Integration of submersible transect data and high-resolution multibeam sonar imagery for a habitat-based groundfish assessment of Heceta Bank, Oregon*

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Abstract—In the face of dramatic declines in groundfish populations and a lack of sufficient stock assessment information, a need has arisen for new methods of assessing groundfish populations. We describe the integration of seafloor transect data gathered by a manned submersible with high-resolution sonar imagery to produce a habitat-based stock assessment system for groundfish. The data sets used in this study were collected from Heceta Bank, Oregon, and were derived from 42 submersible dives (1988–90) and a multibeam sonar survey (1998). The submersible habitat survey investigated seafloor topography and groundfish abundance along 30-minute transects over six predetermined stations and found a statistical relationship between habitat variability and groundfish distribution and abundance. These transects were analyzed in a geographic information system (GIS) by using dynamic segmentation to display changes in habitat along the transects. We used the submersible data to extrapolate fish abundance within uniform habitat patches over broad areas of the bank by means of a habitat classification based on the sonar imagery. After applying a navigation correction to the submersible-based habitat segments, a good correlation with major boundaries on the backscatter and topographic boundaries on the imagery were apparent. Extrapolation of the extent of uniform habitats was made in the vicinity of the dive stations and a preliminary stock assessment of several species of demersal fish was calculated. Such a habitat-based approach will allow researchers to characterize marine communities over large areas of the seafloor.

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Dramatic declines in several groundfish populations have occurred along the U.S. West Coast during the last decade (Ralston, 1998; PFMC[1]; Sampson,[2] Bloeser[3]). One problem exacerbating these declines is that current stock assessments are not sufficiently precise or accurate to effect empirically based management. This is especially true for commercially important species of rockfish (Scorpaenidae, *Sebastes),* which comprise major groundfish fisheries along the Pacific Coast. Although evidence has accumulated for substantial declines in the abundance of several species of rockfish, the overall picture is unclear because 42 of 54 rockfish species (78%) have never been assessed (Ralston, 1998; NMFS, 1999; Bloeser[3]). Of the 12 species that have been assessed by the National Marine Fisheries Service, five were listed as "overfished" and one species was listed as "approaching overfished condition" (NMFS, 1999).

A possible alternative to single-species stock assessments of demersal fishes is a habitat-based community assessment, which serves to estimate groundfish population sizes by recognizing that species are not randomly distributed among varying habitats. It is known that the diversity, quality, and extent of bottom habitats are important in determining the distribution, abundance, and diversity of rockfishes (Carlson and Straty, 1981; Pearcy et al., 1989; Carr, 1991; Stein et al., 1992; O'Connell and Carlile, 1993). It has been previously demonstrated, within local study areas, that species richness and composition correlate with seafloor texture (Hallacher and Roberts, 1985; Richards, 1986; Love et al., 1991; Stein et al., 1992; Krieger, 1993; Yoklavich et

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[1] PFMC (Pacific Fishery Management Council). 1999. Status of the Pacific Coast groundfish gishery through 1999 and recommended acceptable biological catches for 2000: stock assessment and fishery evaluation, 75 p. Pacific Fishery Management Council, 7700 NE Ambassador Place, Suite 200, Portland, OR 97220.

[2] Sampson, D. B. 1997. Effective fishing effort in the Oregon groundfish trawl fishery. Final report to the Oregon Trawl Commission, 80 p. Oregon Trawl Commission, P.O. Box 569, Astoria, OR 97103.

[3] Bloeser, J. A 1999. Diminishing returns: the status of west coast rockfish. Pacific Marine Conservation Council, P.O. Box 59, Astoria, OR 97103.

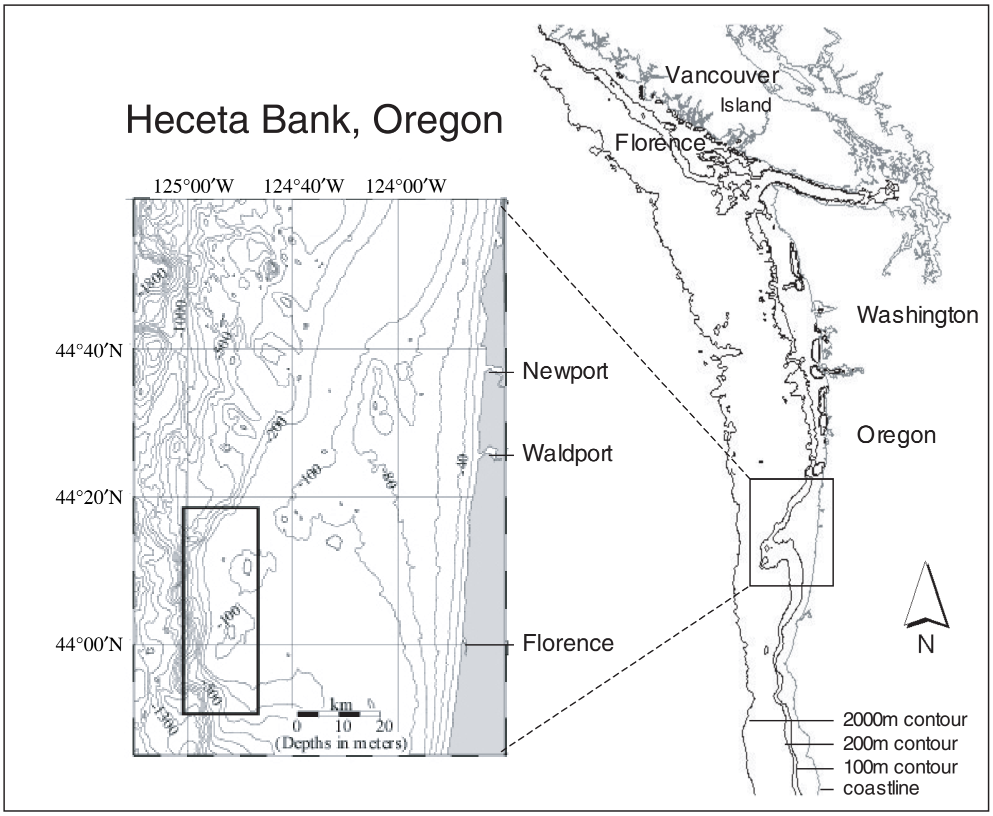

Figure 1

Location of Heceta Bank and the adjacent continental margin in relation to the Oregon coast. The survey area is outlined in bold lines.

al., 2000; Hixon et al.[4]; Hixon and Tissot[5]). Correlations over larger regions have been difficult to determine because of the limitations in the resolution and areal coverage of bathymetric charts, which are crucial in providing broad-scale habitat data. However, this difficulty no longer exists with the advent of differential GPS and high-resolution sonar systems (Hughes Clarke et al., 1996). When adequately groundtruthed, these new systems provide bathymetric and backscatter data with sufficient resolution to formulate habitat classifications over broad areas of the continental shelf and slope (Able et al., 1987; Yoklavich et al., 1995; Greene et al.[6]; Fox et al.[7]).

