

# Diel vertical migration and shoaling heterogeneity in Atlantic redfish: effects on acoustic and bottom-trawl surveys

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A series of experiments comparing acoustic and bottom-trawl surveys was conducted on Atlantic redfish (*Sebastes* spp.) on the edge of the Green and Grand Banks of Newfoundland, Canada. Redfish were on or near bottom by day and migrated vertically in the water column at night. In an attempt to account for biases attributable to the presence of fish in the near-bottom dead zone (DZ), a correction factor was applied based on density values measured within the first few metres above the detected bottom. Acoustic densities within increasing range increments above the bottom were compared with densities estimated from the trawl catch. Swept area was calculated using both the trawl's wing spread and door spread as proxies for the minimum and maximum fishing widths. Uncorrected acoustic densities were significantly higher during the night than during the day. No significant day/night differences for the entire water column were observed after DZ corrections. Close agreement between acoustic and trawl densities was obtained by integrating within the first 10 to 20 m off the bottom, with or without the DZ corrections, for both day and night experiments, but regression slopes differed. Trawl catchability appeared to be density-dependent at night, being higher at lower fish densities. Daytime acoustic estimates were more variable than those made at night, as indicated by consecutive passes of several transects and CVs of density (means of 131% during day, 35% at night). We conclude that acoustic measurements made at night provide the most reliable and least variable density estimates, and make recommendations for surveys.

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## Introduction

Redfish (*Sebastes* spp.) are a commercially important species with semi-pelagic to demersal distribution in the North Atlantic. These species have been surveyed using both bottom trawls and acoustic methods (Atkinson, 1989; Reynisson *et al.*, 1995; Vaskov *et al.*, 1998). Redfish migrate from the ocean floor to intermediate layers at night where they form scattered layers (Beamish, 1966). Several types of demersal and pelagic aggregations have been observed during daytime, from dense schools to the more common scattered bottom layers (Gauthier and Rose, 2002a). Such behaviour affects the catchability of redfish and generally results in higher bottom-trawl catch rates during the day than at night (Konstantinov and Shcherbino,

1958; Beamish, 1966; Parsons and Parsons, 1976; Pálsson *et al.*, 1985; Atkinson, 1989; Casey and Myers, 1998; Aglen *et al.*, 1999; Hjellvik *et al.*, 2002). Diel vertical migration and shoaling behaviour can also influence abundance estimates derived from acoustic surveys (Olsen, 1990; Simmonds *et al.*, 1992; Petitgas and Levenez, 1996; Aglen *et al.*, 1999). For demersally orientated species such as redfish, an important source of bias in acoustic measurements may be the inclusion of fish in the bottom echo, the so-called "deadzone problem" (Mitson, 1983). Hence, diel changes in the distribution of fish in relation to the ocean floor influence detectability and the reliability of acoustic estimates (Lawson and Rose, 1999; Hjellvik *et al.*, 2003).

In this paper, we report on experiments conducted at sea in several seasons designed to test the effects of shoaling

behaviour and vertical migration on the abundance assessment of redfish. We compare density estimates obtained simultaneously with bottom trawl and acoustic methods and assess the impacts of the scale of patchiness and shoaling behaviour on survey methods. We also examine acoustic detectability with respect to the near-bottom zone. Our overall objective is to recommend survey strategies that minimize biases attributable to the effects of shoaling behaviour and diel vertical migration in *Sebastes*.

## Material and methods

The study site was located on the edge of the Green and Grand Banks of Newfoundland in NAFO Subdivisions 3Ps and 3N (Figure 1). Experiments were conducted from the Canadian Coast guard Ship "Teleost" on large and virtually monotypic aggregations of beaked redfish (*Sebastes mentella* and *S. fasciatus*) during 24–27 July 1996 (eight bottom-trawl stations), 10–14 January 1997 (seven bottom-trawl stations), 30 March–2 April 1998 (18 bottom-trawl stations), and 24 June 1998 (two bottom-trawl stations). All aggregations were observed between depths of 100 to 450 m.

