ICES Journal of Marine Science, 57: 1035–1049. 2000
doi:10.1006/jmsc.2000.0588, available online at http://www.idealibrary.com on IDEAL®

Estimation of a widow rockfish (*Sebastes entomelas*) shoal off British Columbia, Canada as a joint exercise between stock assessment staff and the fishing industry

R. D. Stanley, R. Kieser, K. Cooke, A. M. Surry, and
B. Mose

Stanley, R. D., Kieser, R., Cooke, K., Surry, A. M., and Mose, B. 2000. Estimation of a widow rockfish (*Sebastes entomelas*) shoal off British Columbia, Canada as a joint exercise between stock assessment staff and the fishing industry. – ICES Journal of Marine Science, 57: 1035–1049.

We conducted an acoustic study of widow rockfish (*Sebastes entomelas*) to test the feasibility of using acoustic methods to estimate the biomass of near-bottom shoals of rockfish, and to estimate the biomass of a particular mid-winter shoal, which the fishing industry suggested might be large enough to change current government perceptions of stock biomass. We repeated the acoustic survey of the study site 20 times. The total area backscattering coefficient (Sa) per survey ranged from 808–452 m^2 n.mi^{-2}. Total biomass estimates for the 21–28 km^2 area were 1000–2630 t. Trawl catches indicated that the species composition was approximately 88% widow rockfish. The variances in mean Sa for each of the micro-surveys were estimated with spatial analysis using either a unique or a global variogram. The coefficient of variation (CV) ranged from 4.8–17.8% when using individual variograms and from 9.6–29.5% when using a global variogram. The observed CV among the 20 estimates was 31%, almost three times the average CV based on the unique variograms, and almost two times the average CV derived from a global variogram. Although echograms indicated a diel movement, from near bottom during the day, to off-bottom at night, we observed no strong correlation of acoustic fish density with time of day or state of the diel tide. During the cruise, biomass estimates were derived within 24 hours of the completion of each micro-survey so that industry participants could review results and request changes to survey design. Although the estimates failed to indicate that current harvest recommendations were too conservative and were therefore a disappointment to industry, accommodating their scepticism during the cruise allowed us to provide scientifically credible estimates. The estimates now provide a shared reference point between fishers and stock assessment biologists for discussion about anecdotal sounder observations. The overall methodology can be implemented using portable equipment on commercial fishing vessels and will be useful for either scheduled or "ship of opportunity" surveys of specific shoals. Application to larger scale biomass estimation of widow rockfish stocks remains problematic, owing to problems of near-bottom detection, species resolution, and unpredictability of fish distribution.

Key words: acoustics, rockfish, *Sebastes entomelas*, biomass, Pacific Ocean, spatial analysis.

Received 9 August 1999; accepted 12 February 2000.

R. D. Stanley, R. Kieser, K. Cooke, and A. M. Surry: Fisheries and Oceans, Canada, Pacific Biological Station, Nanaimo, British Columbia, Canada, V9R 5K6. B. Mose: 641 Hollywood Rd, Qualicum Beach, British Columbia, Canada, V9K 1M3. Correspondence to R. D. Stanley: tel: +1 250 756 7134; fax: +1 250 756 7053; email: StanleyR@pac.dfo-mpo.gc.ca

Introduction

Widow rockfish are an important component of the trawl fishery on the west coast of North America. Annual coastwide landings are about 8000 t, of which 80% are captured in US waters and 20% in Canadian waters (Stanley and Haist, 1997; Ralston and Pearson, 1997). They are one of over 60 species of the genus

1054–3139/00/041035+15 $30.00/0

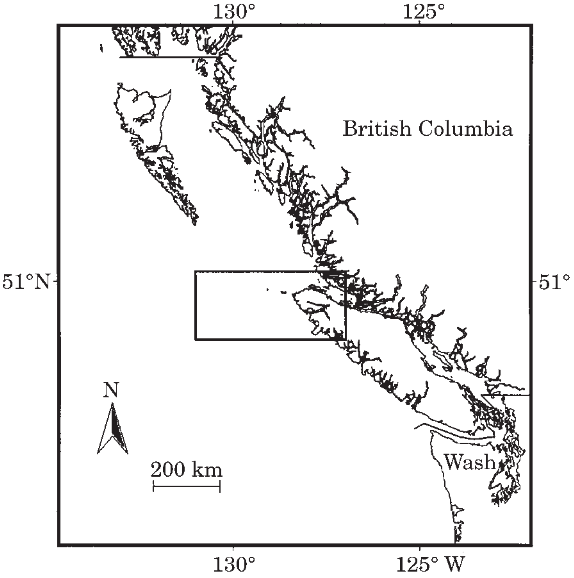

Figure 1. Location of study site off the west coast of North America.

Sebastes inhabiting the eastern Pacific Ocean waters, many of which are important in commercial and sport fisheries (Eschmeyer *et al.*, 1983). While widow rockfish landings have been significant in Canada since 1988, the lack of an absolute estimate or relative index of abundance has hindered stock assessment (Stanley and Haist, 1997).

Acoustic surveys present an alternative approach that has been used effectively for stock assessment of redfish species (*Sebastes mentella*) in the North Atlantic (Magnússon *et al.*, 1994). However, in the North Pacific, use of the technique for rockfish has not progressed beyond trial studies. Wilkins (1986), using a combination of quantitative echosounding and sonar visual recording, demonstrated the feasibility of quantitative estimation of widow rockfish in US waters, as did Stanley *et al.* (1999) for yellowtail rockfish using echosounding alone. The problems of species recognition among the numerous rockfish species of the North Pacific, their close affiliation to bottom, the relatively small and dispersed populations and the difficulty in predicting their distribution have acted to discourage routine use of acoustics for Pacific Ocean rockfish stock assessment.

During an observer trip in October 1996, the fishing skipper (B.M.) commented to R.D.S. that, in the opinion of the industry, the quotas for widow rockfish (Stanley and Haist, 1997) were overly conservative. Furthermore, the industry suggested that if a biomass estimate could be obtained for a shoal known to regularly appear off the central coast of British Columbia in mid-winter (Fig. 1), the estimate of this shoal, by itself, might alter perceptions of exploitable stock biomass. They commented that the shoal was predominantly widow rockfish, off bottom at certain times of the day, and predictable in its appearance during the winter, thus making it a reasonable candidate for acoustic estimation. They noted that even if the study failed to indicate a large biomass, it would be the first directed field research on this species in Canadian waters. Furthermore, it might provide a meaningful quantitative reference point for dialogue between the fishing industry and stock assessment staff in that it would provide a quantitative link between a biomass estimate and what fishers observe on their sounders and in their nets.

To test the industry's perception of the shoal's biomass, we conducted a joint acoustic biomass survey of the shoal in 1998. The primary objective of the study was to obtain a biomass estimate. Additional objectives included examining the impact of widow rockfish diel behaviour on the biomass estimates as well as testing the feasibility of expanding the survey to cover larger areas of the coast. The study principals also hoped that the program would serve as a model for developing closer research collaboration between industry and government staff.

Methods

The cruise was conducted with a 39-m chartered commercial fishing trawler, "Frosti", acting as the scout and catcher vessel. The chartered vessel conducted an acoustic reconnaissance of the site to choose transects. During the study, it conducted trawl hauls to identify species and size composition of the shoal. It also sounded the perimeter of the study site to look for evidence of movement to and from the study area and sounded within the study site to confirm to industry participants that transect placement provided a credible representation of fish abundance. The 59-m government research vessel, "W. E. Ricker", conducted the systematic acoustic recording and oceanographic sampling. Weather conditions were severe throughout the study, resulting in only 4 days at the site, 29 January, and 2–4 February 1998. Remaining days were spent on other tasks or at anchor waiting for the weather to improve.

Study site

The study site was at the edge of the continental shelf off the northwest tip of Vancouver Island, British Columbia, Canada (Figs 1 and 2). The high relief bottom topography and strong tides make it impossible to fish with bottom trawls and difficult to fish near bottom with midwater trawls.