We developed this habitat-based groundfish assessment strategy by integrating a comprehensive submersible survey with new high-resolution sonar imagery of the seafloor. Sonar images produce habitat data by using acoustic signals to differentiate areas of hard substrata from surrounding soft sediments based on differences in the intensity of reflected sound. This technology has the distinct advantage of examining large regions of seafloor sediment and geological topographic features without relying on expensive direct underwater bottom sampling and observation techniques. Sonar data can be used in an assessment of seafloor habitat and fish density over large areas by extrapolating from direct observations of fish and seafloor morphology transects using manned submersibles or remotely operated vehicles.

The study site for this assessment was Heceta Bank, a 50-km long outcrop on the outer shelf of central Oregon (Fig. 1). Heceta Bank is the largest rocky reef of the Pacific Northwest and is characterized by high variability in bottom types and textures. The bank provides a diversity of habitat types for many species of groundfish and

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[4] Hixon, M. A., B. N. Tissot, and W. G. Pearcy. 1991. Fish assemblages of rocky banks of the Pacific northwest. Final report, OCS Study MMS 91-0052, 410 p. USDI Minerals Management Service, 770 Pasea, Camarillo, CA 93010.

[5] Hixon, M. A., and B. N. Tissot. 1992. Fish assemblages of rocky banks of the Pacific northwest. Final report supplement, OCS Study MMS 92-0025, 128 p. USDI Mineral Management Service, 770 Pasea, Camarillo, CA 93010.

[6] Greene, H. G., M. M. Yoklavich, D. Sullivan, and G. Cailliet. 1995. A geophysical approach to classifying marine benthic habitats: Monterey Bay as a model. Alaska Department of Fish and Game Special Publ. 9, p. 15-30. Alaska Department of Fish and Game, P.O. Box 25526, Juneau, AK 99802.

[7] Fox, D., M. Amend, and A. Merems. 1999. Nearshore rocky reef assessment. Coastal Management Section 309 Grant. Contract No. 99-072. Oregon Department of Fish and Wildlife, 2040 SE Marine Science Drive, Newport, OR 97365

invertebrates. These characteristics have made Heceta Bank one of the largest and most important of the heavily fished rocky banks in the Pacific Northwest. Along with its commercial importance, the bank has been the subject of substantial scientific research, which has made it an ideal site for developing these methods.

Direct observations of Heceta Bank were first made in 1987 in a series of 16 submersible dives used to characterize fish populations and habitats on the bank (Pearcy et al., 1989). These initial dives were used to select representative transects which were repeated in 1988, 1989, and 1990 using the manned research submersible *Delta* (Hixon et al.[4]; Stein et al., 1992). The objective of these surveys was to investigate relationships between the abundance of groundfish and macroinvertebrates and the topography and texture of the seafloor, as well as to document interannual variation in these relationships. Fish observed during these surveys included 69 taxa, representing 24 families, dominated by 24 species of rockfish. Multivariate analysis detected statistical relationships between habitat characteristics and fish distribution and abundance by species and provided comprehensive data on fish-habitat associations, as well as a baseline for future comparisons.

Although invaluable, data from this set of submersible dives provided detailed “snapshots” of very limited areas of the Bank. To complement this study and to provide a broad view of the bank, a survey was performed in 1988 with hull-mounted, Simrad EM300 multibeam sonar, which provided high-resolution bathymetry and backscatter imagery of most of Heceta Bank (Merle et al.[8]).

Materials and methods

Submersible dives

Submersible observation data were collected by using the manned submersible *Delta* at six predetermined stations along Heceta Bank. Detailed descriptions of submersible operations used in our study can be found in Hixon et al.[4] and Stein et al. (1992), and a brief description follows. Surveys were conducted in the month of September and consisted of 18 dives in 1988, 12 in 1989, and 12 in 1990, for a total of 42 dives and 84 transects (Fig. 2). Each dive consisted of two 30-minute timed transects and a 10–15 minute “quiet period” between transects to assess the effects of the submersible’s lights and motors on local fish distribution. The average length of each 30-minute transect was approximately 1015 m. Data on fish species, size, and abundance were collected by direct observations through the forward view port from approximately 2 m above the bottom, providing a bracketed transect width of about 2.3 m. During the transects, observations were verbally tape-recorded and visually recorded with a VHS

