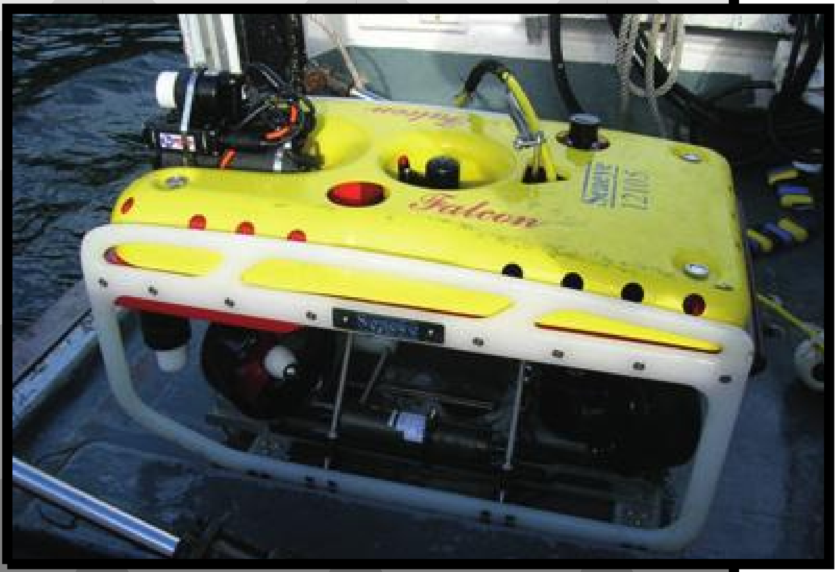
STATE OF WASHINGTON **January 2013**

Estimating Fish Abundance and Community Composition on Rocky Habitats in the San Juan Islands Using a Small Remotely Operated Vehicle



by Robert E. Pacunski, Wayne A. Palsson,
and H. Gary Greene

Washington Department of
FISH AND WILDLIFE
Fish Program
Fish Management Division

FPT 13-02

Estimating Fish Abundance and Community Composition on Rocky Habitats in the San Juan Islands Using a Small Remotely Operated Vehicle

Robert E. Pacunski[1], Wayne A. Palsson[1,2], and H. Gary Greene[3]

[1]Washington Department of Fish and Wildlife, 600 Capitol Way N., Olympia, WA 98501
[2]Present Address: Alaska Fisheries Science Center, 7600 Sand Point Way NE, Seattle, WA 98115.

[3]Tombolo Habitat Institute, 2267 Deer Harbor Road, East Sound, WA 98245

Abstract

Estimating the abundance of marine fishes living in association with rocky habitats has been a long- standing problem because traditional net surveys are compromised by the nature of the seafloor and direct visual methods, such as scuba or submersibles, are limited or costly. In this study we used a small ROV to survey rocky habitats in the San Juan Islands (SJI) of Washington State to estimate the abundance of rockfishes (*Sebastes* spp), greenlings (Hexagrammidae), and other northeastern Pacific marine fishes living in nearshore, rocky habitats. The sampling frame was generated by multibeam echosounding surveys (MBES) and geological interpretation and by using charts of known rocky habitats where MBES data were not available. The survey was a stratified-random design with depths less than, or greater than, 36.6 m (120 ft) as the two depth strata. The ROV was deployed from a 12 m survey vessel fitted with an ultra-short baseline tracking system and a clump weight tethered to the ROV during most transects. Twenty-seven sampling days were expended between 29 September and 26 November 2008, during which 207 transects were conducted at depths ranging between 0 (surface) and 234 m. Transect distances were determined via the georeferenced tracking system and widths were determined by using two parallel, forward-facing lasers mounted on the ROV to measure the field of view. Densities were determined for each transect by dividing the number of individuals counted during video review by the transect area. Seafloor and biological features were evaluated throughout each transect and used to identify habitat patches that were subsequently related to mapping precision and fish occurrence. Abundance estimates were made by averaging the species densities among transects and multiplying the mean by the area of the stratum. Coefficients of variation were calculated as the percentage of the square root of the population variance divided by the population estimate.

We found that the habitat map based on the geophysical MBES interpretations always contained some rock and was highly accurate. The map based upon known or charted rocky seafloor only contained rock on 82% of transects. As expected, most rockfish were highly associated with rock, and since more rocky habitats were found in the western portion of the SJI, more rockfish were found there than in the eastern SJI. Species composition differed by depth stratum: kelp greenling, copper rockfish, Puget Sound rockfish, and lingcod were the most abundant species in the shallow stratum while quillback rockfish, Puget Sound rockfish, codfishes, spotted ratfish, lingcod, and yelloweye rockfish were the most abundant species in the deep stratum. Puget Sound rockfish was the most abundant species overall, with an estimated 4.5 million individuals. Copper and quillback rockfish abundance was 546,000 and 440,000 individuals, respectively, and survey precision was high with respective CVs of 14% and 10.5%. There was an estimated 47,000 yelloweye rockfish (25% CV), a population that is a heavily depleted in the SJI and Puget Sound. We found the ROV to be an effective survey tool for rocky habitat species living in semi-protected nearshore waters and determined that by focusing on rocky habitats, high precision was obtained for the most common species.

Table of Contents

List of Figures

List of Tables

Introduction

Long-lived, slow-growing, and late-maturing rockfishes (*Sebastes* spp.) present some of the greatest challenges to fishery management in the world. In Puget Sound, Washington, conducting age-based stock assessments of diverse rockfish populations is compromised by poor catch data, a lack of age estimates, and poorly known life history parameters (Palsson et al. 2009). Such nearshore fisheries are often managed in a data-limited context, requiring risk-averse measures such as marine reserves (Yamanaka and Logan 2010) or managing fisheries with other precautionary approaches (Parker et al. 2000, Palsson et al 2009). A variety of relative abundance indices and other qualitative information has shown that several key species of rockfish have declined in Puget Sound (Palsson et al. 2009), and the lack of detailed stock information has led to several stocks being assigned a status of depleted. Additionally, canary (*Sebastes pinniger*) and yelloweye rockfish (*S. ruberrimus*) in Puget Sound have been listed as threatened and bocaccio (*S. paucispinus*) has been listed as endangered under the terms of the U.S. Endangered Species Act (Drake et al. 2010).

Survey estimates of abundance can be used to inform demographic models of stock abundance or as an independent baseline for population abundance for data-limited management (Doak et al. 2005, Royle et al. 2007, Dick and MacCall 2011). However, since many northeastern Pacific rockfishes are highly associated with rocky habitats (Love et al. 2002), conducting direct surveys using bottom trawls is not usually successful (Zimmerman 2003) and does not provide sufficient assessment information for most species. A variety of visual survey methods have been used to estimate rockfish abundance, but each has its limitations. Scuba surveys are effective and often used throughout rocky habitats (Marliave and Challenger 2009), but are typically limited to depths of 30 to 40 m and, thus, cannot capture the broad depth range of many rockfishes. Small, manned submersibles have been used extensively along the Pacific coast (Brylinsky et al. 2007, Yoklavich et al. 2007, Love et al. 2009), but are a costly survey option (Pacunski et al. 2008). In the early 1990s the Washington Department of Fish and Wildlife (WDFW) developed a drop-camera system that was used to conduct quantitative surveys throughout Puget Sound in water depths less than 36.6 m, but these surveys had difficulties in estimating the surveyed area (Palsson et al. 2009) and were discontinued in 2004. Towed cameras have been used in British Columbia to examine the density and distribution of rockfishes and their habitat associations (Martin and Yamanaka 2004). Remotely-operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) have been used for comparative and experimental studies but until now have not been used to conduct regional, quantitative surveys.

Surveys focusing on rockfish may be particularly effective when geophysical information exists to develop a sampling frame of potential habitats. Jagielo et al. (2003), Brylinsky et al. (2007), and Yoklavich et al. (2007) used geophysical maps to identify rocky outcrops and other likely rockfish habitats, allowing them to successfully estimate rockfish density and abundance with a small submersible. The rationale for focusing sampling efforts on rocky and complex habitats is supported by several other studies. Richards (1986) and Murie et al. (1994) observed quillback rockfish (*Sebastes maliger*) and yelloweye rockfish (*S. ruberrimus*) from a small submersible in British Columbia and found these species in greatest abundance on bedrock slopes and walls and in complex habitats, including areas of broken rock and boulders. In southeastern Alaska, Johnson et al. (2003) examined the distribution of rockfishes and reported that most observations (>75%) were made on complex boulder or rock bottoms or against steep rocky walls. Martin et al. (2006) found significantly higher densities of quillback rockfish over bedrock than over mud in the southern Strait of Georgia.

By taking advantage of new technologies, such as low-cost ROVs and electronic cameras, a habitat-specific approach can be employed on a broad scale to estimate fish abundance. Bottomfish surveys conducted in San Juan Channel in Washington in 2004 and 2005 using a small ROV demonstrated the utility and efficiency of this technology to obtain quantitative estimates of fish abundance (Pacunski et al. 2008). The ROV was piloted to pre-selected geographic coordinates in a strip-transect survey, and the resulting density patterns and variances strongly suggested that an ROV could be used as a sampling vehicle in a large-scale, regional survey based upon known distributions of rocky habitat. Small ROVs have also been used by the Oregon Department of Fish and Wildlife (Fox et al. 2000, Amend et al. 2001, Merems 2003) and the California Department of Fish and Game (Cal. Dept. Fish and Game 2009a,b) to evaluate bottomfish distributions and collect density information to aid in making management decisions.

The San Juan Islands (SJI) in northern Puget Sound, WA were formed by numerous geological processes, resulting in a diversity of benthic marine bedforms (Tilden 2005) that contain the majority of nearshore rocky habitats in Puget Sound (Pacunski and Palsson 1998). We used geophysical maps generated from multi-beam echosounder (MBES) surveys and drop-camera surveys to identify rocky habitats in the SJI. The map was used as a sampling frame to conduct an ROV survey focusing on rockfishes, lingcod (*Ophiodon elongatus*), and other species of interest. The goals of the survey were to estimate the total abundance of key species and to evaluate the accuracy of the geophysical maps interpreted from the MBES surveys. A secondary objective was to examine the associations of bottom-dwelling fishes with key habitat features.

Methods

Benthic Maps of Rocky Habitat

Benthic maps of rocky habitat in the SJI were generated from geophysical data of the seafloor collected by the Center for Habitat Studies of Moss Landing Marine Laboratories in collaboration with the Canadian Hydrographic Service and the Canadian Geological Service (Endris and Picard 2010). The survey area encompassed all of the islands in the SJI (Figure 1). From 2003 to 2008, the geophysical consortium surveyed most of the region west of Rosario Strait with MBES and produced a series of high-resolution (one depth reading per 1-5 m^2) bathymetric maps (Figure 1). All depths were referenced to mean lower, low water (mllw). Detailed descriptions of the geology and habitat maps are presented by Tilden (2005), Lopez (2007) and Endris and Picard (2010).

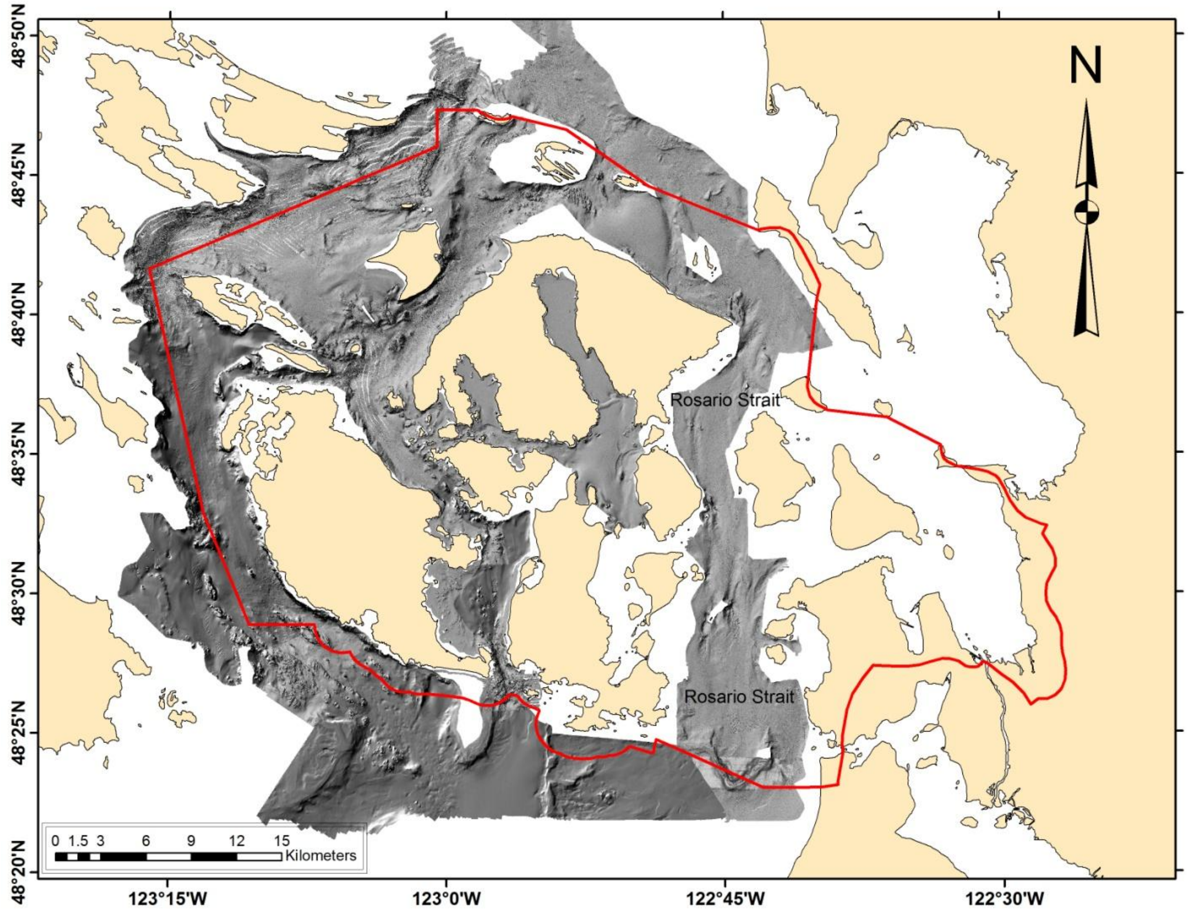


Figure 1. The San Juan Islands of Puget Sound, Washington showing hill-shaded, high-resolution bathymetry obtained from multi-beam sonar systems. The red line delineates the extent of the area surveyed in this study.

The MBES bathymetric and backscatter data were interpreted into potential benthic habitats organized by the type of substrates comprising the seafloor (Greene et al. 1999, 2007; Endris and Picard 2010). Substrate types included bedrock and unconsolidated materials such as mud, sand, pebbles, cobbles, and boulders. Other significant features, such as habitat forming species, were also used to delineate seafloor habitats. The resultant map included over 40 unique bedforms from which we selected only those identified as bedrock and boulders as the sampling frame for the survey (Figure 2). We did not include sediment-covered bedrock because earlier video sampling did not reveal any exposed rock. Equipment and vessel limitations precluded a complete mapping of the nearshore habitats in the SJI with MBES, thus an alternate map of potential rocky habitat was required to complete the sampling frame. This alternate map (hereafter referred to as the WDFW map) identified potential rocky habitats in depths shallower than 36.6 m MLLW and was based upon the slope and bottom type identified on navigational charts, by local knowledge, and from the results of two nearshore drop-camera surveys conducted by WDFW in 1994 and 2000 (Palsson et al. 2009; WDFW, unpublished data). For areas where the geophysical map intersected the WDFW map, only the geophysical data were used. Once a complete sampling frame of known and expected rocky habitats was developed, the habitat was divided into shallow and deep strata at the 36.6 m MLLW depth contour. This depth contour was developed from bathymetric data obtained from the National Geophysical Data Center (www.ngdc.noaa.gov) and gridded into cells with sides of 5 m, and a geographic information system (GIS) was used to interpret the raster data into the 36.6 m bathymetric contour. Because the original MBES surveys did not occur east of Rosario Strait (Figure 1), no rock habitat was identified in the deep stratum of the eastern SJI and thus was not included in the survey design, although it is likely that deep rocky habitat exists in the area. We applied a buffer around all of the rock polygons that increased the polygon border by 30 m. This buffer was advantageous to: 1) account for positional variances inherent in the ROV tracking system (described below); 2) compensate for imprecisely drawn rock boundaries identified during sampling frame development; and 3) include important "edge" habitats not easily identified during geophysical surveys.

