Abstract—Demersal groundfish densities were estimated by conducting a visual strip-transect survey via manned submersible on the continental shelf off Cape Flattery, Washington. The purpose of this study was to evaluate the statistical sampling power of the submersible survey as a tool to discriminate density differences between trawlable and untrawlable habitats.

A geophysical map of the study area was prepared with side-scan sonar imagery, multibeam bathymetry data, and known locations of historical NMFS trawl survey events. Submersible transects were completed at randomly selected dive sites located in each habitat type. Significant differences in density between habitats were observed for lingcod (*Ophiodon elongatus*), yelloweye rockfish (*Sebastes ruberrimus*), and tiger rockfish (*S. nigrocinctus*) individually, and for "all rockfish" and "all flatfish" in the aggregate. Flatfish were more than ten times as abundant in the trawlable habitat samples than in the untrawlable samples, whereas rockfish as a group were over three times as abundant in the untrawlable habitat samples.

Guidelines for sample sizes and implications for the estimation of the continental shelf trawl-survey habitat-bias are considered. We demonstrate an approach that can be used to establish sample size guidelines for future work by illustrating the interplay between statistical sampling power and 1) habitat specific-density differences, 2) variance of density differences, and 3) the proportion of untrawlable area in a habitat.

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Demersal groundfish densities in trawlable and untrawlable habitats off Washington: implications for the estimation of habitat bias in trawl surveys

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Despite their utility, trawl surveys cannot obtain quantitative samples from rough, rocky habitats, and thus have a limited ability to sample all habitats representatively (Uzmann et al., 1977; Kulbicki and Wantiez, 1990; Krieger, 1993; Gregory et al., 1997). Since 1977, triennial bottom trawl surveys have been used to estimate the abundance of commercially and recreationally exploited groundfish species in the continental shelf waters off Washington, Oregon, and California (Shaw et al., 2000). The data generated from these NMFS surveys are often a key component of groundfish stock assessments which are used to set levels of acceptable biological catch (ABC) for selected species (PFMC, 2001). Clearly, proper interpretation of these survey data with respect to fish habitat preferences is an important part of developing unbiased stock assessments for fisheries management.

In trawl survey methodology, population biomass is related to *CPUE* by the following equation (Dark and Wilkins, 1994):

$$B_i = \frac{A_i}{a_i}\left(\overline{CPUE}_i \times \frac{1}{q}\right),$$

where i = area-depth stratum;
B_i = estimated biomass in the ith area-depth stratum;
A_i = total area in the ith stratum;
a_i = total area swept during a standard trawl haul in stratum i;
$\overline{CPUE}_i$ = mean catch per unit of effort in the ith stratum; and
q = the catchability coefficient of the sampling trawl.

For this model to be an unbiased estimator of abundance, it is necessary to assume that the area sampled by the trawl is representative of the entire area-depth stratum of interest (i.e. a_i is representative of A_i). Validating this assumption becomes particularly important where untrawlable habitat comprises a significant proportion of the total area assessed, and where species composition and density vary between habitats. We shall refer to error in trawl survey estimates of abundance due to differences in groundfish density between habitat types as the trawl-survey habitat-bias.

The trawl-survey habitat-bias may be substantial on the west coast continental shelf because of the considerable spatial extent of untrawlable habitat in some management regions (Shaw et al., 2000). It is also widely recognized that demersal groundfish species composition and density can vary considerably by bottom type (Richards, 1986;

Matthews and Richards, 1991; Stein et al.,1992; O'Connell and Carlile, 1993; Gregory et al., 1997; Krieger and Ito, 1999; Nasby, 2000; Yoklavich et al., 2000). Thus, there is considerable interest in evaluating alternative survey tools.

One alternative to trawl surveys that has gained increased attention in recent years is the method of direct observation of the seafloor, typically conducted with a remotely operated vehicle (ROV) or with an occupied submersible (Auster et al., 1989; Krieger, 1993; Caimi et al., 1993; Adams et al., 1995; Gregory et al., 1997; Nasby, 2000). We evaluated the sampling power of the benthic video-strip transect method, using videotapes of the sea floor collected *in situ* with an occupied submersible. Our goal was to judge the feasibility of using this approach to provide meaningful comparisons of demersal groundfish densities between trawlable and untrawlable habitats on spatial scales large enough to be useful for west coast fisheries management.

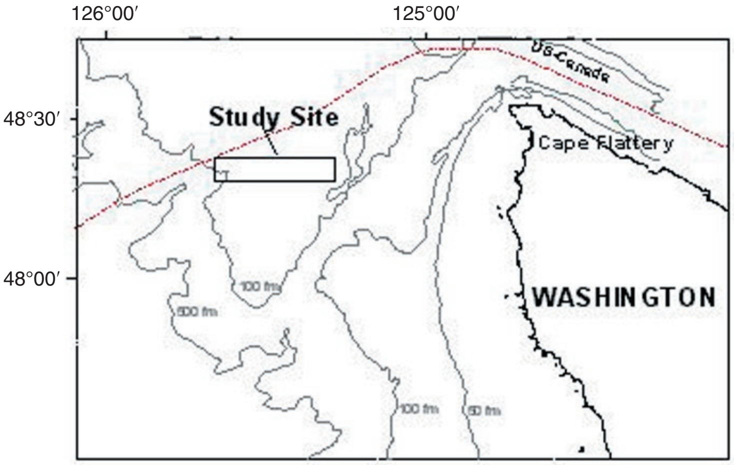

Figure 1

Location of the study area (marked "study site" on map) on the continental shelf off Washington State.

We prepared a geophysical map of the bottom and conducted a submersible survey at a study site located on the continental shelf off Cape Flattery, Washington. Our objective was to provide guidelines on sample sizes (number of submersible transects) that would be needed to characterize differences in density between the two habitat types, and specifically, sample sizes that would be needed to estimate the trawl survey habitat bias in subsequent studies designed to cover wider geographic areas. The study was structured to answer the following questions: 1) what species occupy trawlable and untrawlable habitats off Washington; 2) what magnitude of density differences can be expected between trawlable and untrawlable habitats; 3) what is the variability of fish density within each habitat type; and 4) what sample sizes are required to estimate density differences between habitats, and the trawl survey habitat bias, in a statistically reliable manner. Our focus was on the benthic species and species groups that could be assessed reliably with our submersible survey method; primarily rockfish (*Sebastes* spp.), lingcod (*Ophiodon elongatus*), and flatfish (Pleuronectiformes).

Materials and methods

Study site

Selection of the study site was aided by examination of historical NMFS trawl survey records and Washington Department of Fish and Wildlife (WDFW) trawl fishery logbook data. We chose a rectangular area west of the Point of Arches, Washington, which extends from the Juan de Fuca Canyon in the east (125°17′W) to Nitinat Canyon in the west (125°37′W) and ranges from 48°13′ in the south to 48°16′ in the north (Fig. 1). We selected this area because 1) this portion of the Washington coast has been the site of a productive groundfish fishery since the 1940s (Alverson 1951), 2) this location has been surveyed tri-annually since 1977 as part of the NMFS west coast shelf survey, 3) the area has demersal groundfish species of interest, and 4) the area contains both trawlable and untrawlable habitats. The seafloor of this area was sculpted and shaped by ice movements during the late Pleistocene period (approximately 18–20 thousand years ago) and is characterized by boulder fields resulting from glacial deposition that cover substantial portions of the area (Goldfinger[1]). Planning for the submersible survey required geodetically precise knowledge of the seafloor characteristics of the study area. This was facilitated by conducting geophysical surveys and by preparing a detailed map, which was instrumental to the submersible survey design.

Geophysical surveys and map preparation

Geophysical surveys of the study site were conducted by collecting side-scan sonar and multibeam bathymetry data simultaneously during a five-day effort on board the USN *Agate Passage* (YP-697) in May 1998. Slant-range-corrected side scan sonar data were collected by using a Waverly widescan 100-kHz system, with a swath width of 800 m. Eighteen parallel track lines were conducted with 100% overlap. The resulting imagery was assembled into a mosaic map of the bottom relief for a rectangular area measuring approximately 5.6 by 24.8 km (13,888 hectares). Bathymetric data, with resolution on the order of ±0.4 m were collected with a Reson Model 8101 multibeam bathymetry system. The multibeam bathymetry data were processed to produce a detailed map of the bottom topography with 1-m depth contour intervals.

Map overlays were prepared that showed the locations of trawl survey events and trawl fishery tows. Detailed NMFS records were used to identify the location of various events associated with historical surveys of the area. The NMFS survey event types included good hauls, bad hauls, short hauls (tows ended early because of rough bottom),

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[1] Goldfinger, C. 2001. Personal commun. Department of Geology, Oregon State University, Corvalis, OR 97331.

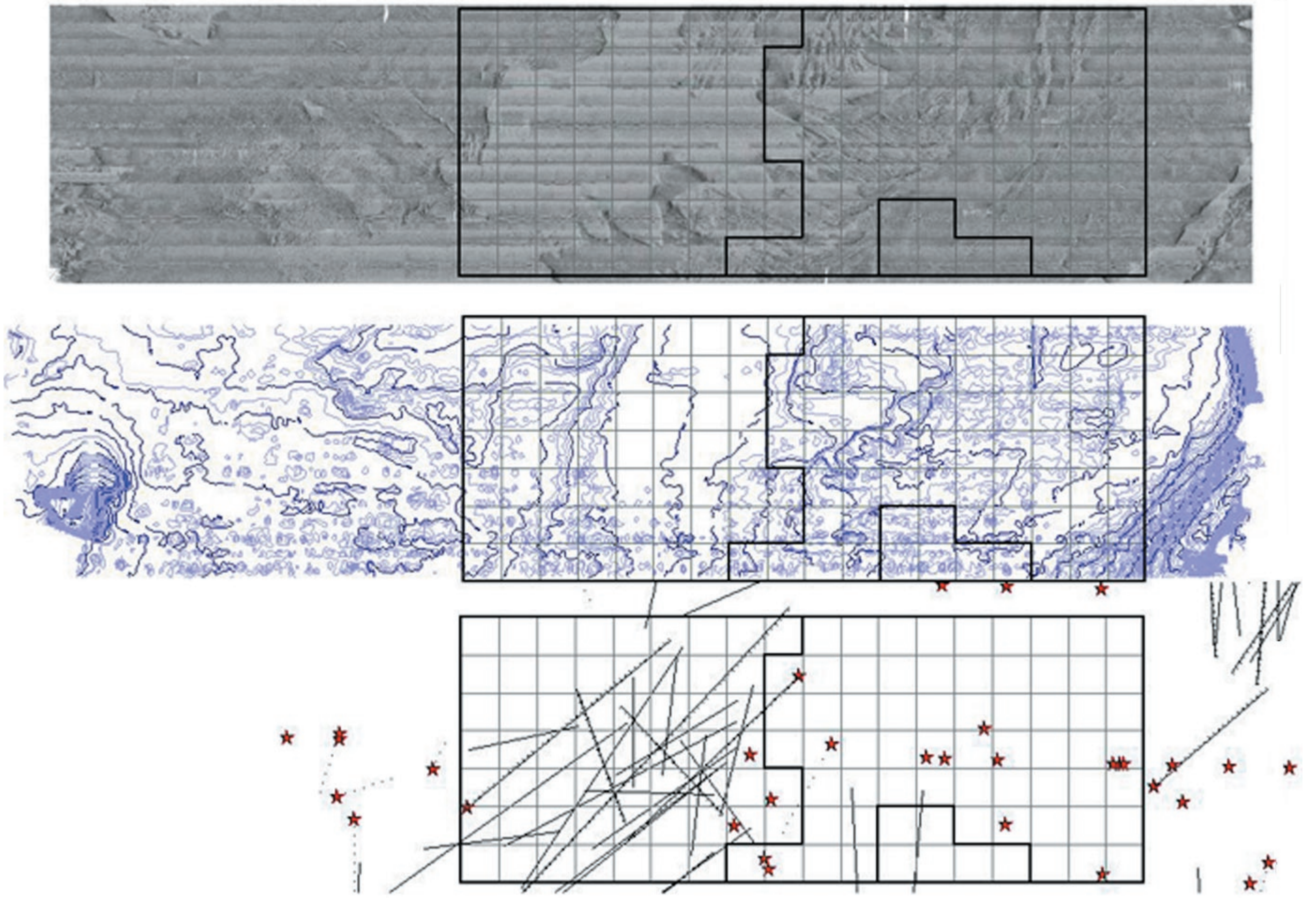

Figure 2

Geophysical map of the study area with associated overlays. Area outlined in bold is the submersible survey area. The grid squares are 800 by 800 m sample units. (**Top**): Mosaic of side-scan imagery of the seafloor. (**Middle**): Depth contours (1-m isobaths) obtained from multibeam bathymetry. (**Bottom**): Locations of historical NMFS shelf trawl survey events. Hatched lines = chain drags, stars = chain snags, unhatched lines = successful tows.

