield, pers. comm.). These macrohabitats were not apparent in historical or recent analyses of transect data, but the ability to map these features can be accomplished using methods similar to those presented in this paper.

One additional dataset that would have been beneficial in this classification is precisely positioned surface sediment data. During *ROPOS* dives at Heceta Bank in 2000 and 2001, numerous rock samples were collected, but no systematic sampling of sediments on or off the Bank was initiated. For this reason, sediment sample data from numerous historical cruises and studies was acquired for the Heceta Bank area in an attempt to differentiate predominantly sand sediments from mud. Since most of these cruises occurred before the advent of GPS, and sample locations were recorded using Loran A, Loran C, or some other navigation system, the poor precision of the navigation precluded any meaningful analysis. For example, cruise reports from these past cruises and a Loran-C handbook (Melton 1986) cite positional accuracies of +/- 2 km and +/- 0.5 km for Loran A and C, respectively. Clearly the precision of these data are not sufficient for groundtruthing at the scales relevant to this study; thus future sediment sampling using GPS navigation would provide the means to describe unconsolidated sediments in more detail.

From an ecological perspective, one limitation of this habitat classification is that it is entirely based on lithologic substrate. Numerous factors describe fish habitats including depth, temperature, salinity, nutrient availability, biogenic structures, and social aggregation to name a few. Accordingly, this habitat classification would be improved by the integration of a variety of ecological indices. Although time precluded it for this study, future analyses of relevant data would help increase the utility of the habitat map presented in this study.

Although Heceta Bank and the surrounding area have been the focus of numerous oceanographic investigations, analyses of oceanographic data collected concurrently with submersible operations have not yet been published. In order to create a more detailed map of local habitats in the future, dynamic data on current velocities, temperature, salinity, and oxygen should be integrated into a multivariate analysis of habitat parameters. For Heceta Bank, preliminary data analyses suggest no significant variations of bottom temperature and salinity. Nonetheless, such variations if evident could significantly effect the distributions of benthic macroinvertebrates and resident groundfish. The presence of two ongoing process-oriented oceanographic programs off Oregon – Global Ocean Ecosystems Dynamics, Northeast Pacific (GLOBEC-NEP) and Coastal Ocean Advances in Shelf Transport (COAST) – presents a unique opportunity to analyze many high-resolution data sets and construct a more detailed picture of seafloor habitats on Heceta Bank.

Applications and Management Implications

The major utility of this habitat classification and map is that it provides a spatial context for the integration of other data of ecological importance. Encyclopedia Britannica (2003) defines habitat as the, "place where an organism or community of organisms lives, including all living and nonliving factors and conditions of the surrounding environment". Due to dynamic environmental conditions and a variety of anthropogenic impacts, the identification of 'all living and nonliving factors and conditions of the surrounding environment' is problematic. Furthermore, with our growing understanding of natural processes the notion of habitat has become increasingly complex – this is evidenced in the increasing complexity of marine habitat classification schemes (e.g. Greene et al. 1999; Allee et al. 2000).

Despite our increasing understanding of natural processes, habitat loss is still identified as among, "the greatest long-term threats to the future viability of U.S. fisheries" (Mace 2000). For that reason, the National Marine Fisheries

Service (NMFS) created a Habitat Research Plan whose goal is to "conserve, protect, and restore valuable habitats needed to sustain marine and anadromous communities" (Mace 2000) through numerous research focuses including:

- Characterization and relating of benthic habitats to the distributions and abundances of fisheries species;
- Identification of habitat properties that contribute most to survival, growth, and productivity;
- Determination of habitat properties important in recruitment; and
- Testing of harvest refugia concept for selected areas and managed species.

These are congruent with the research objectives of the habitat-based fisheries investigation conducted at Heceta Bank; and the habitat map presented in this study is an initial step to achieving some of the above research focuses. Specifically, there are three major applications of this habitat classification: demersal fish stock assessments, mapping of essential fish habitats, and design of marine reserves.

One application of the habitat map presented in this study is to the regional stock assessment process. Nasby-Lucas et al. (2002) discovered that GIS could be used to integrate high-resolution seafloor imagery and observational data from submersibles to estimate demersal fish abundances within small selected homogeneous habitat patches. They also proposed that a similar methodology would be useful in conducting assessments over the entire geographic area of Heceta Bank, once there was a better understanding of habitats throughout the multibeam sonar survey area (Nasby-Lucas et al. 2002). Now that a map of these macrohabitats has been created for Heceta Bank, estimating abundances for resident groundfish species over the entire survey area can be initiated.