The shoal was distributed in an "L-shaped" orientation around a westward facing bluff. While we would

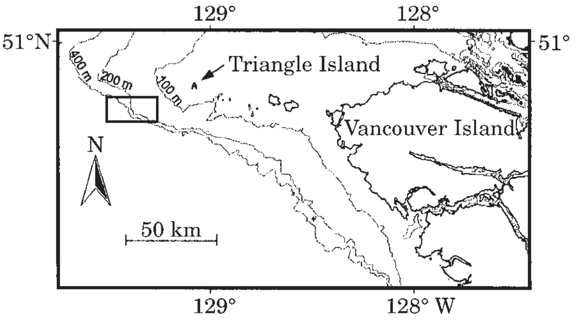

Figure 2. Location of study site off northwest tip of Vancouver Island.

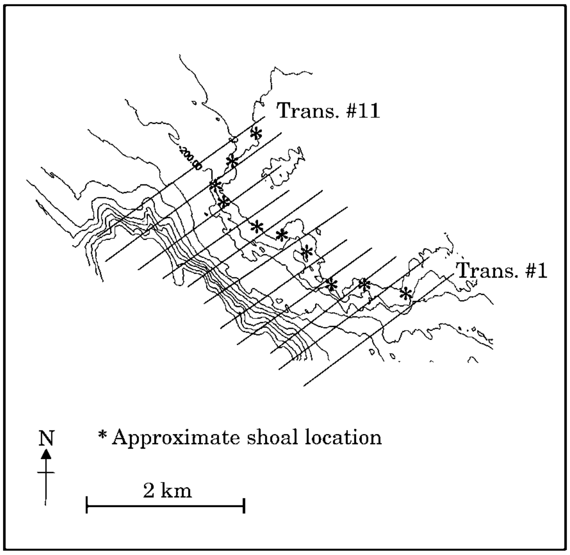

Figure 3. Shoal location and approximate survey transect pattern. Start and end transect numbers are shown.

have preferred to orient the acoustic transects perpendicular to the longitudinal axis of the fish shoal (MacLennan and Simmonds, 1992), prevailing sea conditions precluded varying the vessel path through a range of bearings. Since most of the shoal was aligned along a southeast-northwest axis, we aligned the transects in a southwest direction, perpendicular to the shoal (Fig. 3).

The 11 SW transects covered the entire shoal by extending across the shelf break, from about 140 m in bottom depth to beyond the shelf edge. Transect spacing was 0.54 km. The set of transects covered an area 21–28 km^2 and was repeated 20 times. The transects were travelled in the same direction and order each time, starting at the northeast end of the southern most transect. At completion of the set, the vessel returned to the start point to conduct the same set again. Each micro-survey and return trip to the start point required two hours.

The same SW pattern was repeated on micro-surveys B1–B10, B14, and B17–B20. Starting with micro-survey B11, the entire pattern was offset to the northwest by approximately 180 m. The offset was further incremented by 180 m on subsequent micro-surveys B12–B13. Micro-survey B14 was the same as the standard set; B15 and B16 were repeats of B11 and B12, respectively. Fishers requested the offsets to examine the sensitivity of the acoustic density estimates to the placement of transects.

While returning to the start point after each micro-survey, the commercial fishing captain on board the "W. E. Ricker" chose a route to travel back over the longitudinal axis of the shoal. These transects effectively followed the 150-m contour at the shelf break over which most of the acoustic sign was observed. Acoustic fish density estimates for these transects were extrapolated to a path 0.54 km wide, the approximate average width of the shoal as it appeared in the echogram. This "fisher transect" was completed following each of micro-surveys B1–B7 and B9–B18. The intent was to provide an alternative acoustic density estimate that mimicked the search mode a commercial fisher would use.

Acoustic observations

The acoustic system on the "W. E. Ricker" included a SIMRAD EK500 38/120 kHz split beam echosounder (SIMRAD, 1993a; Bodholt and Solli, 1992; Bodholt, 1990), and a SIMRAD BI500 data logging and processing system (SIMRAD, 1993b). The 38 and 120 kHz transducers were mounted on a single retractable ram located midships at keel depth, 4.3 m below the surface and 1.1 m below the keel. The charter vessel used a Shipmate RS5310 38 kHz sounder with a hull-mounted transducer. Standard sphere calibration of the "W. E. Ricker" system was conducted 19 January, prior to the cruise. Target calibration followed procedures outlined in the EK500 manual (SIMRAD, 1993a) and Foote *et al.* (1987).

We used the SIMRAD scrutinizing program (SIMRAD, 1993b) to display consecutive 9.3 km sections of the echogram, to select rockfish and to remove any bottom signal from the backscatter values. Bottom removal was aided by reliable bottom tracking and a bottom offset parameter of 0.5 m. The echo selection process was guided by input from commercial fishers, location, catch composition, bottom structure and depth, echo intensity, layering of the echo information, and target strength (TS). Local fish density was assumed to be proportional to the average area backscattering coefficient on the physical scale ("Sa") in units of m^2 n.mi^{-2}. This was obtained by averaging scrutinized echoes over an elementary sampling distance interval (ESDU) of 180 m.

Species composition

The charter vessel conducted five successful midwater fishing tows with a “Super Mesh” midwater trawl and a 5-cm codend liner. Inclement weather precluded additional fishing effort. Total catch weight was estimated visually by the skipper and ranged from 2–23 t. Species proportions were estimated by sampling the catch.

Target strength and biomass estimation

We were not able to measure target strength for widow rockfish during this study and there were no published TS estimates for widow or yellowtail rockfish, but results for Atlantic redfish (*S. mentella*) have been reported by Foote *et al*. (1985), Orlowsky (1987), Reynisson (1992), Reynisson and Sigurosson (1996), and Gauthier and Rose (1998). The redfish measurements by Foote *et al.* (1985) ($c_1 = -67.1$) and Gauthier and Rose (1998) ($c_1 = -67.6$) agreed with the TS length relationship given by Foote (1987) for physoclist fishes ($c_1 = -67.5$) where,

$$TS = 20 \log L + c_1.$$

However, those published by Orlowsky (1987) ($c_1 = -69.4$) and Reynisson (1992)) ($c_1 = -71.3$) were lower. We note that the two groups of measurements were performed on two different redfish stocks, and it is conceivable that differences in physiology, depth adaptation and behaviour could result in the observed difference. Based on this review, we chose the $c_1 = -67.5$ (Foote, 1987) to estimate widow rockfish TS.

Mean length from the combined sets (Table 1) was used to compute a TS of -34.35 dB. The difference between day and night TS (0.64 dB) was sufficiently small to use a single TS value. The set information was also used to derive a length/weight relationship:

$$W_g = 0.009917 \times L_{cm}^{3.091}.$$

The mean weight was then used to convert fish number density to fish weight density. We assumed that 100% of the measured backscatter from the selected part of the water column was from the fish species, identified in the catch composition.

We assumed constant mean length, TS and species composition over the 20 micro-surveys. The difficulty in fishing made it impractical to provide representative samples corresponding to each micro-survey. The impact of this set of assumptions would be to underestimate actual variance in mean biomass. However, the impact would presumably be small. Unlike herring or other species, where size composition among shoals can vary radically, widow rockfish shoals tend to be more homogenous in size and age composition owing to the similarity in size among fully recruited age groups.

Comparison of catch rates with acoustic biomass estimates

For the biomass estimates to have credibility with fishers, the acoustic estimates of the shoal biomass should be congruent with fishers’ catch rates. To calculate theoretical catch rates based on net specifications and our estimates of density, we assumed a catchability coefficient of 1.0 in the vertical and horizontal plane, equating to a simple swept-area estimate. Since the 22 m theoretical vertical opening of the “Frosti’s” net is the approximate depth of the shoal (Fig. 5a, b), the assumption of a catchability of 1.0 in the vertical plane may be generous, owing to avoidance by the fish. However, the fishers target under the shoal to catch the fish as they dive. They report that, on some occasions, they seem to correctly anticipate the diving rate, since few fish show above or below the net opening in the sonar image from the headrope transducer. Since we assume that on some occasions they capture everything in the vertical plane, the calculation simplifies to a two-dimensional problem and corresponds to the area-based acoustic density estimates.

On the horizontal plane, we assumed an opening corresponding to the distance between the wingtips (53 m) or the doors (84 m). A tow through a body of fish would therefore fish a path 53–84 m wide at 1.45 ms^{-1} (2.9 knots) and the swept area fishing rate would approximate 100 $m^2 s^{-1}$.