skipped hauls, chain drags, and chain snags. Interviews with knowledgeable fishermen were also conducted to establish the locations of known trawling sites within the area. The resulting geophysical map, with overlays, provided a geographically accurate reference of the study area that allowed *a priori* classification of the bottom into trawlable and untrawlable habitat types (Fig. 2). The final map consisted of the following layers: 1) a mosaic of side-scan imagery of the bottom (Fig. 2, top); high-resolution depth contours (1-m isobaths) obtained from multibeam bathymetry (Fig. 2, middle); and 3) locations of historical NMFS trawl survey events (Fig. 2, bottom).

Experimental design

Our survey design process made use of the detailed map of the study area for 1) definition of the sampling unit, 2) classification of all sampling units as trawlable or untrawlable habitats, and 3) specification of the *in situ* survey area. A sample of units to be surveyed by submersible was selected from each habitat type by using computer-generated pseudo-random numbers.

In defining the size of the sampling unit, we sought to strike a balance between a spatial scale that was small enough to have homogeneity but large enough to have meaning as a trawlable or untrawlable space. We chose square sample units of 800 by 800 m in size. This size was smaller than the standard NMFS tow length of about 3,000 m and was well within the order of resolution of the multibeam bathymetry and side-scan imagery used for discerning rock outcrops. A grid consisting of the 800 by 800 m sampling units was prepared and overlaid onto the map of the study area (Fig. 2).

Classification of the sampling units into "trawlable" and "untrawlable" habitats was facilitated by examination of the geophysical map of habitat features, together with an evaluation of historical NMFS trawl survey records. The survey map layer helped us to interpret the appearance of trawlable and untrawlable habitat on the bathymetric and side-scan geophysical map layers. Trawlable bottom

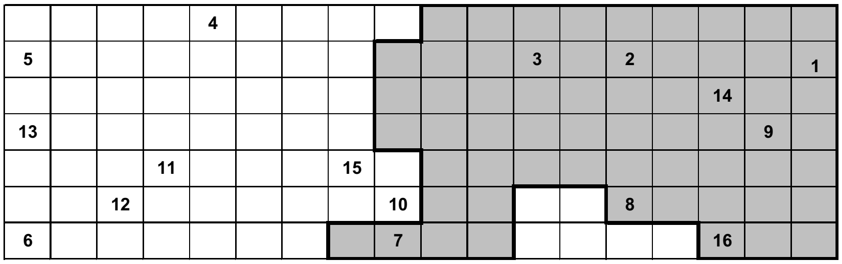

Figure 3

Schematic diagram of the study area divided into 800 m by 800 m sample units and classified *a priori* as untrawlable (shaded) and trawlable (unshaded) habitat types. The numbered sites represent the eight sample units selected at random from each habitat type, which were numbered sequentially for the cruise plan.

was inferred from locations with good hauls and uneventful chain drags; untrawlable bottom was inferred from bad hauls, short hauls, skipped hauls, and chain snags. On the side-scan mosaic layer, untrawlable locations were typically darker than surrounding areas, indicating boulder fields or hard, rocky bottom. Such areas often showed high bottom relief, as evidenced by shadows on the mosaic, and bathymetric contours that indicated abrupt topographic features, such as sharp ridges or pinnacles. A sample unit was classified as untrawlable habitat when 1) NMFS survey events within the unit indicated rough bottom, or 2) the mosaic or bathymetric layers of the unit resembled other units that were classified as untrawlable, or 3) a sample unit of unknown habitat type was completely surrounded by untrawlable habitat. A sample unit was classified as trawlable habitat when 1) NMFS survey events indicated successful trawl tows in the unit or 2) when the mosaic or bathymetric layers of the unit resembled other units that were classified as trawlable. Our trawlable and untrawlable habitat assignments agreed well with information obtained from knowledgeable fishermen. Each sampling unit in the entire mapped area was examined visually in detail according to the above procedure and was classified accordingly as trawlable or untrawlable habitat.

We selected the eastern portion of the mapped area for the submersible survey (Figs. 2 and 3). Our focus was restricted to this section to minimize the difference in bottom depths between the trawlable and untrawlable areas as a factor, and for logistical convenience to complete the most submersible dives possible within our survey budget. Because the 800 m by 800 m sampling units were too large to be surveyed in their entirety, we sampled using the strip transect method at each location. Logistically, this was accomplished by conducting 2–3 nonoverlapping passes across the sampling unit and by pooling these segments together to form a single transect for analysis.

Submersible survey

We used the submersible *Delta* to conduct the fish survey with the support vessel FV *Auriga* in July of 1998. The *Delta* is 4.7 m long, accommodates one observer and one pilot, and has a maximum operating depth of 365 m. An acoustic Trak-Point system was used with differential GPS and WinFrog navigational software (Thales GeoSolutions (Pacific), San Diego, CA) to track and log the position of the submersible from the support vessel. The *Delta* was equipped with halogen lights, external video cameras, an external Photosea 35-mm camera with strobe, and a Pisces Box data-logging system that recorded 1) the time of day, 2) depth of the submersible, 3) its distance from the bottom, and 4) sea temperature at 5-second intervals. Strip transects were conducted 1–2 m off bottom at a cruising speed of approximately 2.5 km/h. All dives were made during daylight hours.

To quantify fish density, each strip transect was documented with a high 8-mm video camera mounted externally on the bow of the *Delta,* and pointed forward. The camera was equipped with two parallel lasers, spaced 20 cm apart, which were used for estimating the area that was swept. The scientific observer onboard the *Delta* verbally annotated the videotape record with observations taken through the submersible viewing ports, to help identify fish and interpret the videotapes during subsequent analysis. The high 8-mm tapes were copied to S-VHS format to facilitate videotape analysis. The transect area that was swept (m^2) was estimated as the product of average area swept per second (m^2/min) and the total transect duration in minutes (see Appendix I for details). The average area that was swept per second (m^2/min) was determined from a set of 30-second samples randomly selected from the transect. On average, approximately 29% of each transect was subsampled in this manner. Bottom habitat type was also visually characterized for the transect subsamples. Following the method of Stein et al. (1992) and using the classification criteria developed by Greene et al. (1999), we categorized bottom microhabitat type (mud, pebble, cobble, boulders, and rock ridge) as primary (at least 50% of the area viewed) or as secondary (>20% of the area viewed). The bottom-type measurements observed directly in the transect subsamples were expanded to estimate microhabitat coverage for each transect.

Fish were enumerated by identifying and counting only those fish observed in the lower portion of the video monitor screen (counting area), below the imaginary line connecting the laser spots. Lighting and visibility was greatest in this zone, and we assumed that the probability of observing and counting fish in this portion of the video image was 100% (i.e. q=1). A fish was counted if any portion of the fish was visible in the counting area. The distance observed between the two laser spots was used as a reference to classify fish into two size categories: large (>20 cm) and small (<20 cm). Fish were identified to the lowest taxonomic level possible. We recognized that fish detection and identification were subject to observer error. The variability describing that error was obtained by conducting a repeat counting of a sample of transects by the same observer. Additional validation checks were made between multiple observers.

Analytical methods

Fish density estimates (number/10^3 m^2) were computed by dividing the total number of fish counted by the total estimated area-swept at each sample-unit site. Statistical comparisons of fish density estimates between the trawlable and untrawlable habitat types were limited to the level of classification (e.g. species or species group) where identifications were considered to be reliable. Estimates of the sample variance of fish density for the trawlable and untrawlable habitats (s_t^2 and s_u^2, respectively) were estimated as the sample variance of the fish density estimates among sites within each habitat type.

We used a power analysis for detecting differences in fish density between habitat types to generate sample size requirements to describe the sampling power of the submersible survey. The greater the sampling power, the fewer samples needed. Statistical power (i.e. the probability of correctly rejecting a false null hypothesis) is inversely related to the significance criterion (α) and is positively correlated with sample size and effect size (Peterman, 1990). The significance criterion is the rate of rejecting a true null hypothesis (the probability of type-I error) and was fixed at 0.05 for our analysis. Effect size can be thought of as the degree to which a phenomenon exists (Cohen, 1988). In our study, the effect size was the hypothesized true difference in fish densities between trawlable and untrawlable habitats. Given a significance level and effect size, power is a function of sample size. Because the effect size is the quantity being tested, it is unknown. Therefore a power analysis is a theoretical "what if" exercise, which asks the question: "If the effect is this big, would the test be likely to detect it with this sample size?" Although the choice of effect size values used for a power analysis are arbitrary, they should be set at some meaningful threshold level, such that if the true effect is less than this threshold, it would not be important to detect it.

In our power analysis we used the approximation

$$Z_{1-b} = \frac{d(n-1)\sqrt{2n}}{2(n-1)+1.21(Z_{1-\alpha}-1.06)} - Z_{1-\alpha} \qquad (1)$$

(Dixon and Massey, 1957; Cohen, 1988),

where $Z_{1\text{-}b}$ = the percentile of the unit normal which gives power;
$Z_{1\text{-}\alpha}$ = the percentile of the unit normal for the significance criterion; for a two-tailed test, $\alpha = \alpha_{(2)}/2$;
d = the standardized effect size index for the two-tailed t-test calculated as

$$d = \frac{|m_t - m_u|}{s_p}, \qquad (2)$$

where m_t and m_u = the true densities in trawlable and untrawlable habitat, respectively; and
s_p^2 = the true pooled variance of the submersible survey density estimator.

By design, our study drew independent samples of equal size from each of the two habitat types, and s^2_p=(s^2_t+s^2_u).

The power approximation procedure was convenient to use, in lieu of an exact method, because it was dependent only on the effect size-index (d) and sample size. Note from Equation 2 that d is unitless, so that statistical power and sample size could easily be compared across a range of species groups, where the absolute density differences between trawlable and untrawlable habitats can vary considerably (Cohen, 1988).