### Acoustic measurements

Acoustic data were collected with an EK500 (Kongsberg, SIMRAD) echosounder equipped with a hull-mounted, 38 kHz split-beam transducer (model ES38B) with

beam-width of  $7.1^\circ$  between half-power points. Calibration was performed using tungsten-carbide and copper spheres following recommended procedures (Foote *et al.*, 1987). During each experimental period, several transects of 1 to 9 km length were surveyed transmitting 1 ms pulses at a rate of  $1\text{--}2\text{ s}^{-1}$ . Each transect was run more than once and a total of six sites were monitored over a 24 h period. Volume-backscattering coefficients ( $s_v$ ,  $\text{m}^{-1}$ ) were estimated for every ping in bottom-locked vertical bins of 1 m resolution. An area-backscattering coefficient ( $s_a$ ,  $\text{m}^2\text{ m}^{-2}$ ) was obtained by integrating  $s_v$  over depth range  $z_1$  to  $z_2$ :

$$s_a = \int_{z_1}^{z_2} s_v dz. \quad (1)$$

The area fish density ( $\rho^{\text{acoust}}$ ,  $\text{fish m}^{-2}$ ) was obtained by dividing  $s_a$  by the expected mean backscattering cross-section of redfish  $\langle \sigma_{bs} \rangle$ :

$$\langle \sigma_{bs} \rangle = 10^{\text{TS}/10}, \quad (2)$$

where target strength (TS) was estimated using the TS-Length equation for redfish developed by Gauthier and Rose (2002b) and the mean total length ( $L$ ) of fish at each site:

$$\text{TS}(\text{dB}) = 20 \log[L] - 68.7. \quad (3)$$

Bottom and midwater trawls were used to identify species and estimate the size composition at a time and

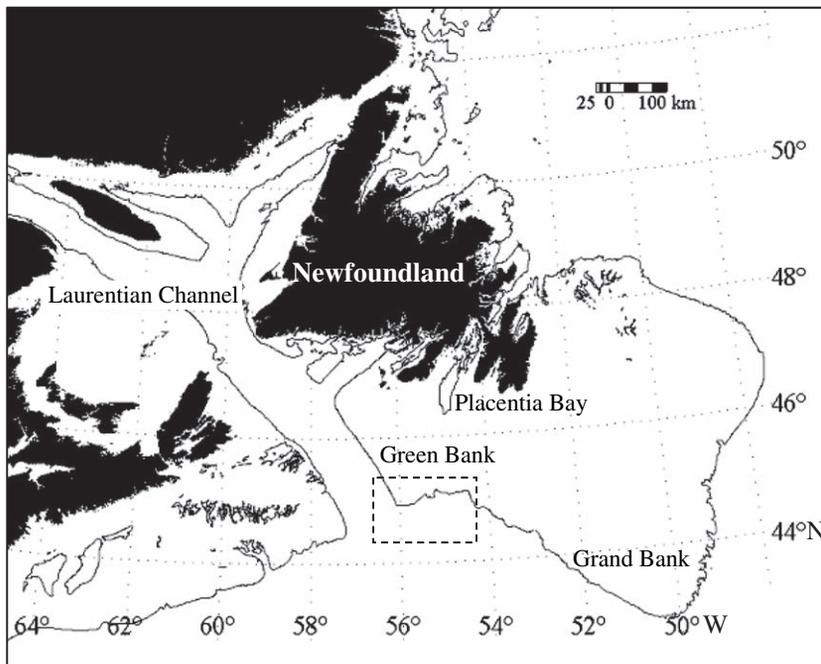


Figure 1. A map of Newfoundland and Atlantic Canada with 200-m depth contour lines. All acoustic and trawl stations were made in the area delimited by the dashed-line box.

location as close as possible to the acoustic observations. For this study, only acoustic and trawl data in which redfish dominated the catch (>90% by weight) were used. The size distribution of the redfish was determined by measuring the length and weight of 200–500 individuals from each catch. Length distributions were typically unimodal and spanned less than 20 cm (Gauthier and Rose, 2002b), hence mean length was used to calculate mean TS. IYGPT and Diamond-9 midwater trawls, both with 13 mm codend, were used at 10, 25, 50, 75, and 100 m off the bottom to identify pelagic traces when present. Midwater trawl results were inconsistent (mostly due to the crew’s inexperience with this type of gear) and were consequently used only as confirmation of redfish presence in the water column when strong acoustic signals were observed.

