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Twenty Years of Fish-Habitat Studies on Heceta Bank, Oregon

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Abstract
Heceta Bank is a major area for commercial fishing off Oregon and provides a wide range of structural habitats for demersal fishes, particularly rockfishes. In 2006, the bank was designated as an Essential Fish Habitat (EFH) Conservation Area closed to bottom trawling. A series of human-occupied (HOV) and remotely operated (ROV) submersible studies focusing on the fishes, invertebrates, and seafloor habitat of Heceta Bank began in 1987, and has largely continued until the present. Early studies focused on characterizing fishes and megafaunal invertebrates and describing the distributions of these assemblages in relation to habitat. As stocks of West Coast groundfish declined, research priorities shifted to a habitat-based strategy to develop methods for estimating the abundance of fishes in untrawlable habitats, identifying fish-habitat associations and potential essential fish habitat, and expanding the inference of the data to larger spatial scales in order to provide reliable data for fishery management. This shift in priorities coincided with the application of new technologies that provided a detailed multibeam sonar map of the bank, more accurate geographic positioning of the in situ platform (e.g., submersible and support ship), higher resolution video, greater capability to collect samples, and the development of more sophisticated statistical methods. Future research will likely continue to be driven by emerging fishery issues and developing advanced technologies. Research will need to focus on new priorities as they emerge, such as the development of ecosystem-based management, the effects of climate change, and offshore mining and energy development. One of the challenges now is to efficiently relate small-scale observations and assessments of animal-habitat associations collected by direct observations from submersibles and other in situ platforms to the larger geographic scales upon which fisheries operate.

Introduction
Prominent offshore rocky banks, formed by subduction of oceanic plates, occur along the continental shelf of Oregon (Kulm and Fowler 1974, Romsos 2004, Romsos et al. 2007). The largest of these banks, Heceta Bank, is a major area for commercial fishing, comprising part of the California Current Large Marine Ecosystem (Fig. 1) (Sherman 1988). Of all the deepwater rocky banks in the Pacific Northwest, Heceta Bank is one of the largest and arguably the most important in terms of fisheries and provides a wide range of structural habitats for demersal fishes, particularly rockfishes of the genus *Sebastes* (Hixon et al. 1991, Stein et al. 1992, Tissot et al. 2007). Historically, there were several kinds of fisheries in the area around Heceta Bank: (1) a demersal trawl fishery for many species of flatfish, rockfish, and sablefish; (2) a midwater trawl fishery for rockfishes and Pacific hake; (3) a longline fishery for rockfishes, sablefish, and Pacific halibut; (4) a vertical longline fishery for rockfishes; and (5) during upwelling, a troll fishery for salmon (Hixon et al. 1991). In 2006, the bank was designated as an Essential Fish Habitat (EFH) Conservation Area closed to bottom trawling (NMFS 2005, Federal Register 2006).

Many stocks of assessed West Coast groundfish have undergone declines in biomass during the 1980s and 1990s with a total of nine species declared overfished by 2001 (PFMC 2008). These declines coincided with a period of reduced productivity of the California Current Large Marine Ecosystem as well as harvest levels that were not consistent with what is now known to be the productivity levels for a number of the depleted groundfish stocks (Ralston 1998, Parker et al. 2000, Hare and Mantua 2000, Peterson and Schwing 2003). Rockfishes suffered particularly severe declines with seven of nine overfished species represented by the genus *Sebastes*. By 2007, a total of four groundfish

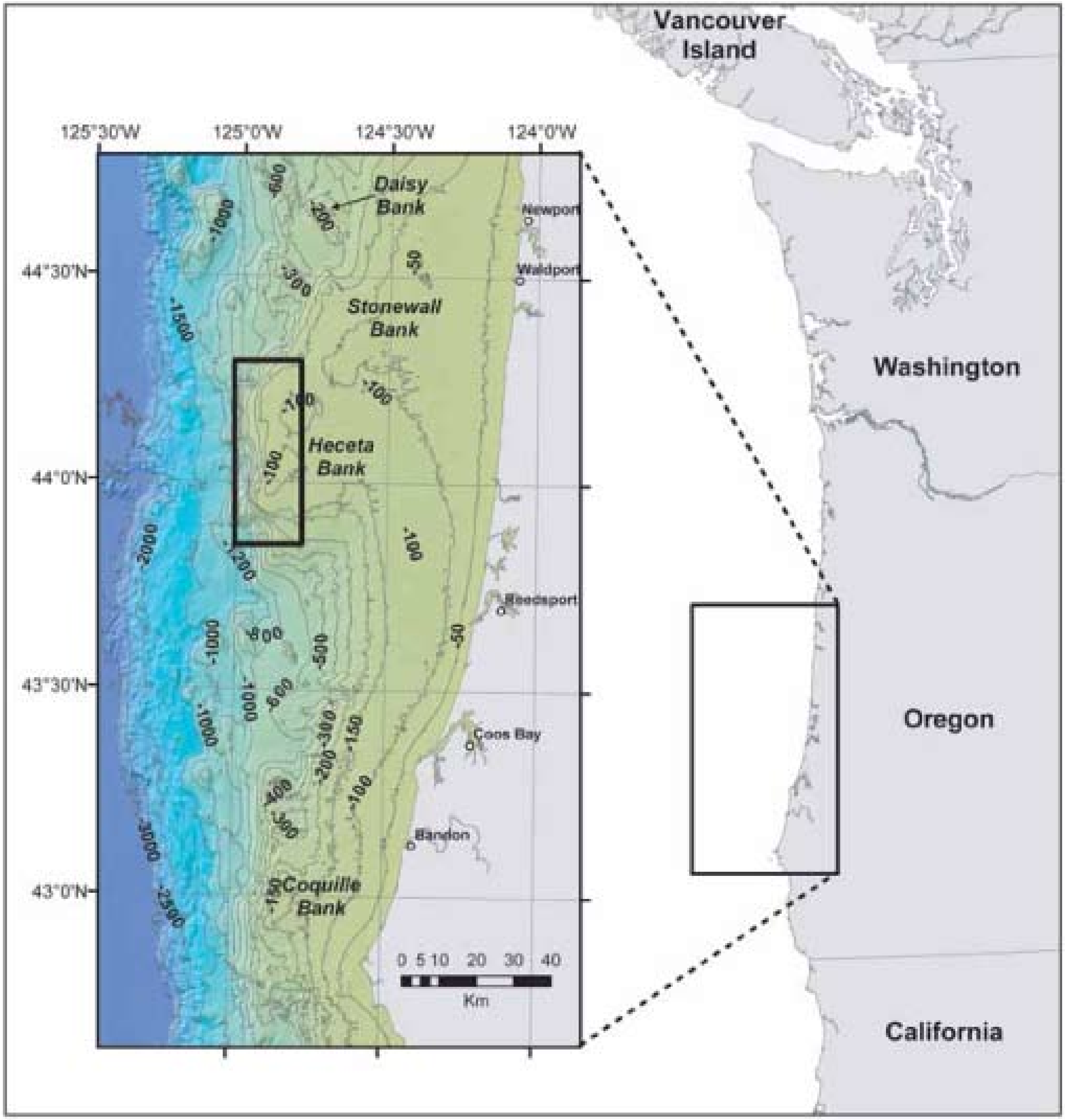

Figure 1. Location of Heceta Bank in relation to the Oregon coast. The inset delineates the area mapped using multibeam sonar system in 1998 (MBARI 2001; from Whitmire et al. 2007).

Table 1. List of submersible dives, main personnel, and funding sources for dives conducted on Heceta Bank, 1987-2002.

Year	No. dives	Submersible	Support vessel	Main personnel	Funding
1987	16	*Mermaid II*	F/V *Aloha*	Pearcy, Barss, Hixon, Pikitch, Starr, Stein	NURP
1988	18	*Delta*	F/V *McGaw*	Hixon, Barss, Benech, Pearcy, Stein, Tissot	MMS, NURP
1989	12	*Delta*	F/V *McGaw*	Hixon, Barss, Benech, Pearcy, Stein, Tissot	MMS, NURP
1990	12	*Delta*	F/V *McGaw*	Hixon, Barss, Benech, Pearcy, Stein, Tissot	MMS, NURP
2000	13	*ROPOS*, *Delta*	NOAA ship *Ronald H. Brown*	Wakefield, Barss, Embley, Tissot, Yoklavich	NURP, NMFS
2001	14	*ROPOS*	NOAA ship *Ronald H. Brown*	Wakefield, Barss, Embley, Tissot, Yoklavich	NURP, OE, NMFS
2002	12	*Delta*	F/V *Velero IV*	Wakefield, Barss, Hixon, Stein, Tissot	NMFS

The *Mermaid II* and *Delta* are HOVs, and *ROPOS* is an ROV. Funding agencies: NURP = NOAA National Undersea Research Program; MMS = Minerals Management Service; OE = NOAA Ocean Exploration; NMFS = NOAA National Marine Fisheries Service.

species were categorized as overfished (out of 23 assessed species), with lingcod, hake, widow rockfish (*Sebastes entomelas*), canary rockfish (*S. pinniger*), and Pacific ocean perch (*S. alutus*) either recovered or undergoing rebuilding (NMFS 2008, PFMC 2008).