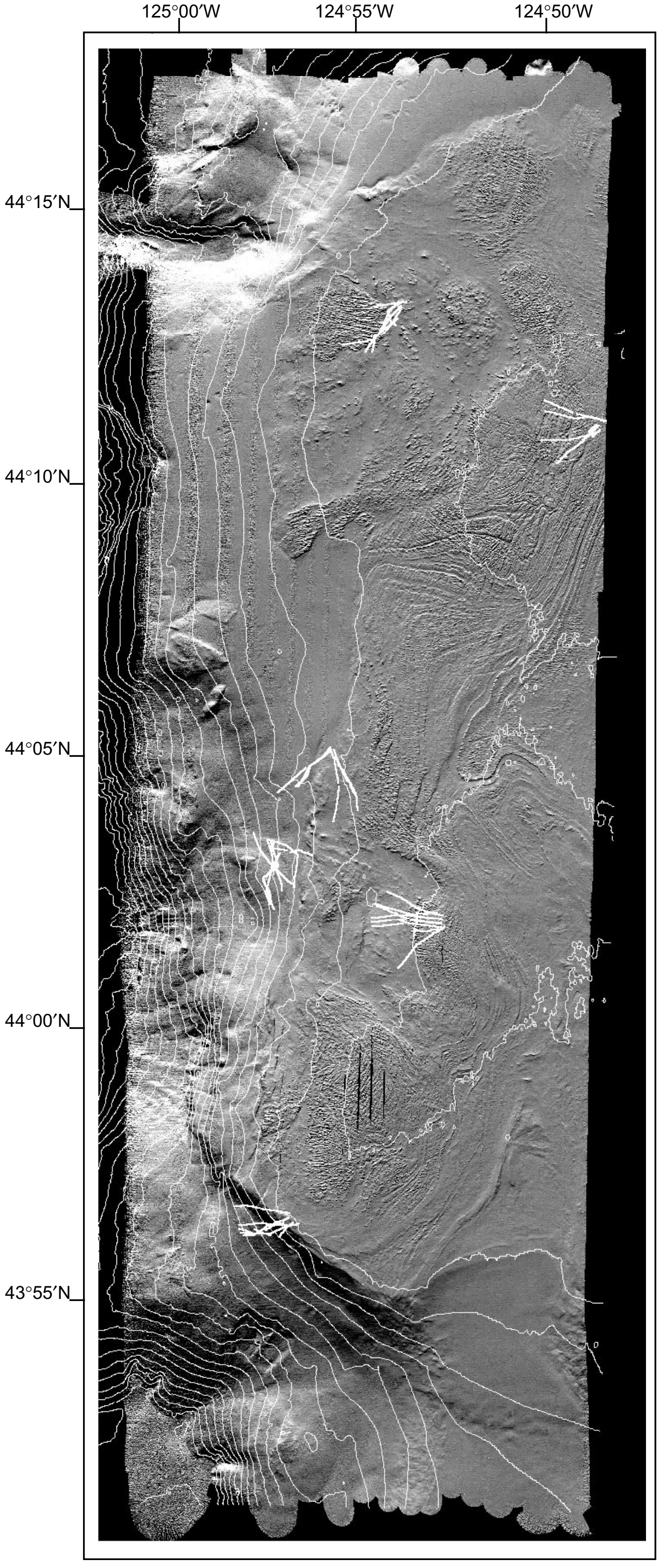

Figure 2

Simrad EM300 multibeam bathymetry illuminated from the northwest, which creates shadows to the southeast of the relief. The 1988, 1989, and 1990 *Delta* submersible transects (six clusters of white lines) have been overlaid on top of the bathymetric data. The isobathymetric contours are at 50-m intervals, beginning with 100 m on the east side of the bank.

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[8] Merle, S., R. W. Embley, J. Reynolds, D. Clague, C. Goldfinger, and R. Yeats. 1998. A high-resolution image over the Heceta Bank off Central Oregon. Trans. Am. Geophys. Union 78, Fall Meeting Suppl., F818.

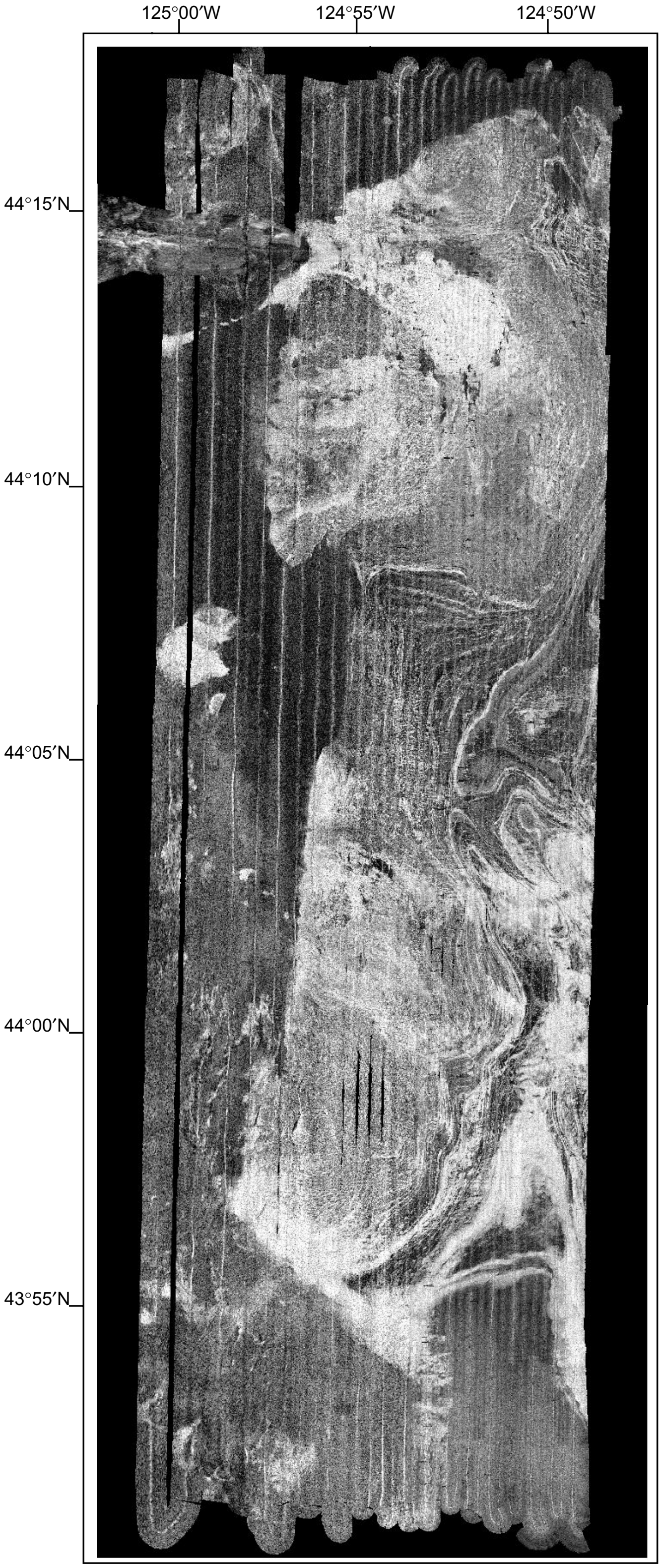

Figure 3

Backscatter imagery of Heceta Bank from Simrad EM300 multibeam survey. The lighter the shading the higher the reflectivity of the substratum.

videotape equipped with a timed data logger and audio track.

Direct and videotaped observations along the transects consisted of the number of species of fish and macroinvertebrates, and bottom-type characteristics. Fishes along the transects were identified, counted, and lengths were estimated to the nearest decimeter with a three-decimeter fiberglass rod suspended within the observer's view. Bottom type was categorized from videotapes by using a two-code combination, the first letter indicating the primary substratum (defined as covering at least 50% of the area viewed) and the second letter indicating the secondary substratum (defined as covering more than 20% of the area viewed). If the field of view was a single substratum, or the second most abundant substratum covered less than 20% of the field, the same letter was employed twice (e.g. MM for pure mud). The seven possible categories in order of increasing particle size or relief were mud (M), sand (S), pebble (P, diameter <6.5 cm), cobble (C, >6.5 and <25.5 cm), boulder (B, >25.5 cm), continuous flat rock (F, low vertical relief), and diagonal rock ridge (R, high vertical relief). The latitude and longitude positions of each transect were determined by using Loran-C with a Trackpoint II ultrashort baseline tracking system and by positioning the vessel directly above the submersible every 10 to 15 minutes. At least three position points were made per transect and the locations of bottom type and biological data were interpolated between these points. The absolute accuracy of the submersible's position, obtained by using Loran-C, was within about 150 to 500 m (Melton, 1986).