A correction for the acoustic near-bottom deadzone was applied using information from the  $s_v$  values in the first measurable layers above the detected bottom (as identified by the EK500 bottom algorithm). The DZ height was estimated as the sum of the bottom vertical offset (which varied between 0 and 1 m in this study, depending on bottom conditions), the partial integration zone ( $c\tau/4$ ) estimated using sound speed ( $c$ ,  $m\ s^{-1}$ ) and pulse duration ( $\tau$ , s), and the effective height loss due to beam convolution ( $h^{beam}$ , m). Ona and Mitson (1996) showed that this height could be estimated as:

$$h^{beam} = 2404 \left[ \frac{d \times \tan^4(\theta_3 \times \frac{\pi}{180})}{\theta_3^2} \right], \quad (4)$$

where  $\theta_3$  is the half-beam angle to the -3 dB point (in degrees) and  $d$  is the depth in m. A flat and horizontal bottom is assumed. To estimate the value of  $s_v$  within the DZ, we took into account the distribution of the density in the first six layers (1-m depth for each layer) above the detected seafloor and the distance (bin size) between consecutive  $s_v$  estimates, i.e. the DZ height and  $s_v$  estimation cell height (1 m in this case):

$$s_v^{deadzone} = s_v(b_1) + 0.5(h^{cell} + DZ) \left[ \frac{\sum_{i=1}^n (s_v(b_i) - s_v(b_{i+1}))}{(n-1)} \right], \quad (5)$$

where  $b_i$  denotes a depth layer above the detected sea floor (so that  $b_1$  represents the first layer),  $n$  the number of layers (six in our case),  $h^{cell}$  the height of the cells (bin size) used to estimate  $s_v$  (1 m in our case), and DZ the equivalent height of the dead zone (i.e. sum of the vertical offset, the partial integration zone, and the effective height). The resulting  $s_v^{deadzone}$  was then multiplied by the estimated height of the DZ to obtain the corresponding  $s_a^{deadzone}$ .

“Trawl-acoustic” comparisons

Fishing sets were conducted at a speed of three knots using a Campelen 1800 bottom trawl with 1400 kg poly oval

doors and a 44 mm codend. A SCANMAR system recorded the dimensions of the net while fishing (distance from seafloor, door and wing spread, distance of bottom to headrope). In March–April 1998, this information was used to estimate the mean wing spread and door spread during each haul (Figure 2). For sets in 1996, 1997, and June 1998 mean wing spread (WS) between depths of 100 and 450 m was estimated using a linear regression obtained from the data collected in 1998 ( $r^2 = 0.73$ , d.f. = 1, 22,  $F = 63.4$ ,  $p < 0.001$ ):

$$WS = 0.004 \times d + 15.4, \quad (6)$$

where  $d$  is the depth of the trawl in m. Door spread (DS) was estimated using the same approach ( $r^2 = 0.82$ , d.f. = 1, 22,  $F = 107.1$ ,  $p < 0.001$ ):

$$DS = 0.019 \times d + 44.5. \quad (7)$$

The number of fish caught at each site was estimated by dividing the weight of the total catch by the mean individual weight derived from a subsample of 200–500 fish. Area fish density along the trawl path ( $\rho^{trawl}$ ) was estimated as:

$$\rho^{trawl} = \frac{n}{WS \times v \times t}, \quad (8)$$

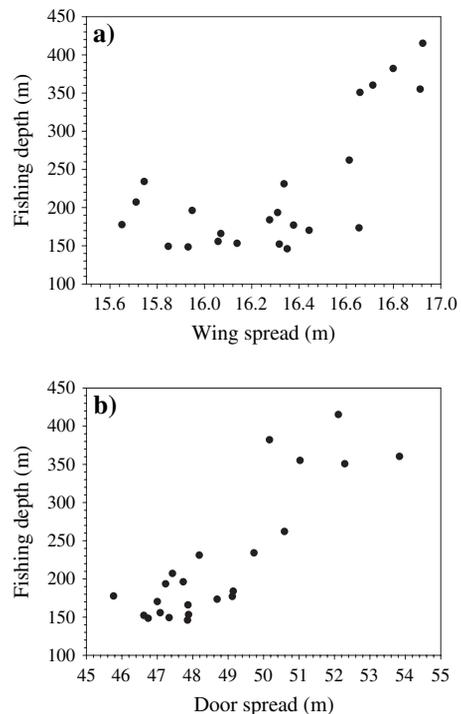


Figure 2. Wing spread (a) and door spread (b) of the Campelen 1800 bottom trawl as a function of fishing depth for the 1998 survey.

where  $n$  was the number of fish caught,  $WS$  was the mean wing spread of the net in m,  $v$  was the vessel speed in  $\text{m s}^{-1}$  and  $t$  was the duration of the tow in s. Densities were also estimated based on the trawl-door spread (substituting  $WS$  for  $DS$ ).