Mean and variance estimation

The transects represent a sytematic grid with a random choice of starting point; therefore, an equal area of influence was given to each sample. The mean Sa, $\bar{z}_i$, of each micro-survey i, corresponds to the simple average of the individual sample values, z_{ijk}, of all observations k of all transects j for each micro-survey i (Petitgas and Lafont, 1997). Sample size (N_i) varied from 126–150. We used three methods to estimate the variance of mean Sa. Methods 1 and 2 involved applying spatial analysis to each micro-survey (EVA2 spatial analysis software, Petitgas and Lafont, 1997). For method 3, we estimated the overall variance in mean Sa among surveys.

For method 1, we treated each micro-survey as independent and conducted a unique spatial analysis. Sa values for each of the micro-surveys were examined for evidence of directional effects on the variance (anisotropy) and fitted to variograms (Petitgas, 1993). These variograms are vectors (g_{ih}) of the variance between sample observations as the lag distance (h) between paired observation increases.

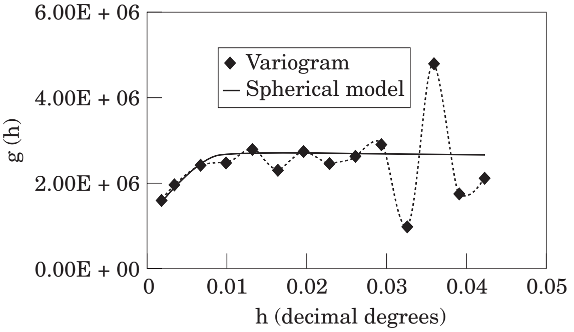

Figure 4. Omni-directional variogram and fit of spherical model for micro-survey #7.

All possible pairs of observations were divided into increasing distance intervals of h. The range of the variogram corresponds to the distance between points at which the variance tends to reach an asymptote. The sill is the asymptotic value as h increases. The nugget is the theoretical variance between repeated measurements at the same location (zero lag) (Petitgas, 1993). The variogram reflects the underlying spatial autocorrelation. No anisotropy was found for 17 of the 20 micro-surveys. For each of these, a single spherical model was fit to the omni-directional variogram (Petitgas and Lafont, 1997) (Fig. 4).

Two of the micro-surveys exhibited geometric anisotropy, indicating that the variance between two points increases more rapidly with distance in one direction than another, but both variances reach the same sill. The variance in this case, was modelled as an ellipse with three coefficients (Petitgas and Lafont, 1997). One coefficient provides the angle of rotation; the other two provide the scaling on the *x* and *y*-axis to transform the range-ellipse into a circle. The observations of one micro-survey indicated zonal anisotropy, wherein the sill of the variogram was higher in one direction than the other but both have the same range. This is accommodated in EVA2 through the addition of a second model.

The models of the spatial structure for each micro-survey were then used to estimate the variance of each estimate of mean Sa. We used the intrinsic method in two dimensions (scheme A) provided in the EVA2 software (Petitgas and Lafont, 1997). For each micro-survey the regularly spaced transects divide the survey area into 11 rectangles of length b_{ij} and constant width a, corresponding to the inter-transect distance of 0.54 km. Each transect provides a continuous sample along the middle line of the rectangle. The error is the difference between the true mean of the rectangle, and the true mean along the transect. The continuous sampling along the transect permits the assumption that the observed mean is the true mean. The transects are of variable length, therefore the estimation variance (σ_i) is the weighted average of the elementary variances:

$$\sigma_i^2 = \frac{\sum_{j=1}^{11} b_{ij}^2 \sigma_{ij}^2}{\left(\sum_{j=1}^{11} b_{ij}\right)^2},$$

where the elementary variance, σ_{ij}^2, is estimated using the variogram model for each rectangle j (see Petitgas and Lafont, 1997). The variogram models also permits the prediction of the middle line or theoretical transect estimate. These can be solved formally; EVA2 uses charts developed by Journel and Huijbrets (1978). The elementary variances for each of the 11 rectangles are combined in a final variance of estimation for each micro-survey (σ^{*2}_i) as:

$$\sigma_i^{*2} = \frac{C_{i0}}{N_i} + \sigma_i^2,$$

where C_{i0} is the nugget value. The coefficient of variation was expressed as:

$$CV_i^* = 100 \frac{\sigma_i^*}{\bar{z}_i}.$$

Method 2 was similar to method 1, except that we assumed a constant underlying spatial correlation for all 20 micro-surveys. We derived a global omnidirectional variogram that we applied to all 20 micro-surveys. The global variogram was derived by first calculating an omni-directional variogram for each micro-survey. The set of 20 variograms was standardized by dividing each of the variograms by the variance of its mean density, $s_{\bar{z}_i}^2$ where:

$$s_{\bar{z}_i}^2 = \frac{\sum_{j=1}^{11} \sum_{k=1}^{K_{ij}} (\bar{z}_i - z_{ijk})^2}{N_i - 1},$$

and

$$g_i'(h) = g_i(h)/s_{\bar{z}_i}^2.$$

The global variogram, $g''(h)$, was the average variance across individual variograms for each lag, weighted by the number of observations from each lag:

$$g''(h) = \frac{\sum_{i=1}^{20} (N_{ih} g_i'(h))}{\sum_{i=1}^{20} N_{ih}}$$

The isotropic model was then fit to the global variogram and used to provide a global estimation variance for 20 micro-surveys. The actual estimates of variance per micro-survey differed slightly because of varying sample size (126–150).

The procedure for method 3 was to calculate the actual observed variance among the 20 estimates of mean Sa (MacLennan and Simmonds, 1992), wherein the overall mean Sa ($\bar{Z}$) for the micro-surveys was:

$$\bar{Z}=\frac{\sum_{i=1}^{20}\bar{z}_i}{20},$$

and the overall variance of the observations of mean Sa was:

$$s^2_{\bar{z}*}=\frac{\sum_{i=1}^{20}(\bar{z}_i-\bar{Z})^2}{20-1}.$$

Results

Fishing and biological sampling

The dense fish signal was consistently observed near the shelf edge and over peaks that rose to more than 30 m over local bottom depth (Fig. 5a, b). The vertical scale in the figures is exaggerated about 10 times over the horizontal scale.

Mid-day distributions tended to be nearer the peaks, tower-shaped, and more closely associated with the bottom. Dusk and dawn distributions resembled a dispersed cloud. Distributions during the middle of the night were varied, sometimes resembling dawn or mid-day displays. Fisher participants confirmed that the shoal was a typical showing, although not necessarily the largest display they had ever seen at the study site. The "Frosti" completed six midwater trawl tows at the study site on 2–4 February, at various times of the day (Table 1), of which five captured fish.

Widow rockfish dominated the five successful sets at the study site (62–92%), comprising 88% of the overall catch. Yellowtail rockfish (*S. flavidus*) accounted for 1–32% of the catch, 10% overall. Other rockfish accounted for up to 10% in individual sets, but only 2% overall. Non-rockfish fish species contributed less than 1%. For subsequent biomass calculations we assumed that 100% of the total catch was rockfish, of which 88% was widow rockfish.

Estimates of mean Sa and variance

The distribution of Sa observations (Fig. 6) supported the assumption of a closed system, in that the fish remained within the study area for the duration of the study. Fish were concentrated mostly to the northwest zone of the study site through micro-surveys 1–9, with some indication of a shift to the centre of the study site in later passes. Peak Sa values consistently corresponded to the high relief at the shelf break. We did not observe any evidence of rapid horizontal movement in or out of the study site. This was further supported by the acoustic display of the charter vessel. The displays of micro-surveys B1, B6, B8 and B17 in Figure 6 implied tht the southwestern end of the transects may have cut off the shoal as the maximum Sa values were observed at the southwest end of the transects. However, the transects were terminated over deep water where the shoal terminated abruptly.

Since there was no clear zonation in Sa from the centre to the perimeter (border effect), we applied the "intrinsic" methodology (Petitgas, 1993). The spatial analyses indicated isotropic spatial correlation (no directional effects) for most of the micro-surveys. There was no evidence of spatial correlation for B10. As described earlier, B3 and B4 exhibited a weak geometric anisotropy but in differing directions, while B16 exhibited weak zonal anisotropy. The model fits to the variograms corresponding to each micro-survey (except B10) were then used to estimate variance in mean Sa for each micro-survey (Table 3). The CVs inferred from these individualized variograms ranged from 4.8–17.8% with an average of 11.2%. The spatial correlation of B1 was examined after a normal score transformation (Petitgas, 1993) but the transformation had little impact on the assumptions regarding the underlying spatial correlation.