Multibeam sonar

The acoustic survey of Heceta Bank was conducted in May of 1998 with a Simrad EM300 (30 kHz) multibeam sonar system on the RV *Ocean Alert* (Merle et al.[8]). This survey provided a highly detailed, precisely navigated seafloor map of bathymetry and seafloor texture (Figs. 2 and 3). The data were processed with Swathed software (Hughes-Clarke et al., 1996). The data processing steps used in Swathed were the following: navigation and sounding editing, roll bias correction, tide correction, refraction correction, map sheet setup, gridding, and mosaicing which resulted in a composite map made up of acoustic backscatter imagery. The survey consisted of 47 overlapping north–south swaths up to 45 km long, which provided images of approximately 725 km^2 of the seafloor and nearly 100% coverage of high-resolution bathymetry and backscatter amplitude. These data were displayed in grids with a resolution of less than 5 meters on the shallowest portions of the bank from depths of 70 to 150 meters, and of about 5 to 10 meters at depths down to about 500 meters.

Data integration and habitat assessment

The sonar and submersible transect data were combined by using ArcView and ArcInfo geographic information system (GIS) software. The sonar data used were bathymetry and backscatter and the submersible transect data included bottom type characteristics and fish density data. In order to represent the dive transects in GIS as linear features displaying changes in habitat and fish density, a dynamic segmentation data structure was used (ESRI, 1994).

Bottom type and fish density data to be displayed using dynamic segmentation were derived from transect observation data. Transects were divided into segments by uniform bottom type. Fish density was calculated along each segment of habitat type by using the data for the most common species observed, accounting for 90% of the total, plus a few rare species of commercial importance (i.e. lingcod, sablefish, Dover sole and rex sole). This complex of species consisted of a mixture of demersal and benthopelagic species. The following species were assessed: juvenile *Sebastes* sp. (unknown juvenile rockfish), *Sebastes chlorostictus* (greenstriped rockfish), *Sebastes wilsoni* (pygmy rockfish), *Sebastes helvomaculatus* (rosethorn rockfish), *Sebastes zacentrus* (sharpchin rockfish), *Sebastes flavidus* (yellowtail rockfish), *Ophiodon elongatus* (lingcod), *Sebastolobus alascanus* (shortspine thornyhead), *Anoplopoma fimbria* (sablefish), *Microstomus pacificus* (Dover sole), and *Errex zachirus* (rex sole). The density of fish (number per hectare) was calculated by taking the number of fish sighted in that habitat segment, dividing by the area of the habitat segment in meters, and multiplying by 10,000 square meters per hectare.

The use of dynamic segmentation data structure allowed for the display of changes in bottom type and fish density data within the transect lines. This was done by creating a "route" system in ArcInfo from the dive transect data and associating it with an "event table." The event table consisted of bottom type and fish density data, and their corresponding locations along the transect, and a route-identifier number to link the information to the corresponding transects in the route system. For visual display, bottom type segments were combined into three major habitat groups: 1) mud, which consisted of "MM" observations, 2) rock ridge, which consisted of "RR" observations, and 3) mixed substrate habitat, which consisted of combinations of all other bottom type observations.

In order to combine the sonar and submersible data sets, all segmented dive transect data were then reprojected with a 500-meter offset to the east. This was determined to be the best correction for discrepancies between the transect position data which were acquired by Loran-C and the sonar data which came from GPS positions. It was determined that this offset was necessary by comparing the two data sets and matching depth contours and borders of well-defined habitat, specifically interfaces between the mud and rock features of the bank. There did not appear to be a significant north–south offset, although this effect was more difficult to determine because the submersible transects did not cross any well-defined north–south boundaries. Transects segmented by both bottom type and fish density were overlaid on the sonar data in ArcView (Fig. 4, A–C).

Assessments of fish abundance within large habitat areas were performed by selecting patches of relative habitat homogeneity on the sonar map around the location of each submersible transect. These patches were chosen by examining both patterns in the backscatter values and topographic features indicated by the backscatter and bathymetric data. In areas of mud off the bank, borders were chosen by maintaining constant depth as well as equal distance from the bank. In selecting patches to represent areas of similar habitat, the boundaries were relatively well defined in areas of rock and mud, but for mixtures of sand, cobble, pebble, and boulder, it was more difficult to distinguish distinct boundaries and therefore these patch borders were drawn conservatively.

Using the observational data from the transects from all three years, we were able to characterize each habitat patch by percent bottom type, density of fish, and estimated abundance of fish as extrapolated from the dive transect data contained within that patch. The grand mean density and standard error for each species was determined by using a weighted density for each habitat segment based on a proportion of the length of that segment to the overall transect distance within that habitat patch. The grand mean density was calculated as

$$x = \sum_{i=1}^{n} d_i p_i, \tag{1}$$

where $x = \bar{x}$;

d = density of fish within a segment of continuous bottom type; and

p = bottom type segment length/total transect length within the patch.

This calculation used the associations of the fish species with substrate type and weighted its contribution to the overall density by the comparative length of that segment. Total fish abundance for each habitat patch was determined by multiplying the area of the patch and the grand mean density and standard error of each species. The total abundance for each species for all habitat patches was determined by adding the abundance for that species for all eight habitat patches. The standard error for the total abundance for each species was determined by calculating a grand mean standard error weighted by using the standard error of each habitat patch multiplied by the proportion of the abundance of that species for that habitat patch to the overall abundance for that species. Total abundance standard error was calculated by using Equation 1 where x = SE; d = standard error of fish abundance within a habitat patch; and p = abundance within that habitat patch/total abundance in all eight patches.

Results

Comparing the submersible data with the sonar data, we found that there was high correlation between the direct observations of bottom type and the habitat type indicated by the sonar data. Side-lit bathymetry revealed areas of outcropping substrata and the backscatter data