For the analysis, we derived a standardized effect size-index for the density comparison (d_b). The derivation was based on the relationship between density, abundance, and an effect size-threshold selected for abundance (Appendix II). The effect size-threshold for the abundance estimator was arbitrarily chosen to be equal to its standard error under the assumption that a lesser effect size would be difficult to detect. Under this assumption, the standardized effect size index is given by

$$d_b = \left[\frac{A}{A_u} SD(\hat{D}_t) / s_p \right], \qquad (3)$$

where A_u = the area of untrawlable habitat;
A = the total area;
$SD(\hat{D}_t)$ = the standard deviation of the trawl survey abundance estimator; and
s_p = the pooled standard deviation of the submersible survey density estimates.

The standardized effect size index (d_b) depends on 1) the proportion of untrawlable habitat in the total area (A_u/A), and 2) the variability in the trawl survey density estimator in relation to the variability in the submersible survey density estimator ($SD(\hat{D}_t)/s_p$) (Eq. 3). One can see that as A_u/A increases, d_b decreases; conversely, as $SD(\hat{D}_t)/s_p$ increases, d_b increases.

The relationship between the standard deviations ($SD(\hat{D}_t)/s_p$) and d_b creates an apparent paradox. Greater uncertainty in the trawl survey estimator ($SD(\hat{D}_t)$) in relation to the submersible survey estimator (s_p) causes d_b to increase, and thus the power of the submersible survey. Because

Table 1

Summary of the depth range in meters (m) and estimates of the area-swept (10^3 m^2) for randomly chosen sample units. Site type: T = trawlable, U = untrawlable.

				Surveyed area		
Site	Site type	Depth (m)	Transect duration (minutes)	(10^3 m^2)	CV (%)	SE
4	T	130–135	53.0	5.08	24	0.22
5	T	130–135	46.5	5.77	9	0.10
6	T	145–148	49.5	4.68	19	0.15
10	T	106–110	54.5	6.06	12	0.14
11	T	132–140	48.5	4.46	13	0.11
12	T	137–141	49.5	5.40	14	0.14
13	T	136–141	50.5	5.17	13	0.12
15	T	117–119	54.0	4.77	18	0.14
1	U	95–102	52.8	4.59	21	0.21
2	U	95–100	53.5	4.73	13	0.11
3	U	105–109	43.5	5.57	11	0.11
7	U	110–118	55.0	5.66	16	0.17
8	U	102–105	55.0	6.93	16	0.21
9	U	90–98	53.5	5.90	24	0.26
14	U	96–100	39.0	4.67	21	0.21
16	U	105–105	53.5	6.45	11	0.12

greater power results in lesser sample size requirements, it appears that species with higher trawl survey uncertainty require fewer submersible survey samples. The reason fewer samples are required is that the effect size-index threshold has been increased and, generally, fewer samples are needed to detect larger effects. The key to understanding this relationship is that effect size is related to $SD(\hat{D}_t)$, but power is a function of that effect size in relation to the uncertainty in the data (s_p). Essentially, the greater the effect size in relation to the uncertainty in the data, the greater the power. As $SD(\hat{D}_t)/s_p$ increases, the level of resolution that can be detected by the trawl survey decreases. Thus, our choice to set the effect size-threshold (the level of bias we need to be able to detect) equal to the uncertainty of the trawl survey estimator (Appendix II) created a tradeoff between the level of resolution of the hypothesis test and the power to detect that level. This criterion was an arbitrary choice; a different relationship to describe this tradeoff would yield different results. In practice, the relative level of acceptable bias versus precision will depend on particular management objectives.

To obtain sample size guidelines for estimating the trawl survey habitat bias, we calculated d_b using estimated values for $SD(\hat{D}_t)$, s_p, and a range of assumed values for A_u/A for selected groundfish groups. We used information from our submersible survey to characterize the variability of density estimates within trawlable and untrawlable habitats (s_p), and information from past trawl surveys to characterize the variability in trawl survey estimates of abundance ($SD(\hat{D}_t)$). The trawl survey statistics used were derived from the 1998 survey estimates available for the US-Vancouver International North Pacific Fisheries Commission (INPFC) area shallow stratum (55–183 m) (Shaw et al., 2000), which encompasses the study area location. By substituting the calculated d_b for d in Equation 1, we solved iteratively for sample size (n) using Excel Solver (Excel 2000 vers. 9.0.2720, Microsoft Corp., Redmond, WA). The sample sizes obtained provide guidelines so that a similarly designed study will have an $x\%$ chance (e.g. power of 0.80=80% chance) of detecting a difference in mean density at least as large as the random noise inherent in the trawl survey density estimator.

Results

Submersible survey

Sixteen dive sites were sampled—eight in each habitat type (trawlable and untrawlable) (Table 1). In total, an estimated 85,900 m^2 was covered across all sites. The untrawlable sites (90–118 m) tended to be somewhat shallower than the trawlable sites (106–148 m); however, we assumed that this difference had little effect on fish density and species composition within the study area. In general, we were not successful in obtaining useful transect plots or reliable distance-traveled information with the WinFrog navigational software package; however, we found the Trak-Point acoustic tracking system to be useful for obtaining the location of the submersible with respect to the ship's position. We used this information, together with the subsea communication system, to guide the submersible along the predesignated transect segments at each dive site.

Our video survey largely confirmed our *a priori* assignments of trawlable and untrawlable habitat (Table 2). At the dive sites designated trawlable prior to the video transect survey, mud bottom predominated (78.5%), followed by pebble (11.5%), mud-pebble (3.7%), and pebble-cobble (3.3%). At the sites designated *a priori* to be untrawlable, pebble bottom was most common (62.0%) followed by pebble-boulder (14.6%), mud (7.8%), boulder-pebble (6.3%), and boulder-cobble (6.0%). Microhabitat classifications unique to untrawlable habitat comprised 14.5% of the total and included cobble-pebble, cobble, boulder-pebble, boulder-cobble, rock-ridge, boulder, and cobble-boulder. The mud-pebble microhabitat was observed at trawlable sites but not at untrawlable sites. Bottom perturbations, which we presumed were trawl-door tracks, were observed at 6 of 8 *a priori* trawlable locations (sites 4, 5, 10, 12, 13, and 15), and at 2 of 8 *a priori* untrawlable locations (sites 3 and 14).

We counted 3647 fishes representing 26 species or generic group classifications (Table 3). Some fishes were readily identifiable to species; for example, lingcod, ratfish (*Hydrolagus colliei*), canary rockfish (*Sebastes pinniger*), and wolf-eel (*Anarrhichthys ocellatus*) were very distinctive. Other fishes could not always be identified to species level. In such cases, fish were assigned to the generic groups of "unidentified" rockfish, flatfish, or roundfish. It is likely that greenstriped (*S. elongatus*), redstripe (*S. proriger*), rosethorn (*S. helvomaculatus*), silvergray (*S. brevispinis*), and yellowtail rockfish (*S. flavidus*) were sometimes classed as unidentified rockfish; more rarely, large quillback (*S. maliger*), tiger (*S. nigrocinctus*), and yelloweye rockfish (*S. ruberrimus*) may have been assigned to this category. Flatfish were very difficult to identify to species; it is very likely that arrowtooth (*Atheresthes stomias*), Dover sole (*Microstomus pacificus*) and Pacific halibut (*Hippoglossus stenolepis*) were sometimes classed as unidentified flatfish.

The reliability of our fish counts was in part a function of fish size.

Table 2

Characterization of bottom type at sites classified *a priori* as trawlable (T) and untrawlable (U) habitat. Microhabitat type classifications include a primary (at least 50% of the area viewed) and a secondary (over 20% of the area viewed) component; M = mud, P = pebble, C = cobble, B = boulder, R = rock ridge.

		Estimated coverage (10^3 m^2)													
		Low relief						High relief							
Site	Site type	M-M	M-P	P-P	P-C	C-P	C-C	Total	M-B	P-B	C-B	B-P	B-C	B-B	R-R	Total	Station total
4	T	5.08	0.00	0.00	0.00	0.00	0.00	5.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.08
5	T	0.00	0.00	4.42	1.35	0.00	0.00	5.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.77
6	T	4.68	0.00	0.00	0.00	0.00	0.00	4.68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.68
10	T	6.04	0.00	0.00	0.00	0.00	0.00	6.04	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.02	6.06
11	T	4.46	0.00	0.00	0.00	0.00	0.00	4.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.46
12	T	5.40	0.00	0.00	0.00	0.00	0.00	5.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.40
13	T	2.07	1.51	0.33	0.00	0.00	0.00	3.91	0.46	0.80	0.00	0.00	0.00	0.00	0.00	1.26	5.17
15	T	4.77	0.00	0.00	0.00	0.00	0.00	4.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.77
1	U	0.00	0.00	3.04	0.04	0.00	0.01	3.09	0.00	1.05	0.08	0.05	0.31	0.00	0.00	1.49	4.59
2	U	0.00	0.00	2.66	0.00	0.00	0.00	2.66	0.00	0.44	0.00	0.63	1.00	0.00	0.00	2.07	4.73
3	U	0.00	0.00	4.65	0.30	0.30	0.00	5.24	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.33	5.57
7	U	3.48	0.00	1.51	0.00	0.00	0.00	4.99	0.17	0.50	0.00	0.00	0.00	0.00	0.00	0.67	5.66
8	U	0.00	0.00	6.36	0.00	0.00	0.00	6.36	0.00	0.45	0.00	0.00	0.00	0.05	0.07	0.57	6.93
9	U	0.00	0.00	1.71	0.00	0.00	0.00	1.71	0.00	1.95	0.00	0.84	1.36	0.04	0.00	4.19	5.90
14	U	0.00	0.00	3.47	0.00	0.00	0.00	3.47	0.00	0.56	0.00	0.26	0.01	0.07	0.29	1.19	4.67
16	U	0.00	0.00	4.17	0.00	0.00	0.00	4.17	0.00	1.23	0.00	1.01	0.00	0.05	0.00	2.28	6.45
Totals	T	32.50	1.51	4.75	1.35	0.00	0.00	40.11	0.48	0.80	0.00	0.00	0.00	0.00	0.00	1.28	41.39
	U	3.48	0.00	27.57	0.34	0.30	0.01	31.69	0.17	6.51	0.08	2.80	2.69	0.20	0.36	12.80	44.50
Percent	T	78.5%	3.7%	11.5%	3.3%	0.0%	0.0%	96.9%	1.2%	1.9%	0.0%	0.0%	0.0%	0.0%	0.0%	3.1%	100.0%

A summary of counts for large (>20 cm) and small (<20 cm) fish is shown in Table 4. Small flatfish and rockfish were very difficult to count, often becoming indistinguishable from the background when the videotape was paused, and their counts are most likely underestimated. Among the large fish, "total rockfish" as a group was the most abundant numerically followed by "total flatfish" as a group. Of the large rockfish identified to species (Table 5), rosethorn rockfish were the most abundant followed in order by yellowtail, greenstriped, yelloweye, tiger, and redstripe rockfish. Unidentified rockfish represented 30% of the total large rockfish enumerated. Of the large flatfish identified to species (Table 6), Dover sole were most abundant followed in order by arrowtooth flounder and Pacific halibut. Unidentified flatfish represented 78% of the total large flatfish counted. Other individual fish species and groups identified below the generic classification level were dominated by eelpout (Zoarcidae), ratfish , skates and rays (*Raja*), and greenling (*Hexagrammos* spp.) (Table 7).