Acoustic records were matched to fished swept area as closely as possible. The distance of the net behind the vessel ( $X$ ) was estimated with the Pythagorean theorem (assuming no cable sagging) using the amount of tow wire out ( $L_w$ ) and the trawl depth ( $d$ ) in m.

$$X = \sqrt{L_w^2 - d^2}. \quad (9)$$

Once the location of the trawl was determined, the acoustic backscatter within the fishing interval was integrated in sequential 1 m vertical layers off the detected bottom. Area densities obtained at different heights above bottom ( $\rho^{\text{acoust}}$ ) were compared to the trawl density ( $\rho^{\text{trawl}}$ ). Linear regression analyses were performed on the log-transformed density estimates [ $\log(\rho + 1)$ ] to find the height at which acoustic integration best predicted densities based on the catch. Separate analyses were performed for wing and door spread, trawl density estimates and for time of day (day or night):

$$\log(\rho_m^{\text{trawl}} + 1) = a + b \times \log(\rho_i^{\text{acoust}} + 1) + \epsilon, \quad (10)$$

where  $m$  represents the method used to calculate density within the trawl path (wing spread vs. door spread),  $i$  represents the depth above the detected bottom (i.e. including all bottom layers up to  $i$ ),  $a$  is the intercept of the regression,  $b$  the slope of the regression, and  $\epsilon$  the error term. The best prediction of trawl density was based on goodness-of-fit ( $r^2$ ) and on slope value. A slope close to 1 indicates a proportional increase of trawl density with acoustic density. The point of inflexion in goodness-of-fit, at the height above bottom where  $r^2$  values no longer increase but begin to decrease was chosen as the best match between acoustic- and trawl-density estimates. Daytime and night-time were categorized according to local time of sunrise and sunset.

To obtain a relative index of catchability, the area density based on the catch (using either the wing or door spread) was divided by the area density obtained by the acoustic method at different heights above bottom. A value equal or close to unity indicated that the trawl caught the same amount of fish as predicted using acoustic integration. Values higher and lower than 1 indicated that the trawl caught more or fewer fish than the acoustic estimate, respectively.

### Density variability

In all, 24 acoustic paired transects of  $\sim 1400$  m (500 pings) were run during day and night. On each transect, the density was estimated for every ping and the coefficient of variation

(CV) within each transect was expressed as a percentage (standard deviation over the mean, multiplied by 100). Paired t-test analyses were employed to determine if acoustic transect mean area density differed between day and night (before and after DZ corrections). Separate paired t-test analyses were also performed on catch from trawls made at the same station during day and night. In addition, several acoustic transects were run twice over a relatively short period of time ( $< 1$  h). A reduced major axis (model II) regression analysis (Sokal and Rohlf, 1981) was performed between the first and second passes of each transect for both day and night experiments to assess the effect of local variance on these density estimates.

## Results

A distinct pattern of diel migration was observed in all three years of this study, and for fish of all the size classes measured (mean lengths from 14.8 to 32.4 cm). During the day, fish were concentrated close to the bottom and the densities were highly variable (Figure 3a). At night, fish were distributed more uniformly in scattered layers above the ocean floor (Figure 3b). These changes in the distribution patterns occurred at sunset and sunrise during all years and seasons of this study.

Estimated  $s_v$  within an equivalent dead zone of 1 m for four different density distributions is illustrated in Figure 4. Estimates for the  $s_v^{\text{dead zone}}$  followed the trend of the  $s_v$  in the first layers off bottom. For all daytime echo-integration data analyzed in this study, the  $s_a^{\text{dead zone}}$  represented on average 21% of the total  $s_a$  (maximum 46%). In contrast, the  $s_a^{\text{dead zone}}$  represented on average only 10% of the total  $s_a$  during the night (maximum 20%).

Using actual trawl geometry (measured wing spread and height of the headrope), area fish densities from acoustic integration were lower than area densities estimated from the trawl catch (Figure 5). The best predictions of trawl density were obtained by integrating within the first 10 to 20 m off the bottom, with or without the DZ corrections, for both day and night experiments (Tables 1 and 2). Regression slopes of trawl on acoustic densities differed significantly from and were  $\geq 1$  during the day but close to unity during the night. Correcting acoustic densities for the dead zone lowered the value of the slopes in both cases. Slope values dropped significantly if door spread instead of the wing spread was used to estimate area density within the trawl path. The best prediction of trawl catch was nonetheless still obtained by integrating the acoustic densities within 10 to 20 m off bottom. Day and night-time slopes were now greater than or near 1 and  $\leq 1$ , respectively.