The global variogram was also fitted to a spherical model with a nugget value of 0.6×10^7, range of 0.015 and sill of 1.0×10^7 (Fig. 7). We then used the model of the global variogram to re-analyse each micro-survey. Owing to variation in the means, the CV varied from 9.6–29.5% with an average of 16.7%.

The observed variation in mean Sa among the 20 micro-surveys ranged from 800–2452 for a mean of 1590 and a CV of 30.9% (Fig. 8). This variability also includes the effect of combining the micro-surveys of the initial set of transects (1–10, 14, 17–20) with those of the offset series (11–13, 15–16).

Diel and tidal effects on mean density estimates

The diel variation in distribution was apparent when we plotted the proportion of the total Sa value that originates from greater than 10 m off bottom against the time of day. The observation indicate a higher proportion is more than 10 m off bottom near sunrise and following sunset (Fig. 9); however, there was no obvious indication that mean overall Sa was higher at specific times of the day (Fig. 10).

We did not observe an obvious relationship between mean Sa in the 20 micro-surveys over 52 hours and the daily tidal cycle (Fig. 10). Since our study only

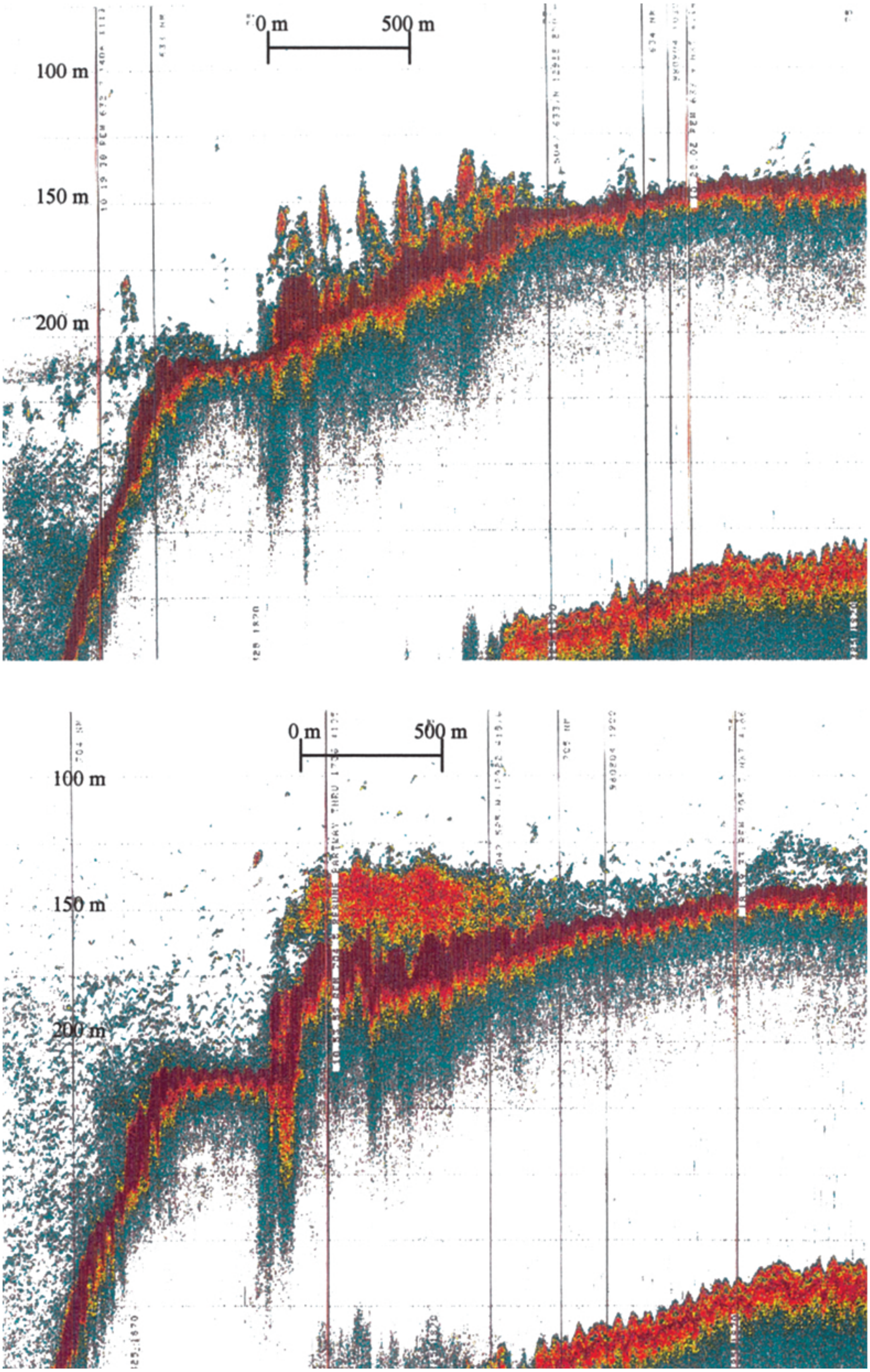

Figure 5. Rockfish echogram during mid-day (a) and after dusk (b).

Table 1. Summary of widow rockfish length data.

	Tow 1	Tow 2	Tow 3	Tow 4	Tow 6
Length range (cm)	32–52	34–57	37–56	39–54	34–54
Mean length (cm)	41.8	47.2	47.8	47.5	43.3
TS (dB)	− 35.08	− 34.02	− 33.91	− 33.97	− 34.77
Day or night	Night	Day	Day	Night	Night
Start time of tow (PST)	11:21 PM	9:13 AM	9:20 AM	1:00 PM	8:45 PM

corresponded to the tides of first quarter of the moon when the diel flux was at a minimum, we also could not examine the impact of the tidal variation as it varied through the lunar month.

Biomass estimates

Total biomass for the 20 micro-surveys averaged 1909 t (Table 3). Results from the offset versions were similar. The individual fisher transects provided biomass estimates of 199–17566 t (Table 3). Our estimates of biomass were congruent with the catch rates reported by fishers. We observed numerous peak Sa values of 10 000–50 000 $m^2 n.mi^{-2}$, equivalent to biomass estimates of 0.84–4.18 kg m^{-2}. Given that fishers can focus their efforts on areas of maximum density, the biomass density and swept area rate could provide catch rates of 5–25 t min^{-1}, if they fished along the longitudinal axis of the shoal (parallel to the bathymetry). Figures 5a and b show that they could tow in these densities across at least three transects for a distance of 2.2 km or duration of 24 minutes. Assuming the Sa range indicated above, such a tow could produce 120–600 t. Fishers report that they have observed catch rates at the lower end of this range. It is a rare occurrence, however, since catches of this size will destroy the net owing to expansion of the fish swim bladders as the net approaches the surface.

We also expected that our biomass estimates would be congruent with commercial catch records for the area. While different shoals may move along the edge of the continental shelf, we expected that an acoustic point estimate would at least be equal to any harvesting that had been conducted over a short period of time. The catch records of Table 4 reflect an area of 648 km^2 around the survey area of 28 km^2. The landings appear consistent with our estimates in that no amounts in excess of 2000 t have been caught over a period of a few months.

Table 2. Catch composition in tows.

Tow	Widow rockfish (kg)	Yellowtail rockfish (kg)	All species (kg)	% Widow rockfish
1	10 156	2106	12 338	82.3
2	5349	747	6804	78.6
3	13 010	199	13 607	95.6
4	1408	719	2268	62.1
5	0	0	0	—
6	20 879	1801	22 680	92.1

3D graphics displays

The acoustic backscatter measurements (Sas) of each micro-survey were displayed over interpolated bottom bathymetry in 3D imagery (Fig. 11) (Greene *et al.* 1998; Hajirakar *et al*., 1999).

Discussion

The mid-winter aggregation or shoal (Pitcher, 1983) of rockfish appears to stay near an underwater bluff at the edge of the continental shelf, typical of the high-relief affiliation of widow rockfish (Wilkins, 1986). The research trawl catches and history of commercial landings suggest that this shoal near Triangle Island is virtually all widow rockfish. The actual percentage can, however, be expected to differ from the catch composition, owing to the species-specific catchability of midwater trawl gear. Longline fishers suggest that some of the acoustic signal during the night might include other rockfish which, although benthic during the day, seem to rise off bottom during the night.