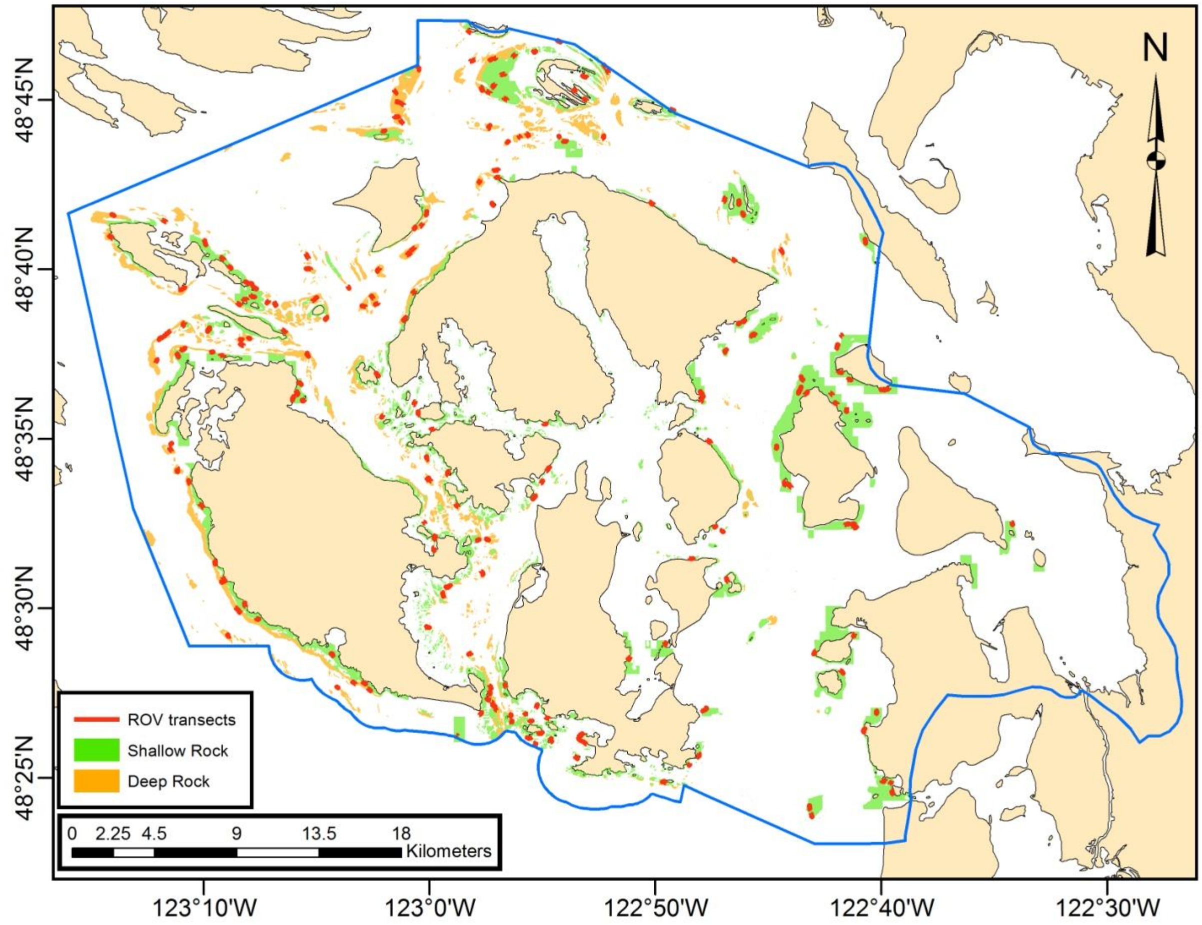


Figure 2. Rocky habitat polygons of the San Juan Islands interpreted from backscatter data from multi-beam sonar systems and previous nearshore rocky surveys conducted by the Washington Department of Fish and Wildlife. ROV transect paths are shown in red.

Habitat polygons for both depth strata were constructed in ESRI™ ArcInfo 9.0/9.2, and Hawth's Tools for ArcGIS was used to calculate the two-dimensional (2D) area of each stratum and to generate random sampling points. The survey area containing rocky habitats encompassed 120.1 km^2, with 78.6 km^2 and 41.5 km^2 in the Shallow Rock and Deep Rock strata, respectively. The number of sampling stations was selected proportionally to the amount of 2D area within each stratum; 65.5% Shallow and 34.5% Deep (Table 1). Based on the twenty-five available sampling days and an expected sampling rate of 8 transects/day, we planned to conduct a minimum of 200 transects (131 Shallow and 69 Deep). Supplementary random coordinates were selected if additional sampling days were allotted or the survey proceeded more quickly than planned. Supplementary stations were numbered and occupied sequentially to assure randomness.

Table 1. **Rocky strata areas and number of planned and completed transects.**

	Two Dimensional Surface Area (m^2)	% Area	# of planned transects	# of completed transects
Shallow Rock	78,642,075	65.5	131	136
Deep Rock	41,500,292	34.5	69	71
Total	120,142,367	100.0	200	207

ROV Surveys

We used a Seaeye Falcon® ROV to conduct strip transects in a stratified-random survey design with two depth strata. The ROV measures 1.0 m in length, 0.6 m in width, and 0.5 m in height and was equipped with a 0.35 lux high-resolution (540 lines) electronic color camera and three variable-intensity 50 W incandescent lights (Figure 3). The ROV was connected to the support vessel via a 330 m umbilical, allowing the ROV to reach all but the deepest areas within the survey region. Two DeepSea Power and Light® 5 mW red diode lasers were mounted in parallel at 10 cm separation distance and projected into the center of the camera's field-of-view to provide reference points for estimating transect width and measuring organisms (Caimi and Tusting 1987, Tusting and Davis 1992). All video imagery was recorded on digital Hi-8 videotape. The time, date, and calculated position of the ROV were imprinted onto the video signal with a Pisces Design® video-text overlay system, allowing organisms and seafloor features observed during the survey to be referenced by position and depth for spatial analysis in ArcGIS®. We assumed that all visible organisms within the strip were detected with equal probability (Barry and Baxter 1993). Transects were conducted during daylight hours to minimize the effects of diurnal fish behavior and maintain efficient ROV operations.

Figure 3. The SeaEye Falcon® ROV equipped with parallel lasers.

The sampling platform for all ROV operations was the 12 m *R/V Molluscan*, owned and operated by the WDFW. Deployment and retrieval protocols for the ROV are described in Pacunski et al. (2008). Tracking and navigation of the ROV was accomplished with a LinkQuest® 1500CH ultra-short baseline (USBL) acoustic tracking system linked to a KVH Fluxgate® compass and WAAS-enabled DGPS. The LinkQuest transponder was powered via the ROV umbilical, providing a constant signal to the vessel-mounted transceiver throughout deployment. Tracking data were collected at 1 to 2-second intervals and the geographically referenced positions of the ROV were calculated with Hypack Max® navigation software. The tracking system and fluxgate compass were calibrated according to manufacturer's recommendations at regular intervals during the survey, although strong magnetic anomalies, seafloor rugosity, and rough sea conditions occasionally produced spurious ROV position calculations. To estimate individual transect lengths the raw tracking data were edited with Hypack Max and ArcGIS 9.3 to remove outlying data points and match the video and transect start and end times as determined during videotape review. Portions of transects that occurred outside of the 30 m polygon buffer (described above) were removed and the video data edited to match the edited transect path. The edited track lines were then smoothed with ArcGIS 9.3 using the Polynomial Approximation with Exponential Kernal (PAEK) method, and the smoothed 2D line length was calculated with Hawth's Tools for ArcGIS.

Most transects were conducted while piloting the ROV into the prevailing current, although several transects were conducted by allowing the support vessel and ROV to drift with the current using the ROV's thrusters to slow the vehicle to a workable speed (<0.5 m/sec) for collecting analyzable video. At each station, the ROV was deployed so that it could be piloted through or near the pre-selected random coordinate during the transect. The ROV was typically driven 0.25 to 1 m above the seafloor at an average speed of 0.33 m/s, although varying current speeds and extreme changes in seafloor rugosity occasionally resulted in heights and speeds in excess of these values. The camera was oriented at a fixed 45 degree angle to the seafloor under level flight conditions, but was tilted up or down when necessary to maintain visual contact with the seafloor. When fish were observed oriented perpendicularly to the ROV, we slowed briefly and attempted to place the laser dots on the fish to obtain size class measurements. When operating along steep slopes and walls we attempted to survey as much of the depth range as possible within the limits of safe vessel and ROV operations. The minimum lineal (2-D) target distance for each transect was 250 m, but the transect distance was allowed to vary depending upon the size of the habitat polygon being surveyed. If the selected station occurred within a polygon that was too small to meet the target transect length, but was separated from other rock polygons by less than several minutes, we drove the ROV to the nearest rock polygon until a cumulative distance of 250 m across rock polygons was attained. When conditions precluded this option, we surveyed as much rock habitat within the selected polygon as possible, often using the deployment as an opportunity to survey surrounding non-rock habitats for ground-truthing the geophysical map.

Video review

Following the survey the video tapes were reviewed to enumerate fishes, categorize habitat, and measure transect width using the methods of Pacunski et al. (2008). All observed fish were identified to the lowest possible taxonomic level, counted, and measured, when possible. For a fish to be counted, half of the body of the fish had to pass through the lower horizontal half of the video screen (i.e., below the plane of the laser dots). If a fish was repulsed by the ROV but could be positively identified, the original location of the specimen must have passed through the lower half of the screen. All non-schooling fish observations were geographically referenced and habitat features associated with the fish were recorded. When the laser dots could be placed on or near a fish, we estimated fish total length to the nearest 10 cm and assigned fish to general life stages based on literature values. For rockfishes other than Puget Sound rockfish (*S. emphaeus*), we considered all fish < 20 cm to be juveniles and all fishes ≥ 20 cm to be adults, assuming most rockfish are mature at about 25 cm (Palsson et al. 2009). For hexagrammids, we considered kelp greenling < 20 cm and lingcod <40 cm to be juveniles.

Habitat segments (patches) were delineated within each transect based on the two most abundant substrate types apparent on the video. Substrate categories included rock (bedrock), boulder, cobble, pebble (including gravel), sand, and mud (definitions modified from Greene et al. (1999), pinnacles are herein designated as boulders). Using a two-code method modified from Stein et al. (1992), each patch was assigned a primary (greatest proportion of the viewed area) and secondary (next most dominant substrate) substrate code, with patches comprised of a single substrate assigned the same code to both categories. Habitat segments were delineated when a change in the proportion of substrate types was observed continuously for more than 20 seconds. The designation of primary and secondary substratum type was subject to viewer interpretation when proportions approached a 50/50 ratio, although this was a rare situation. In most cases the dominant substrate was obvious, although it was sometimes difficult to distinguish substratum type under poor visibility conditions (e.g., cobbles vs. scallop shells) or when a heavy biological cover was present. For our analysis we defined rocky habitat as any patch with rock or boulder as either a primary or secondary substrate.

The parallel lasers were used to estimate transect width at 1-minute intervals during each transect, or at the first possible time when the lasers were visible on the seafloor, and averaged to obtain a mean width for each transect. Transect width (W) in meters was calculated using the relationship:

$$W = 0.1W_m/W_l$$

where W_m is the fixed display width of the video monitor, W_l is the laser width measured on the video monitor, and 0.10 m is the fixed laser separation distance. All measurements assumed a flat substrate with the ROV flying a level attitude, though this was seldom the case during the survey due to inherent rugosity of the habitat being surveyed. To minimize the potential bias of lens curvature on laser measurements, the paired lasers were projected at the center of the camera's field of view where curvature is essentially null. We tested the laser width ratio method by piloting the ROV over a grid of 0.25 m^2 cells placed over a flat section of seafloor as described by Pacunski et al. (2008) and found high agreement (less than 10% difference) between estimated and actual widths.

Total Abundance

The area surveyed within each transect (A_i) was calculated by averaging transect width (W_i) estimates and multiplying by the smoothed transect length (L_i). Species densities for each transect were estimated by dividing the species count (C) by the transect area.

$$D = \sum_{i=1}^{N} \frac{C_i}{L_i \overline{W_\iota}} = \sum_{i=1}^{N} \frac{C_i}{\overline{A_\iota}}$$

Total abundance (P) in number of individuals was estimated for each species (or other taxonomic grouping) by multiplying mean species density for each stratum, calculated across all transects, by the 2-D surface area of the stratum (A) calculated using ArcGIS.

$$P = \overline{D}A$$

The population variance of the average stratum density was estimated as the simple random sampling variance divided by the number of samples:

$$Var(\overline{D}) = \sum_{i=1}^{N} \frac{(D_i - \overline{D})^2}{(N-1)N}$$

Coefficients of variation were calculated as the percentage of the square root of the population variance divided by the population estimate.

Analysis

Chi-squared tests were used to detect differences in species occurrence among habitat patches, and ANOVA tests were used to evaluate differences between strata with regard to species density and depth (Zar 1999). We compared the observed frequency of species and species groups to the expected frequency based upon the prevalence of rocky and non-rocky habitats using the Goodness of Fit Log-likelihood ratio (Zar 1999).

Statistical analyses of species counts (i.e., biodiversity) from ROV transects were conducted with the community analysis software PRIMER (Plymouth Marine Laboratory, Plymouth United Kingdom) and followed the approach outlined by Clark and Warwick (2001). The data were square-root transformed and a Bray-Curtis matrix of similarity was compiled by ROV station and species. Similarity among species compositions among stations was examined graphically using multi-dimensional scaling (MDS) and subsequently testing for basin and depth differences using a non-parametric analysis of similarity (ANOSIM). Specific-species associations were evaluated using similarity-percentage analysis (SIMPER).

Results

The survey was conducted between 29 September and 26 November 2008, with 207 transects completed in 27 sampling days ($\bar{x}$ = 7.7 transects/day); 136 in the Shallow stratum and 71 in the Deep stratum (Table 1, Figure 2). Sampling depths ranged from 0 m (surface) to 234 m, although transects at depths between 5 m and 20 m were limited due to the presence of kelp beds (primarily *Nereocystis leutkeana*) that interfered with safe operation of the ROV. The proportion of Shallow and Deep strata area (65:35) closely matched the proportion of successful transects between strata (66:34). Transects varied in length from 110 m to 695 m ($\bar{x}$= 310 m, std. dev. = 72.9 m), with transect widths ranging from 1.0 m to 3.0 m ($\bar{x}$= 1.85 m, std. dev. = 0.35m). Depending upon weather and current conditions, transects ranged in duration from 10 to 25 minutes, with a typical transect lasting between 12 and 15 minutes. The total amount of area viewed in the survey was 115,928 m^2; 76,350 m^2 in the Shallow stratum and 39,578 m^2 in the Deep stratum (Table 2). There were 115 transects that originated in the geophysical map and 92 transects originating in the WDFW map, with 22 transects that crossed between the two map sources.

Table 2. Frequency of encountering rocky habitats by depth stratum and map origin.