Beginning in 1987, a series of submersible studies focusing on the fishes, invertebrates, and seafloor habitat of Heceta Bank were conducted by various investigators. These studies have largely continued intermittently until the present, representing over 20 years of research in this region. The goal of this paper is to review these studies and provide a summary of their approaches and findings (Table 1). Particular attention will be devoted to describing how the studies adapted to emerging research priorities in response to changing management issues, and in the development and adoption of new technology. This paper builds on previous reviews of Heceta Bank provided by Hixon et al. (1991), Reynolds et al. (2001), and Wakefield et al. (2005).

Early submersible studies: 1987-1990

1987 NURP study

Before submersible studies began in the late 1980s, very little was known about the distribution and abundance of fishes inhabiting Heceta Bank. Although soft-bottom areas in the region were relatively well-sampled (Alverson et al. 1964, Alton 1972, Pearcy 1978, Gabriel and Tyler 1980, Weinberg 1994), surface-based sampling gear was ineffective in high-relief habitats and thus these areas were largely unknown. Previous surface-based sampling on rocky areas relied on bottom trawls, which were limited to relatively low-relief areas (Gunderson and Sample 1980, Barss et al. 1982, Dark et al. 1983, Brodeur and Pearcy 1984, Weinberg et al. 1984), or employed bioacoustics (e.g., Wilkins 1986).

The goals of the first submersible dives in 1987 were to characterize the fish assemblages in and around Heceta Bank, relate the distributions and species assemblages with habitat types and depth, and evaluate the importance of the bank as nursery areas and refugia for commercially important species (Pearcy et al. 1989). Funded by the NOAA National Undersea Research Program (NURP), and using the three-person occupied submersible *Mermaid II* and the surface vessel *Aloha*, 16 dives were conducted during August 1987 at depths ranging from 64 to 305 m. Sampling stations were defined based on bathymetric charts (Fig. 2) and the limited available habitat information, with an overall goal to sample a broad array of habitats on the bank (compare Fig. 2 with Figs. 3 and 4 for later surveys). Two to three 30-minute visual belt transects were made during each dive, and the position of the submersible and the distance covered in 30 min was determined by Loran C fixes by the surface vessel as it followed a surface buoy towed by the submersible. Fish were recorded between two fixed points on the submersible's bumper and data were recorded on an audiotape and/or event recorder by one of the two scientists on the team. Fish were identified to species whenever possible, counted, and their total lengths were estimated to the nearest 10 cm. A fiberglass T-shaped rod, protruding from the bow of the submersible, was used to estimate fish lengths. Video transects from a relatively low-resolution externally mounted video camera were recorded in NTSC format on VHS tape. In addition, an externally mounted 35 mm emulsion film camera synchronized to external strobe lighting was used to assist in the identification of fishes after each dive.

A total of 42 fish taxa were observed, 31 of which were identified to species. Rockfishes (12 species) were by far the most speciose and abundant group. Using cluster analysis, two species groups of demersal fishes were identified based on transects over the diverse seafloor habitats around the bank: one composed primarily of rockfishes in shallow water on rock and cobble, and the other composed of flatfishes, poachers, sablefish, and some rockfishes in deep water over mud and cobble (Fig. 5). Dense schools of juvenile rockfishes and large yellowtail rockfish (*Sebastes flavidus*) were observed mostly over high-relief areas near the two shallower (~70 m) topographic highs of the bank, and the highest densities of small benthic rockfishes (up to 5-10 per m2) were observed on the flanks of the bank. These observations suggested that shallow, rocky portions of Heceta Bank were important nursery areas for juvenile rockfishes.

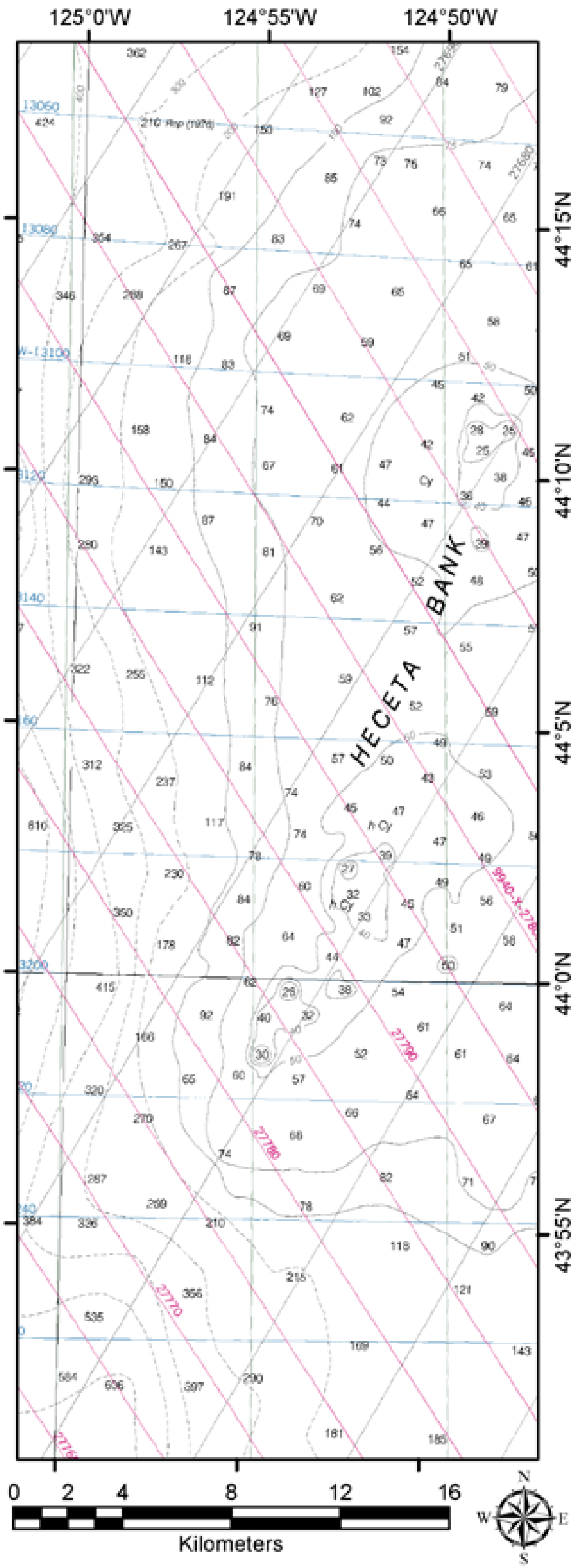

Figure 2. Bathymetric map of Heceta Bank used in the 1987 study, as represented on a NOAA National Ocean Service "standard nautical chart" (scale = 1:191,730 and soundings in fathoms) (from Pearcy et al. 1989).

This first study was crucial for long-term work on the bank as it provided an overview of the range of habitats and assemblages on Heceta Bank (Pearcy et al. 1989), which assisted in developing a sampling strategy for future studies. In addition, analysis of the data from the project facilitated the development of standardized observational and statistical designs (by M. Hixon and B. Tissot, respectively) used in subsequent years (Hixon et al. 1991, Tissot et al. 2007), and widely adapted elsewhere (e.g., Yoklavich et al. 2000).

1988-1990 MMS study

From 1988 to 1990, a descriptive survey of demersal fish assemblages, megafaunal invertebrate assemblages, and their associated habitat characteristics was conducted at Heceta Bank and three other rocky banks (Coquille, Daisy, and [in 1991] Stonewall) using the two-person submersible *Delta* that included several individuals from the 1987 cruise (M. Hixon, W. Barss, W. Pearcy, and D. Stein) (Hixon et al. 1991, Hixon and Tissot 1992). The impetus for this survey was the mandate of the U.S. Minerals Management Service (MMS) to produce a baseline description of the bottom-associated communities in this region in anticipation of future offshore oil exploration. As a result, this study provided a habitat-specific assessment of groundfish assemblages and other demersal fishes that served as a long-term baseline for conditions just prior to the time when impacts of overfishing became obvious (Tissot et al. 2007) and have been additionally useful in describing fishing gear impacts, such as bottom trawling (Hixon and Tissot 2007).

Surveys were conducted at Heceta Bank during the month of September from 1988 to 1990, using *Delta* to make 42 dives ranging from 67 to 360 m depth. These dives were made at six representative stations selected from sites sampled during exploratory dives in 1987 (Pearcy et al. 1989). Stations were chosen to be representative sites in terms of the fauna and bottom types encountered earlier. A detailed description of the data derived from each dive is reported by Hixon et al. (1991).

The survey methodology was modified from the earlier study to minimize observer bias and develop a rigorous three-year baseline for 1988-1990. In addition to identifying and enumerating fishes on the bank, this study developed several significant new approaches to describe fish-habitat associations, including both the classification of the seafloor into habitat types, and the integration of fish, invertebrate, and habitat information using multivariate analyses.

At each station, three daylight dives were made in 1988, and two daylight dives in both 1989 and 1990. Dives began and ended at least an hour after dawn and an hour before sunset, respectively, minimizing possible effects of diel changes in fish behavior and movements (Hart 2004). Each year, almost all dives at each station were made on the same day. To minimize systematic bias among observers, no two dives at the same station were conducted by the same observer during the same year, and the same three observers (M. Hixon, D. Stein, and W. Barss) participated in all three years of the study.