In addition to abundance estimates, this habitat map provides the means to perform spatial analyses of other relevant data. For example, abundance data collected from trawl surveys are not currently assessed in the context of habitat. Furthermore, the spatial coverage of trawl surveys is limited by topography; many habitats (including High-Relief Rock on Heceta Bank) are not accessible to bottom trawl gear and thus are not systematically sampled. The utility of habitat maps are that "untrawlable" areas can be identified and alternative survey techniques can be designed to target these areas. Also, throughout the investigations at Heceta Bank it has become evident that many factors influence groundfish distributions, including benthic macroinvertebrate community composition, food availability, and social interaction to name a few. The challenge is now to integrate specific habitat parameters into current modeling approaches to assessing fish stocks.

A second application is the mapping of essential fish habitat (EFH), defined by Congress as "those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity" (Sustainable Fisheries Act, 16 U.S.C. 1802). In 1996, Congress mandated the "identification of essential fish habitat, the adverse impacts on that habitat, and the actions that should be considered to ensure the conservation and enhancement of that habitat" (Sustainable Fisheries Act, 18 U.S.C. 1855). Again, the extensive observational data sets collected at Heceta Bank from submersibles and ROVs facilitated the identification of fish-habitat associations of individual species of resident groundfish. These important findings increased our understanding of groundfish habitat requirements off the U.S. West Coast and can be used to identify and locate EFH.

A third application of this habitat classification is the design and siting of marine protected areas (MPAs) and fully-protected, no-take marine reserves (e.g. fishery reserves and ecological reserves). One integral part of the marine reserve design process is the identification of critical habitats that help achieve the proposed management and/or conservation objectives. Accordingly, this habitat map provides a catalog of four habitats for a major portion of the continental shelf off Oregon. In addition, this habitat map can serve as a base map for the spatial analyses of other data sets relevant to the design process, such as oceanographic and fishery-dependent data (i.e. effort data).

In light of the current groundfish crisis, marine reserves may soon serve as a fishery management tool for the West Coast. Due to the urgency of the situation and the need for more progressive management measures, mapping of marine habitats in a systematic and efficient way is critical to providing the spatial context necessary for reserve design. The approach and associated habitat map presented in this study provides one example of how habitat mapping will aid in this very timely process.

CONCLUSIONS

This study has proven that benthic habitats can be systematically mapped through an integration of remote sensing data, in situ observations, and GIS techniques. Using data from high-resolution multibeam sonar, direct observation, and spatial analytical tools, four habitat classes at Heceta Bank were mapped that relate demersal fish species to benthic substrata at the macroscale level (1-10 meters). While similar studies have effectively mapped large areas via the qualitative interpretation of sidescan imagery (Wakefield et al. 1998), this study extrapolated small-scale observations of fish-habitat associations to larger geographic areas of varying relief and texture using quantitative parameters derived from both topographic and acoustic backscatter imagery. By using quantitative parameters, this approach is both repeatable and easily modified with additional groundtruthing.

The major limitation of this study is that the habitat classes are based entirely on lithologic substrate. In order to prove more beneficial for estimating fish abundance, defining EFH, and assisting the design of marine reserves, additional parameters of ecological importance must be integrated. Layers describing benthic macroinvertebrate community structure and dynamic data on temperature, salinity, nutrient availability, and current velocities would strengthen the future utility of this habitat map.

The current utility of this map is that it affords a context for spatial analyses of a variety of geo-referenced data. Considering the dearth of relative abundance data for many groundfish species, habitat maps like the one presented in this study provide an efficient means to estimate abundances of demersal fish species residing in diverse habitats than currently afforded by traditional survey techniques. This method is not intended to replace current survey approaches; rather to compliment annual shelf and slope trawl surveys by facilitating abundance estimates of groundfish species that tend to associate with substrata of rugged and varying relief. For the regional stock assessment process, this map provides one additional spatial parameter besides depth and latitude that can be used to stratify catch data. Also, multivariate analysis of trawl survey data with abiotic data of ecological importance such as temperature, salinity, and nutrient availability can be used to define additional relationships between groundfish species and their habitats. The improved knowledge of these relationships will not only aid in the assessment process but will also provide more detailed descriptions of essential fish habitats. Finally, the habitat map presented in this paper will serve as a context for spatial analyses of data pertinent to the design of marine reserves and protected areas.

This study presents one approach to classifying and mapping benthic habitats, but is not ideal in all situations. Depending on the quality and availability of high-resolution data, other approaches may prove more practicable for a particular set of circumstances. Due to extensive groundtruthing and the availability of high-resolution seafloor imagery for Heceta Bank, the quantitative approach described here provided a good mix of quality and efficiency. Regardless of what method is chosen, the continued acquisition of high-resolution seafloor imagery is necessary to improve our understanding of benthic habitats and our ability to map them at a scale pertinent to regional fisheries management.

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