	Shallow **<36.6 m**	**Deep** **>36.6 m**	**Geophysical map**	**WDFW map**	**Total**
Number of Transects	136	71	115	92	207
Two dimensional surface area (m^2)	76,350	39,578	64,922	51,006	115,928
Number (and percent) of transects with rocky habitat segments	119 (87.5%)	71 (100%)	115 (100%)	75 (81.5%)	190 (91.8%)
Number of habitat segments	238	120	200	158	358
Number (and percent) of rocky habitat segments	175 (73.5%)	109 (90.8%)	174 (87.0%)	110 (69.6%)	284 (79.3%)
Surface Area (and percent) of rocky habitat (m^2)	62,458 (81.8%)	38,225 (96.6%)	62,265 (95.9%)	38,418 (75.3%)	100,683 (86.9%)

Habitat map

Classifying the seafloor substrates into discrete patches along each transect allowed us to evaluate the quality of the habitat map sources for predicting the occurrence of rocky habitats. Among the 207 transects we identified 358 distinct substrate patches consisting of 28 combinations of primary and secondary substrate types (Figure 4). An average transect had 1.7 patches, fifty-five transects had one patch, 92 had two patches, 45 had three patches, thirteen had four patches, and three had five patches. Substrate patches containing rock as the primary substrate and boulder as the secondary substrate constituted 53% of the surveyed area (Figure 4). Overall, patches containing rock or boulders as the primary or secondary substrates occurred in 91.8% of transects, constituted 86.9% of the surveyed area and accounted for 79.3% of all patches (Figure 4, Table 2). Seventeen transects (8.2%) consisted only of coarse or fine unconsolidated substrates, and all of these transects were on the WDFW map. The frequency of rocky patches differed between the Shallow and Deep strata, and was significantly higher in the Deep stratum (Chi-square, P = 0.004). All transects in the Deep stratum contained some rocky substrate while only 87.5% of the Shallow stratum transects contained rocky habitat. By area, rocky patches constituted 81.8% of Shallow transects and 96.6% of Deep transects.

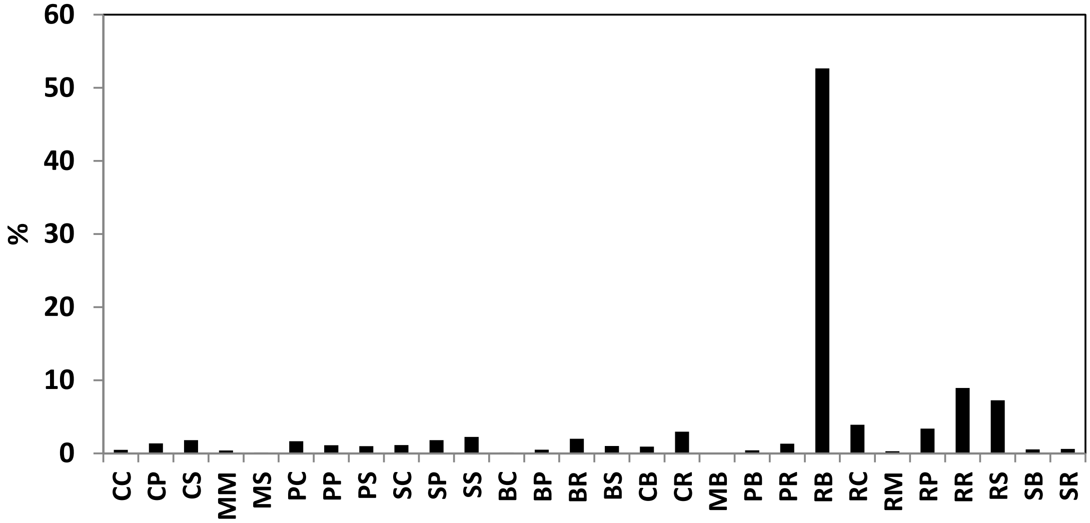


Figure 4. Percent of habitat patch area for each combination of primary and secondary seafloor substrate. Letters of patches indicate substrate type: M=mud, S=sand, P=pebble, C=cobble, B=boulder, and R=rock.

The frequencies of rocky substrate patches differed between transects originating in the Geophysical map and the WDFW map. All transects with starting points in the Geophysical map included some rocky substrate, whereas only 81.5% of transects with starting points in the WDFW map contained rocky substrates (Table 2). Eighty-seven percent of patches from the Geophysical map contained some rocky substrate, accounting for 95.9% of the total transect area. In contrast, 69.6% of patches from the WDFW map contained rock and comprised only 75.3% of the total transect area.

Species composition

During videotape review we identified and counted 9,280 demersal and semi-pelagic fish comprised of thirty nominal species and twelve families (including unidentified fishes) (Table 3). The most abundant species was Puget Sound rockfish Sebastes emphaeus, which accounted for 52.6% of all observed fishes, seconded by unidentified codfishes at 17.6%. Eleven species of identifiable large-bodied rockfishes accounted for 12.5% of the observed fish, with copper rockfish S. caurinus (5.7%) and quillback S. maliger rockfish (4.5%) dominating this group. Greenlings comprised 9.4% of the fish assemblage, with kelp greenling Hexagrammos decagrammus (7.2%) and lingcod Ophiodon elongatus (1.8%) being dominant. The remaining 8% of fishes were comprised of tubesnouts Aulorhynchus flavidus, unidentified fish, spotted ratfish Hydrolagus colliei, sculpins, flatfishes, pricklebacks, gunnels, surfperches, northern ronquil Ronquilis jordani, Pacific cod Gadus macrocephalus, and wolf-eel Anarrhichthys ocellatus.

Table 3. Observations of fish and frequency of occurrence (%FO) within shallow and deep ROV transects.

Common Name	Scientific Name	Shallow Number	Shallow %FO	Deep Number	Deep %FO	Total Number	Total %FO
Spotted ratfish	*Hydrolagus colliei*	0	0.0	114	2.3	114	1.2
Other Unidentified rockfish	*Sebastes* spp.	2	0.0	25	0.5	27	0.3
Copper rockfish	*Sebastes caurinus*	502	11.4	30	0.6	532	5.7
Quillback rockfish	*Sebastes maliger*	157	3.6	259	5.3	416	4.5
Black rockfish	*Sebastes melanops*	121	2.7	0	0.0	121	1.3
Brown rockfish	*Sebastes auriculatus*	13	0.3	0	0.0	13	0.1
Yellowtail rockfish	*Sebastes flavidus*	19	0.4	10	0.2	29	0.3
Puget Sound rockfish	*Sebastes emphaeus*	2368	53.7	2510	51.5	4878	52.6
Tiger rockfish	*Sebastes nigrocinctus*	0	0.0	6	0.1	6	0.1
Yelloweye rockfish	*Sebastes ruberrimus*	1	0.0	38	0.8	39	0.4
Bocaccio	*Sebastes paucispinis*	0	0.0	4	0.1	4	<0.1
Canary rockfish	*Sebastes pinniger*	0	0.0	1	0.0	1	<0.1
Widow rockfish	*Sebastes entomelas*	0	0.0	1	0.0	1	<0.1
Greenstriped rockfish	*Sebastes elongatus*	0	0.0	1	0.0	1	<0.1
Unidentified red rockfish	*Sebastes* spp.	0	0.0	4	0.1	4	<0.1
Unidentified greenling	Hexagrammidae	8	0.2	1	0.0	9	<0.1
Lingcod	*Ophiodon elongatus*	119	2.7	51	1.0	170	1.8
Kelp greenling	*Hexagrammos decagrammus*	560	12.7	107	2.2	667	7.2
Whitespotted greenling	*Hexagrammos stelleri*	27	0.6	2	0.0	29	0.3
Painted greenling	*Oxylebius pictus*	6	0.1	0	0.0	6	<0.1
Unidentified codfish	Gadidae	92	2.1	1541	31.6	1633	17.6
Pacific cod	*Gadus macrocephalus*	2	0.0	5	0.1	7	0.1
Unidentified surfperches	Embiotocidae	15	0.3	0	0.0	15	0.2
Striped seaperch	*Embiotoca lateralis*	24	0.5	0	0.0	24	0.3
Shiner perch	*Cymatogaster aggregata*	4	0.1	0	0.0	4	<0.1
Unidentified flatfish	Plueronectiformes	10	0.2	8	0.2	18	0.2
Rock sole	*Lepidopsetta* spp.	3	0.1	0	0.0	3	<0.1
English sole	*Parophrys vetulus*	0	0.0	4	0.1	4	<0.1
Unidentified sculpin	Cottidae	20	0.5	14	0.3	34	0.4
Buffalo sculpin	*Enophrys bison*	2	0.0	0	0.0	2	<0.1
Red Irish lord	*Hemilepidotus hemilepidotus*	23	0.5	11	0.2	34	0.4
Cabezon	*Scorpaenichthys marmoratus*	8	0.2	0	0.0	8	<0.1
Great sculpin	*Myoxocephalus*	0	0.0	1	0.0	1	<0.1
Wolf-eel	*Anarrhichthys ocellatus*	2	0.0	0	0.0	2	<0.1
Unidentified prickleback	Stichaeidae	3	0.1	41	0.8	44	0.5
Snake prickleback	*Lumpenus sagitta*	21	0.5	0	0.0	21	0.2
Blackeye goby	*Rhinogobiops nicholsii*	8	0.2	0	0.0	8	0.1
Northern ronquil	*Ronquilus jordani*	1	0.0	7	0.1	8	0.1
Unidentified gunnel	Pholidae	1	0.0	6	0.1	7	0.1
Unidentified eelpout	Zoarcidae	4	0.1	46	0.9	50	0.5
Unidentified fish	Osteichthyes	99	2.2	26	0.5	125	1.3
Tubesnout	*Aulorhynchus flavidus*	161	3.7	0	0.0	161	1.7
TOTAL		**4406**	**100.0**	**4874**	**100.0**	**9280**	**100.0**

The proportion of Shallow and Deep stratum transects (and area surveyed) closely matched the proportion of stratum areas, thus we could easily compare the occurrence patterns and depth distributions of several key species in the survey (Figure 5, Table 3). Copper rockfish, black rockfish and kelp greenling were significantly more frequent in the Shallow stratum, while quillback rockfish, yelloweye rockfish, Puget Sound rockfish and spotted ratfish were significantly more frequent in the Deep stratum (chi-square P<0.0001 for all species). No significant difference in stratum occurrence was seen for lingcod.

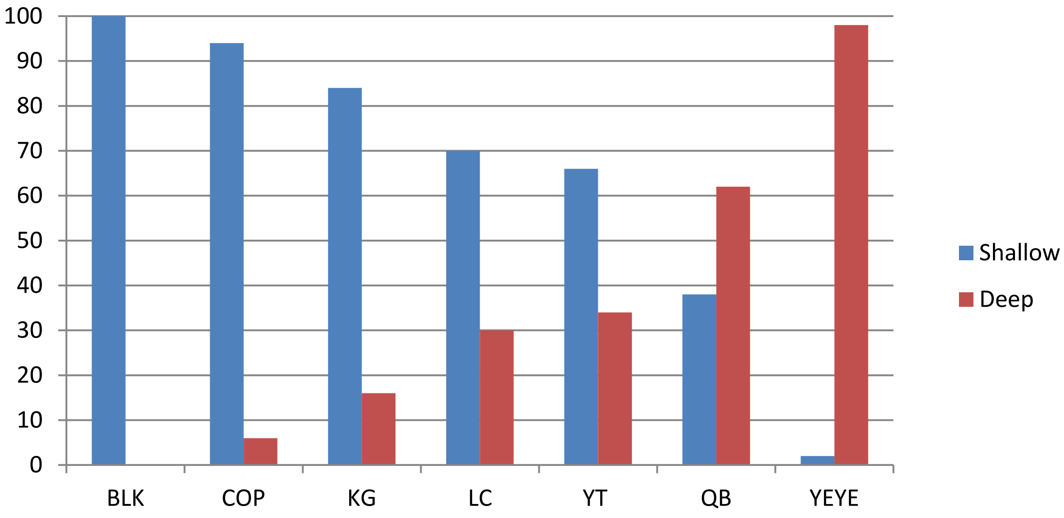


Figure 5. Frequency of occurrence of key species by depth stratum. BLK=black rockfish, COP=copper rockfish, KG=kelp greenling, LC=lingcod, YT=yellowtail rockfish, QB=quillback rockfish, YEYE=yelloweye rockfish.

The depth distributions of the most common species differed amongst each other (ANOVA, F=130.3, DF=2254, p <0.0001) (Figure 6, Table 4). Post-hoc analysis revealed a shallow depth group consisting of striped seaperch, painted greenling, black rockfish, cabezon, white-spotted greenling, and copper rockfish with mean depths ranging from 19 to 23 m (Tukey HSD, p<-0.05). Others species intergraded into an intermediate depth group with mean depths ranging from 26 to 64 m and consisted of kelp greenling, lingcod, Puget Sound rockfish, yellowtail rockfish, quillback rockfish, and red Irish lord. A deep group consisted of tiger and yelloweye rockfishes, codfishes, and spotted ratfish, with mean depths ranging from 76 to 182 m.

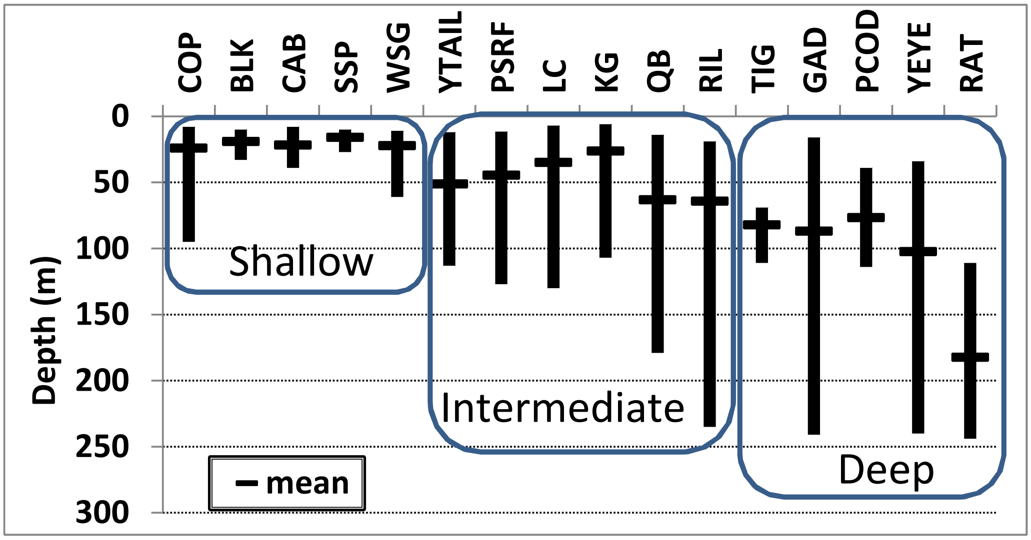


Figure 6. Mean depth and ranges for key species of fish observed during the 2008 ROV survey of the San Juan Islands (see Table 4 for species abbreviations). COP=copper rockfish, BLK=black rockfish, CAB=cabezon, SSP=striped seaperch, WSG=whitespotted greenling, YTAIL=yellowtail rockfish, PSRF=Puget Sound rockfish, LC=lingcod, KG=kelp greenling, QB=quillback rockfish, RIL=red Irish lord, TIG=tiger rockfish, GAD=codfish, PCOD=Pacific cod, YEYE=yelloweye rockfish, RAT=spotted ratfish.

Table 4. Mean depths of key fish species.

Species	**Abbreviation**	**Number**	**Average depth (m)**	**Minimum depth (m)**	**Maximum Depth (m)**
Black rockfish	BLK	120	19.0	10	33
Bocaccio	BOC	4	157.5	155	159
Brown rockfish	BRN	13	19.4	13	22
Canary rockfish	CAN	1	109.0	109	109
Copper rockfish	COP	530	23.9	8	95
Greenstriped rockfish	GRN	1	122.0	122	122
Puget Sound rockfish	PSRF	4878	44.4	12	127
Quillback rockfish	QB	416	63.1	14	179
Tiger rockfish	TIG	6	76.3	48	111
Widow rockfish	WID	1	63.0	63	63
Yelloweye rockfish	YEYE	39	103.7	34	240
Yellowtail rockfish	YT	29	51.1	12	113
Lingcod	LC	170	34.8	7	130
Kelp greenling	KG	648	26.2	6	107
Painted greenling	PG	6	18.2	14	25
Whitespotted greenling	WSG	29	22.1	11	61
Cabezon	CAB	8	21.6	8	39
Red Irish lord	RIL	21	64.1	19	235
Spotted ratfish	RAT	20	182.2	111	244
Striped seaperch	SSP	18	16.5	10	27
Wolf eel	WE	2	28.5	24	33
Pacific cod	PCOD	6	76.5	39	114
Juvenile codfish	JCOD	1632	86.8	16	167

As observed in the species frequencies and distributions, depth was an important factor predicting species density (Table 5). Densities of copper rockfish were significantly higher on shallow transects than on deep transects (6.5 vs. 0.9 fish/1000 m^2, ANOVA, log-transformed densities, F=32.6, df=1, 205, p<0.001), while quillback rockfish densities were higher on deep transects (2 vs. 6.7 fish/1000 m^2, ANOVA, log-transformed densities, F=57.9, df=1, 205, p<0.001). Puget Sound rockfish occurred in higher densities on deep transects (65 vs. 28 fish/1000 m^2, ANOVA, log-transformed densities, F=5.45, df=1, 205, p<0.02), as did yelloweye rockfish (1.1 vs 0.01 fish/1000 m^2, ANOVA, log-transformed densities, F=52.9, df=1, 205, p<0.001). Kelp greenling densities were higher on shallow transects (7.3 vs. 2.5 fish/1000 m^2, ANOVA, log-transformed densities, F=43.2, df=1, 205, p<0.001), but no difference was seen in lingcod densities between depth strata (1.5 vs. 1.3 fish/1000 m^2, ANOVA, log-transformed densities, F=1.0, df=1, 205, p=0.327).