Consistent with Wilkins (1986), we observed a maximal display near dawn. We sometimes observed specific schools during the daytime, but also observed that the fish moved closer to bottom during daylight, in some cases almost disappearing from the sounder display. In contrast with Wilkins (1986) and with what fishers had reported, we did not observe any daily offshore movement. Our observations were conducted over a short period of time and in mid-winter as opposed to those of Wilkins (1986), which were conducted in March–April or August. The offshore movement may be associated with parturition in the early spring, or with more active feeding in the summer.

The precision among surveys was acceptable given that we were attempting to resolve abundance within "orders of magnitude"; however, it is not clear whether or not the mean of the 20 micro-surveys is the most

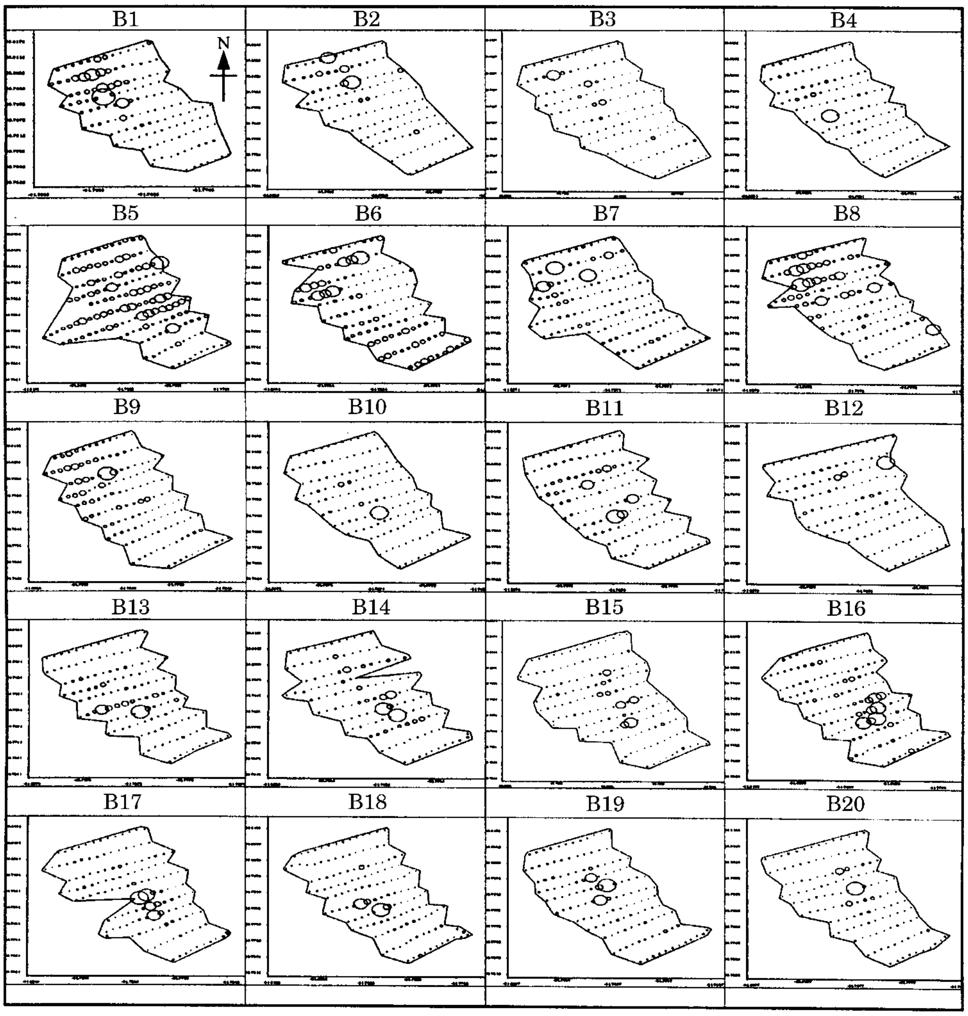

Figure 6. Distribution of fish density (Sa) within each micro-survey (from EVA2) (radius of the circle is proportional to Sa values).

appropriate point estimate of biomass. Bias towards underestimation of widow rockfish biomass may arise through difficulty in near-bottom detection, vessel avoidance, variation in target strength, signal attenuation in high density aggregations, and mis-identification with other species. For stock assessment, it may be more realistic to choose from the higher or maximum estimates.

The strong affinity to the high relief bottom, especially during the day, (Fig. 5a), implies that significant proportions of the biomass may be close enough to the bottom to be within the acoustic dead zone. On flat, smooth bottom, the dead zone for a given depth can be theoretically estimated based on beam angle and pulse length (Mitson, 1983, p. 161). For example, the dead zone should extend to 0.74 m above bottom at approximately

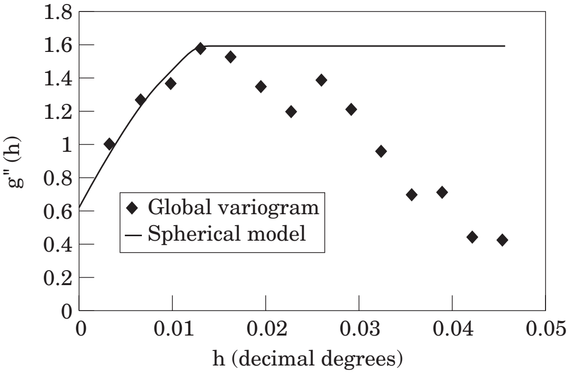

Figure 7. Fit of spherical relationship to global variogram.

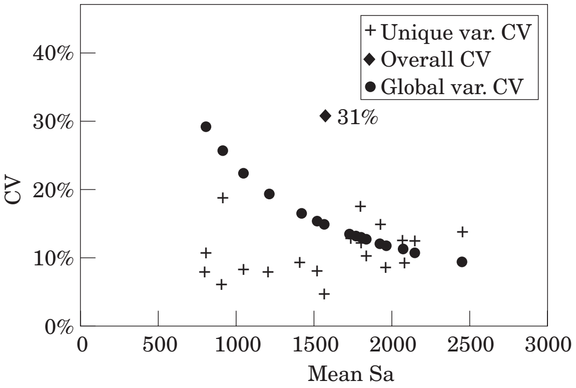

Figure 8. Observed CV for the mean Sa from the 20 micro-surveys and overall CV among surveys.

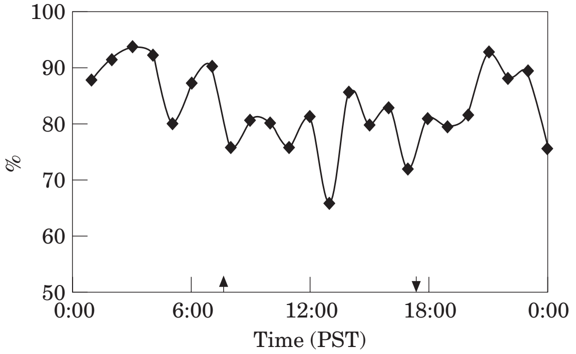

Figure 9. Percentage of fish density (Sa) >10 m off bottom against time of day (PST) (arrows indicate time of sunrise and sunset).

150 m bottom depth for the pulse length of 0.06 ms and beam angle of 7.1° used in this study. However, the actual altitude of the dead zone increases with increasing bottom slope and roughness, and rolling or pitching of the vessel. Steep rock faces provide additional dead zones, as the side lobes also may also interfere with fish detection. Since we observed transects when 40–60% of the backscatter originated from within 10 m of the acoustically defined bottom, we assume that some proportion was invisible to our equipment at these times. However, from Fig. 9 it also appears that there are times when over 90% of the acoustic backscatter was more than 10 m off bottom and the observed shoal appeared to be clearly separated from bottom. At these times, we could assume that only a small proportion of the potential backscatter from widow rockfish was in the dead zone. It seems unlikely that a high proportion of the widow rockfish was in the dead zone throughout all 20 micro-surveys.