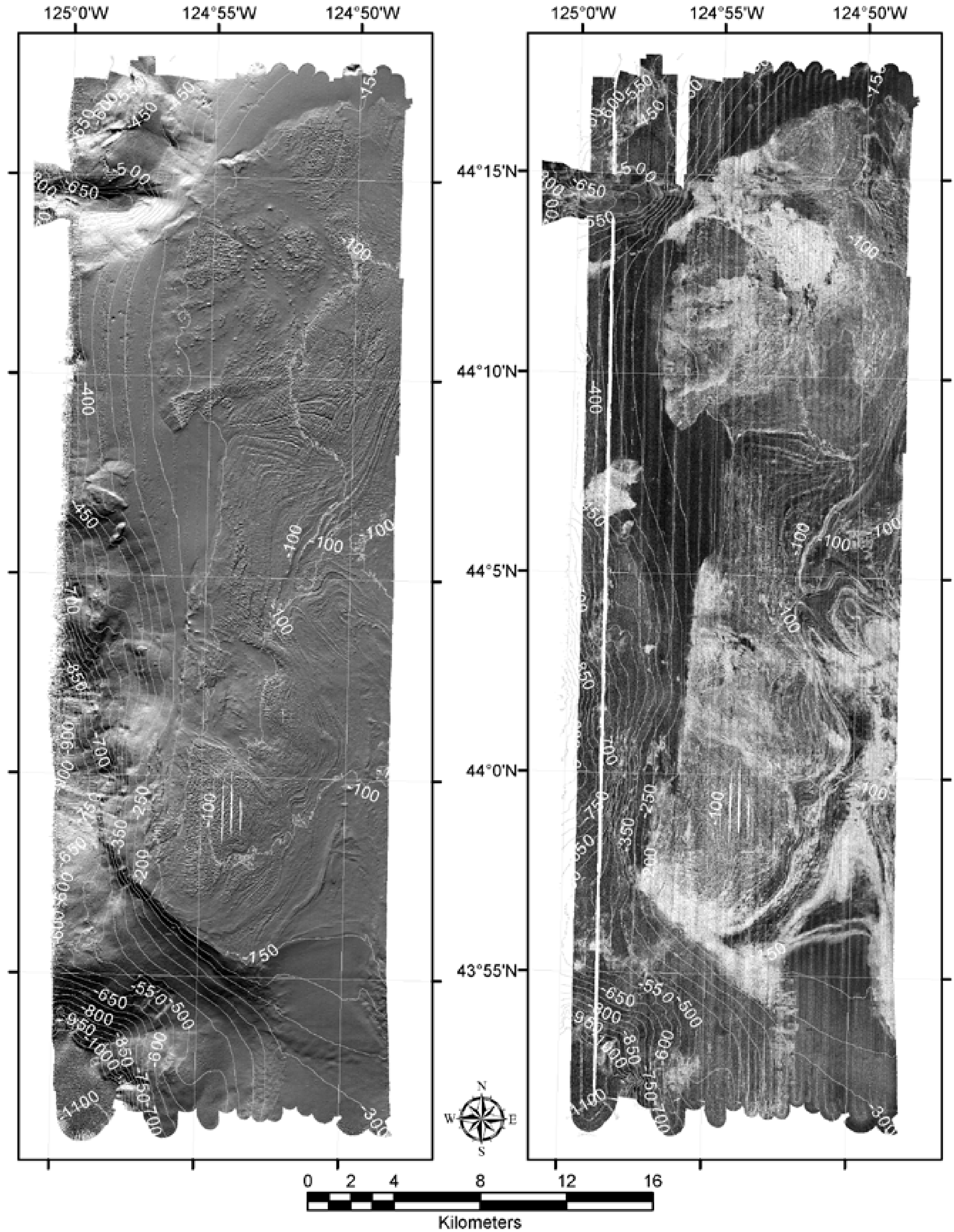

Figure 3. Map of Heceta Bank developed in 1998 with bathymetric contours underlain by sun-illuminated multibeam sonar bathymetry (left panel) and multibeam sonar backscatter (right panel) where decibel values have been converted to 255 gray-scale values. White depicts high reflectivity and grays depict low reflectivity (NOAA OAR PMEL; MBARI 2001; Nasby-Lucas et al. 2002).

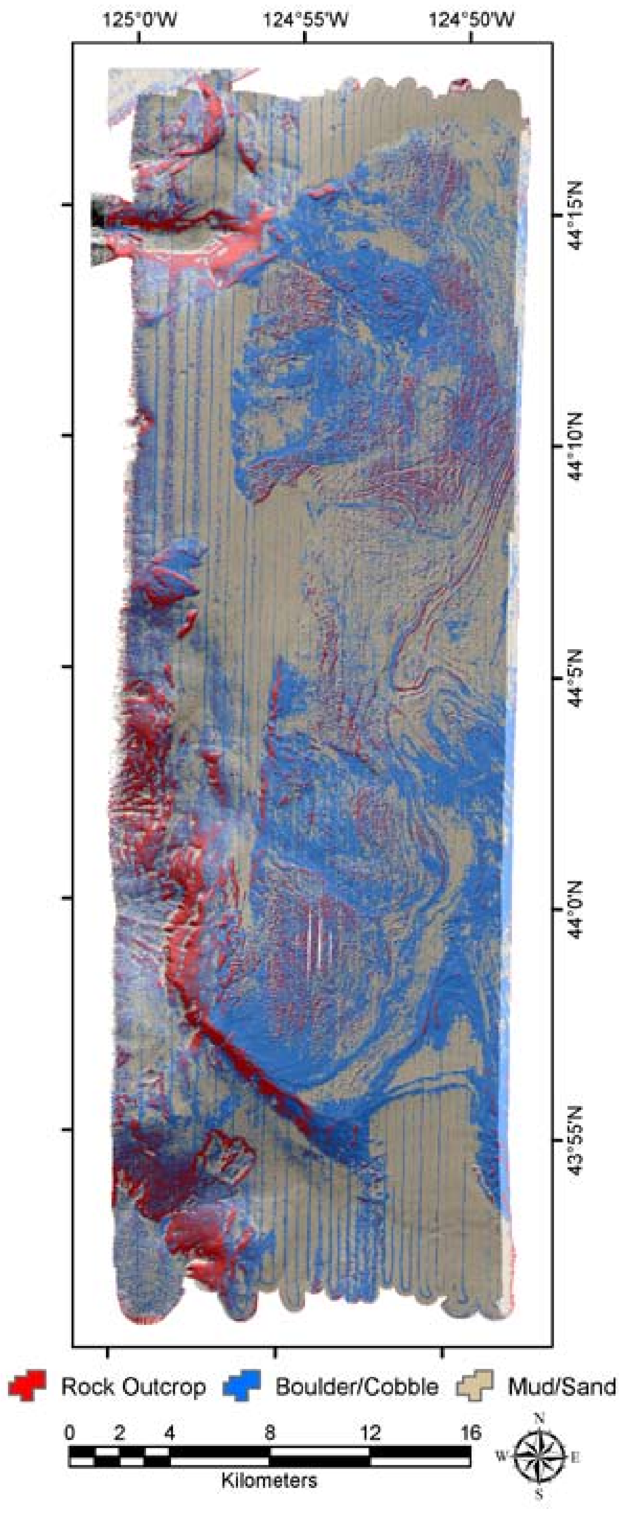

Figure 4. Habitat classification scheme for Heceta Bank integrating submersible and multibeam data (after Whitmire et al. 2007).

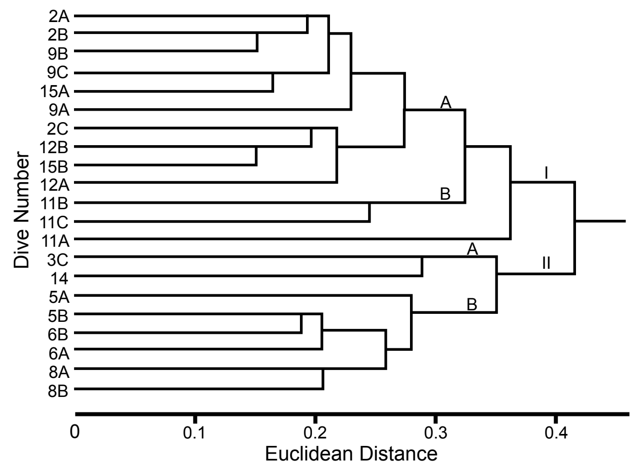

Figure 5. Dendrogram showing results of cluster analysis of fishes from 21 transects from Heceta Bank in 1987 (from Pearcy et al. 1989). Roman numerals indicate major habitat groups while letters indicate subgroups: (I) Shallow rock and cobble. (IA) Rock. (IB) Cobble. (II) Deep mud and cobble. (IIA) Cobble. (IIB) Mud.