Table 5. Mean densities (fish/1000 m^2) and population estimates of fishes the San Juan Islands.

	Shallow			**Deep**			**Total**	
Common Name	**Mean density**	**Abundance**	**%CV**	**Mean**	**Abundance**	**%CV**	**Abundance (numbers)**	**%CV**
Spotted ratfish	0.000	0		2.943	122,123	25.6	122,123	25.6
Unidentified rockfish	0.026	2,017	100.0	0.647	26,854	31.9	28,871	30.5
Copper rockfish	6.460	508,056	14.7	0.911	37,803	42.0	545,859	14.0
Quillback rockfish	2.047	160,991	19.9	6.732	279,382	12.0	440,372	10.5
Black rockfish	1.653	130,021	48.9	0.000	0		130,021	48.9
Brown rockfish	0.155	12,229	93.0	0.000	0		12,229	93.0
Yellowtail rockfish	0.307	24,119	87.9	0.279	11,586	83.5	35,705	65.3
Puget Sound rockfish	27.954	2,198,372	24.6	55.551	2,305,382	34.8	4,503,755	21.5
Tiger rockfish	0.000	0		0.182	7,561	45.3	7,561	45.3
Yelloweye rockfish	0.013	992	100.0	1.118	46,415	25.2	47,407	24.8
Bocaccio	0.000	0		0.111	4,606	100.0	4,606	100.0
Canary rockfish	0.000	0		0.041	1,697	100.0	1,697	100.0
Widow rockfish	0.000	0		0.031	1,292	100.0	1,292	100.0
Greenstriped rockfish	0.000	0		0.022	922	100.0	922	100.0
Unidentified red rockfish	0.000	0		0.100	4,166	50.4	4,166	50.4
Unidentified greenling	0.105	8,235	52.9	0.021	866	100.0	9,101	48.8
Lingcod	1.491	117,274	13.1	1.283	53,252	25.9	170,526	12.1
Kelp greenling	7.322	575,826	8.3	2.529	104,953	25.7	680,779	8.1
WS greenling	0.356	28,029	27.1	0.061	2,535	73.7	30,564	25.6
Painted greenling	0.075	5,860	46.8	0.000	0		5,860	46.8
Unidentified codfish	1.194	93,899	45.8	34.201	1,419,333	34.8	1,513,232	32.7
Pacific cod	0.021	1,616	100.0	0.118	4,894	50.7	6,510	45.5
Unidentified surfperch	0.165	12,944	78.8	0.000	0		12,944	78.8
Striped seaperch	0.302	23,751	38.5	0.000	0		23,751	38.5
Shiner perch	0.057	4,506	100.0	0.000	0		4,506	100.0
Unidentified Flatfish	0.146	11,472	42.5	0.207	8,604	67.6	20,076	37.8
Rock sole	0.046	3,654	58.2	0.000	0		3,654	58.2
English sole	0.000	0		0.194	8,037	70.9	8,037	70.9
Unidentified sculpin	0.278	21,861	23.6	0.404	16,774	31.1	38,635	19.0
Buffalo sculpin	0.028	2,220	70.5	0.000	0		2,220	70.5
Red Irish lord	0.371	29,178	53.0	0.308	12,777	34.5	41,955	38.3
Cabezon	0.102	8,008	38.2	0.000	0		8,008	38.2
Great sculpin	0.000	0		0.018	750	100.0	750	100.0
Wolf-eel	0.026	2,056	70.5	0.000	0		2,056	70.5
Unidentified prickleback	0.042	3,297	74.8	1.219	50,582	54.9	53,878	51.8
Snake prickleback	0.458	36,021	91.7	0.000	0		36,021	91.7
Blackeye goby	0.115	9,054	100.0	0.000	0		9,054	100.0
Northern ronquil	0.009	728	100.0	0.200	8,299	63.5	9,027	58.9
Unidentified gunnel	0.016	1,235	100.0	0.260	10,794	79.8	12,029	72.3
Unidentified eelpout	0.072	5,623	84.4	1.112	46,151	52.7	51,774	47.9
Tubesnout	2.594	203,965	55.0	0.000	0		203,965	55.0
Unidentified fish	1.352	106,314	47.0	0.864	35,851	29.7	142,166	36.0
Total fish	**55.357**	**4,353,425**	**15.0**	**111.668**	**4,634,240**	**20.1**	**8,987,665**	**12.6**

Stratum depth was a significant factor discriminating species compositions derived from comparing similarities among transect frequencies (ANOSIM, Global R=0.323. p<0.001). The initial MDS plot revealed two major station groupings, with two stations forming a closely-related group separate from all others (Figure 7a). An examination of these two stations (RS47 and RS90) found that the species composition were unlike any other stations and consisted almost entirely of surfperches, and these stations were removed from further analysis. The species compositions of the remaining stations still differed by depth and formed two relatively distinct groups with little overlap (Figure 7b, ANOSIM, Global R=0.338, p<0.001). The most important Shallow stratum species in descending rank were kelp greenling, copper rockfish, Puget Sound rockfish, and lingcod, while the most important Deep stratum species were quillback rockfish, Puget Sound rockfish, codfishes, spotted ratfish, lingcod, and yelloweye rockfish (Table 6). In both strata the dominant species accounted for 90% of the similarity in species composition among transects within their respective strata (SIMPER). Differences in abundance of Puget Sound rockfish, codfishes, kelp greenling, quillback rockfish, copper rockfish, spotted ratfish, and lingcod accounted for 75.73% of the dissimilarity in species composition between depth strata (Table 7).

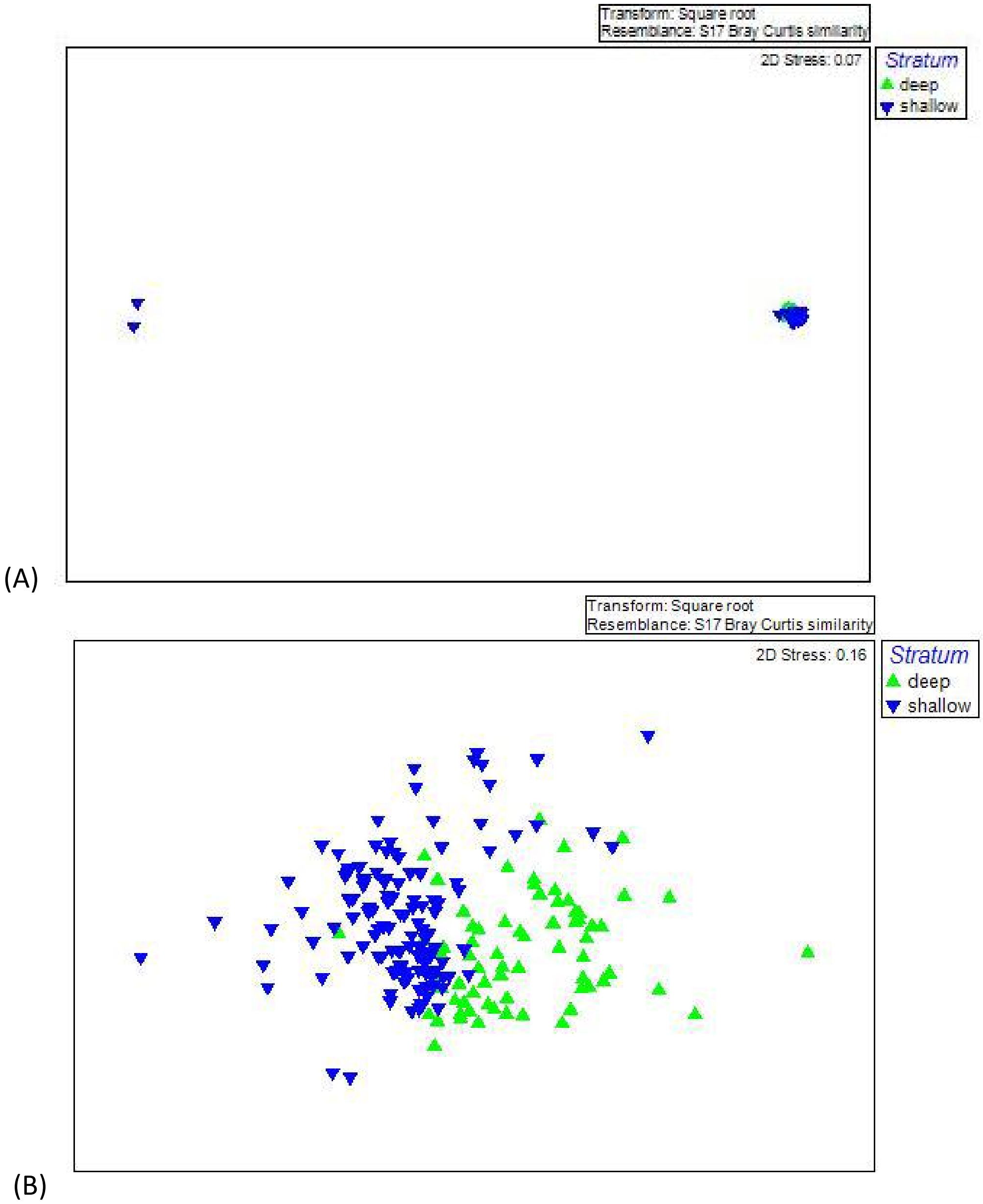


Figure 7. Multidimensional scaling plot of the similarity of species compositions between depth strata; A. All stations, B. Stations RS47 and RS90 removed.

Table 6. Similarity percentages and species similarities between shallow and deep transects.

Species	Average Abundance	Average Similarity	Similarity Std Dev	Contribution %	Cumulative %
Shallow		31.15			
Kelp greenling	1.83	15.58	1.06	50.02	50.02
Copper rockfish	1.38	5.35	0.63	17.18	67.20
Puget Sound rockfish	2.32	4.63	0.45	14.87	82.07
Lingcod	0.64	2.49	0.47	8.00	90.07
Deep		28.58			
Quillback rockfish	1.58	8.96	0.99	31.35	31.35
Puget Sound rockfish	3.42	7.08	0.56	24.77	56.12
Codfishes	2.37	5.56	0.55	19.46	75.58
Spotted ratfish	0.63	1.90	0.27	6.64	82.22
Lingcod	0.49	1.21	0.38	4.23	86.45
Yelloweye rockfish	0.42	1.16	0.32	4.04	90.49

Table 7. Average species abundance and dissimilarity between shallow and deep transects.

Species	Average Abundance	Average Abundance	Average Dissimilarity	Dissimilarity Std. Dev.	Contribution %	Cumulative %
	Shallow	Deep	82.24			
Puget Sound rockfish	2.32	3.42	17.41	1.07	21.17	21.17
Codfishes	0.19	2.37	11.64	0.75	14.16	35.32
Kelp greenling	1.83	0.64	9.50	1.14	11.55	46.87
Quillback rockfish	0.61	1.58	8.48	1.07	10.31	57.18
Copper rockfish	1.38	0.24	6.57	0.96	7.99	65.17
Spotted ratfish	0.00	0.63	4.68	0.53	5.69	70.86
Lingcod	0.64	0.49	4.00	0.89	4.86	75.73

Size distribution of important fishes

Size class information could not be determined for all fishes, but we did observe small and large fishes for several key species (Figure 8). All black, yellowtail, and yelloweye rockfishes and unidentified gadids were in the small category (<20 cm), as were most of the quillback rockfish (<20 cm) and lingcod (<40 cm). Conversely, at least 70% of copper rockfish and kelp greenling were classified as large fish. Densities of large copper rockfish (≥20 cm) and kelp greenling (≥20 cm) were greater than smaller fish (log transformed densities, ANOVA, F=6.08, p<0.014

and F=27.7, p<0.001, respectively), whereas densities of small quillback rockfish were greater than large quillback rockfish (log-transformed densities, ANOVA, F=4.749, p<0.001). No difference was seen in the densities of small and large lingcod. For most species there was no interaction between size class and stratum (Figure 9), although a significant size-depth interaction was seen for kelp greenling (two-way ANOVA, F=30.743, p<0.001), with large greenling being more abundant in the Shallow stratum.

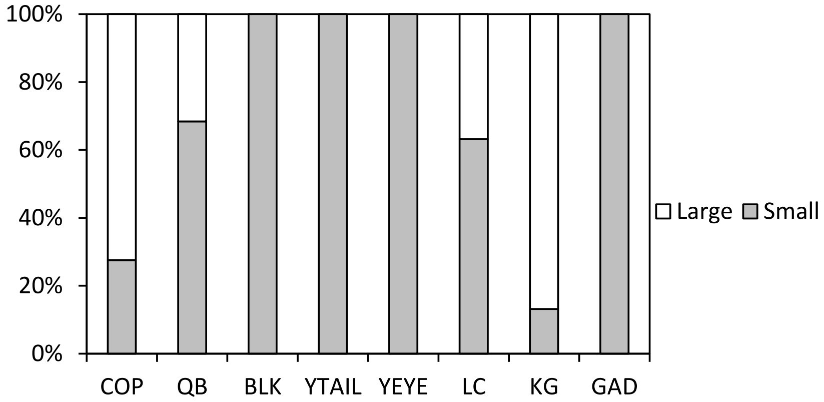


Figure 8. Figure 8. Proportion of small and large fish observed for key species during the ROV survey of the San Juan Islands. COP=copper rockfish, QB=quillback rockfish, BLK=black rockfish, YTAIL=yellowtail rockfish, YEYE=yelloweye rockfish, LC=lingcod, KG=kelp greenling, GAD=codfish,

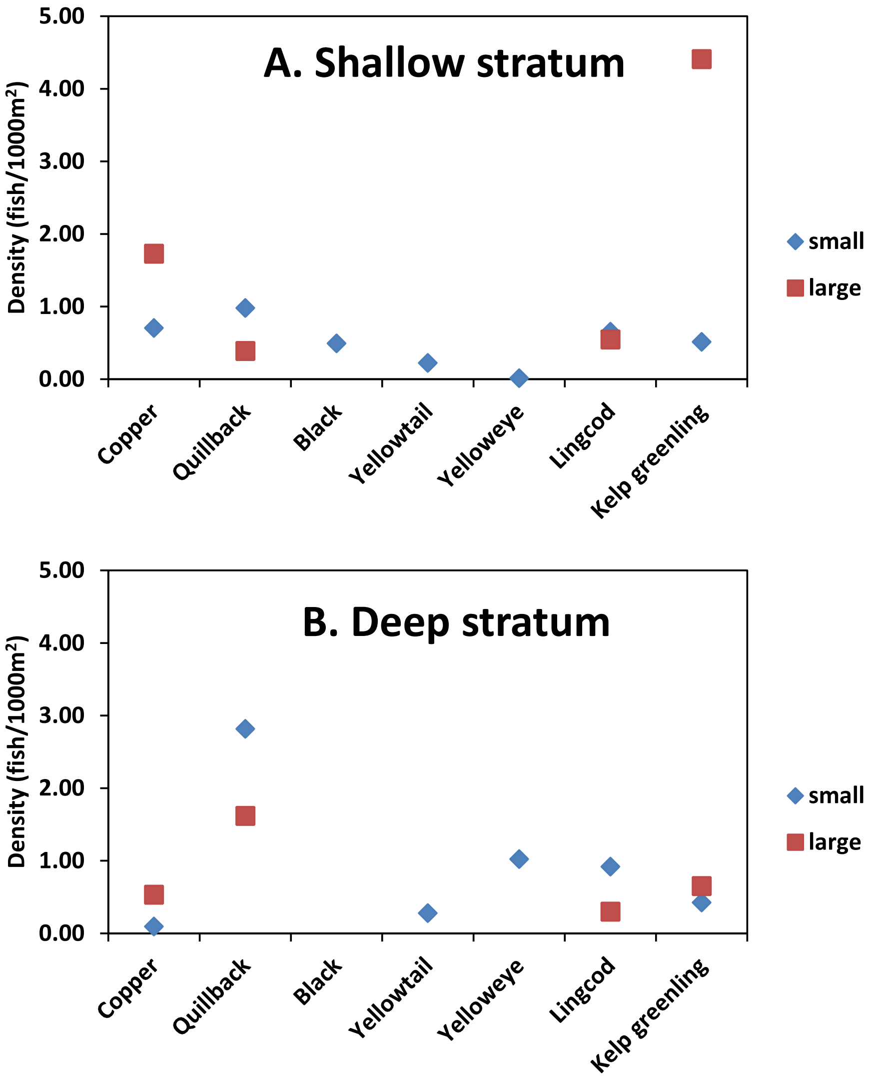


Figure 9. Densities of large and small size categories of key species between depth strata. A. Shallow Stratum, B. Deep Stratum.