Species composition differed considerably between habitats. The number of individually identified species was 15 in the trawlable habitat, and 18 in the untrawlable habitat (Table 8). Flatfish dominated in the trawlable habitat, and rockfish in the untrawlable habitat. Yelloweye, redstripe, silvergray, and quillback rockfish, as well as greenling and wolf-eel were observed in the untrawlable habitat but not in the trawlable habitat. Spiny dogfish (*Squalus acanthias*), Pacific cod (*Gadus macrocephalus*), and salmon (*Oncorhynchus* spp) were observed in the trawlable habitat but not in the untrawlable habitat.

Comparisons of fish densities and variances between habitat types were made only for fish >20 cm in length and in taxonomic units where reliable identification and enumeration could be assured (Table 9). Thus, density comparisons were performed at the species level for distinctive species (i.e. lingcod, yelloweye rockfish, and tiger rockfish), but were made at the group level for "all rockfish" and "all flatfish" bwcause of the presence of fish that could not be identified to individual species within each of these groups. For all comparisions, tests of homogeneity of variance of fish density between habitats (H_0: $s^2_t=s^2_u$) were rejected using Cochran's test (Winer, 1971) (α=0.05, k=2, df=7), indicating heteroscedastisity (Table 9). Significant differences in densities between habitats were found for each of the species and group comparisons using the Mann-Whitney two-sample test on ranks (Winer, 1971) (α=0.05, 2) (Table 9). Densities were higher in the untrawlable habitat for the "all rockfish" group, tiger rockfish, yelloweye rockfish, and lingcod; densities were higher in the trawlable habitat for the "all flatfish" group.

Statistical power analysis

The validity of our approach for analyzing the statistical sampling power of the submersible survey depends upon, among other things, fidelity to the assumptions of the two-sample t-test of means. The t-test requires that 1) the two sample means are estimated from random samples drawn from normally distributed populations, and that 2) the variance of the two populations are equal. Because our estimates of variance differed considerably between habitats (Table 9), we examined the properties of our data in more detail to confirm the reliability of using the t-test for our statistical power analysis. We conducted a bootstrap simulation experiment, in which we compared estimates of empirical power derived from our study (n=8) with the estimates of power obtained with Equation 1, under the assumption of asymptotic normality. The results of this comparison indicated that estimates of statistical power obtained from Equation 1 were generally conservative (indicated lower power) in relation to the empirical estimates of power for simulated known differences in density (Fig. 4). Given this result, we proceeded with our power analysis based on the t-test, under the assumption that, based on our observations, this approach will tend to err in the conservative direction; that is, it will tend to understate statistical power.

It is evident that, as it becomes necessary to detect smaller effect sizes, the required sample size increases accordingly. The relationship between sample size (n=the number of sample units [submersible dive sites] in each habitat type) and the effect size-index (d) for density comparisons

Table 3

Common and scientific names of fishes observed at 16 submersible dive sites off Cape Flattery, Washington.

Common name	Scientific name
Canary rockfish	*Sebastes pinniger*
Greenstriped rockfish	*Sebastes elongatus*
Quillback rockfish	*Sebastes maliger*
Redstripe rockfish	*Sebastes proriger*
Rosethorn rockfish	*Sebastes helvomaculatus*
Silvergray rockfish	*Sebastes brevispinis*
Tiger rockfish	*Sebastes nigrocinctus*
Yelloweye rockfish	*Sebastes ruberrimus*
Yellowtail rockfish	*Sebastes flavidus*
Greenling	*Hexagrammos* spp.
Lingcod	*Ophiodon elongatus*
Pacific cod	*Gadus macrocephalus*
Arrowtooth flounder	*Atheresthes stomias*
Dover sole	*Microstomus pacificus*
Pacific halibut	*Hippoglossus stenolepis*
Spotted ratfish	*Hydrolagus colliei*
Spiny dogfish	*Squalus acanthias*
Longnose skate	*Raja rhina*
Big skate	*Raja binoculata*
Salmon	*Oncorhynchus* spp.
Wolf-eel	*Anarrhichthys ocellatus*
Eelpout	Zoarcidae
Poacher	Agonidae
Generic group classifications	
Unidentified rockfish	*Sebastes* spp.
Unidentified flatfish	Pleuronectiformes
Unidentified roundfish	Osteichthyes

Table 4

Summary of fish counts for large (>20 cm) and small (<20 cm) fish for major fish groups. Site type: T = trawlable, U = untrawlable.

		Number of large fish (> 20 cm)					Number of small fish (< 20 cm)			
Site	Site type	Rockfish	Lingcod	Flatfish	Other	Total	Rockfish	Flatfish	Other	Total
4	T	0	1	77	8	86	0	95	48	143
5	T	8	0	54	17	79	0	94	15	109
6	T	2	0	76	12	90	0	68	63	131
10	T	7	3	29	5	44	0	26	107	133
11	T	0	1	35	10	46	0	8	101	109
12	T	0	0	46	5	51	0	6	63	69
13	T	39	1	119	19	178	0	77	37	114
15	T	0	0	31	2	33	0	70	64	134
1	U	115	1	6	16	138	43	0	10	53
2	U	128	14	12	28	182	348	3	52	403
3	U	9	2	28	10	49	41	9	58	108
7	U	43	9	13	22	87	0	21	46	67
8	U	32	3	4	9	48	40	2	12	54
9	U	206	5	6	14	231	339	0	11	350
14	U	30	3	8	11	52	38	7	27	72
16	U	111	5	30	9	155	28	4	17	49
Totals	T	56	6	467	78	607	0	444	498	942
	U	674	42	107	119	942	877	46	233	1156
	All	730	48	574	197	1549	877	490	731	2098

Table 5

Summary of fish counts by site for large rockfish (>20 cm). Site type: T = trawlable, U = untrawlable.

		Number of fish (>20 cm)										
Site	Site type	Rosethorn	Yellowtail	Silvergray	Greenstriped	Canary	Quillback	Redstripe	Tiger	Yellow eye	Unidentified	Total
4	T	0	0	0	0	0	0	0	0	0	0	0
5	T	0	0	0	8	0	0	0	0	0	0	8
6	T	0	0	0	2	0	0	0	0	0	0	2
10	T	0	0	0	0	2	0	0	0	0	5	7
11	T	0	0	0	0	0	0	0	0	0	0	0
12	T	0	0	0	0	0	0	0	0	0	0	0
13	T	2	1	0	14	0	0	0	1	0	21	39
15	T	0	0	0	0	0	0	0	0	0	0	0
1	U	31	1	0	9	0	1	0	0	8	65	115
2	U	88	3	0	0	0	0	0	7	12	18	128
3	U	8	0	0	0	0	0	0	0	1	0	9
7	U	16	14	0	1	0	0	0	2	3	7	43
8	U	25	2	0	1	2	0	0	1	0	1	32
9	U	121	1	1	3	0	0	16	6	5	53	206
14	U	15	10	0	1	0	0	0	1	0	3	30
16	U	34	17	3	0	0	0	0	2	7	48	111
Totals	T	2	1	0	24	2	0	0	1	0	26	56
	U	338	48	4	15	2	1	16	19	36	195	674
	All	340	49	4	39	4	1	16	20	36	221	730

Table 6

Summary of fish counts by site for large flatfish (>20 cm). Site type: T = trawlable, U = untrawlable.

		Number of fish (>20 cm)				
Site	Site type	Arrowtooth flounder	Dover sole	Pacific halibut	Unidentified	Total
4	T	3	6	2	66	77
5	T	3	8	1	42	54
6	T	15	2	6	53	76
10	T	0	3	3	23	29
11	T	1	3	3	28	35
12	T	5	2	5	34	46
13	T	10	13	7	89	119
15	T	0	2	1	28	31
1	U	0	4	0	2	6
2	U	0	2	0	10	12
3	U	0	4	2	22	28
7	U	0	0	5	8	13
8	U	0	0	0	4	4
9	U	0	1	1	4	6
14	U	0	1	0	7	8
16	U	1	0	0	29	30
Totals	T	37	39	28	363	467
	All	38	51	36	449	574

Table 7

Summary of fish counts by site for other large (>20 cm) fish. Site type: T = trawlable, U = untrawlable.

		Number of fish (>20 cm)								
Site	Site type	Greenling	Pacific cod	Ratfish	Spiny dogfish	Skates/Rays	Eelpout	Salmon	Unidentified	Total
4	T	0	0	0	0	0	8	0	0	8
5	T	0	0	6	1	0	10	0	0	17
6	T	0	0	0	0	1	11	0	0	12
10	T	0	0	0	0	4	1	0	0	5
11	T	0	0	0	0	1	8	1	0	10
12	T	0	2	0	0	1	2	0	0	5
13	T	0	1	1	6	5	5	0	1	19
15	T	0	0	0	0	0	1	0	1	2
1	U	2	0	1	0	0	12	0	1	16
2	U	1	0	1	0	0	26	0	0	28
3	U	1	0	1	0	1	6	0	1	10
7	U	3	0	0	0	4	15	0	0	22
8	U	2	0	2	0	0	5	0	0	9
9	U	2	0	6	0	0	5	0	1	14
14	U	0	0	2	0	0	9	0	0	11
16	U	1	0	5	0	0	3	0	0	9
Totals	T	0	3	7	7	12	46	1	2	78
	U	12	0	18	0	5	81	0	3	119
	All	12	3	25	7	17	127	1	5	197

between trawlable and untrawlable habitats is shown in Figure 5. To achieve power of 80% (α=0.05), the required number of dives ranges from n = 5 (d=2.0) to n = 17 (d=1.0); similarly, to obtain 90% power would require 8 to 27 dives. Empirical estimates of d from our study ranged from 1.1 for tiger rockfish to 2.0 for flatfish. This result suggests

Table 8

Composition of fish densities in trawlable and untrawlable sites by species (>20 cm), ranked in descending order of observed abundance (avg. no./hectare). Italicized species were not found in the other habitat type.

Trawlable sites		Untrawlable sites	
Species or group	Avg. no./hectare	Species or group	Avg. no./hectare
Eelpout	11.46	Rosethorn rockfish	77.78
Dover sole	9.33	Eelpout	19.26
Arrowtooth flounder	9.25	Yellowtail rockfish	10.70
Pacific halibut	6.88	Lingcod	9.78
Greenstriped rockfish	5.65	*Yelloweye rockfish*	8.65
Skate	2.81	Tiger rockfish	4.40
Spiny dogfish	1.67	Spotted ratfish	3.90
Spotted ratfish	1.54	Greenstriped rockfish	3.76
Lingcod	1.39	*Redstripe rockfish*	3.39
Pacific cod	0.70	Dover sole	3.00
Rosethorn rockfish	0.48	*Greenling*	2.67
Canary rockfish	0.41	Pacific halibut	1.77
Salmon	0.28	Skate	1.11
Yellowtail rockfish	0.24	*Silvergray rockfish*	0.79
Tiger rockfish	0.24	*Wolf-eel*	0.49
		Canary rockfish	0.36
		Quillback rockfish	0.27
		Arrowtooth flounder	0.19
Generic group			
All flatfish	114.29	All flatfish	23.90
All rockfish	13.14	All rockfish	155.63
All fish	146.65	All fish	211.70

that it is relatively more difficult (i.e. more dive sites are required) to detect density differences between habitats for tiger rockfish, as compared to flatfish. The associated power curves for these two values of d are illustrated in Figure 6. Figure 6 suggests that, given our observations (for values of d as low as 1.1), a sample size guideline of approximately 15 submersible dive sites in each habitat type would yield approximately an 80% chance of detecting a difference in mean density at least as large as the random noise estimated in the data for a similarly designed study.