Acoustic procedures may also underestimate density through variation in target strength as fish modify their tilt angle as part of their diel movement or vessel avoidance (Misund, 1997). Vessel avoidance may also reduce estimates through a horizontal dilution in front of the vessel. Sound range testing has shown that the "W. E. Ricker" has a relatively noisy acoustic signature. The quantitative impact of these biases cannot be resolved without directed study, but like the problem of near-bottom detection, the presence of these biases argue for adopting biomass values from among the higher estimates of the observed ranges, sampling variability notwithstanding.

Spatial analysis and variance among micro-surveys

The observation of a CV of 31% among the micro-surveys is consistent with other studies that conducted repetitive surveys over a short time period (reviewed in Misund, 1997). These include observations from Strømme and Sætersdal (1987), which indicated CVs of approximately 20% when repeating pelagic surveys off Senegal and Morocco between one and seven days apart. Williamson and Traynor (1996) noted CVs of 22% and 15% among replicate surveys of walleye pollock (*Theragra chalcogramma*) in their studies, which were conducted in two different years. Stanley *et al.* (1999) noted a CV of 14% among repetitive 100 km^2 micro-surveys of yellowtail rockfish conducted over about seven days.

The actual among micro-survey CV is noteworthy in being two to three times higher than the average CVs inferred from analysis of individual micro-surveys. The same observation was reported by Williamson and Traynor (1996), who noted that the CVs inferred from each survey averaged 5% and 6% in the two years as opposed to the 22% and 15% among replicates. This result is not surprising, since the variance "among" rather than "within" surveys incorporates the variation in fish distribution over time as an additional source of variance. Wilkins (1986) also emphasizes the effect of increasing variance with increased lag time between surveys. Here, the micro-surveys were repeated every two hours. In theory, variance inferred from the individual surveys only represents the sampling error for that "instantaneous" realization of fish distribution. Thus, the among-survey estimate includes effects of the changes in fish distribution every two hours over a 52-hour period.

The estimation of variance has serious implications for stock assessments. Many assessments are tuned with the results from single surveys or highly leveraged by the most recent survey, which is rarely replicated. The risk and uncertainty calculations for forward projections are conditioned by the estimated sampling variance of the most recent survey. The estimates of survey variance are intended to reflect the possible variation and background noise among yearly surveys that is not explained

Table 3. Mean density, variance and biomass of each micro-survey.

							Standard deviation of the mean			Biomass (t)	
							From individual variogram		From global variogram (s.d. = 236)		
Survey	Date	Time (PST)	Offset	Area (km^2)	Estimates of Sa (n)	Mean Sa (m^2/n.mi^2)	s.d.	CV	CV	Micro-survey	Fisher transect
1	2 February 1998	20:10	N	15.3	135	2070	264	12.8%	11.4%	2416	1701
2	2 February 1998	23:33	N	15.2	131	1799	321	17.8%	13.1%	2214	439
3	3 February 1998	1:53	N	15.0	131	1216	98	8.0%	19.4%	1467	314
4	3 February 1998	4:53	N	14.8	127	1837	193	10.5%	12.8%	1870	635
5	3 February 1998	7:34	N	17.1	146	1569	76	4.8%	15.0%	2087	372
6	3 February 1998	10:25	N	15.2	130	911	57	6.3%	25.9%	1207	206
7	3 February 1998	13:05	N	17.2	150	808	87	10.7%	29.2%	1221	296
8	3 February 1998	16:21	N	16.0	136	1525	124	8.1%	15.5%	2059	—
9	3 February 1998	20:21	N	16.3	141	800	64	8.0%	29.5%	1073	326
10	3 February 1998	23:00	N	16.0	140	916	173	18.8%	25.8%	1071	477
11	4 February 1998	1:44	Y	15.7	138	1050	89	8.5%	22.5%	1213	352
12	4 February 1998	4:27	Y	14.8	128	1420	134	9.5%	18.6%	1733	336
13	4 February 1998	6:47	Y	15.3	132	1805	223	12.4%	13.1%	1995	351
14	4 February 1998	9:28	N	15.4	126	2452	346	14.1%	9.6%	2630	538
15	4 February 1998	12:09	Y	17.1	149	1923	291	15.1%	12.3%	2361	199
16	4 February 1998	15:00	Y	16.8	147	2083	199	9.5%	11.3%	2510	395
17	4 February 1998	17:51	N	16.0	139	1968	175	8.9%	12.0%	2476	1756
18	4 February 1998	20:40	N	16.6	146	2147	271	12.6%	11.0%	2613	1217
19	4 February 1998	23:27	N	15.6	135	1762	240	13.6%	13.4%	2080	—
20	5 February 1998	3:20	N	15.2	133	1733	227	13.1%	13.6%	1875	—
Mean				15.8	137.0	1589		11.2%	16.7%	1909	583

Table 4. Widow rockfish landings (t) within the "South Triangle" fishing locality by bi-monthly interval.

	Year						
Months	1992	1993	1994	1995	1996	1997	1998
Jan–Feb	0	0	688	117	114	136	200
Mar–Apr	486	19	120	48	101	162	380
May–Jun	128	54	7	21	0	26	33
Jul–Aug	0	90	15	27	0	0	0
Sept–Oct	0	0	93	105	63	0	60
Nov–Dec	0	0	337	464	10	0	62
Total	614	163	1260	782	288	324	735

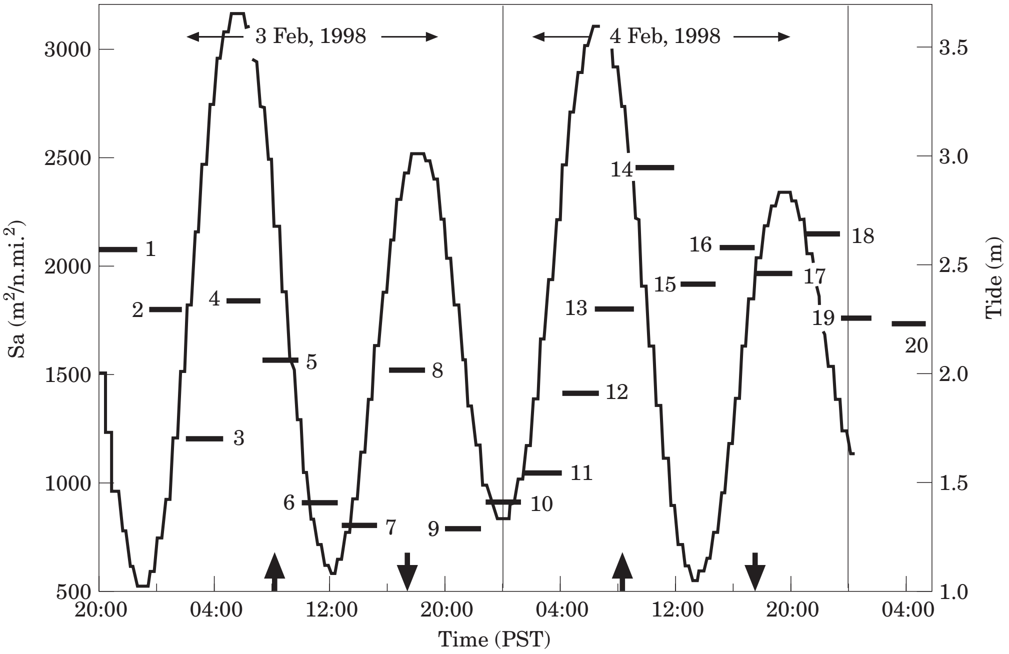

Figure 10. Graph of mean Sa against time of day and state of tide (arrows indicate time of sunrise and sunset).

by actual variation in biomass (Walters, 1998). Since it is impossible to conduct a survey over an identical set of tides, weather and environmental conditions each year, it is clear that an estimate of precision based on a single survey would not fully incorporate these effects. Larger-scale surveys over time and space might incorporate some of these sources of variance, but not all.

When used to condition analyses of uncertainties in forecasting fish populations, it would be more appropriate to use an estimator that reflected something closer to the variation one might actually observe among repeated surveys. This observation is consistent with a concern expressed during meetings with industry wherein fishers often suggest that assessment biologists are overly confident in the precision of their surveys. They suggest that for aggregating and vertically migrating species, availability on the grounds either to fishing gear or even sounding, is highly variable and often approaches a presence or absence phenomenon.