Distribution

Species composition differed between Shallow Stratum transects west and east of Rosario Strait (ANOSIM Global R Statistic=0.161, $p<0.001$), with regional differences driven by the relative contributions of Puget Sound rockfish, kelp greenling, copper rockfish, and lingcod. These species were among the five most important species either west or east of Rosario Strait, but were relatively more abundant in western transects. Among all depth strata, most rockfishes were distributed west of Rosario Strait (Figures 10-13). Copper, quillback, and Puget Sound rockfishes, kelp greenling, and lingcod were only observed in a few locations east of Rosario

Strait, but were widely distributed throughout the western SJI (Figures 10, 12, 13). Yelloweye rockfish were only observed in the northern and western SJI, as were single station occurrences of bocaccio, widow, canary, greenstriped, and widow rockfishes (Figures 11-12). Tiger rockfish were observed only in the western SJI (Figure 12).

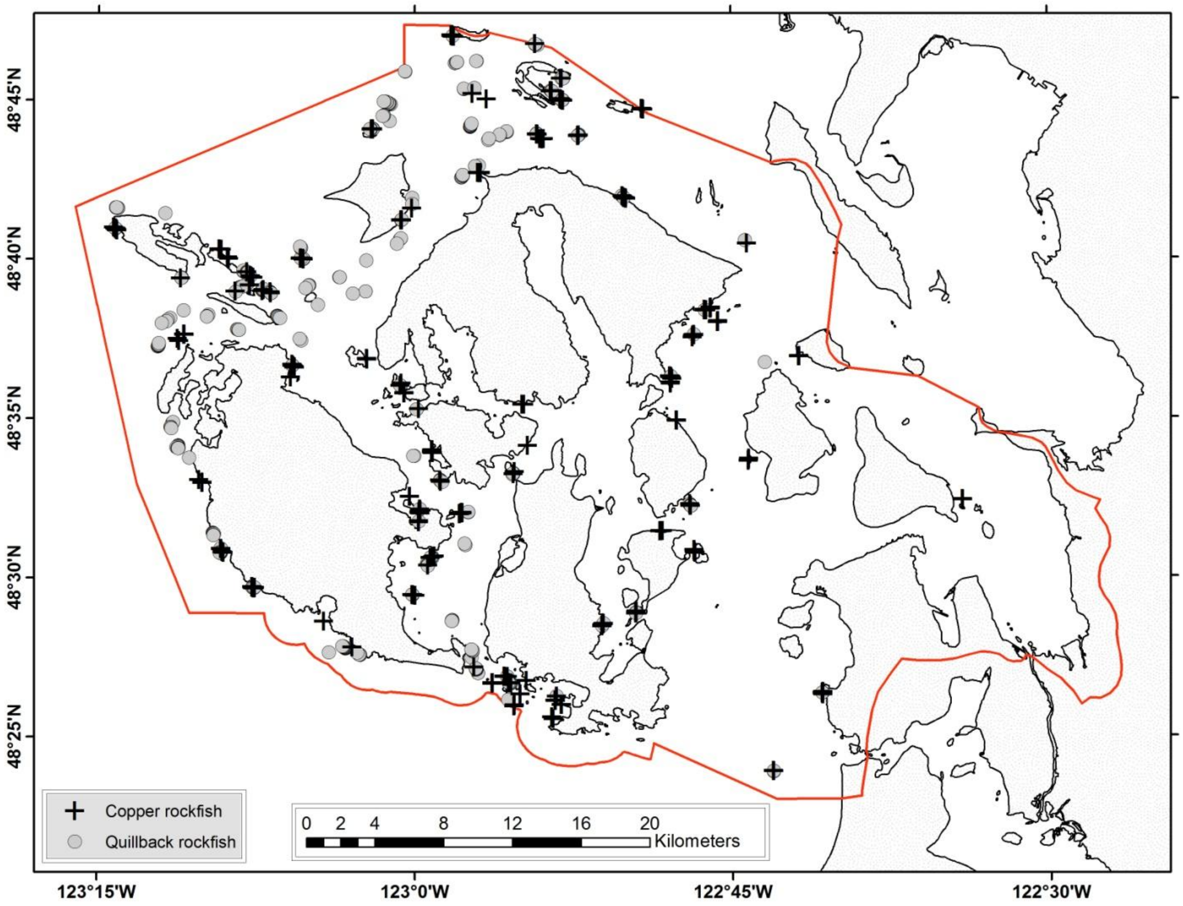


Figure 10. Locations of copper and quillback rockfishes observed during the 2008 ROV survey of the San Juan Islands.

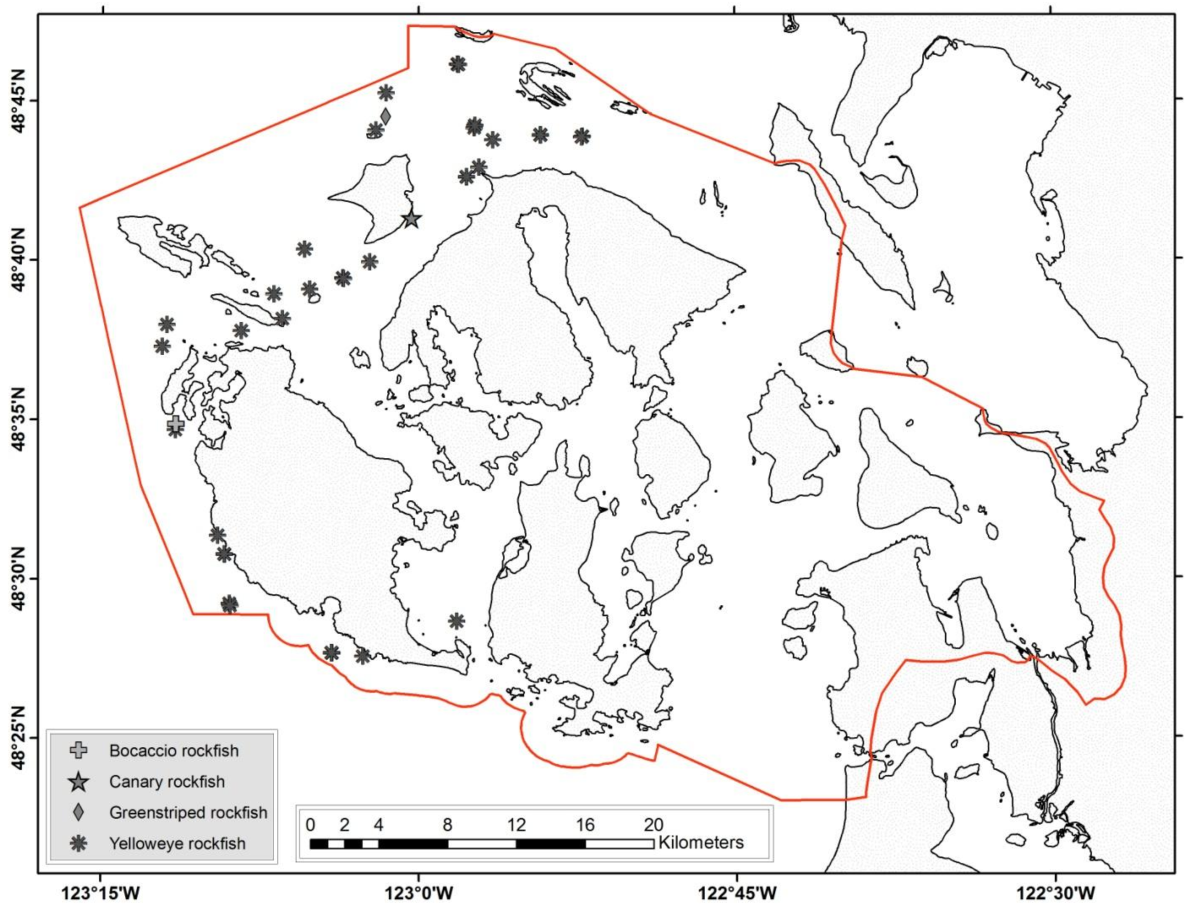


Figure 11. Locations of bocaccio, canary, greenstriped, and yelloweye rockfishes observed during the 2008 ROV survey of the San Juan Islands.

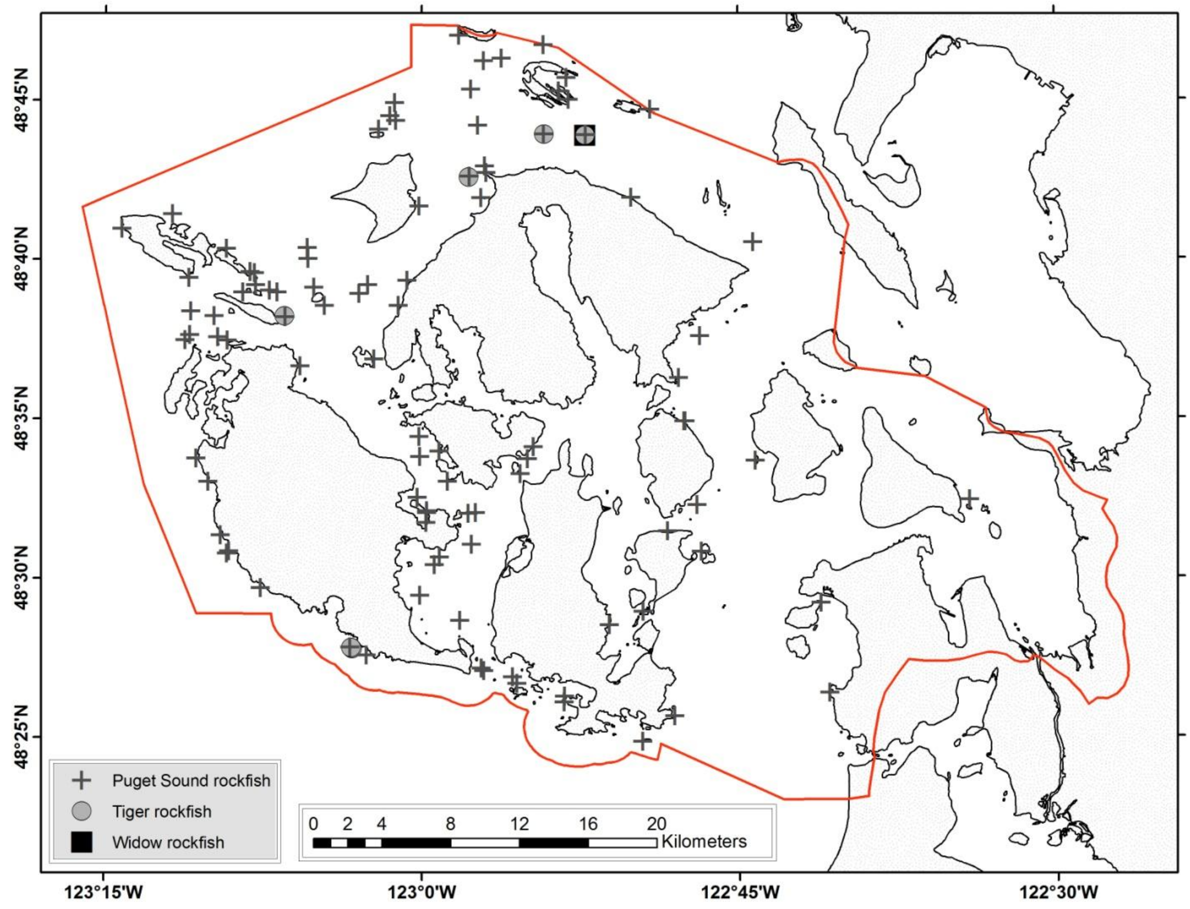


Figure 12. Locations of Puget Sound, tiger, and widow rockfishes observed during the 2008 ROV survey of the San Juan Islands.

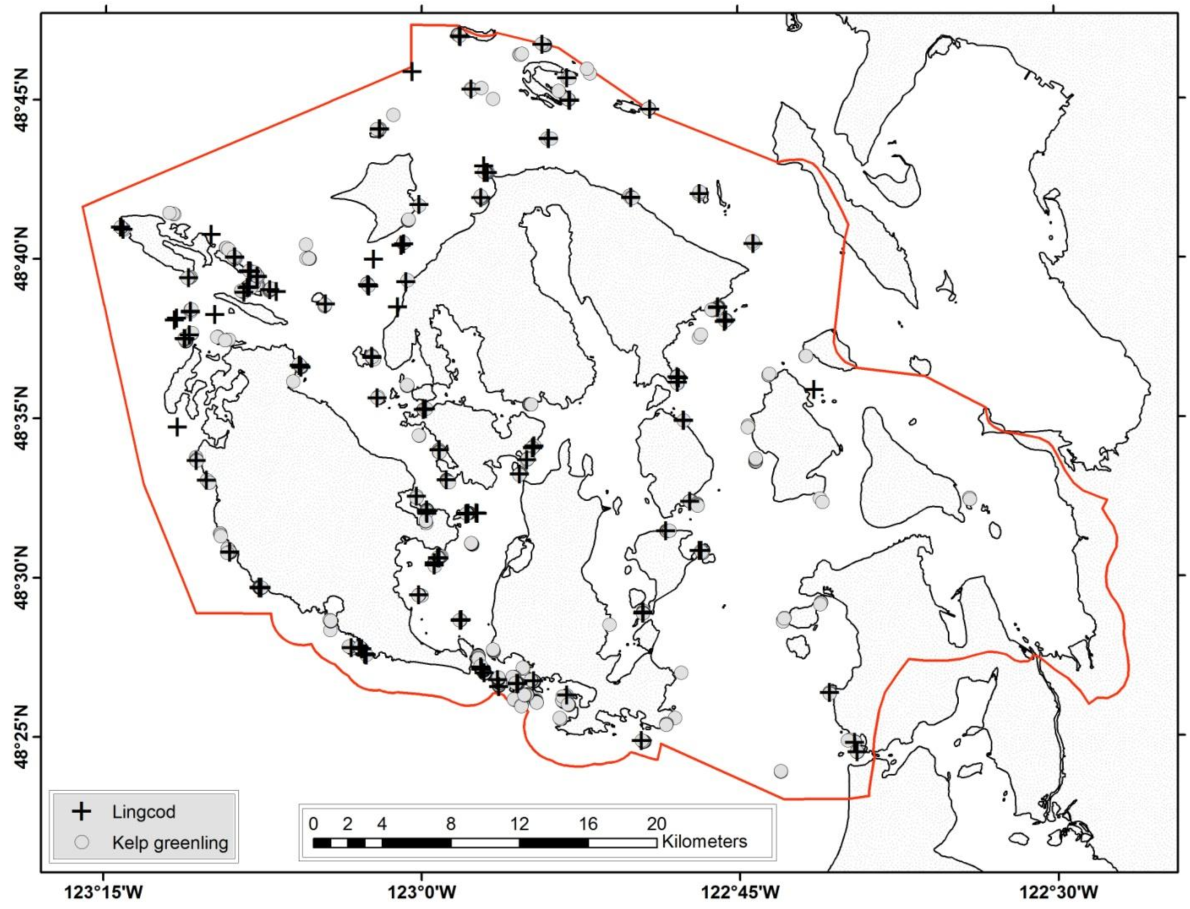


Figure 13. Locations of lingcod and kelp greenling observed during the 2008 ROV survey of the San Juan Islands.