During each dive, a single one-hour transect was completed, separated into two 30 min segments by a 10-15 min "quiet period" to determine the effect of the submersible on fish behavior (Tissot et al. 2007). Transect paths were mapped using a Trackpoint II ultrashort baseline system (USBL) to position the support vessel directly above the submersible every 10-15 min, and geographic position was recorded using Loran C. This approach provided an estimate of transect length, and subsequent habitat patch areas, and provided geographical fixes for major seafloor transitions. Dive transect lengths varied from 868 to 2,974 m in length and a total of 81 km of transects were completed during the three years.

During each transect, the observer verbally tape-recorded data on the species, size class (total length to the nearest 10 cm), abundance, and behavior (e.g., schooling vs. non-schooling) of all demersal fish visible from the forward porthole. To accurately estimate fish lengths and to provide an external scale for photography, a 0.3 m fiberglass rod (marked in decimeter intervals) was suspended by a chain into the transect path. A visual record of the transect path was provided by an externally mounted NTSC video camera recorded to VHS videotape (with timed data logger and audio track) and a 35 mm emulsion film still camera synced to an external strobe at 30 second intervals. Immediately following each dive, the observer transcribed the data on fishes as well as incidental data on megafaunal invertebrates and seafloor type from the tape recorders into a relational database.

Data on megafaunal invertebrates were collected using transect videotapes, still photos, and *Delta*'s 5 cm diameter "slurp gun." Densities of dominant megafaunal invertebrates (generally >5 cm in size) were estimated for two transects at each station for each year using the transect videotapes in the same way fish were counted. Still photographs and voucher specimens collected by the slurp gun were used to verify video identification wherever possible.

Detailed data on seafloor types were extracted from the videotape records of each transect. In an effort to capture the complexity of habitat variability across the bank in an objective and repeatable manner, a seafloor classification system was developed using eight different categories of substratum, based on standard geological definitions. In order of increasing particle size and relief, these substrata were defined as: mud (code M), sand (S), pebble (P), cobble (C), boulder (B), continuous flat rock (F), diagonal rock ridge (R), and vertical rock-pinnacle "top" (T).

To minimize any inherent bias in this method, one observer (B. Tissot) reviewed all the videotapes for all dives, recording a two-character code each time a distinct change in seafloor type was noted. A transect segment of uniform seafloor type was defined as a habitat patch, which was the sampling unit for subsequent statistical analyses. Seafloor type was defined as a two-letter code representing the approximate percent cover of the two most prevalent substrata in a particular uniform patch. The first character represented the substratum that accounted for at least 50% of the patch, and the second represented the second most prevalent substratum accounting for at least 20% of the patch (e.g., "BC" for at least 50% cover by boulders with at least 20% cover by cobble). If the field of view was purely a single substratum, or the second most abundant substratum covered less than 20% of the field, then the observer would enter a single code twice (e.g., "BB" for >80% cover by boulders) (see Tissot 2008, this volume). This method, described in Hixon et al. (1991), Stein et al. (1992), and Tissot et al. (2007) has been widely used in West Coast habitat studies and adapted to a variety of habitat classification schemes and fish-habitat studies (e.g., Greene et al. 1999, Yoklavich et al. 2000, Jagielo et al. 2003, Anderson and Yoklavich 2007).

During 42 dives over the three-year sampling period, a total of 1,058 habitat patches were surveyed, and 216,145 fishes, representing 73 taxa (51 species and 22 nonspecific categories) and 24 families were counted. There was a 74% increase in the number of fish taxa observed relative to the 1987 survey and a 65% increase in the number of observed fish species. These increases are likely due both to the greater sampling effort at each station and the longer time series. In addition, 129,635 megafaunal invertebrates were enumerated representing 44 taxa (30 genera/species and 14 nonspecific categories) (Tissot et al. 2007)

Results of the study showed that the shallower parts of the bank (<100 m) were strongly dominated by rock ridges (code RR) and contiguous large boulders (BB), intermediate depths by combinations of boulders and cobble (mostly BC, CB, and CC), and deeper areas (>150 m) by mostly mud (MM, MP, MC, MB, and CM). Because there was a strong correlation between depth and seafloor type ranked by degree of relief, seafloor type also served as a proxy for seafloor depth in statistical analyses (Hixon et al. 1991, Tissot et al. 2007).

The habitat classification scheme allowed a more holistic and habitat-based approach to examining spatial- and temporal-variation in fish abundance that departed from the geographically fixed or "station-based" approach in previous studies (Fig. 6). The habitat-based approach was especially important given that most transects which started at a single reference point on the bank (i.e., dive stations) tended to run from shallow rocky to deep muddy habitats, precluding exclusive habitat distinctions at the scale of entire stations. Thus, the next step of the analysis was to integrate data on fish abundances, invertebrate abundances, and bottom types to characterize distinct assemblages across the bank by focusing on variation among habitat patches across stations. A multivariate method, canonical correlation analysis, was used to examine joint associations between fishes, invertebrates, and habitats and to provide an integrated summary of ecological patterns on the bank (Fig. 7) (Tissot et al. 2007).

Using this approach, four major habitats and associated benthic invertebrate and demersal fish assemblages were described for Heceta Bank: (1) shallow rock ridges and large boulders (<100 m deep) dominated by basket stars, juvenile rockfishes, yelloweye rockfish (*Sebastes ruberrimus*), and lingcod (*Ophiodon elongatus*); (2) mid-depth small boulder-cobbles (100-150 m) dominated by crinoids, brittle stars, rosethorn (*Sebastes helvomaculatus*), pygmy/Puget Sound (*S. wilsoni/emphaeus*), and canary rockfishes (*S. pinniger*); (3) deep cobble (150-200 m) dominated by crinoids, brittle stars and various small rockfish species; and (4) deep mud slope (>200 m) dominated by the urchin *Allocentrotus fragilis*, shortspine thornyhead (*Sebastolobus alascanus*), and flatfishes.

In addition to a description of the benthic biology and habitats of the bank, the study also examined the extent of interannual variation in 12 of the most abundant and/or commercially important fish taxa sampled. The study showed that although substantial interannual variation in demersal fish abundance among habitat types was evident, high variance resulted in statistically significant differences among years only in juvenile rockfishes, which represented a large group of unknown species of *Sebastes*. There was clear order-of-magnitude variation in the recruitment of juvenile rockfishes as a group at Heceta Bank during the three years, with the greatest abundance of young-of-the year in 1989 and the least in 1990 (Tissot et al. 2007). The three-year baseline data collected during this early study were important in that they served as a basis of comparison against which future regional trends in groundfish abundance could be evaluated, which occurred in 2000-2002 using similar methodology (see below).

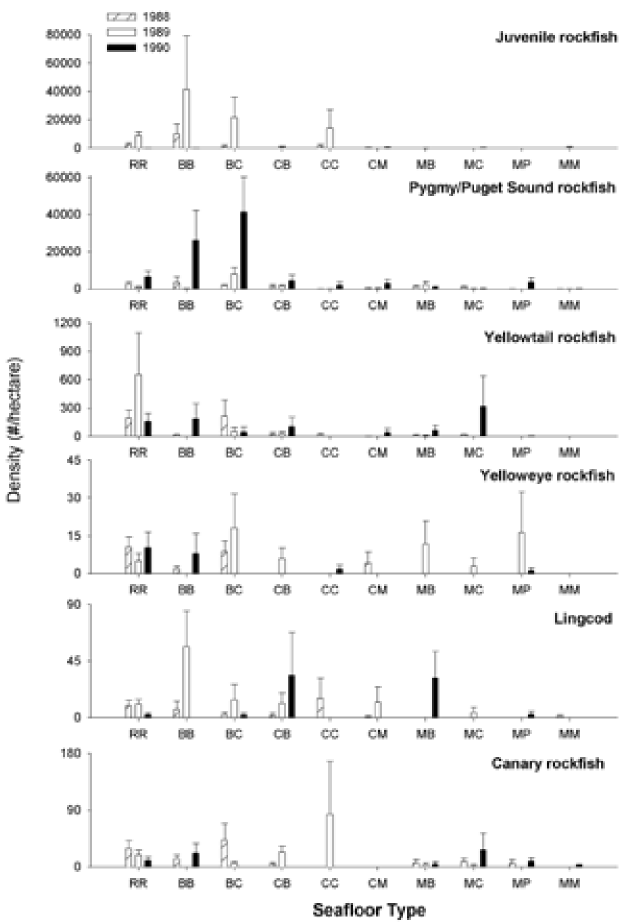

Figure 6. Densities (mean number per hectare ±1 SE) of selected fish taxa among the ten dominant seafloor types at Heceta Bank, 1988-1990 (from Tissot et al. 2007).