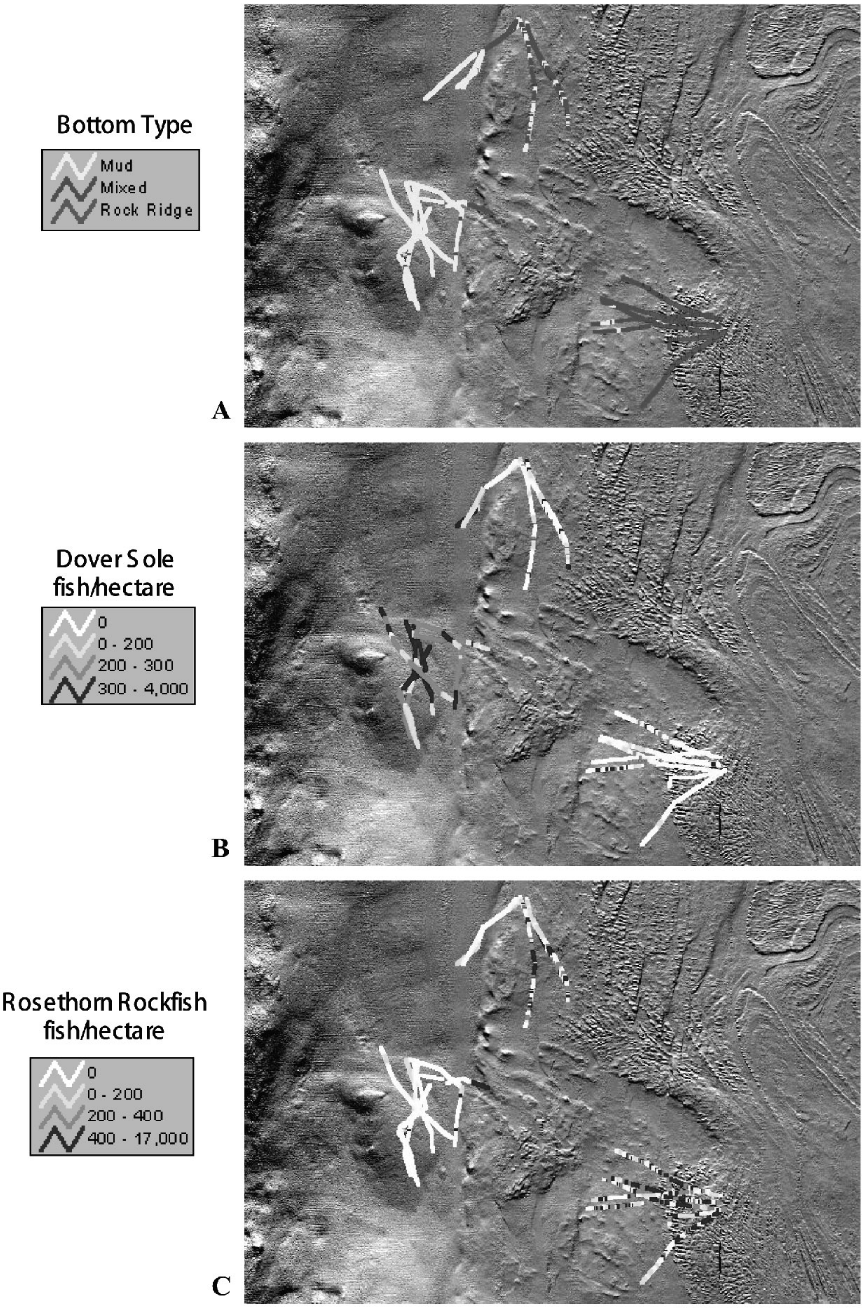

Figure 4

Submersible transects in the middle portion of Heceta bank segmented by observations of (**A**) bottom-type habitat, categorized by mud, mixed substrate, and rock ridge (**B**) density of Dover sole (*Microstomus pacificus*) and (**C**) density of rosethorn rockfish (*Sebastes helvomaculatus).*

showed changes in seafloor texture. Borders of rock ridge and mud observed in the submersible survey matched the bathymetric data, indicating areas of high relief for rocky patches and low relief for areas of mud (Figs. 4A and 5). Changes in backscatter also corresponded with changes observed in bottom type from the submersible data (Fig. 5). It was noted consistently that high-backscatter areas were associated with mixed substrate habitat, comprising a combination of pebble, cobble, and boulder, which due to their size and geologic composition have a relatively high reflectivity. Mid-backscatter values were found to be associated with rock ridge features. These are typically

Figure 5

Habitat patch boundaries and transects segmented by bottom type overlaid on both bathymetric and backscatter sonar images. Habitat patches are labeled A–H. The bottom-type observations were grouped into three predominant habitats: mud, mixed substrate, and rock ridge.

large-scale rolling ridges with less small-scale relief. Low-backscatter values were associated with mud bottoms, which have characteristically low reflectivity.

Eight regional patch boundaries were drawn based on areas of relative homogeneous seafloor sonic characteristics around the six stations surveyed by submersible (Fig. 5). These patches (labeled A–H) ranged from 1.8 km^2 (patch B) to 38.9 km^2 (patch C) (Table 1). Patch boundaries for A, C, and F were drawn around areas of mid-backscatter reflectivity and high relief indicated by the bathymetric data, and were located in relatively shallow areas of the bank (75–125 m). Patch boundaries for D and H were drawn around mud areas located off the edge of the bank, which exhibited low-backscatter values, low relief on the bathymetric data, and were located in deeper waters (150–300 m). Patch boundaries for B, E, and G were drawn around areas of high backscatter and were present in intermediate depths (100–150 m).

Table 1

Estimated mean fish density and abundance (± standard error) by habitat patch (A–H) and species at Heceta Bank, Oregon. Density is in number of fish/hectare, abundance numbers are × 1000, and n = number of bottom type segments.

		Habitat patch								
		A	B	C	D	E	F	G	H	
	Habitat type	Rock ridge	Mixed	Rock ridge	Mud	Mixed	Rock ridge	Mixed	Mud	
	Area (km^2)	6.2	1.78	38.9	25.1	19.9	5.05	15.5	12.0	Total
Fish taxa	n	81	137	262	51	268	219	58	44	124
Juvenile rockfish	density	1140 ±536	1001 ±385	25,577 ±6521	2 ±1	95 ±217	4709 ±5309	30 ±12	0 ±0	
Sebastes sp.	abundance	711 ±335	178 ±69	99,595 ±25,394	6 ±3	190 ±433	2380 ±2683	46 ±18	0 ±0	103,110 ±24,593
Greenstriped rockfish	density	108 ±23	137 ±27	3 ±3	18 ± 13	232 ±23	10 ±4	65 ±23	0 ±0	
S. elongatus	abundance	68 ±15	24 ±5	13 ±10	46 ±32	463 ±46	5 ±2	101 ±35	0 ±0	759 ±37
Pygmy rockfish	density	2195 ±536	12,435 ±3392	3586 ±1264	0 ±0	2260 ±1139	12,119 ±3531	3236 ±581	0 ±0	
S. wilsoni	abundance	1370 ±335	2218 ±605	13,962 ±4922	0 ±0	4509 ±2273	6125 ±1785	5016 ±901	0 ±0	35,041 ±2746
Rosethorn rockfish	density	367 ±56	540 ±54	379 ±55	10 ± 24	238 ±21	473 ±121	595 ±88	5 ±2	
S. helvomaculatus	abundance	229 ±5	96 ±10	1478 ±213	24 ±61	475 ±43	239 ±61	922 ±137	6 ±2	3643 ±134
Sharpchin rockfish	density	265 ±71	1632 ±308	0 ±0	9 ±16	727 ±112	2 ±0.5	2916 ±505	0 ±0	
S. zacentrus	abundance	166 ±44	291 ±55	0 ±0	23 ±40	1450 ±224	1 ±0	4519 ±783	0 ±0	7552 ±515
Yellowtail rockfish	density	885 ±535	639 ±224	287 ±101	0 ±0	6 ±4	1578 ±421	0 ±0	0 ±0	
S. flavidus	abundance	552 ±334	114 ±40	1116 ±391	0 ±0	13 ±8	797 ±213	0 ±0	0 ±0	2747 ±289
Lingcod	density	2 ±5	4 ±5	27 ±5	0 ±0	3 ±2	23 ±70	9 ±3	0 ±0	
O. elongatus	abundance	1 ±3	1 ±1	103 ±19	0 ±0	6 ±3	12 ±35	14 ±4	0 ±0	143 ±17
Shortspine thornyhead	density	0 ±0	0 ±0	0 ±0	228 ±41	0 ±0	0 ±0	199 ±72	457 ±46	
S. alascanus	abundance	0 ±0	0 ±0	0 ±0	575 ±104	0 ±0	0 ±0	309 ±111	549 ±56	1433 ±87
Sablefish	density	0 ±0	0 ±0	0 ±0	52 ±10	0.7 ±0.6	0 ±0	23 ±25	96 ±35	
A. fimbria	abundance	0 ±0	0 ±0	0 ±0	131 ±25	1 ±1	0 ±0	36 ±39	116 ±42	284 ±34
Dover sole	density	28 ±20	41 ±17	0 ±0	312 ±33	79 ±14	8 ±5	137 ±71	217 ±29	
M. pacificus	abundance	17 ±12	7 ±3	0 ±0	786 ±82	158 ±29	4 ±3	212 ±110	260 ±35	1445 ±70
Rex sole	density	0 ±0	7 ±6	0 ±0	143 ±18	23 ±7	0 ±0	3 ±3	24 ±14	
E. zachirus	abundance	0 ±0	1 ±1	0 ±0	359 ±44	46 ±15	0 ±0	5 ±5	29 ±17	440 ±39
	Total abundance	3115 ±288	2932 ±469	116,267 ±22,350	1949 ±28	7312 ±1464	9563 ±1830	11,181 ±738	960 ±47	156,598 ±16,854