Habitat associations of important fishes

Of the 1,194 large-bodied rockfish we observed, virtually all were present on rocky habitat segments (Table 8, Figure 14), with only four fish recorded on non-rocky patches. All but one lingcod were seen on rocky habitat patches and 98% of all kelp greenling were observed on rocky habitat patches (Table 8). Most of the codfishes we encountered (84%) were present on rocky habitat segments, but 13% occurred on cobble-pebble substrate (Table 8, Figure 15). Flatfish showed a wider range of habitat use and had the lowest occurrence on rocky habitat patches of any key species group (36%) (Table 8, Figure 16). Habitat use was examined by comparing the frequency of occurrence of each species or species group to the proportion of rocky habitat surveyed. Rocky habitat constituted 87% of the total area surveyed, and except for sculpins and other greenlings, all species or species groups did not occur in proportion to the amount of rocky habitat surveyed (Goodness of Fit Log-likelihood ratio, Table 8). Rockfish, kelp greenling, lingcod, and surfperches occurred in higher than expected frequencies on rocky habitat, whereas flatfish, codfish, and other fishes occurred in lower than expected frequencies.

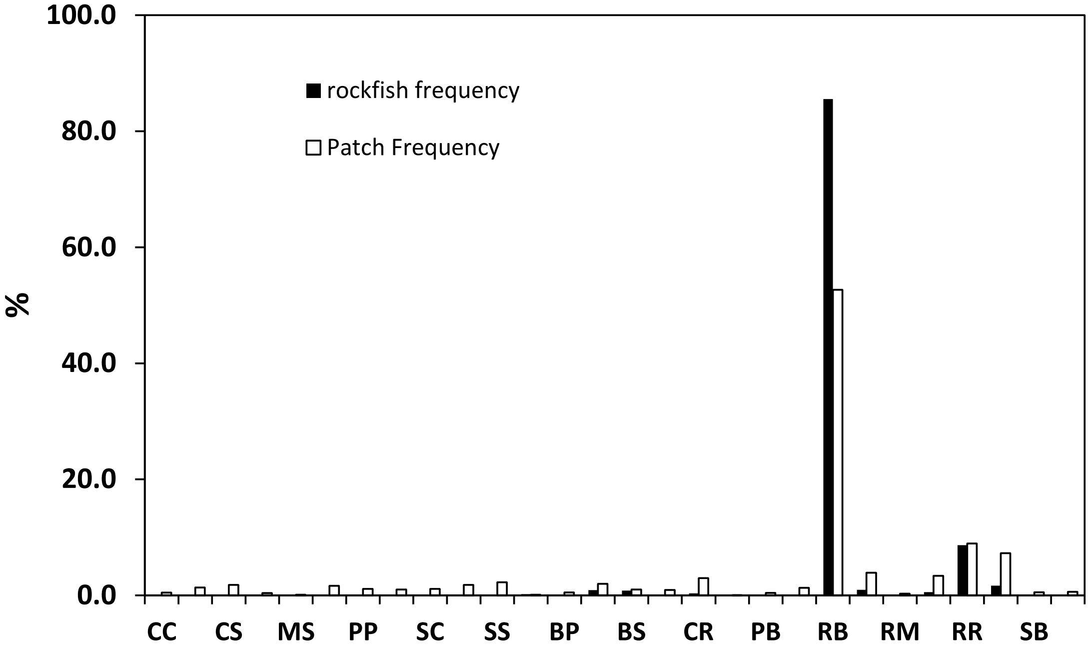


Figure 14. Frequency of rockfish encountered on patches and observed patch frequency. Letters of patches indicate dominant and secondary substrate type: M=mud, S=sand, P=pebble, C=cobble, B=boulder, and R=rock.

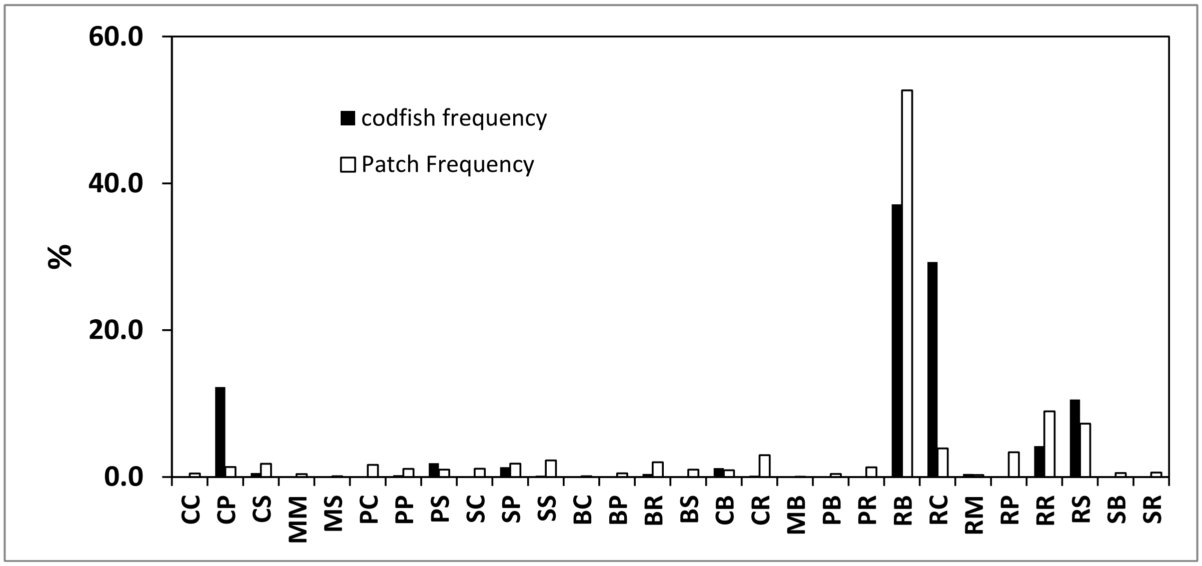


Figure 15. Frequency of codfish encountered on patches and observed patch frequency. Letters of patches indicate dominant and second dominant substrate type: M=mud, S=sand, P=pebble, C=cobble, B=boulder, and R=rock.

Table 8. Percent of species occurring on rocky substrate patches and departure from percentage of rocky habitat patches.

Species	Observed Frequency (%)	Difference in Proportion to Rocky Habitat	Goodness of Fit Log-Likelihood Ratio Statistic	Probability
Codfish	83.5	-3.4	15.9	0.001
Flatfish	36.0	-50.9	34.9	0.001
Kelp greenling	98.3	11.5	115.6	0.001
Lingcod	99.4	12.5	39.0	0.001
Other fish	69.4	-17.5	42.8	0.001
Ratfish	96.6	9.7	9.9	0.002
Rockfish	99.9	13.0	296.9	0.001
Sculpin	89.6	2.7	0.5	
Surfperch	97.7	10.8	6.4	0.012
Other greenling	79.5	-7.3	1.8	

Species composition differed among transects in proportion to the amount of rocky habitat encountered. We categorized the percent of the area covered by rocky habitat patches for each transect into three categories: >50%, 1 to 50%, and none. Species composition differed among all three rocky habitat groups (ANOSIM Global R Statistic=0.396, p<0.001) with all contrasts between groups differing with a minimum probability of 0.02. For Shallow stratum transects, the dominant species occurring on transects with mostly rocky habitat were kelp greenling, copper rockfish, Puget Sound rockfish, and lingcod. Dominant species on transects with up to 50% rocky habitat were kelp greenling, copper rockfish, flatfish, and white-spotted greenling. Dominant species observed on transects with no rock habitat were other fish, sculpins, and codfishes. Since all Deep stratum transects contained >50% rock, there was no difference between the species dominating Deep transects and the Deep stratum overall.

Species Abundance

We estimated there were almost 9 million fish in the surveyed area of the SJI (Table 5). Over half of these were Puget Sound rockfish (4.5 million), followed by 1.5 million codfish, 681,000 kelp greenling, 546,000 copper rockfish, 440,000 quillback rockfish, and 170,500 lingcod. Yelloweye rockfish abundance was estimated at 47,000 individuals, and black rockfish was estimated at 130,000 individuals. The abundance of other, rarer rockfish species ranged from 922 greenstriped rockfish to 12,230 brown rockfish. There were an estimated 1,700 canary rockfish, 4,600 bocaccio, and 1,290 widow rockfish in the SJI.

The more abundant or more uniformly distributed species had coefficients of variation (CV) that were less than 30% (Table 5). Puget Sound rockfish had an overall CV of 21.5%, but the CV was 24.6% in the Shallow stratum and 34.8% in the Deep stratum. Kelp greenling had the lowest CV at 8.1% followed by lingcod with a CV of 12.1%. Copper and quillback rockfishes had CVs of 14% and 10.5%, respectively. Yelloweye rockfish had a CV of 24.8%, while other species had CVs from 50% to 100%.

Discussion

Map Precision

Our survey represents the first regional scale assessment of fishes primarily inhabiting rocky habitats using a single methodology. The combination of the Geophysical and WDFW map was generally good at predicting the presence of rocky habitats, but the Geophysical map proved to be the more accurate of the two. Because all transects selected from the Geophysical map encountered rock and 97% of the encountered habitat was rocky, the Geophysical map appears to be an excellent survey frame for targeting rocky habitat. Although some portions of the Geophysical map did include habitat patches that were not rocky, these patches were often on the boundaries of rocky habitats or were interspersed in the mosaic of rocky substrates that could not be interpreted from the original MBES data. Because the WDFW map was based upon an imprecise set of rocky habitat predictors, several transects were conducted on non-rocky substrates, thus the WDFW map proved to be less useful in assessing species associated with rocky habitats.

The combination of WDFW and Geophysical maps identified 78.6 km^2 as rocky habitat in the Shallow stratum of the SJI. This estimate is near the range provided by Pacunski and Palsson (1998), who estimated 95.3 to 111.8 km^2 in the same depth stratum using charted rocky habitat (from NOAA nautical charts), steep gradients, and local knowledge to identify rocky habitats. While the map we used in the SJI ROV survey included some of the same geographic coverage as Pacunski and Palsson (1998), the use of MBES data allowed some areas previously classified as rocky to be excluded, thereby resulting in a more conservative delineation of rocky habitat in the Shallow stratum. We estimated the amount of deep rocky habitat in the SJI to be 41.5 km^2, or slightly more than half the amount of nearshore rocky habitat. As higher resolution MBES data are collected and habitat classification methods improve, the identification of smaller rocky habitats missed in our current geophysical map could result in an increase in the identified amount of shallow rocky habitat, but will likely remain in the range of the earlier estimates. Because deep rocky habitat east of Rosario Strait was not included in the survey frame, our estimate of deep rocky habitat in the SJI is conservative, and will likely increase as MBES data from that region become available for habitat interpretation.

We did not target non-rocky habitats in our survey and thus could not fully evaluate whether the geophysical map failed to identify rocky habitats outside of the charted rocky polygons. We did encounter rocky habitat outside of the original rocky polygons, usually along the margins of the polygons where differences in observer interpretation of the MBES data or other factors may have affected the placement of an accurate boundary around rocky habitats. To account for these inaccuracies and compensate for navigational imprecision, we expanded the polygons by a buffer of 30 m during post-survey analysis to include habitats found on these margins. These areas were important as they are often associated with steep bedrock slopes that fracture and result in boulder fields at the bottom of the escarpment that provide an ecotone where fish densities were sometimes great.

The success of habitat-based surveys ultimately depends upon the accuracy of geophysical habitat maps and the predictability of encountering target species on the habitats of interest. Tilden (2005), working with an earlier version of the SJI geophysical dataset used here, used an ROV to confirm maps of potential rockfish habitats and found that most of the rocky habitat polygons corresponded to expected rocky habitats. However, Tilden also found that most of the smooth seafloor habitats classified as sand actually consisted of mixtures of pebbles, cobbles, and boulders that may serve as potential rockfish habitat and were missed in the multibeam survey using a 2-m grid of data point acquisition. We expect that higher resolution MBES data and refined habitat classification criteria based on verified results will result in more precise geophysical maps of rocky habitat in the future. Whitmire et al. (2007) used a dynamic segmentation approach based upon a principal component analysis and decision tree to classify seafloor. On a large scale they generally found good agreement between ROV and submersible observations of the seafloor and MBES depth, backscatter, and topographic parameters, but the accuracy of the decision tree model varied between seabed types, with unconsolidated sediment typing being the most accurate and rock outcrops the least. We looked at larger scale classifications (transect level) and found high accuracy with the geophysical maps based upon many of these same predictors but using a geologist's interpretation to identify specific habitat polygons. By integrating the results of our habitat groundtruthing with established classification systems via GIS, it may be possible to produce more accurate seafloor maps with less manual interpretation.

Other Habitat-based Studies

Previous studies of rockfish and other groundfish in the NE Pacific have used substrate combinations as a proxy for habitat (e.g., Nasby-Lucas et al. 2002, Stein et al. 1992, O'Connell and Carlile 1993), while others have also included measures of relief to further characterize their habitat definitions (e.g., Anderson and Yoklavich 2007, Yoklavich et al. 2000). Murie et al. (1994) employed a more descriptive approach, using a combination of substrate and habitat features (cracks and fissures, ledges, boulder fields) to characterize rockfish habitat. While these methods can be useful for describing general species-habitat relationships at various scales, they seldom capture more subtle seafloor features (e.g., fissure size and shape, biological cover) or oceanographic variables that may be critical in determining how fishes are distributed. For example, Nasby-Lucas et al. (2002) reported high variances in fish density estimates between similar patch types, and suggested that depth, food availability, and variations in substrate composition outside their study area may be responsible for the differences. Martin et al. (2006) used an ROV to examine the ability of hydrographic charts and fishery data to predict rockfish habitat but found equivocal results for low and medium values of these habitat variables for quillback rockfish. As more MBES and backscatter data become available, quantifiable measures of depth, slope, and rugosity (i.e., small-scale variations in the height of a surface) can be used in conjunction with substrate observations to create objectively based habitat models, thereby allowing more consistent comparisons across studies. Further, the addition of oceanographic instruments and visual assessment tools will generate continuous data sets that will improve our understanding of how these variables affect benthic fish distributions.

The ROV as a Survey Tool

The ROV provided a consistent platform to obtain habitat and fish density information from the nearshore to depths over 230 m. Despite our success, we recognize that our technique suffers from several biases, including measuring area-swept, detecting cryptic species, and accounting for attraction and avoidance behaviors.

We used a simple approach to estimate transect width based on the proportional relationship between fixed parallel laser spot spacing (10 cm) and the measured distance between the spots on the video screen. This method has been used by others (Karpov et al. 2006, Martin et al. 2006, Martin and Yamanaka 2004), but assumes a flat substrate with the ROV flying a level attitude. Because these conditions rarely occurred in our survey, estimates of transect width undoubtedly vary in accuracy due to the inherent rugosity of the seafloor coupled with pitch and roll of the vehicle. More complex methods of assessing transect width and area swept have also been used. Fox et al. (2000) employed a Canadian-grid (Wakefield and Genin 1987), and multiple-beam laser systems such as those described by Kocak et al. (2002, 2004) and Tusting and Davis (1992) can be used in conjunction with automated software to calculate area swept. Despite their greater sophistication, these techniques also assume a flat substratum and thus are subject to estimation errors in high-relief habitats where this assumption is often violated. Sonar can be used to calculate transect width at high (>1 sec) acquisition rates more accurately than the parallel laser method (Karpov et al. 2006), but is a more expensive option. Karpov et al. (2006) compared transect widths calculated simultaneously with a sonar and the laser method, and found that latter produced more variable measurements in medium and high relief habitats, but that both methods were acceptable for estimating transect width at all habitat relief levels.