Our statistical power analysis also indicated that, when the relative proportions of untrawlable and trawlable habitat, as well as the variability in the trawl survey estimates of abundance, are taken into consideration, the problem of estimating the trawl survey habitat bias can require substantially more samples than would be required simply to compare the density differences between two habitat types. Values of the trawl-survey habitat-bias effect size-index (d_b), calculated for a range of untrawlable habitat proportions with empirical trawl and submersible survey data, are given in Table 10 and are plotted for rockfish and flatfish in Figure 7. Using the calculated values of d_b from Table 10, we derived sample size guidelines for rockfish and flatfish (at power=0.80, α=0.05). The resulting relationship between the sample size required to estimate the trawl survey habitat bias (the n=number of submersible dive sites in each habitat type) and the proportion of untrawlable habitat in a management area (A_u/A) is illustrated in Figure 8. If, for example, the area of untrawlable habitat represented 20% of a management unit, Figure 8 indicates that the sample size required to estimate the trawl survey habitat bias would be n = 31 for rockfish (d_b=0.73), and n = 9 for flatfish (d_b=1.41). Sample sizes for lingcod were much higher (n>100), owing to the comparatively small detectible effect size required (d_b=0.13).

Discussion

Our study successfully obtained a first look at the variability in groundfish densities in trawlable and untrawlable habitats for a study area off Washington. We also developed a framework to use these types of observations to derive sample size guidelines for designing larger-scale studies to estimate the trawl survey habitat bias. The limited geographic scope of our study precludes extrapolation of our specific results to the west coast at large. However, we demonstrated an approach that can be used to establish sample size guidelines for future work by illustrating the interplay between statistical sampling power and 1) habitat-specific density differences, 2) variance of density estimates, and 3) the proportion of untrawlable area in a habitat.

In our study area, we observed striking differences in species composition and fish density between the traw-

Table 9

Summary of estimated fish densities (no./hectare) and summary statistics for selected fish groups (>20 cm). Site type: T = trawlable, U = untrawlable.

		Estimated fish density (number/10^3 m^2)									
		Rockfish		Flatfish		Lingcod		Yelloweye rockfish		Tiger rockfish	
Site	Site type	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
4	T	0.00	0.00	15.16	8.55	0.20	0.28	0.00	0.00	0.00	0.00
5	T	1.39	0.10	9.36	1.26	0.00	0.00	0.00	0.00	0.00	0.00
6	T	0.43	0.63	16.26	3.70	0.00	0.00	0.00	0.00	0.00	0.00
10	T	1.15	1.96	4.78	0.45	0.49	0.02	0.00	0.00	0.00	0.00
11	T	0.00	0.00	7.84	3.54	0.22	0.36	0.00	0.00	0.00	0.00
12	T	0.00	0.00	8.52	1.12	0.00	0.00	0.00	0.00	0.00	0.00
13	T	7.54	9.23	23.01	8.97	0.19	0.40	0.00	0.00	0.19	0.40
15	T	0.00	0.00	6.49	3.13	0.00	0.00	0.00	0.00	0.00	0.00
1	U	25.07	29.36	1.31	0.54	0.22	0.34	1.74	1.79	0.00	0.00
2	U	27.05	19.23	2.54	1.61	2.96	2.49	2.54	2.00	1.48	1.24
3	U	1.61	2.68	5.02	4.63	0.36	0.28	0.18	0.30	0.00	0.00
7	U	7.60	8.83	2.30	1.29	1.59	2.65	0.53	0.88	0.35	0.59
8	U	4.62	0.97	0.58	0.55	0.43	0.06	0.00	0.00	0.14	0.27
9	U	34.92	15.63	1.02	0.12	0.85	0.47	0.85	0.93	1.02	1.19
14	U	6.43	7.41	1.71	1.62	0.64	0.80	0.00	0.00	0.21	0.27
16	U	17.20	7.37	4.65	2.58	0.77	0.51	1.08	0.93	0.31	0.28
Summary statistics											
	m_t	1.31		11.43		0.14		0.00		0.02	
	s^2_t	6.64		37.92		0.03		0.00		0.00	
	m_u	15.56		2.39		0.98		0.87		0.44	
	s^2_u	151.58		2.69		0.82		0.81		0.28	
Cochran's test for homogeneity of variance (Winer 1971); C_{crit} = 0.83											
	C	0.96		0.93		0.96		1.00		0.98	
Mann Whitney test for equality of fish densities (Winer 1971); U_{crit} = 51											
	U	61		63		60		56		51	
Statistics to calculate effect size index (d) for submersible survey power analysis											
	$\|m_t - m_u\|$	14.25		9.04		0.84		0.87		0.42	
	s_p	8.894		4.51		0.65		0.64		0.38	
	d	1.6		2.0		1.3		1.4		1.1	

lable and untrawlable habitats. Flatfish were more than ten times as abundant in the trawlable habitat samples, whereas rockfish as a group were over three times as abundant in the untrawlable habitat samples. Silvergray, quillback, redstripe, and yelloweye rockfish were observed in the untrawlable habitat but not in any of the trawlable habitat samples.

We know of no visual-transect data comparable to that presented here for fish abundances off Washington. However, previous habitat specific studies in other areas have also reported differences in species composition and fish densities between low relief (trawlable) and highly rugose (untrawlable) habitats. Richards (1986) conducted a submersible study in the Strait of Georgia, British Columbia (21–140 m), and observed that the distribution of greenstriped, quillback, and yelloweye rockfish varied by depth and bottom type. Greenstriped rockfish were most abundant in fine sediment habitats, such as mud and cobble terrain. Quillback rockfish were most abundant in complex habitats, and yelloweye rockfish had higher densities in wall and complex habitats than in fine sediment habitats. In the coastal fjord of Saanich Inlet, British Columbia (21–150 m), Murie et al. (1994) also reported that quillback rockfish density was higher in areas of complex or wall habitat, compared to areas of sand-mud habitat. Additionally, tiger, copper (*S. caurinus*), yellowtail, and yelloweye rockfish were observed only over complex or wall habitats, and greenstriped rockfish were seen mostly over sand-mud habitat. Using sunken gill nets to sample trawlable and untrawlable habitats off Vancouver Island, B.C. (198–311 m in depth), Matthews and Richards (1991) reported differences in species composition between trawlable and untrawlable areas and higher species diversity in trawlable habitat. Major species on trawlable bottom were Pacific ocean perch (*S. alutus*), splitnose rockfish (*S. diploproa*), greenstriped rockfish, and bocaccio (*S. paucispinis*). Major species on untrawlable bottom were sharpchin (*S. zacentrus*) and redbanded rockfish (*S. babcocki*). In a submersible study conducted off Southeastern Alaska (188–290 m), Krieger (1993) compared the fish densities of 4 untrawlable sites with 16 trawlable or marginally trawlable sites, and reported that densities of large (>25 cm) rockfish (a category that included Pacific ocean perch, sharpchin rockfish, redstripe rockfish, and harlequin rockfish (*S. variegatus*) were highest at trawlable sites. In a study of shortraker (*S. borealis*) and rougheye (*S. aleutianus*) rockfish conducted on the upper continental slope off southeastern Alaska (262–365 m), Krieger and Ito (1999) reported that soft substrates of sand or mud usually had the greatest densities; hard substrates of bedrock, cobble, or pebble had the least densities; and habitats containing steep slopes and numerous boulders had greater densities of rockfish than habitats with gradual slopes and few boulders. O'Connell and Carlile (1993) conducted a submersible survey off southeastern Alaska in two depth strata; shallow (<108 m) and deep (≥108 m). Yelloweye rockfish were observed in cobble, continuous rock, broken rock and boulder habitats but were most abundant in broken rock and boulder habitats of the deep stratum. Habitat-specific studies in Oregon and California have used finer scales of habitat classification to characterize fish-habitat associations than our comparatively coarse trawlable or untrawlable classification. In Oregon waters, Stein et al. (1992) reported estimates of fish density by habitat-type from a submersible study of six stations at Heceta Bank in waters ranging from 60 to 340 m in depth. Rockfishes, particularly pygmy (*S. wilsoni*), sharpchin, rosethorn, and yellowtail, dominated all substrates except mud, where Dover sole and blackbelly eelpouts (*Lycodes pacificus*) were most abundant. In California waters, Yoklavich et al. (2000) conducted a submersible study at Soquel canyon (94–305 m) in Monterey Bay. Cluster analysis grouped fish densities into six habitat guilds; most distinct were 1) guild I (fish associated with uniform mud bottom of flat or low relief, dominated by stripetail rockfish (*S. saxicola*)) and guild VI (fish associated with rock-boulder habitat of low to high relief, dominated by pygmy rockfish).

To contrast our results in Washington with findings from Oregon and California, we summarized the fish density estimates reported by Stein et al. (1992) and Yoklavich et al. (2000) into a format roughly comparable to our data. Differences in the objectives and methods of their studies precluded a rigorous quantitative comparison with our results, particularly because of differences in habitat classification and survey design (random sampling in our study, purposive sampling in the other two studies). However, some interesting similarities are apparent if the most highly rugose habitats of these two studies are treated as a proxy for untrawlable habitat and if the low bottom relief habitats are treated as a proxy for trawlable habitat (Table 11). Seven species (italicized in Table 11) co-occurred in all three studies. For all three studies, greenstriped rockfish and Dover sole densities were higher in the trawlable habitat, and rosethorn, yelloweye and yellowtail rockfish densites were higher in the untrawlable habitat. Results were mixed for canary rockfish (more abundant in trawlable habitat in Washington but more abundant in untrawlable habitat in the Oregon and California studies) and lingcod (more abundant in trawlable habitat in Oregon but more abundant in untrawlable habitat in the Washington and California studies).