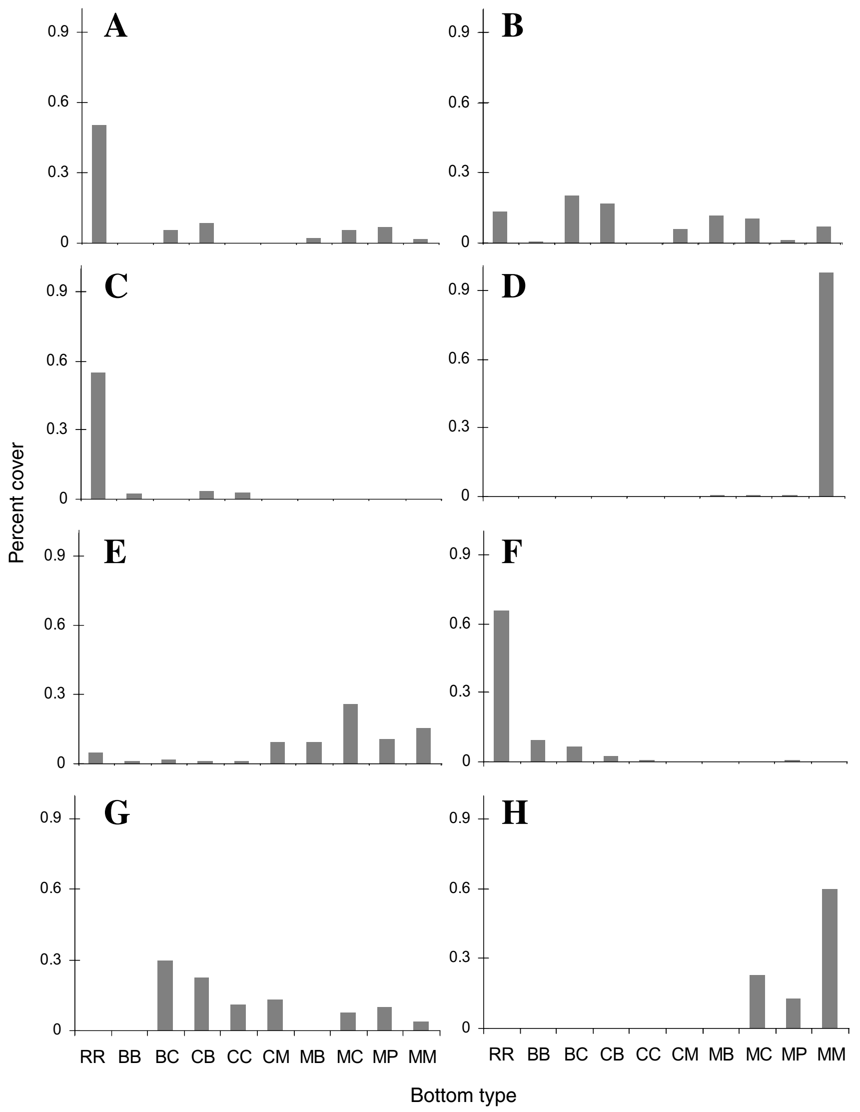

Figure 6

Percent cover of bottom types calculated from observations of all transects contained within each of the eight habitat patches labeled A–H. Bottom types are listed from left to right by decreasing relief and particle size, where the first letter is the dominant substratum and the second letter is the second most prevalent substratum. Substrate categories shown comprise only the 10 most dominant bottom types, consisting of combinations of R = rock ridge, B = boulder, C = cobble, M = mud, and P = pebble.

Combining the sonar-derived habitat patches and submersible observations gave an indication of bottom-type compositions for the defined patches. Of the eight habitat patches analyzed, three of the habitat patches were predominantly rock ridge (patch A—63% RR and 14% RC/RB; patch C—55% RR and 3% RB/RC; and patch F—66% RR), two were predominantly mud (patch D—98% MM; and patch H—60% MM and 36% MC/MP), and three were a mixture of boulder, cobble, pebble, and mud (patch B—75% BC/CB/MB/MC/MM/CM/MP/BM/BB; patch E—83% MC/MM/MP/CM/MB/CP/BM/BC/CB/PM/CC/BB/BP/PB; and patch G—100% BC/CB/CM/CC/MP/MC/MM/PM/BB) (Fig. 6).