The catchability index ( $q$ ) was highly variable, irrespective of the method used to calculate trawl path or acoustic DZ correction (Figure 6). The index was however closer to unity when using the door spread rather than the wing

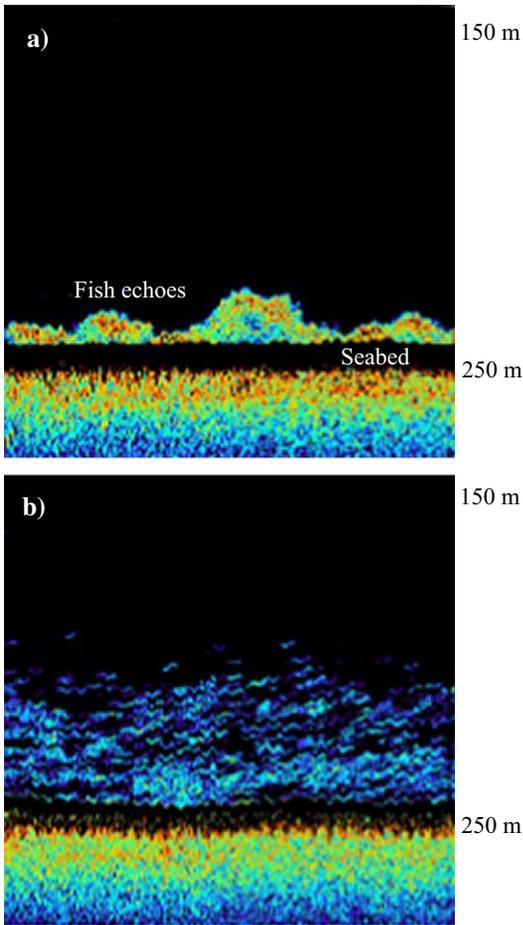


Figure 3. Representative echograms from (a) daytime and (b) night-time redfish aggregations. Each echogram represents approximately 500 pings ( $\sim 1400$  m).

spread to calculate area density within the trawl path. On average, catchability was lower at night than during the day. Using wing spread to calculate area trawl density, catchability was centred around unity only for the night experiment, and when integrating acoustic densities well above the trawl headrope. Within the range of density observed in this study, no significant relationship between catchability and fish density was observed ( $p > 0.05$ ) for pooled night and day data. However, night-time catchability was negatively correlated with acoustic density within the first 4 to 10 m off bottom ( $p$ 's  $< 0.05$ ). Within these intervals, catchability dropped as acoustic density increased (upper panels in Figure 6).

Area trawl densities at the same location were higher during the day than at night (mean difference of  $0.27 \text{ fish} \cdot \text{m}^{-2}$ , d.f. = 7, paired  $t = -2.6$ ,  $p < 0.05$ ). In contrast, acoustic area densities were lower during the day than at night (mean difference of  $0.06 \text{ fish} \cdot \text{m}^{-2}$ , d.f. = 22,  $t = -2.9$ ,  $p < 0.01$ ). No significant differences were

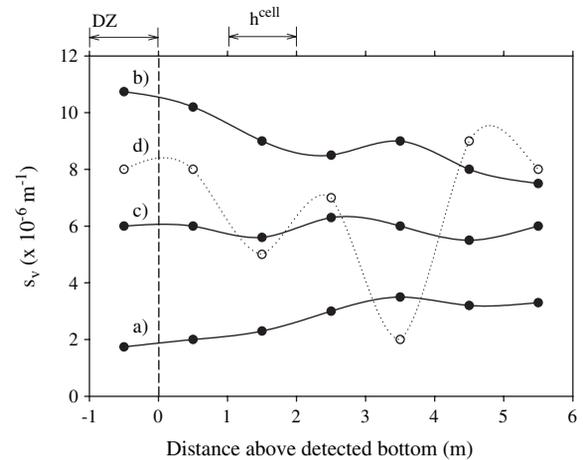


Figure 4. A profile of  $s_v$  in the first 6 m off the detected bottom for four different scenarios (a–d), chosen to represent situations in which density values are (a) increasing, (b) decreasing, (c) relatively constant, or (d) randomly changing with distance from the detected bottom. The vertical dashed line delimits the acoustic deadzone (DZ). The data points were extrapolated to the DZ using the correction factor described in the text.

observed between day and night acoustic estimates when the correction was applied for the acoustic DZ ( $p$ 's  $> 0.05$ ). Nevertheless, variability in fish density along any transect line was much higher during the day than at night (Figure 7). During the day, the CV was on average 131% and ranged from 89% to 215%. During the night the CV was on average 35% and ranged from 15% to 47%. Accordingly, regression analysis between consecutive passes over the same transect indicated that divergences were more pronounced during the day than at night (Figure 8). During the day, the coefficient of correlation for area density between the first and second pass was 0.57 with a slope of 0.76 (d.f. = 1, 46,  $F = 63.18$ ,  $p < 0.001$ ). At night, the correlation coefficient was 0.85 with a slope of 0.92 (d.f. = 1, 41,  $F = 233.48$ ,  $p < 0.001$ ). Intercepts did not differ significantly from zero in either case.