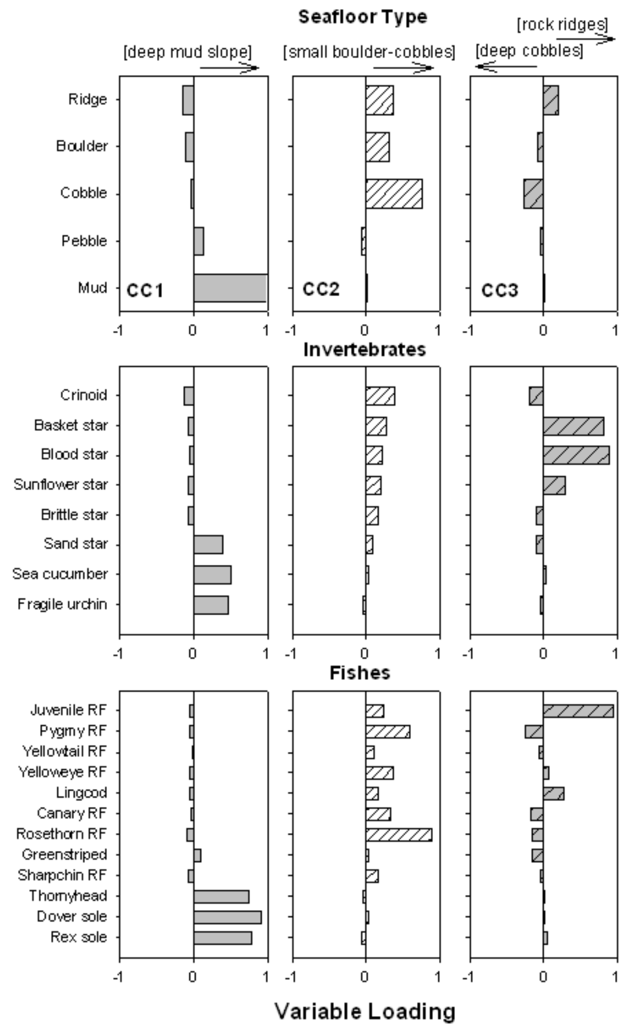

Figure 7. Variable loadings of seafloor types, invertebrates, and fishes on the two axes of the canonical correlation analysis from 1988-1990 studies on Heceta Bank. High positive loadings on axis 1 (CC1) define a mud habitat with associated invertebrates and fishes. High negative loadings on CC1 define a rock habitat, subdivided on CC2. High positive loadings on CC2 define a boulder-cobble habitat with associated species. High positive loadings on CC3 define a rock-ridge habitat with associated species while high negative loadings define a deep cobble habitat with associated species (from Tissot et al. 2007).

Seafloor mapping, geology, and integration with submersible data: 1998-2007

As exploitation of groundfish stocks off the U.S. Pacific coast reached maximum levels during the 1990s, resulting in the depletion of various stocks (Ralston 1998, Bloeser 1999, Parker et al. 2000), studies began to focus on the development of fishery recovery plans, which required broad knowledge of historical distribution and abundance, as well as past levels of interannual variation in abundance. In order to provide meaningful information on groundfish stocks it is important that data are available at a scale similar to management regimes, which are often on the scale of hundreds to thousands of km^2 (Wakefield et al. 2005). Thus, large-scale mapping of the seafloor using multibeam sonar technology (Hughes Clarke et al. 1996) became a priority for many areas on the West Coast as groundfish stocks declined, including Heceta Bank.

A survey of Heceta Bank using a Simrad multibeam echosounder (30 kHz) was conducted in 1998 (Fig. 3) as part of a program to map a larger portion of the Oregon margin (MBARI 2001, Nasby-Lucas et al. 2002). The seafloor map, which covered an area of 725 km^2, provides a striking contrast to the bathymetric charts of Heceta Bank used in the earlier submersible studies (Fig. 2). The bathymetric and backscatter data from the map could be gridded to a resolution of 5 m on the shallowest portions of the bank (depths of 70-150 m) and to 10 m at greater depths down to about 500 m. The seafloor morphology and texture of Heceta Bank is primarily the result of subaerial and wave-base erosion during previous low–sea level stands. The multibeam imagery revealed outcroppings of differentially eroded, jointed and folded strata partly covered by high-backscatter boulder and gravel zones. The outer edge of the bank was clearly defined by a change to low-backscatter muds of the upper slope and by a wave cut bench formed during lowered sea level (Embley et al. 2001, Torres et al. unpubl.). Further, high-backscatter areas of the bank contained extensive cobble and boulder fields resulting from erosion by weathering of the bedrock and/or transportation during low sea level periods. As was described in previous studies (Hixon et al. 1991), the outcrop ridges on the shallower bank tops, and the cobble-boulder fields, represented important habitats for species of rockfish and other groundfish.

The map and associated geospatial database were used by several subsequent studies in different ways to further integrate fish-invertebrate-habitat relations and develop preliminary methods to provide information for a stock assessment for Heceta Bank. Initial efforts with the multibeam data were devoted to an integration with earlier submersible studies to aid in planning for future submersible studies (Nasby 2000, Nasby-Lucas et al. 2002). Using the dynamic segmentation GIS (geographic information system) data structure developed by Environmental Systems Research Institute (ESRI), the combined multibeam, seafloor type, and previous fish data were used to visualize changes in both type of seafloor and fish abundance along dive transect lines across the bank (Fig. 8). Nasby-Lucas et al. (2002) used GIS methods to extrapolate abundances of fish observed from a submersible, overlaid with seafloor type, on the topography of the multibeam map. By delineating areas of similar topography, texture, and seafloor type and extrapolating abundances to the larger area, they were able to develop initial population size estimates over large areas of the bank (Fig. 8).

In order to expand this approach to the entire bank, Whitmire et al. (2007) applied spatial analytical methods to the multibeam sonar data, and mapped three important habitat types on the bank (Fig. 4), demonstrating their statistical relationship with the finer-scale seafloor data derived from the remotely operated vehicle (ROV) *ROPOS* in 2000-2001 (see below). Whitmire et al.'s quantitative model was based on four geomorphological parameters derived from bathymetric and textural patterns in the multibeam data including depth, slope, rugosity, and topographic position index (Whitmire 2003, Whitmire et al. 2007). Using transects from the 2000-2001 ROV *ROPOS* surveys to groundtruth the new map, they extrapolated the data over the entire bank resulting in predicted coverage for the three habitat classes: rock outcrop, boulder/cobble, and mud/sand (Fig. 4). With the availability of a large map of seafloor type and ROV-derived data from wide areas on the map, it is now possible to extrapolate habitat-specific estimates of density for selected groundfish species from submersible transects for the entirety of Heceta Bank (Whitmire et al. 2007).

Based on these studies, as well as additional multibeam and other data collected from a wide variety of sources, a seafloor map for Oregon and Washington was completed that delineated major habitat types across the entire continental margin (Fig. 9) (Goldfinger et al. 2003, Romsos 2004, Romsos et al. 2007). This map and associated geodatabase represent the first coast-wide delineation of seafloor habitats and are important elements in the identification of essential fish habitat for West Coast groundfish (NMFS 2005).

2000-2001 ROV surveys

In 2000, a field program was initiated to utilize the newly acquired high-resolution seafloor map and to provide groundtruthing data using the ROV *ROPOS* for areas of the bank that had not been previously explored. *ROPOS* is a tethered remotely operated vehicle capable of diving to 5,000 m for more than 24 hours at a time, and carries an array of imaging and sampling equipment for both geological structures and megafaunal invertebrates (Shepherd and Wallace 2002). The *ROPOS* was deployed from the NOAA research vessel *Ronald H. Brown*, a dynamically positioned ship that provided accurate navigation and sophisticated visualization tools. These tools are essential to allowing investigators to accurately place the submersible and subsequent ROV transects and associated samples within the context of the high-resolution bathymetric map.