There were differences in fish density within the patches between the three major habitat classification types, as well as differences among patches of similar bottom types (Fig. 7, Table 1). Species with the highest association with rock-ridge habitat patches were yellowtail rockfish, juvenile rockfish, and lingcod. Those primarily associated with mud habitats were Dover sole, rex sole, and shortspine thornyheads. Those associated with mixed substrate patches were sharpchin rockfish, rosethorn rockfish, green-

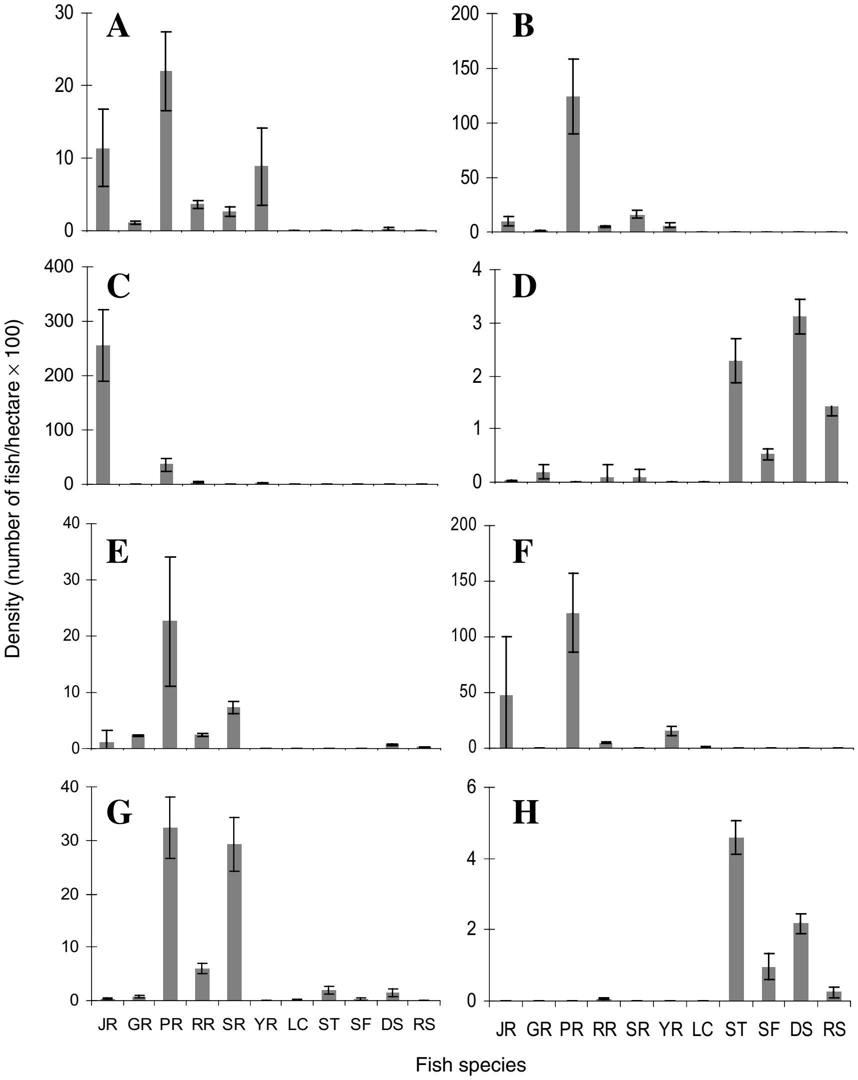

Figure 7

Fish densities (mean ±SE) for each habitat patch calculated from all transects contained within each patch. JR = juvenile rockfish (*Sebastes* species); GR = greenstriped rockfish (*Sebastes elongatus*); PR= pygmy rockfish (*Sebastes wilsoni*); RR = rosethorn rockfish (*Sebastes helvomaculatus*); SR = sharpchin rockfish (*Sebastes zacentrus*); YR = yellowtail rockfish (*Sebastes flavidus*); LC = lingcod (*Ophiodon elongatus*); ST = shortspine thornyhead (*Sebastolobus alascanus*); SB = sablefish (*Anoplopoma fimbria*); DS = Dover sole (*Microstomus pacificus*); and RS = rex sole (*E. zachirus*).

striped rockfish, and pygmy rockfish. Juvenile rockfish were found predominantly in rock-ridge habitats, and found in substantially high density (25,577 [±6521] fish/hectare) in patch C as compared with the other rock ridge patches (patch A 1140 [±536] fish/hectare and patch F 4709 [±5309] fish/hectare). Both Dover sole and rex sole were associated with mud habitat, and both were found in higher densities in patch D (Dover sole—312 [±33] fish/hectare, rex sole—143 [±18] fish/hectare) than patch H (Dover sol—217 [±29] fish/hectare, rex sole—24 [±14] fish/hectare). Pygmy rockfish were found in high density in mixed substrate patches B and F (12,435 [±3392] fish/hectare and 12,119 [±3531] fish/hectare) but at a substantially lower density in patch G (3236 [±81] fish/hectare).

Among all eight patches, the species found in the highest abundance overall were juvenile rockfish and pygmy rockfish, and those in the lowest abundance were lingcod and sablefish (Table 1). The total area of all habitats assessed was 124 km^2, which is approximately 17% of the total area of the sonar survey, and the total number of estimated fish and standard error for that area was 156,598,000 ±16,854,000. The coefficient of variation was relatively low for greenstriped rockfish, rosethorn rockfish, sharpchin rockfish, shortspine thornyhead, and Dover sole (between 3.7% and 6%) and slightly higher for pygmy rockfish, yellowtail rockfish, lingcod, sablefish, and rex sole (between 7.8% and 11.9%).

Discussion

A primary finding of our study was that distinct bottom types found on Heceta Bank are distinguishable through the use of sonar data and that these interpreted habitats correlate with direct submersible observations of bottom type. The determination of habitat information from sonar data is significant in that it provides a broad-scale view of the seafloor habitat, previously unavailable, and allows a habitat-based groundfish assessment. Although seafloor imaging and GIS techniques have previously been used in the study of marine habitats (e.g. Meaden, 1999; McRea et al., 1999; Sherin, 1999; Yoklavich et al., 2000), ours is one of the first published studies where GIS technique was used to combine a detailed analysis of fish and habitat transect data with broad-area high-resolution sonar seafloor imagery and where total fish abundances were calculated for large areas of the seafloor (see also O'Connell et al.[9]).

Habitat type could not be determined by bathymetry or backscatter data alone, but the information provided by both data sets, in addition to groundtruthing by direct submersible observation, gives a clearer picture of the overall habitat environment. The use of the backscatter data combined with the bathymetric data has the advantage of providing an indication of substrate type, which is clearly important in fish-habitat associations. In general, however, backscatter provides a better indication of habitat for fish association purposes. Bathymetric data can provide geological structure on the resolution of five to ten meters, whereas backscatter data give an indication of structural variation on a smaller scale, which is of ecological importance in influencing the distribution of groundfish. For example, the physical properties of a substrate influence the types of invertebrates that colonize the seafloor, and local relief can provide microhabitats for some fish.