## Discussion

Our data indicate that Atlantic redfish vertically migrated from near bottom into the pelagic zone around sunset in all seasons, and returned close to the bottom near sunrise, forming patchy and dense aggregations with substantial densities in the DZ that covers the first few metres above bottom. Visual observation of numerous small redfish groups (10–30 individuals) in Placentia Bay using a submersible (Lawson and Rose, 1999) and observation of larger aggregations in the Laurentian channel using remote-controlled underwater cameras (D. Gordon, Fisheries and Oceans Canada, pers. comm.) confirmed the close association of redfish with the seafloor, especially during daylight hours.

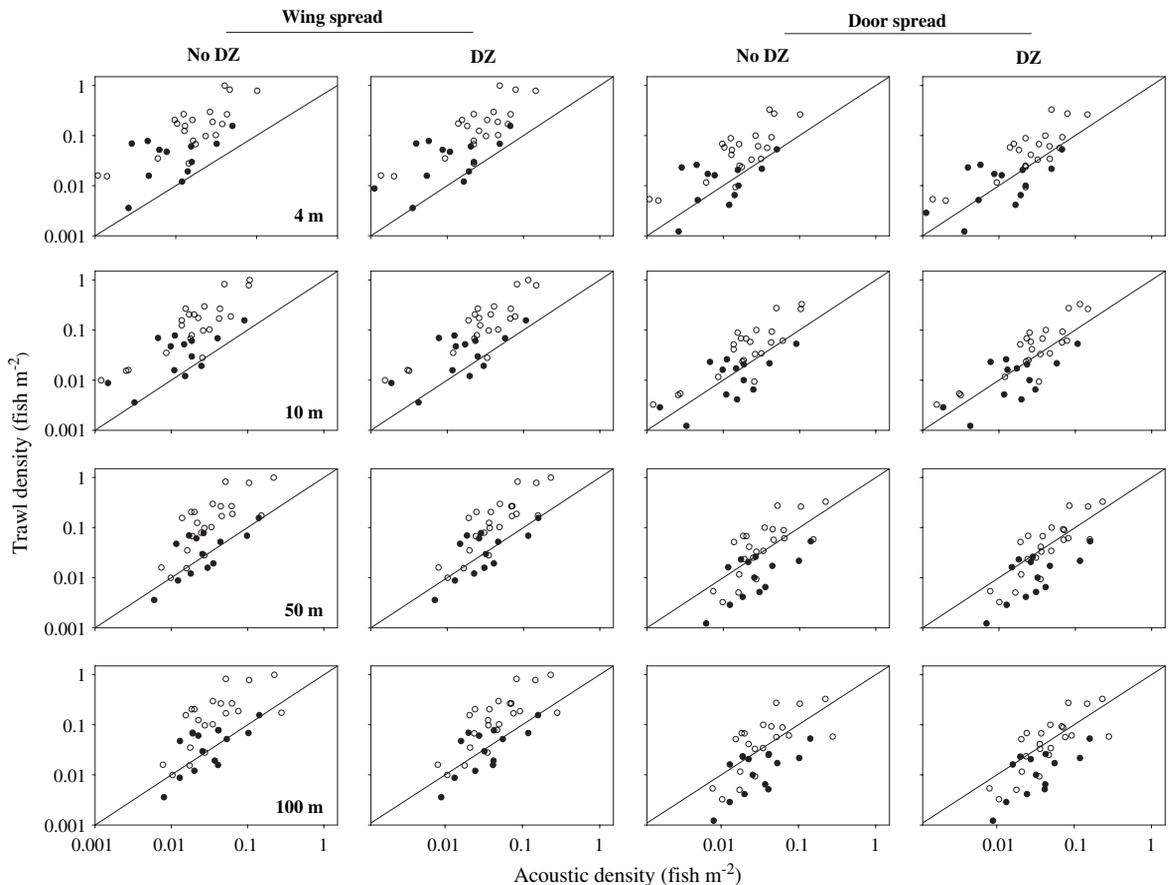


Figure 5. Comparisons of area density (fish  $m^{-2}$ ) estimated from catch and acoustic data. Densities estimated from the trawl catch used the wing-spread and the door-spread method. Acoustic density estimates include different height intervals above the seafloor, and are with and without the deadzone correction. Closed and open circles represent daytime and night-time results, respectively.