Another limitation of remotely-operated visual tools is their ability to detect fishes concealed behind rocks, in deep crevices and below overhangs, although this problem can be compensated for to some degree by submersibles and ROVs by maneuvering the vehicle to orient the observer or camera to a more advantageous field of view. We conducted numerous long transects to increase the probability of encountering cryptic fishes in our survey, but density estimates and abundances were likely underestimated for species such as tiger rockfish and wolf eel, which show a greater affinity for deep crevices under overhangs where the ROV cannot be easily maneuvered. Marliave and Challenger (2009) addressed detection of rockfishes by comparing fish counts obtained simultaneously by one diver, two divers, and a video camera and found that counts from all methods differed among each other. Paired divers observed almost twice the number of fish observed from the videotape and 40% more fish than the single diver. The divers were able to observe fish under crevices, behind rocks, and other places that were not accessible to the camera, and paired divers could spend more time searching a smaller area than a single diver. Marliave and Challenger (2009) went on to develop a model-based index of abundance to compare rockfish occurrences between habitats and different management treatments. Our abundance estimates should be considered likely minimum estimates and treated as relative indices between any treatment types. Production level ROV surveys could be substantially improved by incorporating diver comparisons to evaluate the "catchability coefficient" of the ROV for improving the accuracy of population estimates for shallower occurring species, but accounting for detection bias in deeper species may be difficult.

In clear water conditions, the forward-facing lights on the ROV were generally adequate for detecting and identifying most fishes in rocky habitats, but did not always provide sufficient illumination for detecting flatfish and other small fishes on smoother substrates. When water clarity was compromised by suspended organic matter or sediments, the back-scattering effect of the forward-facing lights often resulted in blooming that markedly reduced the camera's visible range. The addition of downward mounted lights positioned above and ahead of the camera could substantially reduce back-scattering and allow smaller and more cryptic organisms to be detected with greater frequency than with the current lighting configuration.

Since our survey was conducted mainly during daylight hours, we did not account for diel effects on fish behavior or how differences in depth might affect these behaviors. Hart (2004) examined the diel activity patterns of demersal fishes on an offshore bank in Oregon and reported different diel patterns for the few fish species common between his study and ours. Specifically, Puget Sound rockfish were significantly more abundant over medium- to large-grain size substrata during the day than at night, whereas no significant differences in abundance were seen between day and night for yellowtail, canary, yelloweye, and greenstriped rockfishes. The most abundant large-bodied rockfishes seen in our survey were copper rockfish and quillback rockfish. Moulton (1977) conducted day, evening, and night time dives in the SJI and found copper and quillback rockfish active during the day, less active during the evening, and inactive at night. Copper rockfish were less common at night, and quillback rockfishes were scattered in their distribution both day and night. Based on these findings, we conclude that daytime was the optimal period for detecting Puget Sound and copper rockfishes, and that sample timing likely had little effect on our ability to detect other rockfish species.

We could not specifically account for potential biases in our estimates due to the avoidance or attraction of fishes encountered by the ROV. Most fish recorded on videotape had a neutral reaction to the ROV, but we did observe some fish swim away from or towards the vehicle. Stoner et al. (2008) examined the behavior of 48 demersal marine species and found that most showed some reaction to underwater vehicles, but that reaction intensities for rockfishes appeared to be low and bias minimal. Trenkel et al. (2004) found that ROVs systematically did not encounter North Atlantic fishes swimming above the vehicle, that fishes were both repelled by and attracted to the ROV, and that depth, the light level on the ROV, current speed, and direction might all affect the ability of an ROV to accurately estimate the density of fishes. In a laboratory study, Ryer et al. (2009) examined the responses of seven North Pacific marine fishes to a simulated approaching underwater vehicle with lights and found that reaction could vary with ambient illumination intensity. Among the species common to their study and ours, copper and quillback rockfishes demonstrated some movement away from the simulated vehicle, whereas lingcod showed little response. These results are consistent with scuba observations of these species (REP, personal observation), thus we conclude that ROV density estimates for these species are not likely to be significantly biased. Black rockfish responded strongly to the simulated vehicle but the reaction was delayed under high ambient illumination and was characterized by hovering or slow directed swimming. We observed black rockfish in groups of up to 40 individuals on 13% of transects, and most of these fish (99%) occurred between depths of 10 m and 23 m where little or no illumination from the ROV was needed (i.e., high ambient light levels). Based on this result we conclude that reactions to the ROV vehicle were likely minimal and that we were more likely missing fish occurring above the vehicle.

We did not observe any large (>20 cm) yelloweye rockfish in our survey and hypothesize that the ROV may have induced an avoidance response beyond the visual range of the camera, although previous observations of adult yelloweye rockfish with small ROVs do not support this conjecture. During ROV pilot studies in 2004, the author (REP) encountered several adult yelloweye rockfish in the SJI and these fish showed little response to the ROV (WDFW unpublished data). In 2009, using the same ROV as the current survey, the author (REP) observed several adult yelloweye rockfish on rocky outcrops off the coast of Washington, and these fish showed little response unless approached closely (< 0.5 m) with the ROV (WDFW unpublished data). Further, yelloweye rockfish have been observed to be attracted to (Carlson and Straty 1981), or behave ambivalently toward (Stoner et al. 2008), manned submersibles. The

Alaska Department of Fish and Game conducted a survey of rocky habitats in Sitka, Alaska with a small ROV in 2012 and regularly observed adult yelloweye rockfish (Kristin. Green, ADFG, pers. comm.). Given our observations of numerous juvenile yelloweye rockfish and several uncommon rockfish species (e.g., bocaccio, widow) in this survey, we strongly suspect that if adult yelloweye rockfish were present in the study area we could reasonably have expected to detect them.

Despite the biases discussed above, the ROV proved to be a useful tool for sampling benthic fishes living in high-relief rocky habitats. Previous surveys of rocky-bottom fishes by the WDFW utilized a quantitative drop-camera system but were limited to shallow (<36.6 m), nearshore rock habitats (Bradbury et al. 1998, Palsson et al. 2009) to allow the system to be recovered by scuba divers if it became snagged. The system consisted of steel cage with an underwater video camera mounted on a pan-and-tilt motor that was lowered onto rocky habitats where the camera was panned several times through a 360 degree rotation. The functional visibility (i.e., radius) of the video plot was estimated using paired lasers or ambient conditions, but this approach was determined to be inadequate to accurately calculate area swept for making species density calculations. In contrast, the ROV provides a consistent method to estimate area swept, can operate deeper than scuba depths, and can be maneuvered away from potential snagging hazards.

Other investigators have used small ROVs on an experimental or pilot-study basis to assess fishes inhabiting high-relief habitats. Martin et al. (2006) used a SeaEye Falcon to survey rocky habitats, reaching depths comparable to earlier (2003, 2005) manned submersible studies at considerably lower cost. Other studies have used small ROVs and methods similar to ours to estimate densities of rocky-habitat fishes for evaluating the efficacy of existing, and potential locations for future, marine protected areas (Smith and Shull 2009, Grove and Shull 2008, CDFG 2007 and 2008) and for making sound resource management decisions (Weeks and Merems 2004, Amend et al. 2001). The large ROV ROPOS (Shepard and Juniper 1997) has been used to conduct fish/habitat investigations (Tissot et al. 2008), and while it can operate beyond the limits of small ROVs, it is expensive to charter and requires a specialized crew and vessel to operate (Pacunski et al. 2008). Small, manned submersibles have been used to conduct assessments of rockfishes along the coast of Washington (Jagielo et al. 2003), in southeastern Alaska (O'Connell and Carlile 1993, Krieger and Ito 1999), and British Columbia (Richards 1986), and while successful in accomplishing their goals, the limited availability of these specialty vehicles coupled with the greater expense and logistical complexity of their operations make them impractical for conducting production level surveys such as ours. Here, we found that a small ROV struck a reasonable balance between low-cost, efficiency, repeatability, and utility compared to drop and towed-camera systems, large ROVs and manned-submersibles (Pacunski et al. 2008, Martin et al. 2006, Butler et al. 1991).

Species Composition, Distribution, and Habitat Associations

We found that kelp greenling, copper rockfish, Puget Sound rockfish, and lingcod were the dominant species in the Shallow stratum. In contrast, scuba studies of nearshore, rocky habitat fish communities in the SJI by Moulton (1977) found that yellowtail rockfish, black rockfish, kelp greenling, copper rockfish, longfin sculpin, quillback rockfish, lingcod, scalyhead sculpin, and blackeye goby were the dominant species. Small fishes (<10 cm) and cryptic species (e.g., longfin and scalyhead sculpins) are not be easily detected with the camera on our ROV and likely accounts for some differences in species dominance between studies. The non-importance of black and yellowtail rockfishes in our study may be due to a combination of two factors. First, these species have undergone substantial declines in abundance in the SJI since Moulton's 1977 work (Palsson et al. 2009), and second, the semi-pelagic nature of these species may have made them less visible to the ROV (Trenkel et al. 2004) thereby biasing our estimates. Copper rockfish and lingcod were important in both studies while Puget Sound rockfish were important in ours but not Moulton's. There are indications that Puget Sound rockfishes have greatly increased in abundance since the mid-1970s (Fulmer et al. 2007), and our results confirm this species is the most abundant rockfish throughout the SJI. In the eastern SJI, Valz (2007) found that copper and quillback rockfishes, kelp greenling, and lingcod were the most common fishes at several dive sites, a result similar to our observations.

The rockfishes observed in this survey generally conformed to the spatial and depth distributions reported for these species by Love et al. (2002), although our results differed from studies conducted in the adjacent waters of British Columbia. We observed small (<20 cm) quillback rockfish at all depths in our survey (14 m to 179 m). Our results are in contrast to those of Murie et al. (1994), who did not observe any small quillback rockfish deeper than 80 m, and Richards (1986), who did not see quillback rockfish less than 20 cm long in waters deeper than 130 m. Several factors may account for these differences, including recruitment variability among years, variations in habitat type and quality between the two study areas, or food availability.

The 39 juvenile yelloweye rockfish encountered in this study represent a surprisingly high frequency of occurrence. Aside from fishery catch records, previous surveys in the region have never encountered so many yelloweye rockfish in the SJI. The presence of juvenile yelloweye rockfish in our survey may indicate that the western SJI serves as a nursery ground for this species, but the lack of adults raises the question of whether the adult source for recruitment resides locally, in nearby Canadian waters, or along the outside coast of Washington and British Columbia.

The habitat-specific focus of our survey resulted in the detection of several uncommon and rare rockfishes. Brown rockfish are very uncommon in the SJI, typically occurring only in shallow, protected inlets and embayments (Palsson et al. 2009). Our results support this pattern; brown rockfish were only found on shallow transects in protected bays near Sucia Island and Friday Harbor, localities where scuba divers have previously observed this species (WDFW unpublished data). We observed canary, bocaccio, and widow rockfish, species that have rarely been encountered in the SJI (Palsson et al. 2009). We also observed one greenstriped rockfish, a species more commonly encountered on cobble substrates based on their occurrence in WDFW bottom trawl surveys (Palsson et al. 2009).

Rockfishes, lingcod, and kelp greenling exhibited a disproportionate use of rocky habitat in our survey. Rocky habitat patches accounted for 87% of the transect area we surveyed, but 98% of the time these species occurred on rocky patches. An affinity for rocky habitats has been documented for copper, quillback, Puget Sound, yelloweye, black, and yellowtail rockfishes, and occurrence of these species has been linked to key habitat variables such as complexity and relief. In shallow water, quillback rockfish were positively associated with increasing broken rock, relief, and slope, and large copper rockfish were associated with increasing broken rock and relief (Richards 1987). In nearby British Columbia, Marliave and Challenger (2009) found copper and quillback rockfishes were highly associated with bedrock, as well as scattered, and especially piled, boulders. In deeper habitats, Richards (1986) found quillback and yelloweye rockfishes were positively associated with increasing relief and seafloor types ranging from fine, to wall, to complex. Murie et al. (1994) observed quillback, tiger, yellowtail, and yelloweye rockfishes over wall and complex habitats but not on sand-mud habitats. These results strongly support the use of small ROVs for surveying these species in their primary habitats.

Density and Abundance

We constrained our survey to rocky habitats in the SJI, thus our abundance estimates represent only the portions of the species distributions on that habitat and should be considered conservative due to the potential for non-detection of fishes in cracks, under ledges, and behind boulders. Although rockfish can be found on cobble, pebble, artificial and other sunken terrestrial substrates, our estimates likely encompass most of the rockfishes in the SJI based on the results of other local surveys. Trawl surveys of unconsolidated (i.e, non-rocky) substrates in the SJI were conducted by the WDFW in 2001, 2004, and 2006 (Palsson et al. 2003; WDFW, unpublished data), and produced population estimates for all rockfishes combined that comprised 13%, 3%, and 7%, respectively, of the 5.7 million rockfishes estimated in the 2008 ROV survey. These ratios, and the fact that the trawl survey did not detect yelloweye, tiger, widow, bocaccio, and canary rockfishes, suggest that the ROV captures most of the key rockfish abundance in the

SJI. Puget Sound and redstripe rockfishes combined comprised 83% to 94% of the trawl survey estimates for rockfishes in 2001, 2004, and 2006. This result, and the non-detection of redstripe rockfish in the ROV survey, indicates that the ROV is not an adequate tool for assessing these species and significantly underestimates their abundance in the SJI. The estimate for kelp greenling in 2006 represents 9.2% of the 2008 estimate, indicating that the ROV also captures most of this species abundance. The 2006 estimates for lingcod and greenstriped rockfish were 87.4% and 90.1% of the 2008 ROV estimates, suggesting that these species may be as prevalent on cobble and other substrates as they are on rocky bottoms, and will require a combination of survey methods to accurately assess their abundance.

In 2000 the WDFW surveyed the nearshore (<36.6 m) rocky habitat of the SJI with a quantitative drop-camera. The survey area in 2000 included nearly all of the Shallow stratum area in the current survey, but was 25% larger than the 2008 Shallow stratum area due to the inclusion of many non-rocky habitats that could not be discriminated from the navigational charts used in the survey design process. ROV densities for quillback rockfish were 24% greater than the drop camera densities (1.6 fish/1000 m^2in 2000), 2.4 times greater for copper rockfish (2.7 fish/1000 m^2 in 2000), 3.3 times greater for lingcod (0.5 fish/1000 m^2 in 2000) and 4.7 times greater for kelp greenling (1.6 fish/1000 m^2 in 2000) (Palsson et al. 2009, WDFW unpublished data). Interestingly, the density of Puget Sound rockfish was similar between surveys (28.0 fish/1000 m^2 vs. 30.6 fish/1000 m^2). The drop-camera did encounter several canary rockfish less than 36.6 m in 2000 (0.003 fish/1000 m^2), whereas no canary rockfish were observed in the Shallow stratum in 2008. The higher densities of copper and quillback rockfishes, lingcod and kelp greenling from the ROV survey may reflect more concentrated fish on rocky habitats that were better discriminated during the geophysical mapping than the cruder WDFW mapping process. Higher ROV densities of copper and quillback rockfish may also be indicative of increased fish abundance following the implementation of a restrictive recreational daily limit in 2000 from 3 to one fish per day. Most of the species encountered in the current survey are often associated with specific macro- and micro-habitats and are very patchily distributed. The ability to traverse habitat with the ROV increases the probability of encountering these habitats and species, which may also account for the higher densities seen in 2008.

In part, because we focused our sampling effort on rocky habitats and frequently encountered several common species, we obtained coefficients of variation that were less than 15% for copper and quillback rockfishes, lingcod, kelp greenling, as well as for total fish abundance. CVs for the drop camera survey in the SJI were similar and slightly greater, where we obtained values of 18%, 27%, and 30% for copper, quillback, and Puget Sound rockfishes (Palsson et al. 2009). Additionally, the ability to sweep a broader area and better identify fish with the ROV as opposed to the drop camera reduces variability in the estimates of abundance, which is highly desirable for fishery management purposes. Not surprisingly, the CVs from bottom trawl surveys were substantially higher for some of the same species; 55% for Puget Sound rockfish, 100% for quillback rockfish, and 42% for lingcod. Poorer CVs for species that primarily inhabit rocky habitats would be expected from surveys that include unconsolidated habitats, and further strengthen the case for the use of habitat-specific surveys to obtain accurate estimates of abundance.

Conclusions

We conclude that a small ROV is an effective tool to integrate with a geophysical map of rocky habitats and estimate fish abundance in the semi-protected waters of the SJI. Our design could be extended to open coastal waters where conditions are more extreme, but would likely require larger vessels and larger ROVs to achieve similar results, although the increased cost of these operations may exceed the potential economic benefits derived from the data obtained. While we may have missed a portion of the populations of rocky habitat species not within the sampling frame, the low CVs for the more common species indicate this approach is consistent and useful for trend determination and stock assessment.