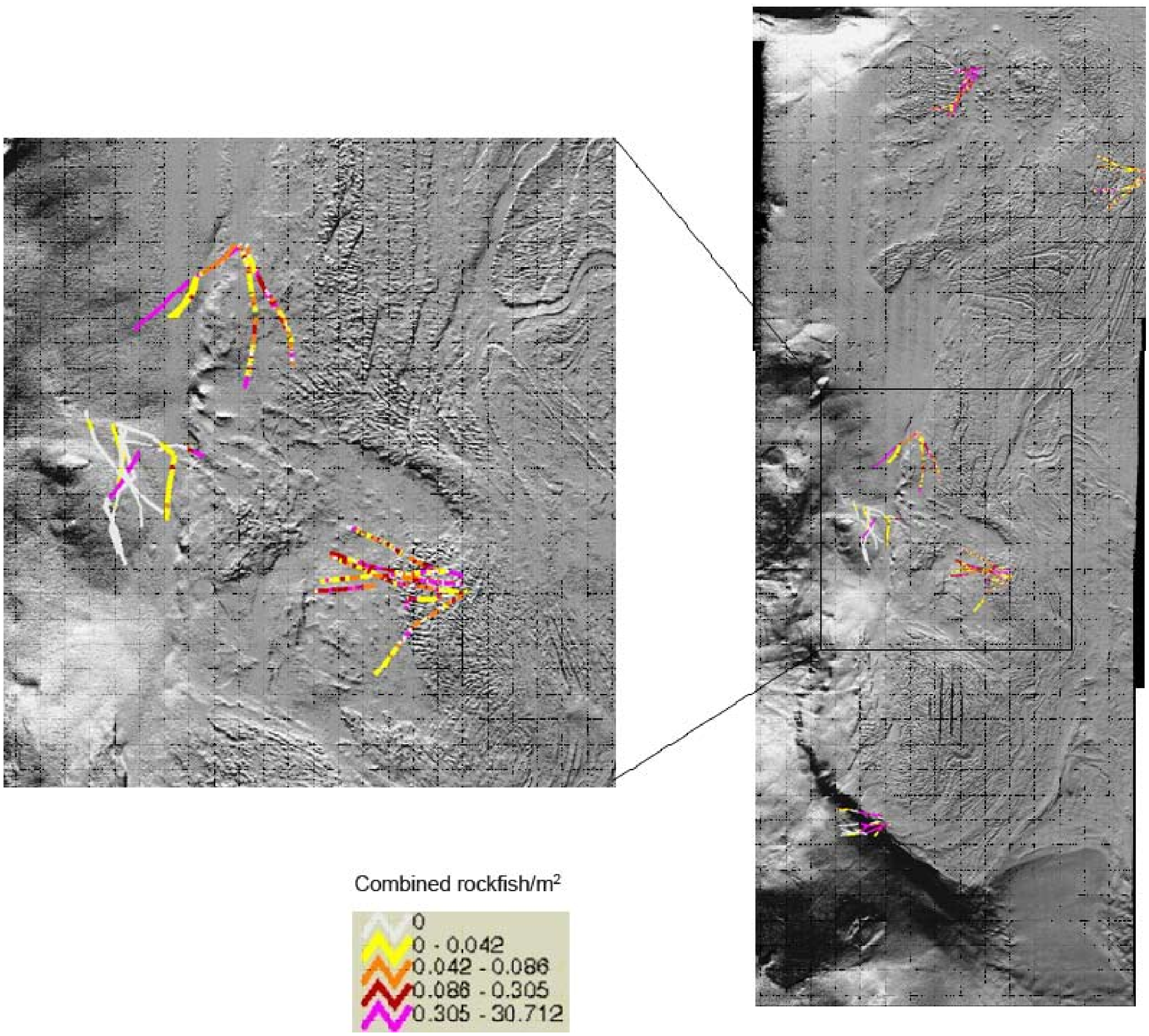

Figure 8. Combined density of greenstriped rockfish (*Sebastes elongatus*), pygmy rockfish (*S. wilsoni*), rosethorn rockfish (*S. helvomaculatus*), and sharpchin rockfish (*S. zacentrus*) observed on Heceta Bank during 1988-1990 *Delta* submersible dives and overlaid on sonar side-lit bathymetry data (after Nasby-Lucas et al. 2002).

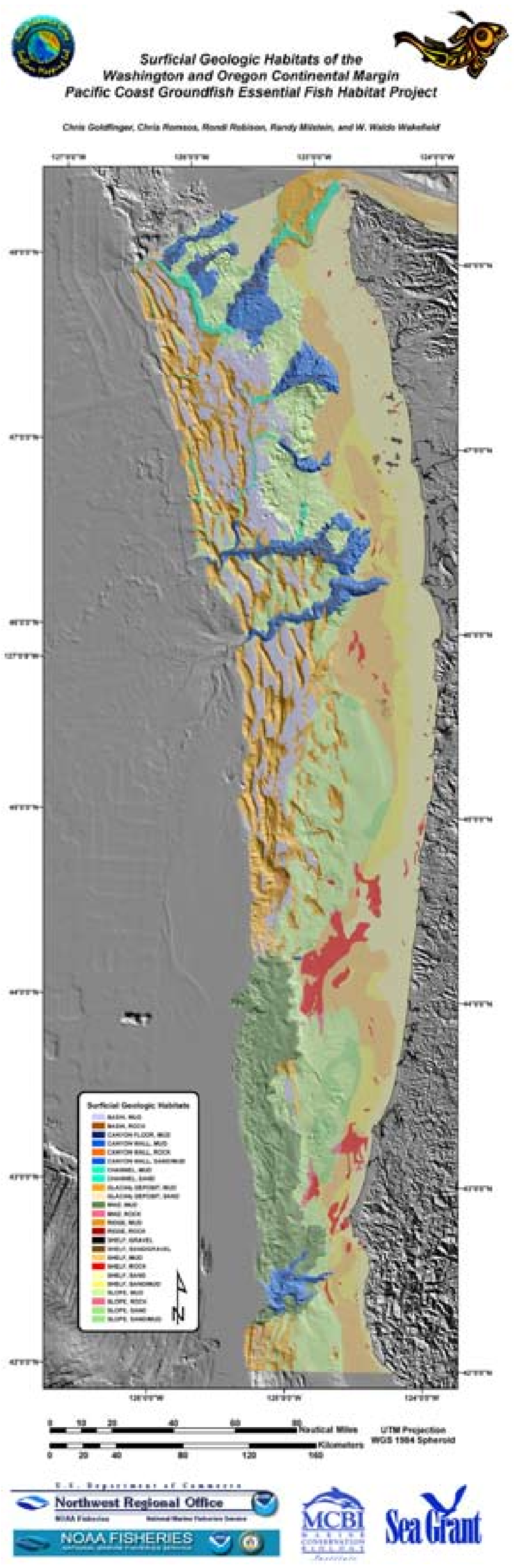

Figure 9. Surficial geological habitats of the Washington and Oregon continental margin (from Romsos et al. 2007).

During June of both 2000 and 2001, a total of 27 dives were completed using *ROPOS*. The transects were distributed among five of the six historical sites from the 1988-1990 studies (10 dives) and previously unexplored areas of the bank (17 dives). The new exploratory dives were located to maximize the overall coverage of the bank and to sample the diversity of habitats based on changes in bathymetry and backscatter intensity in the multibeam data.

Dive transects were conducted on stations using similar methods to those used with *Delta* to minimize bias between surveys. Transects were surveyed using two 30 minute transects, and transect width was delineated using scaling lasers and video from the ROV was recorded using a digital video. *ROPOS* dives in 2000-2001 were longer than *Delta*'s in 1998-1990, ranging from 1 to 11 hours, but the distance covered per dive averaged 1.9 km for both studies, although *Delta* covered a longer distance (53 km in 27 dives, 2000-2001) than previously (81 km in 42 dives, 1988-1990).

Using *ROPOS* a total of 61 fish taxa were described with data on 48 species, a result fairly similar to the 1988-1990 *Delta* surveys. In addition, a total of 579,113 megafaunal invertebrates were enumerated from 64 taxa (39 genera/species and 25 nonspecific categories). This result represents a significant increase over the diversity and abundance of invertebrates enumerated during the earlier studies. These differences could be the result of several changes: (1) observer bias between earlier invertebrate studies (S. Benech in 1988-1990) and the *ROPOS* study (B. Tissot in 2000-2001); (2) the higher resolution video camera used on *ROPOS* relative to *Delta* (digital vs. analog); (3) the greater ability of *ROPOS* to collect samples relative to *Delta* and provide a mechanism for more accurate taxonomic identification of observed taxa (Wakefield et al. 2005); and (4) greater attention to deep-sea corals, which were specifically targeted during these studies due to emerging data on their importance as essential fish habitat (Morgan et al. 2006, Lumsden et al. 2007). During the *ROPOS* surveys significant abundance and distribution data were collected on the coral genera *Stylatula*, *Swiftia*, *Anthomastus*, *Plumarella*, *Stylaster*, *Ptilosarcus*, and *Umbellula*, which had not been well documented previously on the bank.

2002 resurvey of historical sites

In order to replicate the 1988-1990 dives as closely as possible and provide a long-term comparison for changes in groundfish and invertebrate assemblages, additional submersible dives were conducted in 2002 using *Delta*. The goal was to resurvey the original sites during the same season (September) with the same observers (M. Hixon, D. Stein, and W. Barss). Using direct visual counts and video observations, the abundance of fishes along discrete habitat patches at each station were quantified using methods identical to those employed in the 1988-1990 surveys. The density of numerically dominant and commercially important fishes within different habitat types were then examined for changes between surveys to test for statistically significant long-term changes using a two-way repeated-measure ANOVA (Tissot et al. 2004).

Overall, the study revealed few long-term changes in the abundance of fishes and invertebrates on Heceta Bank. The abundance of most fishes and invertebrates in 2002 were within the range of variation observed in 1988-1990. However, four mud-associated species, the three fishes *Sebastolobus alascanus*, *Lyopsetta exilis*, and *Lycodes cortezianus*, and the urchin *Allocentrotus fragilis*, were significantly less abundant in 2002 relative to 1988-1990 surveys and also exhibited distributional changes across seafloor types between the surveys (Fig. 10). These results indicated, to the extent that the data were statistically able to detect significant changes, that some species exhibited shifting abundances and distributions on Heceta Bank over the last decade, particularly soft sediment dwelling species (Fig. 10) (Tissot et al. 2004).