In our study region, redfish tend to occur in aggregations of fish of similar size, minimizing potential bias from the use of TS models based on mean fish length. In addition, TS uncertainties caused by tilt-angle variations during migration are likely to be less for *Sebastes* than for other vertically migrating species such as the gadoids (Gauthier and Rose, 2001) because of the oblong shape of their swimbladder. The aggregations encountered during this study were almost exclusively mono-specific, and biases attributable to species mixing are thought to be minimal. However, euphausiid swarms and scattering layers were common in this region. At a frequency of 38 kHz, low densities or single targets of euphausiids may not be detected, but the scattering layers were at times dense at night, and difficult to separate from redfish. Such conditions will introduce a bias into the night-time acoustic estimates and hence into day/night comparisons and comparison with catch estimates. Reynisson *et al.* (1995) indicated that, in the Irminger Sea, separation of redfish from scattering layer echoes was difficult at night. Reynisson (1996) also demonstrated the importance of threshold-induced bias in

the echo integration of single fish. In the present study, a threshold of  $-75$  dB for volume-backscattering strength (at 20 log R) was chosen as a compromise between bias and the exclusion of exogenous targets, e.g. the euphausiid scattering layer. When discrimination of redfish was thought to be problematic the data were not used. Such conditions occurred in less than 20% of night-time observations.

Another potential source of bias in our acoustic estimates was the extinction of sound, the so-called shadowing effect (Foote *et al.*, 1992), in dense daytime schools with large depth extent. Extinction of sound through fish aggregations depends on fish-scattering properties, volume density, and the vertical extent of the fish layer or school. This bias has been shown to be important for dense schools of herring *Clupea harengus* (Foote, 1999). However, Furusawa *et al.* (1992) showed that extinction was negligible even for the densest Walleye pollock (*Theragra chalcogramma*) school they measured. Comparison of the fish densities and depth range observed in the present study with those reported in the literature suggests that bias due to extinction is likely to

Table 1. Slope and  $r^2$  for the daytime log regressions of trawl density ( $\rho_m^{trawl}$ ) as a function of the acoustic density ( $\rho_i^{acoust}$ ) estimated at different heights above bottom. Wing spread and door spread were used to calculate densities within the trawl path. DZ correction was used for the acoustic estimates. Intercepts were not significantly different from 0 in all regressions ( $p > 0.05$ ). Bold values indicate the point of inflection (maximum  $r^2$ ) and/or the distance at which slopes are closest to 1.

Distance	Wing spread				Door spread			
	No DZ		DZ		No DZ		DZ	
	Slope	$r^2$	Slope	$r^2$	Slope	$r^2$	Slope	$r^2$
1	11.8	0.40	6.0	0.40	4.8	0.39	2.4	0.39
2	7.8	0.46	4.9	0.45	3.2	0.46	2.0	0.44
3	6.9	0.49	4.6	0.47	2.8	0.49	1.9	0.46
4	6.7	0.54	4.6	0.52	2.8	0.53	1.9	0.50
5	6.8	0.58	4.7	0.55	2.8	0.58	1.9	0.54
6	6.7	0.62	4.7	0.59	2.8	0.62	1.9	0.58
7	6.6	0.65	4.8	0.62	2.7	0.65	1.9	0.61
8	6.4	0.67	4.7	0.65	2.6	0.67	1.9	0.64
9	6.2	0.69	4.7	0.68	2.6	0.69	1.9	0.67
10	<b>6.0</b>	<b>0.70</b>	4.7	0.71	<b>2.5</b>	<b>0.71</b>	1.9	0.70
20	4.2	0.68	<b>4.0</b>	<b>0.78</b>	1.7	0.69	<b>1.6</b>	<b>0.78</b>
30	3.6	0.62	3.6	0.74	1.5	0.63	1.5	0.74
40	3.3	0.56	3.4	0.69	1.3	0.56	1.4	0.69
50	2.9	0.48	3.0	0.62	1.2	0.49	1.3	0.62
60	2.2	0.34	2.4	0.46	<b>0.9</b>	<b>0.34</b>	<b>1.0</b>	<b>0.47</b>
70	1.8	0.27	2.0	0.39	0.8	0.27	0.8	0.38
80	1.7	0.26	2.0	0.36	0.7	0.25	0.8	0.36
90	1.7	0.25	1.9	0.30	0.7	0.25	0.8	0.35
100	1.7	0.25	1.9	0.35	0.7	0.25	0.8	0.35

Table 2. Slope and  $r^2$  for the night-time log regressions of trawl density ( $\rho_m^{trawl}$ ) as a function of the acoustic density ( $\rho_i^{acoust}$ ) estimated at different heights above bottom. Wing spread and door spread were used to calculate densities within the trawl path. DZ correction was used for the acoustic estimates. Intercepts were not significantly different from 0 in all regressions ( $p > 0.05$ ). Bold values indicate the point of inflection (maximum  $r^2$ ) and/or the distance at which slopes are closest to 1.