The most striking contrast among the three studies was the much lower overall magnitude of the fish densities in Washington compared to Oregon and California. One possible explanation for this difference could be due to the

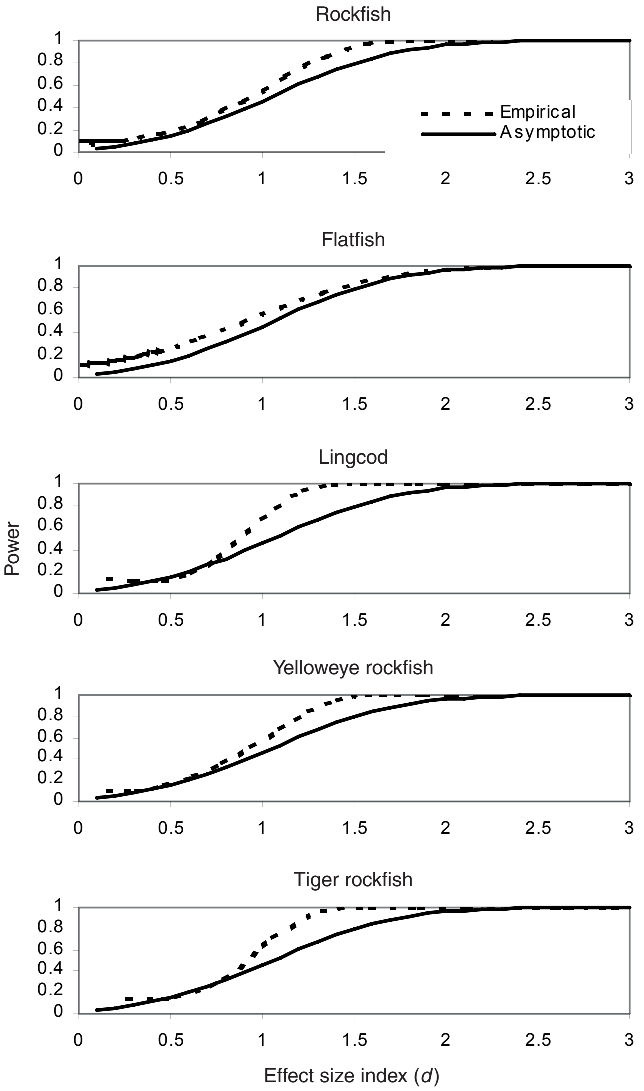

Figure 4

Comparison of empirical power (from bootstrap simulation results) with power calculated by using Equation 1 under the assumption of asymptotic normality (α=0.05, n=8) for rockfish and flatfish in the aggregate and for lingcod, yelloweye rockfish, and tiger rockfish individually.

nature of the respective study designs. The Oregon and California studies both targeted particular substrate types to characterize fish assemblages and fish habitat associations. Our study in Washington was structured to conduct random sampling within each of the two broad habitat classifications and thus did not focus purposively on particular local features (e.g. individual rock outcrops) which could serve as areas of more concentrated fish density. Another factor could be the nature of the fishing history of the study areas; the Washington site has long been subjected to heavy fishing pressure, whereas the other sites, particularly portions of the Soquel canyon site, may have received relatively less fishing pressure (Yoklavich[2]). It is also possible that zoogeographic differences, interannual variability, and the relatively small spatial scales of the sampled areas could also explain the differences in densities observed between the studies.

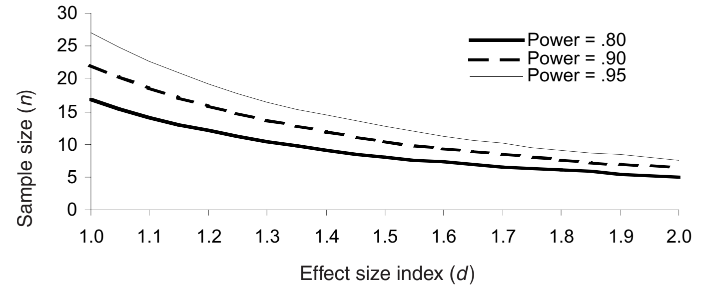

Figure 5

Sample size (n=number of submersible dives in each habitat type) as a function of the effect size index (d) for comparisons of fish density between trawlable and untrawlable habitats (α=0.05).

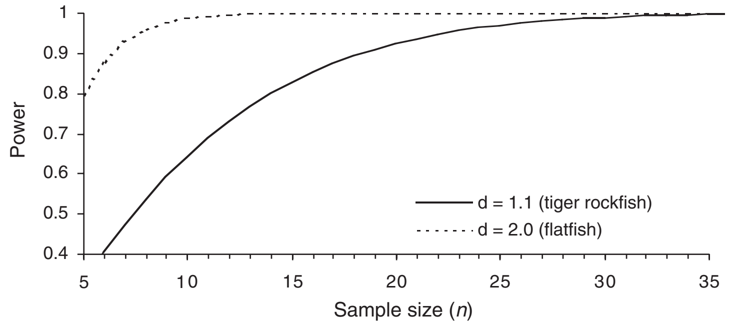

Figure 6

Statistical Power as a function of sample size (n=number of submersible dives in each habitat type) for the lowest (d=1.1) and highest (d=2.0) values of the effect size index observed in the present study (α=0.05).

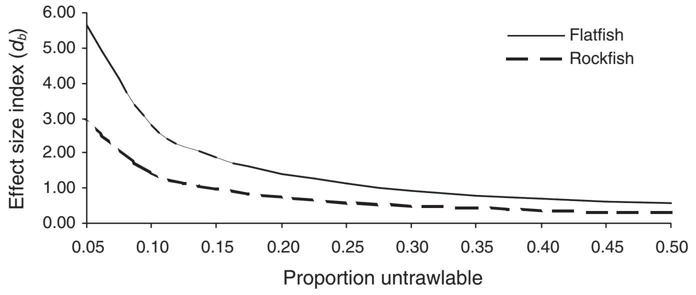

Figure 7

Trawl-survey habitat-bias effect size-index (d_b) as a function of the proportion of untrawlable habitat (A_u/A) in a management area for two categories of fish.

The level of concordance among the habitat-specific studies reviewed in the present study suggests that the potential exists for differences in fish density between trawlable and untrawlable habitats. These differences can be of great importance in the interpretation of trawl survey results for groundfish stock assessments. The presently available data are insufficient, however, to accurately quantify the magnitude of the trawl-survey habitat bias for west coast groundfish stock assessment and management. First, the absolute magnitude of such a bias will depend largely on the amount of untrawlable habitat present, which is not well estimated at this time. Modern benthic mapping technology and geographic information systems are capable of yielding detailed habitat maps over large spatial scales for habitat area quantification, but such maps are not yet available for most of the west coast (Nasby, 2000). Second, although many of the habitat-specific studies conducted to date tend to support the notion of significant fish density differences between trawlable and untrawlable habitats on small scales, studies with larger geographic scope are needed in order to be relevant to the assessment and management of west coast benthic fishery stocks. In particular, studies structured *a priori* with stratified random sampling designs can afford improved statistical inference by providing representative observations and unbiased parameter estimates across a spectrum of habitat types.

Estimation of the trawl-survey habitat-bias may not be the preferred solution to address habitat-specific density differences for all groundfish species. The approach is likely to work best for situations where 1) variability in the density estimates obtained from the survey used to sample both habitats (in our case, visual transects collected by submersible) is relatively small compared to the variability in the trawl survey, and 2) untrawlable habitat does

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[2] Yoklavich, M. 2001. Personal commun. NMFS, Santa Cruz, California 95060.

Table 10

Statistics used to calculate the trawl-survey habitat-bias effect size-index (d_b) derived from observations of the present study.

Species or group	Trawl survey density (D_t) (no./hectare)	Trawl survey $SD(D_t)$	Submersible survey s_p (no./hectare)
Rockfish	58.94	12.97	88.94
Flatfish	141.38	12.72	45.07
Lingcod	0.85	0.17	6.52

Proportion untrawlable A_u/A	Trawls-survey habitats-bias effect size-index (d_b)		
	Rockfish	Flatfish	Lingcod
0.50	0.29	0.56	0.05
0.45	0.32	0.63	0.06
0.40	0.36	0.71	0.07
0.35	0.42	0.81	0.07
0.30	0.49	0.94	0.09
0.25	0.58	1.13	0.10
0.20	0.73	1.41	0.13
0.15	0.97	1.88	0.17
0.10	1.46	2.82	0.26
0.05	2.92	5.65	0.52

not comprise a large portion of the area to be assessed. Our data suggest, for instance, that it would probably be unfeasible to estimate a trawl survey bias correction factor for lingcod. It appears that lingcod density can be estimated with relatively good precision in trawlable areas by the trawl survey (CV=0.20, Table 10). However, our submersible survey found high variability across both habitat types (CV=1.17, Table 9), which resulted in a relatively low-effect size-index threshold values for lingcod (e.g. A_u/A d_b=0.52, Table 10). The required sample size rapidly exceeded n = 100 submersible dive sites as the proportion of the management area that was untrawlable increased above 5% (P=80%, α=0.05; Fig. 8). In cases requiring such large sample sizes, estimation of a trawl-survey bias correction factor would probably not be an acceptable alternative to direct, synoptic surveys structured to obtain unbiased estimates of abundance in untrawlable habitats. By contrast, the trawl survey bias correction factor approach may be more feasible for species where the ratio between the trawl survey and submersible survey variation is smaller. Our data suggest that flatfish may fall into this category. The trawl survey precision (CV=0 .09, Table 10) in relation to the submersible survey precision (CV=0.65, Table 9) resulted in a relatively high-effect size-index threshold value for flatfish at the proportion level of 5% for area that was untrawlable (d_b=5.65, Table 10). The required sample size was less than n = 25 submersible dive sites, even as the ratio of A_u/A (the proportion of the management area that is untrawlable area) exceeded 30% (P=80%, α=0.05; Fig. 8). However, because our analysis aggregated flatfish as a group, these results do not address the estimation of a bias correction factor for individual species, which is a requirement for any correction factor to be useful for stock assessment purposes.

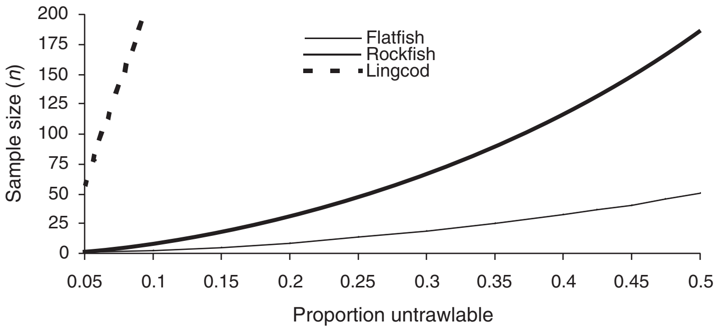

Figure 8

Sample size guidelines for estimating the trawl survey habitat bias (n=the number of submersible dives in each habitat type) as a function of the proportion of untrawlable habitat (A_u/A) in a management area, for power = 80% and α=0.05 for three categories of fish.

As for any survey method, the visual transect survey method has an array of advantages and disadvantages, which have been well chronicled elsewhere (Uzmann et al., 1977; Ralston et al., 1986; Butler et al., 1991; Adams et al.,1995; Starr et al., 1996; Cailliet et al., 1999). Some of the disadvantages include 1) difficulties in fish identification, particularly for small fish or fish with subtle coloration, 2) the potential for attraction or repulsion of fish from the

Table 11

Comparison of fish density estimates (average number of fish/hectare) in trawlable (D_t) and untrawlable (D_u) habitats from submersible studies in Washington, Oregon, and California. Densities for italicized species were reported in all three studies.