We were not successful in defining a clear relationship between acoustic estimates and tidal state or time of day. The limited number of micro-surveys precluded multivariate analysis of the overlapping effects of light intensity and tidal currents. These are often difficult to segregate (Michalsen *et al.*, 1996; Lawson and Rose, 1999). We suspect that dusk and dawn are periods of greater feeding activity, when more fish should be off bottom and, therefore, visible to the acoustic gear since their principal prey are planktonic (Adams, 1982). Fishers comment that many rockfish, and particularly widow rockfish off Triangle Island, appear more abundant during the rising tides following the first quarter of the moon. Since the present survey was constrained by weather to be conducted during the neap

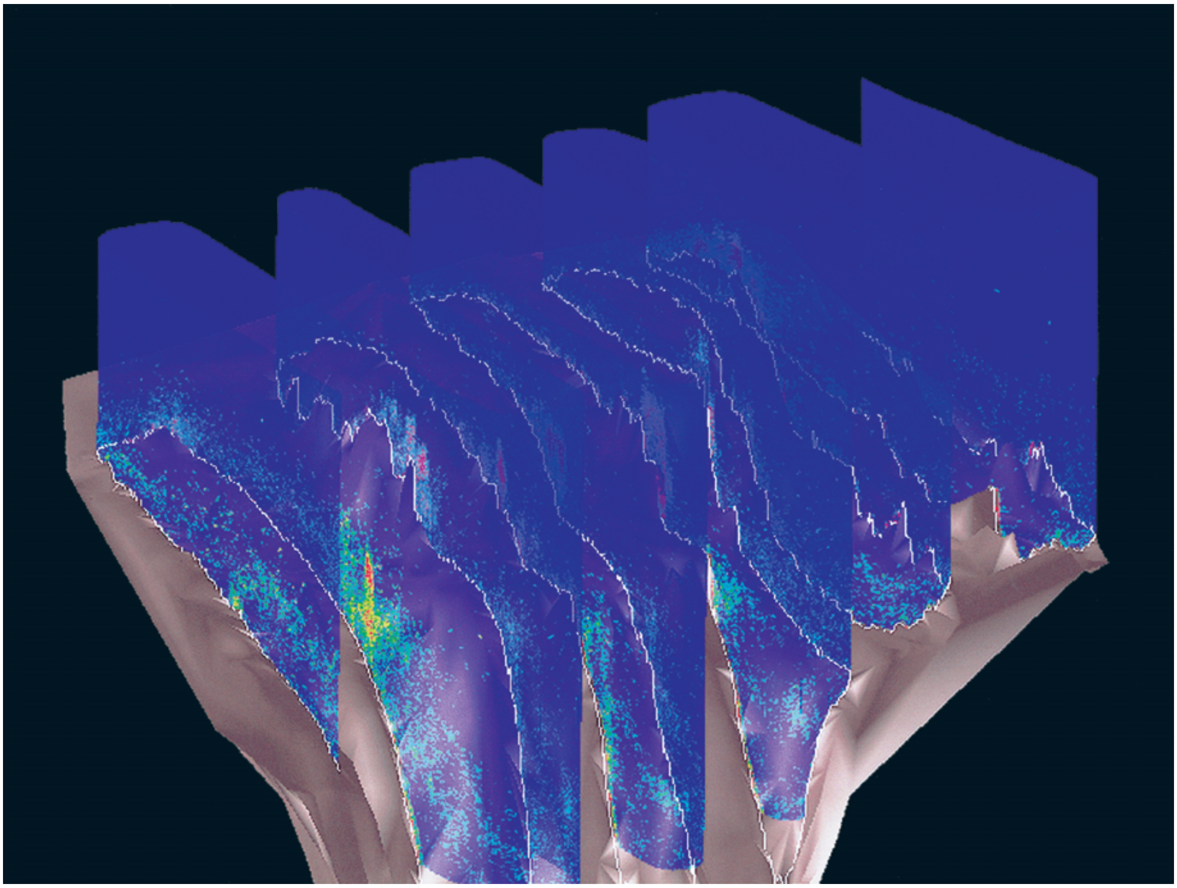

Figure 11. 3D display of micro-survey #3 at 0153 h on 3 February 1998 (1467 t biomass), with a curtain representing the vessel movement and the ensonified column.

tides around the first quarter, we could not examine this issue. The fishers participating in the study, however, agreed that the sounder display during the study was representative of the size of shoal what they wanted estimated and which they thought might change the assessments.

Biomass estimates

The biomass estimates of the study site averaged 1909 t. The biomass density of 76 t km^{-2} was much higher than the densities of 1.7–6.5 t km^{-2} reported by Wilkins (1986). However, his study attempted to cover a much larger area.

A principal objective in estimating biomass was to conduct the study such that it had scientific credibility from the perspective of the fishing community. We were aided in this by our ability to derive the biomass estimates following each micro-survey. The immediate feedback encouraged participating fishers to experiment with the study design. Firstly, they questioned whether the estimates were highly sensitive to choice of transects; however, by varying the set of transects with the offset series, they observed that the choice of transects had little impact.

Secondly, they were sceptical about the transect approach to acoustic surveying. It appeared to them that the survey spent too little time over the main shoal and therefore intuitively must result in a lower biomass estimate. We accommodated this concern by extrapolating a biomass estimate from each fisher transect. They found that even though these transects concentrated on the shoal and provided a consistent display in the sounder monitor, the crude extrapolations did not indicate greater biomass. Finally, we converted the biomass density estimates we observed to the catches that could be expected from commercial tows based on net specifications and simplified assumptions of catchability. This showed that our acoustic estimates were congruent with fishers' catch rates.

Widow rockfish live in excess of 50 years with an estimated instantaneous natural mortality rate of 0.07–0.15. Thus, the current recommended harvest range implies a biomass of 7000–42 000 t, depending on the choice of precautionary strategy (Stanley and Haist, 1997; Clark, 1991). Starting two months before the study, all fishers were asked to report all significant sightings of widow rockfish, but only three reports were submitted. Two were for the study site and one was for an area 40 km to the east, which we visited during the last days of the study without observing a significant shoal. Thus there were no anecdotal reports of large shoals elsewhere concurrent with the appearance of the Triangle Island shoal. While the study was not intended as a stock-wide biomass survey, it did test the hypothesis of whether a biomass estimated for the large Triangle Island shoal could, by itself, invalidate the current precautionary quotas 1100–3000 t (Stanley and Haist, 1997). The estimates of less than 3000 t for this shoal with no concurrent evidence of other shoals on the British Colombia coast failed to invalidate current quota management.

Even though the study was successful in its main objectives, it illuminated the problems that continue to plague the use of acoustics technology for estimating rockfish biomass on the Pacific coast (Wilkins, 1986; Richards *et al.*, 1991; Stanley *et al.*, 1999). Acoustics may work on specific shoals or groups of shoals, but larger-scale stock assessment is hampered by problems of species recognition, near-bottom detection, and our inability to predict the distribution of fish shoals. A variety of tools are leading to progress in resolving species identification (reviewed by Misund, 1997); but they seem unlikely, in the short-term, to be able to distinguish among species of rockfish. A more likely approach is to integrate fishers' knowledge of schooling behaviour and depth preferences while scrutinizing. Their expertise could be augmented with observations from catch records, simultaneous fishing, and camera or submarine work.

The problem of near-bottom detection varies with species. This study and others indicate that for some species there are times of the day when most of the fish are off-bottom. Remote camera or observations aboard submarines may indicate similar behaviour for other rockfish species and define a predictable pattern. The altitude of the dead zone could be reduced through use of a narrower beam transducer mounted on a deep towed body or autonomous underwater vehicle (AUV).

The most difficult aspect from an assessment perspective is the unpredictability of the distribution of semi-pelagic species of rockfish. Fishers report that while large off-bottom shoals of some rockfish species have appeared at some sites, the only predictable shoal is the Triangle Island widow rockfish shoal used in this study. Fishers cautioned researchers that large-scale surveys, scheduled a year in advance, may find nothing during the scheduled time of the cruise. We suggest that the most productive method for these species is to use a "ship-of-opportunity" approach and equip commercial fishers with the capability to capture and store high quality acoustic data from their soundings. This approach has been used successfully in herring stock assessment in eastern Canada (Melvin *et al.*, 1998). Equipment is readily available and requires minimal time for installation and calibration. While the process may not provide coastwide estimates for individual stocks, it can provide an inexpensive means for estimating significant shoals. Fishers have always argued that the existence of these apparently large shoals contradicts restrictive quotas, even though there was no basis for estimating the size of the shoals. During the 1970s and 1980s, rockfish stock assessment biologists on the Pacific coast of Canada and the US became familiar with mail deliveries of paper sounder output from commercial fishers. These were submitted as "evidence" that more fish were present than accounted for in-stock assessments. This study has shown that we can now provide a number to go with these images that is congruent with a fisher's terms of reference.