Acknowledgements

We thank the ROV deck crew of Tony Parra, Lisa Hillier, Laura Arber, Josh Bouma, Eric Eisenhardt, Travis Haring, Cameron Andrews, and Courtney Adkins, who spent many windy and cold hours working aboard the R/V Molluscan to make this survey a success. Extreme recognition is due Jim Beam, who served as master vessel pilot and was responsible for safe navigation and deck crew supervision. In addition, Jim Beam and Tony Parra provided many innovations to deploy and recover the ROV that dramatically improved the safety and efficiency of our operations. We thank Charlie Endris for all his efforts to provide the most accurate geophysical habitat map possible for our survey. We gratefully extend our appreciation to the staff at the University of Washington Friday Harbor Laboratories for physical support provided during this survey. We also thank Dayv Lowry and Theresa Tsou for providing substantive editorial review which greatly improved this manuscript. The ROV survey was supported by Rockfish Research Funds generated by sport fishing and salmon charter licenses in Washington State (RCW 77-65-150) and by the Washington Department of Fish and Wildlife.

Literature Cited

Amend, M., D. Fox, and C. Romsos. 2001. 2001 Nearshore Rocky Reef Assessment ROV Survey. Final Report for 2001 Grant Cooperative Agreement PS01053. Oregon Dept. of Fish and Wildlife. 30 pp.

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

Barry, J.P. and C.H. Baxter. 1993. Survey design considerations for deep-sea benthic communities using ROVs. Mar. Tech. Soc. J. 26(4):20-26.

Bradbury, A., W.A. Palsson, and R.E. Pacunski. 1998. Stock assessment of the sea cucumber *Parastichopus californicus* in Washington. Pages 441-446. In: Echinoderm Studies, Proceedings of the 9th International Echinoderm Conference, San Francisco Aug 5-9, 1996. A.A. Balkema, Rotterdam.

Brylinsky, C., D. Carlile, and J. Stahl. 2007. Chapter 14: Assessment of the demersal shelf rockfish stock for 2007 in the southeast outside district of the Gulf of Alaska. In: North Pacific Fishery Management Council SAFE Document. NPFMC.

Butler, J.L., W.W. Wakefield, P.B. Adams, B.H. Robison, and C.H. Baxter. 1991. Application of line transect methods to surveying demersal communities of ROVs and manned submersibles. In: Proceedings of the IEEE Oceans Conference, pp. 689-696.

Caimi, F.M. and R.F. Tusting. 1987. Application of lasers to ocean research and image recording systems. Proceedings of the International Conference on LASERs ’86, pp. 518-524.

California Department of Fish and Game. 2009a. ROV-based Deep Water Monitoring of the Northern Channel Islands Marine Protected Areas Annual Report – 2007.

California Department of Fish and Game. 2009b. ROV-based Deep Water Monitoring of the Northern Channel Islands Marine Protected Areas Annual Report – 2008.

Carlson, H.R., and R.R. Straty. 1981. Habitat and nursery grounds of Pacific rockfish, Sebastes spp., in rocky coastal waters of southeastern Alaska. Marine Fisheries Review 43:13-19.

Clarke, K.R., and R.M. Warwick. 2001. Change in Marine Fish Communities: An Approach to Statistical Analysis and Interpretation, 2nd edition. PRIMER-E Ltd, Plymouth Marine Laboratory, UK.

Dick, E.J., and A.D. MacCall. 2011. Depletion-based stock reduction analysis: a catch-based method for determining sustainable yields for data-poor fish stocks. Fisheries Research 110: 331-341.

Doak, D.F., K. Gross, and W.F. Morris. 2005. Understanding and predicting the effects of spare data on demographic analysis. Ecology 86 (5): 1154-1163.

Drake, J.S., E.A. Berntson, J.M. Cope, R.G. Gustafson, E.E. Holmes, P.S. Levin, N. Tolimieri, R.S. Waples, S.M. Sogard, and G.D. Williams. 2010. Status review of five rockfish species in Puget Sound, Washington: bocaccio (*Sebastes paucispinis*), canary rockfish (*S. pinniger*), yelloweye rockfish (*S. ruberrimus*), greenstriped rockfish (*S. elongatus*), and redstripe rockfish (*S. proriger*). U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-108, 234 p.

Endris, C., and K. Picard. 2010. Potential marine benthic habitat maps and shaded seafloor relief of the Southern Gulf Islands and San Juan Archipelago, Canada and USA. Map sheets 1-4. Center for Habitat Studies, Moss Landing Marine Laboratories, Moss Landing, California.

Fox, D., M. Amand, A. Merems, and M. Appy. 2000. Coastal Zone Management Section 309 Grant: 2000 Nearshore Rocky Reef Assessment, Final Report for 2000 Grant Contract No. 01-01. Oregon Department of Fish and Wildlife Marine Program.

Fulmer, J., D.R. Gunderson, L. LaFrance, B.S. Miller, B. Goetz, and W.A. Palsson. 2007. Changes in growth and recruitment of the Puget Sound rockfish (*Sebastes emphaeus*) in northern Puget Sound. Biology, Assessment, and Management of North Pacific Rockfishes. Alaska Sea Grant Program, AK-SG-07-01, 2007.

Good, T.P., J.A. June, M.A. Etnier, and G. Broadhurst. 2010. Derelict fishing nets in Puget Sound and the Northwest Straits: Patterns and threats to marine fauna. Marine Pollution Bulletin 60:39-50.

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

Greene, H.G., J.J. Bizzarro, V.M. O'Connell, and C.K. Brylinsky. 2007. Construction of digital potential marine benthic habitat maps using a coded classification scheme and its application. In: B.J. Todd and H.G. Greene (eds.), Mapping the seafloor for habitat characterization. Geol. Assoc. Can. Spec. Pap. 47.

Grove, T.L., and D.H. Shull. 2008. ROV assessment of rockfish abundance, distribution, and habitat in Whatcom County marine waters. Whatcom Marine Resources Committee. Huxley College of the Environment, Western Washington University.

Hart, T. 2004. Diel activity patterns in demersal fishes on Heceta Bank, Oregon. Master of Science Thesis. Oregon State University, Corvallis, Oregon.

Jagielo, T., A. Hoffman, J. Tagart, and M. Zimmermann. 2003. Demersal groundfish densities in trawlable and untrawable habitats off Washington: implications for the estimation of habitat bias in trawl surveys. Fishery Bulletin 101:545-565.

Johnson, S.W., M.L. Murphy, and D.J. Csepp. 2003. Distribution, habitat, and behavior of rockfishes, Sebastes spp., in nearshore waters of southeastern Alaska: observations from a remotely operated vehicle. Environmental Biology of Fishes 66: 259-270.

Karpov, K.A., A. Lauermann, M. Bergen, and M. Prall. 2006. Accuracy and Precision of Measurements of Transect Length and Width Made with a Remotely Operated Vehicle. Mar. Tech. Soc. J. 40(3):79-85.

Kocak, D.M., F.M. Caimi, T.H. Jagielo, and J. Kloske. 2002. Laser Projection Photogrammetry and Video System for Quantification and Mensuration. Oceans '02 MTS/IEEE Vol. 3:1569-1574.

Kocak, D.M., T.H. Jagielo, F. Wallace, and J. Kloske. 2004. Remote Sensing using Laser Projection Photogrammetry for Underwater Surveys. In: Proceedings of the 2004 IEEE International Geoscience and Remote Sensing Symposium. Vol. 2:1451-1454.

Krieger, K.J., and D.H. Ito. 1999. Distribution and abundance of shortraker rockfish, *Sebastes borealis*, and rougheye rockfish (*S. aleutianus*), determined from a manned submersible. Fishery Bulletin 97: 264-272.

Lauth, R.R., S.W. McEntire, and H.H. Zenger, Jr. 2007. Geographic distribution, depth range, and description of Atka mackerel *Pleurogrammus monopterygius* nesting habitat in Alaska. Alaska Fishery Research Bulletin 12:165-186.

Love, M.S., M. Yoklavich, and D.M. Schroeder. 2009. Demersal fish assemblages in the Southern California Bight based on visual surveys in deep water. Environmental Biology of Fishes 84:55–68.

Love, M.S., M. Yoklavich, and L. Thorsteinson. 2002. The rockfishes of the northeast Pacific. University of California Press. 404 p.

Marliave, J., and W. Challenger. 2009. Monitoring and evaluating rockfish conservation areas in British Columbia. Canadian Journal of Aquatic and Fisheries Sciences 66:995-1006.

Martin, J.C., L.C. Lacko, and K.L. Yamanaka. 2006. A Pilot Study Using a Remotely Operated Vehicle (ROV) to Observe Inshore Rockfish (*Sebastes* spp.) in the southern Strait of Georgia, March 3-11, 2005. Canadian Technical Report of Fisheries and Aquatic Sciences 2663. 36 pp.

Martin, J.C., and K.L. Yamanaka. 2004. A Visual Survey of Inshore Rockfish Abundance and Habitat in the Southern Strait of Georgia Using a Shallow-Water Towed Video System. Canadian Technical Report of Fisheries and Aquatic Sciences 2566, 52 p.

Merems, A. 2003. Coastal Zone Management Section 309 Grant: 2002 Nearshore Rocky Reef Assessment ROV Survey Final Report for 2002 Grant Cooperative Agreement [1-1149C]. Oregon Department of Fish and Wildlife. 22 p.

Moulton, L.L. 1977. An ecological assessment of fishes in habiting the rocky nearshore regions of northern Puget Sound, Washington. PhD. Dissertation, University of Washington, Seattle, 181 p.

Murie, D.J., D.C. Parkyn, B.G. Clapp, and G.G. Krause. 1994. Observations on the distribution and activities of rockfish, *Sebastes* spp. In Saanich Inlet, from the Pisces IV submersible. Fishery Bulletin 92: 313-323.

Nasby-Lucas, N.M., B.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. Fishery Bulletin 100:739-751.

O'Connell, V.M., and D.W. Carlile. 1993. Habitat-specific density of adult yelloweye rockfish *Sebastes ruberrimus* in the eastern Gulf of Alaska. Fishery Bulletin 91:304-309.

Pacunski, R.E., and W.A. Palsson. 1998. The distribution and abundance of nearshore rocky-reef habitats and fishes in Puget Sound. Volume 2, pages 545-554, In: Puget Sound Research '98 Proceedings. Puget Sound Water Quality Action Team, Olympia, WA, 947.

Pacunski, R.E., W.A. Palsson, H.G. Greene, and D.R. Gunderson. 2008. Conducting visual surveys with a small ROV in shallow water. Pages 109-128 *in* Marine Habitat Mapping Technology for Alaska, J.R. Reynolds and H.G. Greene, eds. Alaska Sea Grant Program, AK-SG-08-03. 282 p.

Palsson, W.A., T.S. Tsou, G.G. Bargmann, R.M. Buckley, J.E. West, M.L. Mills, Y.W. Cheng, and R.E. Pacunski. 2009. The biology and assessment of Rockfishes in Puget Sound. Washington Department of Fish and Wildlife Report FPT-09-04.

Palsson, W.A., S. Hoffmann, P. Clarke, and J. Beam. 2003. Results from the 2001 transboundary trawl survey of the southern Strait of Georgia, San Juan Islands, and adjacent waters. Washington Department of Fish and Wildlife Report No. FPT 03-09, 100 p.

Parker, S., S. Berkeley, J. Golden, D Gunderson, J. Heifetz, M. Hixon, R. Larson, B. Leaman, M. Love J Musick, V. O'Connell, S Ralston, H. Weeks and M. Yoklavich. 2000. Management of Pacific rockfish. Fisheries 25: 22-29.

Richards, L.J. 1986. Depth and habitat distribution of three species of rockfish (*Sebastes*) in British Columbia: observation from the submersible PISCES IV. Environmental Biology of Fishes 17: 13-21.

Richards, L.J. 1987. Copper rockfish (*Sebastes caurinus*) and quillback rockfish (*Sebastes maliger*) habitat in the Strait of Georgia, British Columbia. Canadian Journal of Zoology 65: 3188-3191.

Rooper, C.N., D. Jones, T. Weber, J. Butler, M. Martin, C. Wilson, A. DeRobertis, M. Wilkins and M. Zimmermann. 2011. Assessment of Rockfish Species in Untrawlable Habitat Using Advanced Acoustic, Optical and Trawl Technologies. North Pacific Research Board Final Report 810.

Royle, J.A., M. Kery, R. Gauthier, and H. Schmid. 2007. Hierarchical spatial models of abundance and occurrence from imperfect survey data. Ecological Monographs 77(3): 465-481.

Ryer, C.H., A.W. Stoner, P.J. Iseri, and M.L. Spencer. 2009. Effects of simulated underwater vehicle lighting on fish behavior. Marine Ecology Progress Series 391:97-106.

Shepard, K., and S.K. Juniper. 1997. ROPOS: Creating a scientific tool from an industrial ROV. Marine Technology Society Journal 31:48-54.

Smith, S.E., and D.H. Shull. 2009. Survey of Whatcom County, Washington nearshore rockfish by remotely operated vehicle and implications for marine protected areas. Huxley College of the Environment, Western Washington University.

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. Fishery Bulletin 90: 540-511.

Stoner, A.W., C.H. Ryer, S.J. Parker, P.J. Auster, and W.W. Wakefield. 2008. Evaluating the role of fish behavior in surveys conducted with underwater vehicles. Canadian Journal of Fisheries and Aquatic Sciences 65:1230-1243.

Tilden, J.E. 2005. Marine geology and potential rockfish habitat in the southwestern San Juan Islands, Washington. Master of Science Thesis, Moss Landing Marine Laboratories, California State University Monterey Bay.

Tissot, B.N., W.W. Wakefield, M.A. Hixon, J.E.R. Clemons. 2008. Twenty years of fish-habitat studies on Heceta Bank, Oregon. Pages 203-207, Marine Habitat Mapping Technology for Alaska, J.R. Reynolds and H.G. Greene, eds. Alaska Sea Grant College Program, University of Fairbanks.

Trenkel, V.M., P. Lorance, and S. Mahevas. 2004. Do visual transects provide true population density estimates for deepwater fish? ICES Journal of Marine Science 61:1050-1056.

Tusting, R.F., and D.L. Davis. 1992. Laser Systems and Structured Illumination for Quantitative Undersea Imaging. Mar. Tech. Soc. J. 26(4):5-12.

Valz, J. Henry. 2007. Variability of groundfish populations in the proposed marine reserves of Skagit County, Washington. Master of Science Thesis, Western Washington University.

Wakefield, W.W., and A. Genin. 1987. The use of a Canadian (perspective) grid in deep-sea photography. Deep Sea Research Part A. Oceanographic Research Papers 34: 469-478.

Weeks, H., and A. Merems. 2004. 2003 nearshore rocky reef habitat and fish survey, and multi-year summary. Final Report for 2033-04 Grant. Cooperative Agreement No. 001-3176C-Fish. Oregon Department of Fish and Wildlife.

Whitmire, C.E., Embley, R.W., Wakefield, W.W., Merle, S.G., and Tissot, B.N., 2007, A quantitative approach for using multibeam sonar data to map benthic habitats, in Todd, B.J., and Greene, H.G., eds., Mapping the Seafloor for Habitat Characterization: Geological Association of Canada, Special Paper 47, p. 111-126.

Yamanaka, L.K., and G. Logan. 2010. Developing British Columbia's inshore rockfish conservation strategy. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 2:28–46.

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. Fishery Bulletin 98: 625-641.

Yoklavich M., Love M.S., Forney K.A. 2007. A fishery independent assessment of cowcod (*Sebastes levis*) using direct observations from an occupied submersible. Canadian Journal of Fishery and Aquatic Sciences 64:1795–1804.

Zar, J.H. 1999. Biostatistical Analysis, 4th Edition. Prentice-Hall, NJ.

Zimmerman, M. 2003. Calculation of untrawlable areas within the boundaries of a bottom trawl survey. Canadian Journal of Fisheries and Aquatic Sciences 60:657-669.

WASHINGTON DEPARTMENT OF FISH AND WILDLIFE