	Washington (present study)		Oregon[1]		California[2]	
Species	D_t	D_u	D_t	D_u	D_t	D_u
Rockfish						
Bank rockfish					0.00	105.00
Bocaccio					6.33	586.00
Canary rockfish	*0.41*	*0.36*		*120.00*	*0.00*	*148.00*
Cowcod				4.33	152.67	
Darkblotched rockfish					86.33	52.00
Greenblotched rockfish					1.33	36.33
Greenspotted rockfish					162.33	237.67
Greenspotted and greenblotched rockfish					1.67	16.33
Greenstriped rockfish	*5.65*	*3.76*	*165.00*	*39.50*	*218.67*	*46.00*
Halfbanded rockfish					220.00	85.67
Pygmy rockfish			510.00	892.50	126.33	734.33
Quillback rockfish		0.27				
Redstripe rockfish		3.39				
Rosethorn rockfish	*0.48*	*77.78*	*479.50*	*574.50*	*40.33*	*175.33*
Sharpchin rockfish					96.50	138.50
Shortspine thornyhead			119.50		41.33	5.33
Stripetail rockfish				304.67	63.67	
Tiger rockfish	0.24	4.40				
Widow rockfish					0.33	33.67
Yelloweye rockfish		*8.65*		*13.50*	*0.67*	*78.67*
Yellowtail rockfish	*0.24*	*10.70*	*33.50*	*95.50*	*2.67*	*28.00*
Flatfish						
Arrowtooth flounder	9.25	0.19				
Dover sole	9.33	3.00	249.50	7.50	58.00	3.00
Pacific halibut	6.88	1.77				
Other Fish						
Eelpout	11.46	19.26				
Greenling		2.67				
Lingcod	*1.39*	*9.78*	*33.50*	*15.00*	*43.67*	*91.67*
Pacific cod	0.70					
Pacific hagfish					25.67	4.00
Pacific hake					14.67	14.00
Poachers			93.00	9.00	138.00	22.67
Spotted ratfish	1.54	3.90				
Salmon	0.28					
Skate	2.81	1.11				
Spiny dogfish	1.67					
Wolf-eel		0.49				

[1] Oregon data source: Table 3 of Stein et al. (1992). Categories "mud" and mud-cobble" were averaged and used as a proxy for trawlable habitat; categories "flat rock" and "rock ridge" were averaged and used as a proxy for untrawlable habitat.

[2] California data source: Table 2 of Yoklavich et al. (2000). Categories "mud," "cobble-mud" and "mud-pebble" were averaged and used as a proxy for trawlable habitat; categories "rock-mud," "rock ridge," and "rock boulder" were averaged and used as a proxy for untrawlable habitat.

submersible, 3) variation in countability due to habitat type; for example, due to reduced visibility when the submersible maneuvered off bottom to avoid large boulders, or the failure to detect fish hiding behind boulders, and 4) the limitation of the technique to quantifying the density of benthic species found in close proximity to the bottom. The advantages of the visual transect survey method include the ability to 1) sample in habitats that are inaccessible to other survey methods, 2) observe *in situ* fish behavior, and 3) observe the distribution of fish and fish-habitat associations on a fine scale. Although our study was subject to the limitations of the visual transect method, we assumed that the method could reliably estimate (with a catchability of q=1.0) the true density of selected demersal bottomfish in both trawlable and untrawlable habitats for evaluation of the habitat bias present in the trawl-survey approach (which does not allow for sampling in untrawlable habitat). We do not feel that this assumption was severely violated, although we have no objective measure of the potential biases of the method, and thus we cannot estimate the consequences of assumption failure. We did recognize clearly that difficulties in fish identification limited the number of species that we could quantitatively sample with this technique. Technological improvements in underwater videography and image recognition software are likely to enhance the capabilities of the visual transect survey technique in the future.

In conclusion, it is clear that relatively large-scale surveys are needed to assess bottomfish densities in habitats that are not accessible to trawl survey gear. For some species, it may be possible to derive an area-specific trawl-survey bias correction factor, but for many other species it is likely that there will be no substitute for direct estimation of densities in untrawlable habitat on a routine and synoptic basis. In either case, stratified random sampling designs should be employed with sample sizes sufficient to ensure acceptable levels of statistical power. At present, the *in situ* visual transect submersible survey method appears to be a useful tool for this purpose, and the utility of this method will likely improve further with technological advances.

Acknowledgments

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Literature cited

Adams, P. B., J. L. Butler, C. H. Baxter, T. E. Laidig, K. A. Dahlin, and W. W. Wakefield.
1995. Population estimates of Pacific coast groundfishes from video transects and swept-area trawls. Fish. Bull. 93:446–455.

Alverson, D. L.
1951. Deep water trawling survey off the coast of Washington (August 27–October 19, 1951) Commercial Fisheries Review 13:11. U.S. Dep. Fish. Wild. Serv., Sep. 292.

Auster, P. J., L. L. Stewart, and H. Sprunk.
1989. Scientific imaging with ROVs: tools and techniques. Mar. Technol. Soc. J. 23(3):16–20.

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 with ROV's and manned submersibles. Proceedings of the Oceans 91 Conference, Honolulu, Hawaii, 1–3 October 1991, p. 689–696. Marine Technology Soc., Columbia, MD.

Cailliet, G. M., A. H. Andrews, W. W. Wakefield, G. Moreno, and K. L. Rhodes.
1999. Fish faunal and habitat analyses using trawls, camera sleds and submersibles in benthic deep-sea habitats off central California. Oceanol. Acta 22(6):579–592.

Caimi, F. M., J. H. Blatt, B. G. Grossman, D. Smith, J. Hooker, D. M. Kocak, and F. Gonzalez.
1993. Advanced underwater laser systems for ranging, size estimation, and profiling. Mar. Technol. Soc. J. 27(1):31–41.

Cohen, J.
1988. Statistical power analysis for the behavioral sciences, 2nd ed., 567 p. L. Erlbaum Associates, Hillsdale, NJ.

Dark, T. A., and M. E. Wilkins.
1994. Distribution, abundance, and biological characteristics of groundfish off the coast of Washington, Oregon, and California, 1977–1986. U.S. Dep. Commer. Nat. Mar. Fish. Serv., NOAA Tech. Rep. NMFS 117, 73 p.

Davis, D. L., and R. F. Tusting.
1991. Quantitative benthic photography using laser calibrations, 5 p. Undersea World, San Diego, CA.

Dixon, W. F., and F. J. Massey.
1957. Introduction to statistical analysis, 2nd ed., p. 244–255. McGraw-Hill, New York, NY.

Greene, H. G., M. M. Yoklavich, R. M. Starr, V. M. O'Connell, W. W. Wakefield, D. E. Sullivan, J. E. McRea, Jr., and G. M. Cailliet.
1999. A classification scheme for deep seafloor habitats. Oceanol. Acta 22(6):663–678.

Gregory, R. S., J. T. Anderson, and E.L. Dalley.
1997. Distribution of juvenile Atlantic cod *Gadus morhua* relative to available habitat in Placentia Bay, Newfoundland. Northwest Atl. Fish. Organ. Sci. Counc. Stud. 29:3–12.

Krieger, K. J.
1993. Distribution and abundance of rockfish determined from a submersible and by bottom trawling. Fish. Bull. 91:87–96.

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. Fish. Bull. 97: 264–272.

Kulbicki, M., and L. Wantiez.
1990. Comparison between fish bycatch from shrimp trawlnet and visual censuses in St.Vincent Bay, New Caledonia. Fish. Bull. 88:667–675.

Matthews, K. R., and L. J. Richards.
1991. Rockfish (Scorpaenidae) assemblages of trawlable and untrawlable habitats off Vancouver Island, British Columbia. N. Am. J. Fish. Manage. 11:312–318.

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 Sannich Inlet, British Columbia, from the Pisces IV submersible. Fish. Bull. 92:313–323.
Nasby, N. M.
2000. Integration of submersible transect data and high-resolution sonar imagery for a habitat-based groundfish assessment of Heceta Bank, Oregon. M.S. thesis, 50 p. Marine Resource Management Program, College of Oceanic and Atmospheric Science, Oregon State Univ., Corvallis, OR.
O'Connell, V. M., and D. W. Carlile.
1993. Habitat-specific density of adult yelloweye rockfish *Sebastes ruberrimus* in the eastern Gulf of Alaska. Fish. Bull. 91:304–309.
PFMC (Pacific Fishery Management Council).
2001. Status of the Pacific Coast groundfish fishery through 2001 and recommended biological catches for 2002: stock assessment and fishery evaluation, 26 p. [Document prepared for the Council and its advisory entities]. Pacific Fishery Management Council, Portland, OR.
Peterman, R. M.
1990. Statistical power analysis can improve fisheries research and management. Can. J. Fish. Aquat. Sci. 47:2–15.
Ralston, S., R. M. Gooding, and G. M. Ludwig.
1986. An ecological survey and comparison of bottom fish resources assessments (submersible versus handline fishing) at Johnston Atoll. Fish. Bull. 84:141–155.
Richards, L. J.
1986. Depth and habitat distributions of three species of rockfish (*Sebastes*) in British Columbia: observations from the submersible Pisces IV. Environ. Biol. Fish. 17(1): 13–21.
Shaw, F. R., M. E. Wilkins, K. L. Weinberg, M. Zimmermann, and R. R. Lauth.
2000. The 1998 Pacific West Coast bottom trawl survey of groundfish resources: estimates of distribution, abundance, and length and age composition. NOAA Technical Memorandum NMFS-AFSC-114, 138 p.
Starr, R. M., D. S. Fox, M. A. Hixon, B. N. Tissot, G. E. Johnson, and W. H. Barss.
1996. Comparison of submersible-survey and hydroacoustic-survey estimates of fish density on a rocky bank. Fish. Bull. 94:113–123.
Stein, D. L., B. N. Tissot, M. A. Hixon, and W. Barss.
1992. Fish-habitat associations on a deep reef at the edge of the Oregon continental shelf. Fish. Bull. 90:540–551.
Uzmann, J. R., R. A. Cooper, R. B. Theroux, and R. L. Wigley.
1977. Synoptic comparison of three sampling techniques for estimating abundance and distribution of selected megafauna: submersible vs. camera sled vs. otter trawl. Mar. Fish. Rev. 39(12):11–19.
Winer, B. J.
1971. Statistical principles in experimental design, 2nd ed., 907 p. McGraw Hill, New York, NY.
Yoklavich, M. M., H. G. Greene, G. M. Cailliet, D. E. Sullivan, R. N. Lea, and M. S. Love.
2000. Habitat associations of deep-water rockfishes in a submarine canyon: an example of a natural refuge. Fish. Bull. 98:625–641.

Appendix I: Procedure used for estimating the swept transect area

At each sample unit (submersible dive site), we estimated the total swept transect area, where the swept area (m^2) = (average area swept per second [m^2/sec]) × (total elapsed time [seconds]). The average area swept per second (m^2/sec) was computed for a set of randomly selected thirty second portions of each transect. Conceptually, we determined the average area swept per second for the subsampled areas from a series of adjacent trapezoids (Fig. 1).

For each trapezoid, we determined swept area (A_i) by measuring the width that was swept (l_i) and distance that was swept (T_i), where

$$A_i = \frac{1}{2}(l_i + l_{i+1})T_i.$$

The process involved a frame-by-frame analysis of the video image, which required tracking an object from the center of the video monitor display to the bottom edge of the video display for a known time interval (Fig. 2). The elapsed time for this interval was obtained from the video frame count, and was used to calculate area swept per second.