Acknowledgements

Fisheries and Oceans, Canada and the Canadian Groundfish Research and Conservation Society jointly funded the project. The cost of the charter was covered by a voluntary allocation of fish that was removed from the overall industry's quota. We appreciate the advice of Dr Pierre Petitgas and Dr Yvan Simard with the spatial analysis, although any mistakes are ours alone. The paper was also much improved by the review comments of Dr Neal Williamson and an anonymous reviewer.

References

Adams, P. B. 1982. Feeding behavior of the widow rockfish (*Sebastes entomelas*), a diurnally feeding rockfish. *In* Gutshop '81, pp. 198–204. Ed. by G. M. Cailliet, and C. A. Simenstad. Washington Sea Grant Program, Seattle, USA.

Bodholt, H. 1990. Fish density derived from echo-integration and *in situ* target strength measurements. ICES CM 1990/B:11.

Bodholt, H., and Solli, H. 1992. Split beam techniques used in SIMRAD EK500 to measure target strength. World Fisheries Congress, May 1992, Athens, Greece, pp. 16–31.

Clark, W. G. 1991. Groundfish exploitation rates based on life history parameters. Canadian Journal of Fisheries and Aquatic Sciences, 48: 734–750.

Eschmeyer, W. N., Herald, E. S., and Hamman, H. 1983. A field guide to the Pacific Coast fishes of North America. The Petersen Field Guide Series. Houghton Mifflin Co, Boston. 336 pp.

Foote, K. G. 1987. Fish target strengths for use in echo integrator surveys. Journal Acoustics Society of America, 82: 981–987.

Foote, K. G., Knudsen, H. P., Vestnes, G., MacLennan, D. N., and Simmonds, E. J. 1987. Calibration of acoustic instruments for density estimation: A practical guide. ICES Co-operative Research Report, 144: 69 pp.

Foote, K. G., Aglen, A., and Nakken, O. 1985. *In situ* fish target strengths derived with a split-beam echo sounder. ICES Fish Capture Committee. ICES CM 1985/B:28, 14 pp.

Gauthier, S., and Rose, G. 1998. An *in situ* Target Strength model for Atlantic redfish. *In* Proceedings of the 16th International Congress on Acoustics and of the 135th meeting of the Acoustical Society of America, Seattle, Washington, Vol. III, pp. 1817–1818. Ed. by P. K. Kuhl, and L. A. Crum.

Greene, C. H., Wiebe, P. H., Pelkie, C., Benfied, M. C., and Popp, J. M. 1998. Three dimensional acoustic visualization of zooplankton patchness. Deep Sea Research Part II. Tropical Studies in Oceanography, 45: 1201–1217.

Hajirakar, M., Kieser, R., Stanley, R. D., Cornthwaite, A. M., and Huang, P. Y. 1999. Three-dimensional visualization of fishery acoustic data and bathymetry using IBM Visualization Data Explorer. Canadian Manuscript Report Fisheries Aquatic Science: No. 2486: 54 pp.

Journel, A. G., and Huijbrets, C. J. 1978. Mining Geostatistics. Academic Press, New York. 600 pp.

Lawson, G. L., and Rose, G. A. 1999. The importance of detectability to acoustic surveys of semi-demersal fish. ICES Journal of Marine Science, 56: 370–380.

MacLennan, D. N., and Simmons, E. J. 1992. Fisheries acoustics. Fish and Fisheries Series. Chapman and Hall, 2–6 Boundary Row, London, SE1 8HN.

Magnússon, J., Nedreaas, K. H., Magnússon, J. V., Reynisson, P., and Sigurdsson, Th. 1994. Report on the Joint Icelandic/Norwegian Survey on Oceanic redfish in the Irminger Sea and Adjacent Waters, in June/July 1994. ICES CM 1994/G:44, 29 pp.

Melvin, G., Li, Y., Mayer, L., and Clay, A. 1998. The development of an automated sounder/sonar acoustic logging system for deployment on commercial fishing vessels. ICES CM 1998/S:14, 23 pp.

Michalsen, K., Godo, O. R. O., and Ferno, A. 1996. Diel variability in the catchability of gadoids and its influence on the reliability of abundance indices. ICES Journal of Marine Science, 53: 389–396.

Misund, O. A. 1997. Underwater acoustics in marine fisheries and fisheries research. Reviews in Fish Biology and Fisheries, 7: 1–34.

Mitson, R. B. 1983. Fisheries sonar. Fishing News Books, Ltd, 1 Long Garden Walk, Farnham, Surrey, England. 287 pp.

Orlowsky, A. 1987. Acoustic estimation of redfish stocks and their distribution in the Reykjanes Ridge area. Report of the Fisheries Institute, 22: 25–47.

Petitgas, P. 1993. Geostatistics for fish stock assessments: a review and an acoustic application. ICES Journal of Marine Science, 50: 285–298.

Petitgas, P., and Lafont, T. 1997. EVA2: Estimation variance. Version 2. A geostatistical software on Windows 95 for the precision of fish stock assessment surveys. ICES CM 1997/Y:22.

Pitcher, T. J. 1983. Heuristic definitions of fish shoaling behaviour. Animal Behaviour, 31: 611–613.

Ralston, S., and Pearson, D. E. 1997. Status of the widow rockfish stock in 1997. Appendix to: Status of the Pacific coast groundfish fishery through 1997 and recommended acceptable biological catches for 1998. Stock assessment and evaluation. October 1997. Pacific Fishery Management Council, Portland, Oregon.

Reynisson, P. 1992. Target strength measurements of oceanic redfish in the Irminger Sea. ICES Fish Capture Committee. ICES CM 1992/B:8, 13 pp.

Reynisson, P., and Sigurosson, P. 1996. Diurnal variation in acoustic intensity and target strength measurements of oceanic redfish (*Sebastes mentella*) in the Irminger Sea. ICES Demersal Fish Committee. ICES CM 1996/G:25, 15 pp.

Richards, L. J., Kieser, R., Mulligan, T. J., and Candy, J. R. 1991. Classification of fish assemblages based on echo integration surveys. Canadian Journal of Fisheries and Aquatic Sciences, 48(7): 1264–1272.

SIMRAD. 1993a. SIMRAD EK500 scientific echo sounder reference manuals V4.01. SIMRAD Subsea A/S, Strandpromenaden 50, Box 111, N-3191 Horten, Norway.

SIMRAD. 1993b. SIMRAD BI500 post-processing system reference manuals V5.20. SIMRAD Subsea A/S, Strandpromenaden 50, Box 111, N-3191 Horten, Norway.

Stanley, R. D., and Haist, V. 1997. Shelf rockfish assessment for 1997 and recommended yield options for 1998. Canadian Stock Assessment Secretariat Research Document, 97/132.

Stanley, R. D., Kieser, R., Leaman, B. M., and Cooke, K. 1999. Diel vertical migration by yellowtail rockfish (*Sebastes flavidus*) and its impact on acoustic biomass estimation. Fishery Bulletin, 97: 320–331.

Strømme, T., and Sætersdal, G. 1987. Consistency of acoustic biomass assessments tested by repeated survey coverage. International Symposium on Fisheries Acoustics, Seattle, Washington, USA, June 22–26, 1987 (unpublished).

Walters, C. J. 1998. Evaluation of quota management policies for developing fisheries. Canadian Journal of Fisheries and Aquatic Science, 55: 2691–2705.

Wilkins, M. E. 1986. Development and evaluation of methodologies for assessing and monitoring the abundance of widow rockfish, *Sebastes entomelas*. Fishery Bulletin, 84: 287–310.

Williamson, N. J., and Traynor, J. J. 1996. Fisheries acoustic surveys of Alaskan pollock. ICES Journal of Marine Science, 53: 423–428.