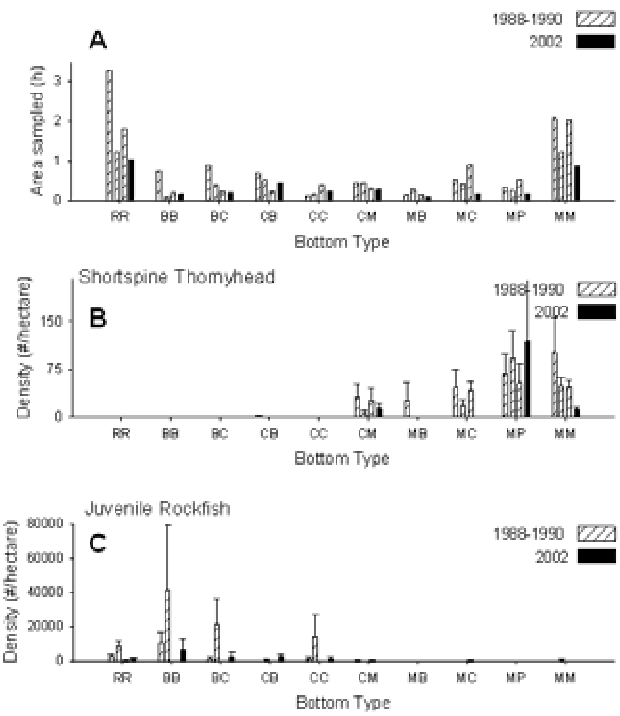

Figure 10. Distribution and abundance of habitats and selected fishes on Heceta Bank between 1988-1990 and 2002 surveys. (A) Area of habitats sampled. (B) Shortspine thornyhead (*Sebastolobus alascanus*), which were significantly less abundant in 2002 relative to earlier surveys. (C) Juvenile rockfishes (*Sebastes* spp.), which did not vary among years. (After Tissot et al. 2004).

Conclusions and future directions

The history of in situ observational studies at Heceta Bank illustrates an evolving approach to describing fish assemblages in response to shifts in research priorities—as fishery and habitat issues became more central—and the role of emerging technology in the development of new tools that progressively integrated greater quantities and types of data to address these priorities. Early studies focused on the characterization of the fishes and habitats on the bank, then shifted to developing a baseline to quantify long-term changes due to potential human impacts associated with offshore oil exploration. These pioneering studies developed a unique, quantitative measure of habitat-specific fish abundances that integrated megafaunal invertebrates providing a holistic view of fish communities. These methods included the development of a small-scale seafloor classification scheme that simplified the range of habitat diversity on the bank, which has served as a model for a wide variety of in situ/direct observation studies on the West Coast.

One important development was the shift from describing surveys from a single geographical reference point (i.e., sampling station) to a habitat-based patch approach, which provided a more ecologically relevant way to describe, quantify, and measure changes over time. An important component of the development of these tools was an application of statistical and multivariate methods to describe patterns and test hypotheses regarding spatial and temporal variation.

The development of a multibeam map in 1998, along with an increasing focus on declining groundfish stocks, shifted research priorities to developing a habitat-based strategy to examine methods for assessing fish abundance in untrawlable habitats, identify fish-habitat-invertebrate associations and potential essential fish habitat, and expand the inference of the data to larger spatial scales in order to provide reliable data for fishery management. This work included the development and integration of data derived from submersible operations, a multibeam sonar survey, and geological data. These efforts were instrumental in the development of preliminary population size estimates that ultimately could provide important information for stock assessments in untrawlable habitats. Studies initiated in 2000-2002 developed a new time-series that provided a link to the historical data and served as an additional baseline for future studies.

The development and adoption of new technology was integral to the increased capacity to collect a broader array of data with increased accuracy. Use of an ROV provided more bottom time to collect data, an improved method for collecting samples for taxonomic purposes, and an improved geographic referencing where GPS navigation (as opposed to Loran C) of the support ship was integrated with underwater acoustic positioning of the ROV. A dynamically positioned surface vessel assisted in increasing the accuracy of replicating earlier transects. The integration of higher resolution video cameras with digital video recording systems was a significant advance over lower resolution video recorded in Hi8 and VHS format and assisted in more accurate abundance estimates and in the identification of species, including fishes and deep-sea corals. Geological studies increased the understanding of geological processes that contributed to habitat complexity across the bank. The development of geospatial tools to classify large-scale habitat diversity using multibeam data groundtruthed with ROV data provided a mechanism to estimate fish population abundances.

Future research in and around Heceta Bank will likely continue to be driven by emerging fishery priorities, especially the continued recovery of depleted stocks and their response to the development of EFH Conservation Areas closed to protect habitat (NMFS 2005, Federal Register 2006). These studies will also need to focus on new priorities as they emerge, such as the development of ecosystem-based management, the effects of climate change, and offshore mining and energy development. Given the scale of these issues, work will need to expand from Heceta Bank to encompass other important fishery areas (e.g., Nehalem, Daisy, Coquille, and Stonewall banks) and the adjacent continental shelf and margin—ideally supported by comprehensive high-resolution seafloor mapping efforts.

These future studies will need to relate information on habitat associations of commercially important fishes to other aspects of fisheries, including design of surveys, stock assessments, identification of essential fish habitat and habitat areas of particular concern, risks to habitat from fishing gear impacts, and the design of marine reserves. Furthermore, there needs to be better coordination and integration of non-benthic studies in and around Heceta Bank, including biological, physical, and chemical oceanographic data sets. One of the challenges now is to efficiently relate small-scale observations and assessments of animal-habitat associations collected in situ to the larger geographic scales upon which fisheries operate. Although a coast-wide map has been developed that describes seafloor complexity off Oregon and Washington (Romsos et al. 2007), much of the seafloor of the continental shelf and slope within the EEZ of the Oregon continental margin is based on very little seafloor mapping data and virtually no in situ/direct observations, and is thus unmapped and uncharacterized. Ultimately fish-habitat data will be needed from these areas to provide an effective mechanism to implement ecosystem-based management.

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References

Alton, M.S. 1972. Characteristics of the demersal fish fauna inhabiting the outer continental shelf and slope off the northern Oregon coast. In: A.T. Pruter and D.L. Alverson (eds.) The Columbia River estuary and adjacent ocean waters. University of Washington Press, Seattle, pp. 583-634.

Alverson, D.L., A.T. Pruter, and L.L. Ronholt. 1964. A study of demersal fishes and fisheries of the northeastern Pacific Ocean. H.R. Macmillan Lectures in Fisheries. Institute of Fisheries, University of British Columbia, Vancouver.

Anderson, T.J., and M.M. Yoklavich. 2007. Multiscale habitat associations of deepwater demersal fishes off central California. Fish. Bull. U.S. 105:168-179.

Barss, W.H., S.L. Johnson, and R.L. Demory. 1982. Biological studies on rockfish and associated species from Heceta Bank off Oregon, 1980-81. Oregon Department of Fish and Wildlife Completion Report. Project 1-151-R2, Contract 81-ABD-ORAC. NOAA NMFS Commercial Fisheries Research and Development Act. 28 pp.

Bloeser, J.A. 1999. Diminishing returns: The status of West Coast rockfish. Pacific Marine Conservation Council, Astoria, Oregon.

Brodeur, R.D., and W.G. Pearcy. 1984. Food habits and dietary overlap of some shelf rockfishes (Genus *Sebastes*) from the northeastern Pacific Ocean. Fish. Bull. U.S. 82:269-293.

Dark, T.A., M.E. Wilkins, and K. Edwards. 1983. Bottom trawl survey of canary rockfish (*Sebastes pinniger*), yellowtail rockfish (*S. flavidus*), bocaccio (*S. paucispinis*), and chilipepper (*S. goodei*) off Washington-California, 1980. NOAA NMFS Tech. Memo. F/NWC-48. 40 pp.

Embley, R.W., W.W. Wakefield, J. Clemons, K. Bosley, N.M. Nasby, S. Van Laningham, B.N. Tissot, S.G. Merle, M.A. Hixon, M.M. Yoklavich, W.A. Barss, and G.L. Hendler. 2001. Fisheries habitat studies at Heceta Bank on the Oregon outer continental shelf: Combining high-resolution sonar and seafloor investigations with GIS techniques. Poster presented at The Geology of Marine Habitat, a special session of the 2001 GAC/MAC annual meeting, May 27-31, 2001, St. John's, Newfoundland. Abstract.

Federal Register. 2006. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, 50 CFR Part 660, Docket No. 051213334–6119–02; I.D.112905C, RIN 0648–AT98RIN 0648–AT98, Magnuson-Stevens Act Provisions; Fisheries off West Coast States; Pacific Coast Groundfish Fishery, National Marine Fisheries Service (NMFS), National Oceanic and Atmospheric Administration (NOAA), ACTION: Final rule, Vol. 71, No. 91:27408-27426.

Gabriel, W.L., and A.V. Tyler. 1980. Preliminary analysis of Pacific Coast demersal fish assemblages. Mar. Fish. Rev. 42:83-88.

Goldfinger, C., C. Romsos, R. Robison, R. Milstein, and B. Myers. 2003. Interim seafloor lithology maps for Oregon and Washington, Version 1.1. Active Tectonics and Seafloor Mapping Laboratory Publication 03-01, Oregon State University, CD ROM.

Greene, H.G., M.M. Yoklavich, R.M Starr, V.M. O'Connell, W.W. Wakefield, D.E. Sullivan, J.E. McRea, and G.M. Cailliet. 1999. A classification scheme for deep seafloor habitats. Oceanol. Acta 22:663-678.