Width-swept estimates (l_i) were calculated from 1) the distance between the laser spots on the video monitor display (w_i), 2) the width of the video monitor display (V), and 3) the known distance between the lasers (W) (20 cm), where

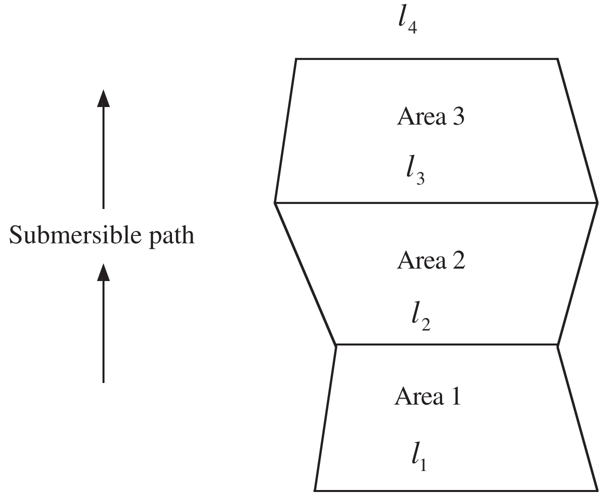
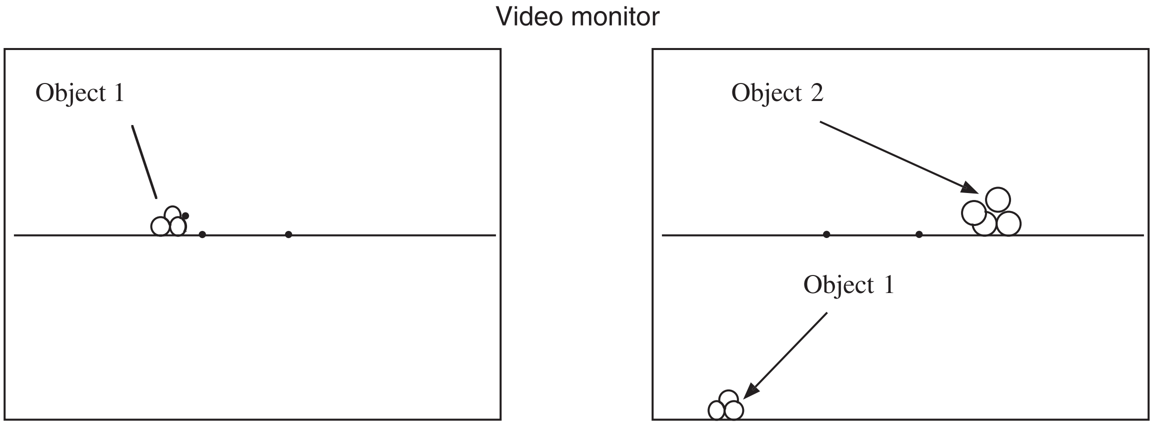


Figure 1
Schematic representation of adjacent trapezoids.

$$l_i = \frac{VW}{w_i}. \quad (1)$$

Because the width that was swept varied as the submersible distance off bottom varied, it was measured for each block. The following procedure was performed in sequence:



Screen 1: Distance between laser spots, w_1, is measured and object adjacent to lasers is identified.

Screen 2: Frame by frame advance until object adjacent to lasers in screen 1 rests at bottom of video screen; then, distance between laser spots, w_2, is measured, and the process repeats.

Figure 2

Illustration of the video-monitor display showing the frame-by-frame screen advance procedure used to determine the area swept per second.

1) w_i was measured to the nearest millimeter, 2) an object on the seafloor adjacent to the laser spots was identified, 3) the videotape was advanced until the object appeared at the bottom of the video monitor display, and 4) w_i was measured again (Fig. 2). The distance that was swept during this interval (T) is calculated trigonometrically by using the angle of the camera and constants estimated with the following procedures of Davis and Tusting (1991). The process is illustrated in Figures 3 and 4.

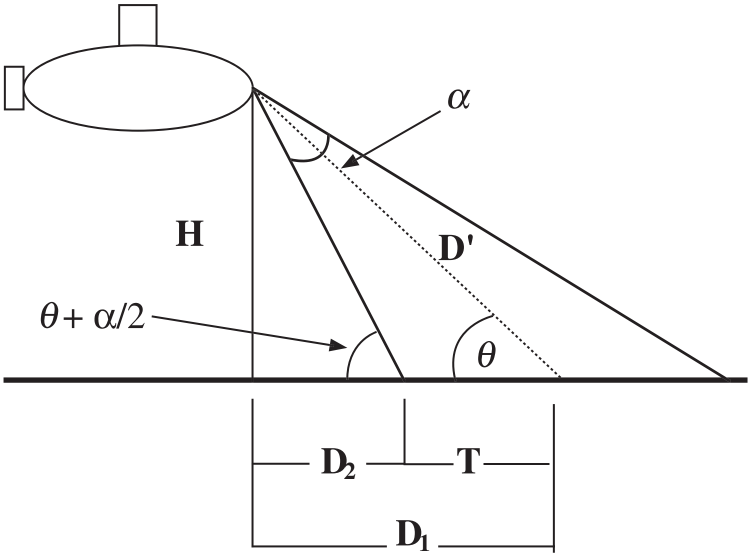


Figure 3

Schematic representation of the submarine and camera orientation to the bottom (the line labeled D′ represents the center line of the camera). Definitions for the variables are provided in the left column of text on this page.

The variables of interest are

T = the geodetic distance between the location of the laser spots on the seafloor and the bottom edge of the camera's field of view (distance swept);
H = the height of the video camera above the sea floor;
α = the angle of the camera lens;
θ = the tilt angle of the camera;
D = the distance between the focal point of the camera and the reflection of the laser spots on the seafloor;
D_1 = the horizontal distance from the camera to a point on the sea floor at the center of the camera's field of view;
D_2 = the horizontal distance from the camera to a point on the sea floor at the bottom edge of the field of view; and
D' = the distance from the camera lens to the reflection of the laser spots on the seafloor;
w = the distance measured between the laser spots as they appear on the video monitor display;
W = the known distance (20 cm) between the lasers mounted in parallel on the camera housing.

Note the following relationships:

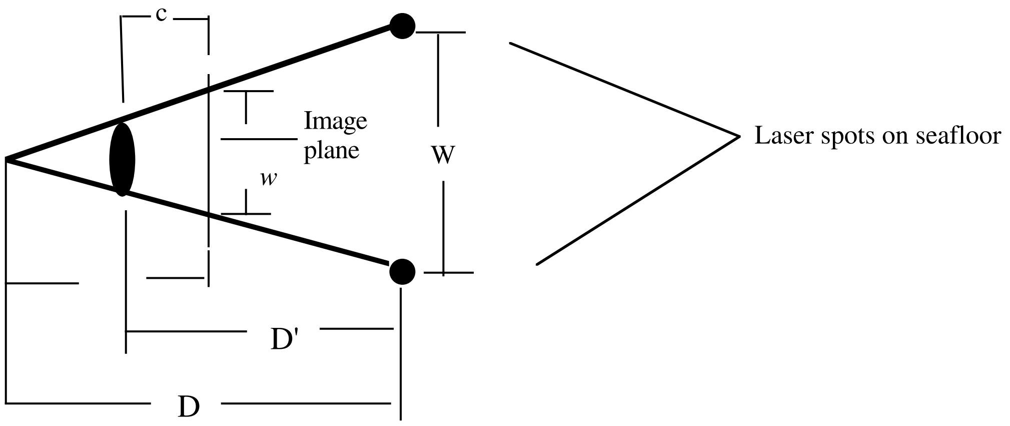


Figure 4

Schematic representation of the relationship between the camera lens, image plane, and laser spots on the seafloor.

$$D_1 = D' \cos\theta, \text{ and } H = D' \sin\theta \tag{2}$$

$$D_2 = \frac{H}{\tan\left(\theta+\frac{\alpha}{2}\right)} = \frac{D'\sin\theta}{\tan\left(\theta+\frac{\alpha}{2}\right)}, \tag{3}$$

In Equation 3, estimation of D_2 requires the height of the camera above the seafloor (H); however, the need for a direct measurement of H can be eliminated by using camera parameters that provide an independent estimate of D' (Fig. 4).

Figure 4 shows the relationships between the camera lens, image plane, and laser spots, where d is a constant representing the distance from the focal point to the image plane, and c is a constant representing the distance from the camera lens to the image plane (note that c may be positive or negative),

Note that both d and c are specific to the video display monitor employed, W, θ, and α are fixed, and w is observed.

$$D' = D - d - c, \text{ and } D = d\frac{W}{w}\cdot \tag{4}$$

Therefore,

$$D' = d\left(\frac{W}{w} - 1\right) - c, \tag{5}$$

Underwater tests were conducted and the constants c and d were estimated for *Delta's* video camera and laser set-up by following the procedures of Davis and Tusting (1991). The distance traveled (T) for each area-swept trapezoid (from the center of the image to the lower edge of camera field of view), then, is

$$T = D_1 - D_2 = D'\left(\cos\left(\frac{\pi}{180}\theta\right) - \frac{\sin\left(\frac{\pi}{180}\theta\right)}{\tan\left(\frac{\pi}{180}\left(\theta+\frac{\alpha}{2}\right)\right)}\right)\cdot \tag{6}$$

Appendix II: Derivation of the trawl-survey habitat-bias estimator, and the trawl-survey habitat-bias effect size-index (d_b)

To estimate the trawl survey habitat bias, we contrasted 1) the traditional abundance estimator, which does not discriminate between fish density differences in trawlable and untrawlable habitats (habitat-biased), with 2) an unbiased abundance estimator that explicitly allows for density differences between trawlable and untrawlable habitats.

Let D_t = the true density in the trawlable habitat;
A_t = the area of trawlable habitat;
D_u = the true density in the trawlable habitat;
A_u = the area of untrawlable habitat;
A = the total area = $A_t + A_u$;
N = total abundance; and
Δ = the difference in true densities = $D_t - D_u$.

Then, for the unbiased estimator,

$$N = D_tA_t + D_uA_u.$$

and for the biased estimator,

$$N = D_tA = D_tA_t + D_tA_u.$$

The habitat bias, then, is the difference of the two estimators, or

$$Bias = (D_tA_t + D_tA_u) - (D_tA_t + D_uA_u) = (D_t - D_u)\,A_u = \Delta A_u. \tag{1}$$

The total error in the abundance estimator is a function of both the bias and the variance $V(\hat{D}_t)$ of the fish density estimator

$$MSE = Bias^2 + (A^2)V(\hat{D}_t), \tag{2}$$

where $V(\hat{D}_t)$ describes the uncertainty in the abundance estimator. If the bias is much less than this uncertainty, then its impact will be minimal. Therefore, we arbitrarily set

$$Bias^2 = (A^2)V(\hat{D}_t), \tag{3}$$

and substituting ΔA_u for bias from Equation 1 into Equation 3 gives

$$\mathrm{A}_u{}^2\Delta^2 = (A^2)V(\hat{D}_t). \tag{4}$$

Solving for Δ gives

$$\Delta = \frac{A}{A_u} SD(\hat{D}_t), \tag{5}$$

where $SD(\hat{D}_t)$ = the standard deviation of the trawl survey density estimator in the trawlable habitat.

Thus, the effect size threshold used for detecting differences in mean density in the power analysis is a product of the arbitrary decision for the bias in the abundance estimator to be equal to its standard error.

For the statistical power analysis, we expressed Δ (the difference in densities between habitats) as the standardized effect size index (d_b) for a two-sample t-test (Cohen, 1988); dividing (Eq. 5) by an estimate of the population standard deviation, which yields

$$d_b = \left[\frac{A}{A_u} SD(\hat{D}_t) / s_p \right].$$