The extent to which a groundfish habitat can be effectively mapped by remote sensing is determined by the resolution of the system used. In general, sonars are optimized for specific operational depth ranges. A system designed for very shallow water can have sufficient resolution to provide contours of features or objects that deeper water (lower frequency and longer range) systems will only "see" as backscatter changes. As more sites are studied by combining visual seafloor transects, high-resolution sonar, and GIS techniques, it is likely the geologic indices most relevant to groundfish habitats will become apparent. These methods should lead to a more coherent approach to habitat-based stock assessments.

One of the limitations of this habitat-based approach to stock assessments has to do with strong reliance upon the fish-substratum association. The distribution and abundance of groundfish has been shown to be strongly correlated with substrate type (see introduction), but fish distributions and densities may vary with other factors as well, such as depth, currents, nutrients, and food availability. In this study there was an attempt to address this potential problem of over emphasizing the fish substratum relationship through the grouping of habitats into patches. The designation of habitat patches allowed the grouping of areas of potentially similar biotic and physical characteristics. Thus, the use of patches as areas for fish density estimates allowed for increased accuracy in forming abundance estimates from the habitat-groundfish association information. For example, this advantage was apparent by high variance in fish density estimates among patches of similar bottom type, such as the high density of juveniles in one of the three rock ridge patches. Variations in density in similar patch types of our study were also observed for Dover sole, rex sole, and pygmy rockfish. These patterns may be due to differences in depth, food availability or variations in percent composition of substrate type in separate areas of the bank. The other benefit of using habitat patches was that it allowed the testing of new groundfish assessment methods without making predictions for areas of high uncertainty where submersible transects were not performed.

Hixon et al.'s study[4] is one of only a few comprehensive habitat-groundfish studies available and has provided a foundation for testing this new approach. Hixon et al's dataset provided invaluable habitat information, but had several shortcomings. One problem was that of the inconsistency in positional data because of the use of Loran-C (GPS was not yet available). Another problem, characteristic of all submersible studies, was the overall limited spatial sampling provided by the survey. The stations for the study were chosen as representative habitats for Heceta Bank from exploratory submersible dives conducted by Pearcy et al. (1989) in 1987. However, not all of the representative habitat areas were sampled because maps of high-resolution bathymetry and backscatter were not available at that time. Lack of complete habitat data made it difficult to extrapolate bottom-type and fish-density data to the entire bank.

The use of observational data from submersibles for determination of fish density, and extrapolation from these data to total abundance within regional habitat patches, were based on several assumptions. First, we assumed that the areas sampled were representative of the entire regional patch to which each transect belonged. Whatever error was associated with this assumption, our approach is certainly more accurate that any method that ignores habitat variation. Second, we assumed that all fish within each submersible transect were accurately identified and counted. Identification of similar species of rockfish can be problematic, and counts clearly become estimates when dense schools are encountered. Third, we assumed

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[9] O'Connell, V., and C. Carlile, and C. Brylinsky. 2001. Demersal shelf rockfish stock assessment and fishery evaluation report for 2002. Regional Information Report 1J01-35, 43 p. Southeast Region, Division of Commercial Fisheries, Alaska Department of Fish and Game, P.O. Box 25526, Juneau, AK 99802.

that avoidance or attraction of fish in response to the submersible was minimal, and thus did not affect counts substantially. This assumption was tested by Hixon et al.[4] by observing the local distribution and abundance of fish around the submersible just before and after the 10–15 minute "quiet periods" on the bottom, during which all motors and lights were turned-off. Quiet periods were conducted for all transect dives, and there was no indication that fish behavior was altered by the presence of the submersible. However, midwater schools of yellowtail rockfish sometimes circled the submersible during transects, which could have affected counts if fish were counted more than once. The final assumption was that transect width, which varied as a function of the altitude of the submersible above the seafloor, was constant. Certainly, there was some variation in altitude, yet the error introduced was presumably insubstantial except perhaps in areas of extremely heterogeneous vertical relief.

This study provides an expanded view of the groundfish habitat of Heceta Bank in areas adjacent to the historical *Delta* transects. In order to perform a full assessment of the bank it will be important to groundtruth habitat types for the entire extent of the bank. The new sonar data have indicated areas on the bank that contain unique habitats that have not been identified. The best study plan would have been to gather the sonar data first, then use the detailed imagery to define patches of uniform bottom type for planning subsequent stratified random sampling and groundtruthing using submersibles. The next phase of our project was initiated in June 2000 and involved operations with the manned submersible used in the original study and an advanced remotely operated vehicle (ROV) to conduct transects on unsurveyed areas, as well as to repeat the original historical transects. Not only will this approach optimize the techniques developed in our project but may also provide the opportunity to estimate changes in fish density on Heceta Bank over the past decade.

Conclusions

In this exploratory project we have demonstrated how sonar and submersible data can be combined to allow habitat-based stock assessments of multiple species of groundfish. Despite its limitations, this method provides the possibility for a detailed look at fish abundance using habitat associations. This approach could be used to address the problem of the high number of groundfish species that are currently unassessed. It offers the prospect of examining multiple species of fish and may provide a better indication of fish abundance estimates, particularly for multiple species, than is possible using current methods.

The method presented in our study provides an alternative for assessing these ten groundfish species and additional groundfish species that are currently unassessed, as well as for monitoring species that are considered to be overfished. Of the groundfish species examined in this study using the 1988–90 submersible observations, the status of all, but the pygmy, rockfish has been reported recently (NMFS, 1999). In the NMFS report on the status of fisheries in the United States, only the lingcod was reported as "overfished." Yellowtail rockfish, shortspine thornyhead, sablefish, and Dover sole were listed as "not approaching overfished," and the status of rex sole, greenstriped rockfish, rosethorn rockfish and sharpchin rockfish was reported as "unknown" (NMFS, 1999). In addition to the ten species that were examined here, the method described in our study would be important for assessing species of rockfish found on Heceta Bank that are considered overfished, such as the canary rockfish, Pacific ocean perch, and darkblotched rockfish. It should be stressed, however, that this method would be useful only for those species that are closely associated with seafloor habitats and spend most of their time near the bottom. For example, yellowtail rockfish are found as high as 25–35 m off the seafloor, so that transect data collected on the seafloor may not accurately reflect their true abundance (Pearcy, 1992).

The preliminary work in this study is a step toward creating a model approach for characterizing and quantifying groundfish and their habitat associations on a scale meaningful to the stock assessment of commercial species and the conservation of benthic communities. Traditional stock assessment methods for groundfish have been inadequate. Our study is the first step in the development of a new quantitative method of assessing groundfish stocks that is independent of traditional trawl surveys. Overall, this habitat-based approach to stock assessment has particular recommendation for defining and mapping essential fish habitat, as well as providing important data for designing and managing marine reserves and protected areas.

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