Gunderson, D.R., and T.M. Sample. 1980. Distribution and abundance of rockfish off Washington, Oregon, and California during 1977. Mar. Fish. Rev. 42:2-16.

Hare, S.R., and N.J. Mantua. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. Prog. Oceanogr. 47:103-145.

Hart, T.D. 2004. Diel activity patterns in demersal fishes on Heceta Bank, Oregon. M.S. thesis, Oregon State University, Corvallis. 81 pp.

Hixon, M.A., and B.N. Tissot. 1992. Fish assemblages of rocky banks of the Pacific Northwest. U.S. Minerals Management Service, Final report supplement, OCS Study 91-0025, Camarillo, California. 128 pp.

Hixon, M.A., and B.N. Tissot. 2007. Comparison of trawled vs. untrawled mud seafloor assemblages of fishes and macroinvertebrates at Coquille Bank, Oregon. J. Exp. Mar. Biol. Ecol. 344:23-34.

Hixon, M.A., B.N. Tissot, and W.G. Pearcy. 1991. Fish assemblages of rocky banks of the Pacific Northwest (Heceta, Coquille, and Daisy banks). U.S. Minerals Management Service, OCS Study 91-0052, Camarillo, California.

Hughes Clarke, J.E., L.A. Mayer, and D.E. Wells. 1996. Shallow-water imaging multibeam sonars: A new tool for investigating seafloor processes in the coastal zone and on the continental shelf. Mar. Geophys. Res. 18:607-629.

Jagielo, T., A. Hoffmann, J. Tagart, and M. Zimmermann. 2003. Demersal groundfish densities in trawlable and untrawlable habitats off Washington: Implications for the estimation of habitat bias in trawl surveys. Fish. Bull. U.S. 101:545-565.

Kulm, L.D., and G.A. Fowler. 1974. Oregon continental margin structure and stratigraphy: A test of the imbricate thrust model. In: C.A. Burk and C. L. Drake (eds.), The geology of continental margins. Springer-Verlag, New York, pp. 261-283.

Lumsden, S.E., T.F. Hourigan, A.W. Bruckner, and G. Dorr (eds.). 2007. The state of deep coral ecosystems of the United States. NOAA Tech. Memo. CRCP-3. 365 pp.

MBARI (Monterey Bay Aquarium Research Institute). 2001. MBARI northern California and Oregon margin multibeam survey. Monterey Bay Aquarium Research Institute, Digital Data Series No. 5, CD ROM.

Morgan, L.E., C.F. Tsao, and J.M. Guinotte. 2006. Status of deep sea coral in US waters, with recommendations for their conservation and management. Marine Conservation Biology Institute, Bellevue, Washington. 68 pp.

Nasby, N.M. 2000. Integration of submersible transect data and high-resolution sonar imagery for a habitat-based groundfish assessment of Heceta Bank, Oregon. M.S. thesis, Oregon State University. 49 pp.

Nasby-Lucas, N.M., R.W. Embley, M.A. Hixon, S.G. Merle, B.N. Tissot, and D.J. Wright. 2002. Integration of submersible transect data and high-resolution multibeam sonar imagery for a habitat-based groundfish assessment of Heceta Bank, Oregon. Fish. Bull. U.S. 100:739-751.

NMFS (National Marine Fisheries Service). 2005. Pacific Coast groundfish fishery management plan: Essential fish habitat designation and minimization of adverse impacts. Final environmental impact statement. NOAA, NMFS, Seattle, Washington.

NMFS (National Marine Fisheries Service). 2008. Office of Sustainable Fisheries: Status of U.S. fisheries. Report to Congress, status determination tables, February 2, 2008. NOAA, NMFS, Silver Spring, Maryland.

Parker, S.J., S.A. Berkeley, J.T. Golden, D.R. Gunderson, J. Heifetz, M.A. Hixon, R. Larson, B.M. Leaman, M.S. Love, J.A. Musick, V.M. O'Connell, S. Ralston, H.J. Weeks, and M.M. Yoklavich. 2000. Management of Pacific rockfish. Fisheries 25:22-30.

Pearcy, W.G. 1978. Distribution and abundance of small flatfishes and other demersal fishes in a region of diverse sediments and bathymetry of Oregon. Fish. Bull. U.S. 76:629-640.

Pearcy, W.G., D.L. Stein, M.A. Hixon, E.K. Pikitch, W.H. Barss, and R.M. Starr. 1989. Submersible observations of deep-reef fishes of Heceta Bank, Oregon. Fish. Bull. U.S. 87:955-965.

Peterson, W.T., and F.B. Schwing 2003. A new climate regime in northeast Pacific ecosystems. Geophys. Res. Lett. 30(17):1896.

PFMC (Pacific Fishery Management Council). 2008. Pacific Coast groundfish fishery stock assessment and fishery evaluation, Vol. I. Pacific Fishery Management Council, Portland, Oregon. March 2008.

Ralston, S. 1998. The status of federally managed rockfish on the U.S. West Coast. In: M. Yoklavich (ed.), Marine harvest refugia for West Coast rockfish: A workshop. NOAA NMFS Tech. Memo. 255, pp. 6-16.

Romsos, C.G. 2004. Mapping surficial geological habitats of the Oregon continental margin using integrated interpretive and GIS techniques. M.S. thesis, Oregon State University.

Romsos, C.G., C. Goldfinger, R. Robison, R.L. Milstein, J.D. Chaytor, and W.W. Wakefield. 2007. Development of a regional seafloor surficial geologic habitat map for the continental margins of Oregon and Washington, USA. In: B.J. Todd and H.G. Greene (eds.), Mapping the seafloor for habitat characterization. Geol. Assoc. Can. Spec. Pap. 47, pp. 219-243.

Reynolds, J.R., R.C. Highsmith, B. Konar, C.G. Wheat, and D. Doudna. 2001. Fisheries and fisheries habitat investigations using undersea technology. Marine Technology Society/IEEE Oceans 2001, Conference Proceedings, Paper MTS 0-933957-29-7.

Shepherd, K., and K. Wallace. 2002. Deep precision deployment and heavy package recoveries by the *ROPOS* R.O.V. system. Marine Technology Society, MTS 0 933057-28-9, 1-6.

Sherman, K. 1988. Large marine ecosystems as global units for recruitment experiments. In: B.J. Rothschild (ed.), Toward a theory on biological-physical interactions in the world ocean. NATO ASI Series, Series C: Mathematical and Physical Sciences, Vol. 239. Kluwer, Dordrecht, Netherlands, pp. 459-476.

Stein, D.L., B.N. Tissot, M.A. Hixon, and W. Barss. 1992. Fish-habitat associations on a deep reef at the edge of the Oregon continental shelf. Fish. Bull. U.S. 90:540-551.

Tissot, B.N., M.A. Hixon, and D.L. Stein. 2007. Habitat-based submersible assessment of macroinvertebrate and groundfish assemblages at Heceta Bank, Oregon, from 1988 to 1990. J. Exp. Mar. Biol. Ecol. 352:50-64.

Tissot, B.N, W.W. Wakefield, M.A. Hixon, D.L. Stein, W. Barss, N. Puniwai, K. York, and C. Whitmire. 2004. Long-term habitat-based assessment of changes in groundfish populations on Heceta Bank, Oregon derived from submersible surveys. Western Groundfish Conference, February 9-13, 2004, Victoria, British Columbia, Canada, Abstract and poster.

Wakefield, W.W., C.E. Whitmire, J.E.R. Clemons, and B.N. Tissot. 2005. Fish habitat studies: Combining high-resolution geological and biological data. In: P.W. Barnes and J.P. Thomas (eds.), Benthic habitats and the effects of fishing. Am. Fish. Soc. Symp. 41:119-138.

Weinberg, K.L. 1994. Rockfish assemblages of the middle shelf and upper slope off Oregon and Washington. Fish. Bull. U.S. 92:620-632.

Weinberg, K.L., M.E. Wilkins, and T.A. Dark. 1984. The 1983 Pacific West Coast bottom trawl survey of groundfish resources: Estimates of distribution, abundance, age and length composition. NOAA Tech. Memo NMFS-F/NWC-70. 376 pp.

Whitmire, C.E. 2003. Using remote sensing, in situ observations, and geographic information systems to map benthic habitats at Heceta Bank, Oregon. M.S. thesis, Oregon State University.

Whitmire, C.E., R.W. Embley, W.W. Wakefield, S.G. Merle, and B.N. Tissot. 2007. A quantitative approach for using multibeam sonar data to map benthic habitats. In: B.J. Todd and H.G. Greene (eds.), Mapping the seafloor for habitat characterization. Geol. Assoc. Can. Spec. Pap. 47, pp. 111-126.

Wilkins, M.E. 1986. Development and evaluation of methodologies for assessing and monitoring the abundance of widow rockfish, *Sebastes entomelas*. Fish. Bull. U.S. 84(2):287-310.

Yoklavich, M.M., H.G. Greene, G.M. Cailliet, D.E. Sullivan, R.N. Lea, and M.S. Love. 2000. Habitat associations of deep-water rockfishes in a submarine canyon: An example of a natural refuge. Fish. Bull. U.S. 98:625-641.