Distance	Wing spread				Door spread			
	No DZ		DZ		No DZ		DZ	
	Slope	$r^2$	Slope	$r^2$	Slope	$r^2$	Slope	$r^2$
1	4.8	0.38	2.3	0.36	1.7	0.38	<b>0.8</b>	<b>0.36</b>
2	2.4	0.36	1.6	0.36	<b>0.9</b>	<b>0.36</b>	0.6	0.35
3	2.2	0.44	1.5	0.41	0.8	0.44	0.5	0.41
4	2.0	0.49	1.4	0.45	0.7	0.49	0.5	0.45
5	1.9	0.52	1.4	0.48	0.7	0.53	0.5	0.49
6	1.7	0.54	1.3	0.50	0.6	0.55	0.5	0.51
7	1.6	0.56	1.2	0.52	0.6	0.57	0.4	0.53
8	1.5	0.57	1.2	0.54	0.5	0.58	0.4	0.54
9	1.4	0.58	1.1	0.55	0.5	0.59	0.4	0.56
10	1.4	0.59	1.1	0.56	0.5	0.60	0.4	0.57
20	<b>1.0</b>	<b>0.63</b>	<b>0.8</b>	<b>0.61</b>	<b>0.3</b>	<b>0.64</b>	<b>0.3</b>	<b>0.62</b>
30	0.9	0.62	0.8	0.60	0.3	0.63	0.3	0.60
40	0.9	0.58	0.8	0.56	0.3	0.58	0.3	0.56
50	0.8	0.56	0.7	0.54	0.3	0.55	0.3	0.53
60	0.8	0.55	0.7	0.54	0.3	0.55	0.3	0.53
70	0.8	0.55	0.7	0.54	0.3	0.55	0.3	0.54
80	0.8	0.56	0.7	0.55	0.3	0.55	0.3	0.54
90	0.8	0.56	0.7	0.55	0.3	0.56	0.3	0.54
100	0.8	0.57	0.7	0.55	0.3	0.56	0.3	0.54

be negligible, with the possible exception of the very highest densities encountered during the day. These high-density conditions were, however, infrequent and consisted of shoals located directly on the bottom floor.

The correction factor we applied for the deadzone appears to fit the trend in density distribution during both day and night: the significant differences in acoustic densities observed between time of day were not evident after its use. The correction factor was much larger during the day. For example, when schools were small and fish were distributed only in the first few metres off the bottom, the DZ correction could represent a major component (>50%) of the density estimate. Such large corrections increase the uncertainty of acoustic measurements and hence should be used with caution.

Trawl and acoustic techniques do not sample the same volume of water, and their success depends on the distribution and availability of fish within the volume of water sampled. It is difficult to estimate the effective swath of a bottom-trawl sample in both the horizontal and vertical planes. There is little doubt that higher bottom-trawl catch rates occurred during the day because a larger proportion of

the fish were closer to the bottom and within the effective sample volume of the net. Fishers have known this for many years. Atkinson (1989) analysed 6898 redfish sets from the Northwest Atlantic and found differences in catch rates of approximately fourfold by number and fivefold by weight among diel periods. However, he reported that these differences did not significantly affect estimated trends in biomass, abundance, and distribution, and concluded that variability in redfish catch as a result of non-uniform horizontal distributions (arithmetic mean catch vs. lognormal or negative binomial distribution) was a more important source of error that masked the effects of diel migration. This conclusion probably depends on the survey design employed and is likely to hold if there is a low sampling density. Several other studies have also reported differences of two to fourfold between day and night catches (Beamish, 1966; Parsons and Parsons, 1976; Pálsson *et al.*, 1985; Casey and Myers, 1998). In addition to the changes in vertical distribution of fish, day/night differences could result from increased visual herding from the trawl during the day (Wardle, 1993) and reduced reaction at night (Michalsen *et al.*, 1996). However, Engaas

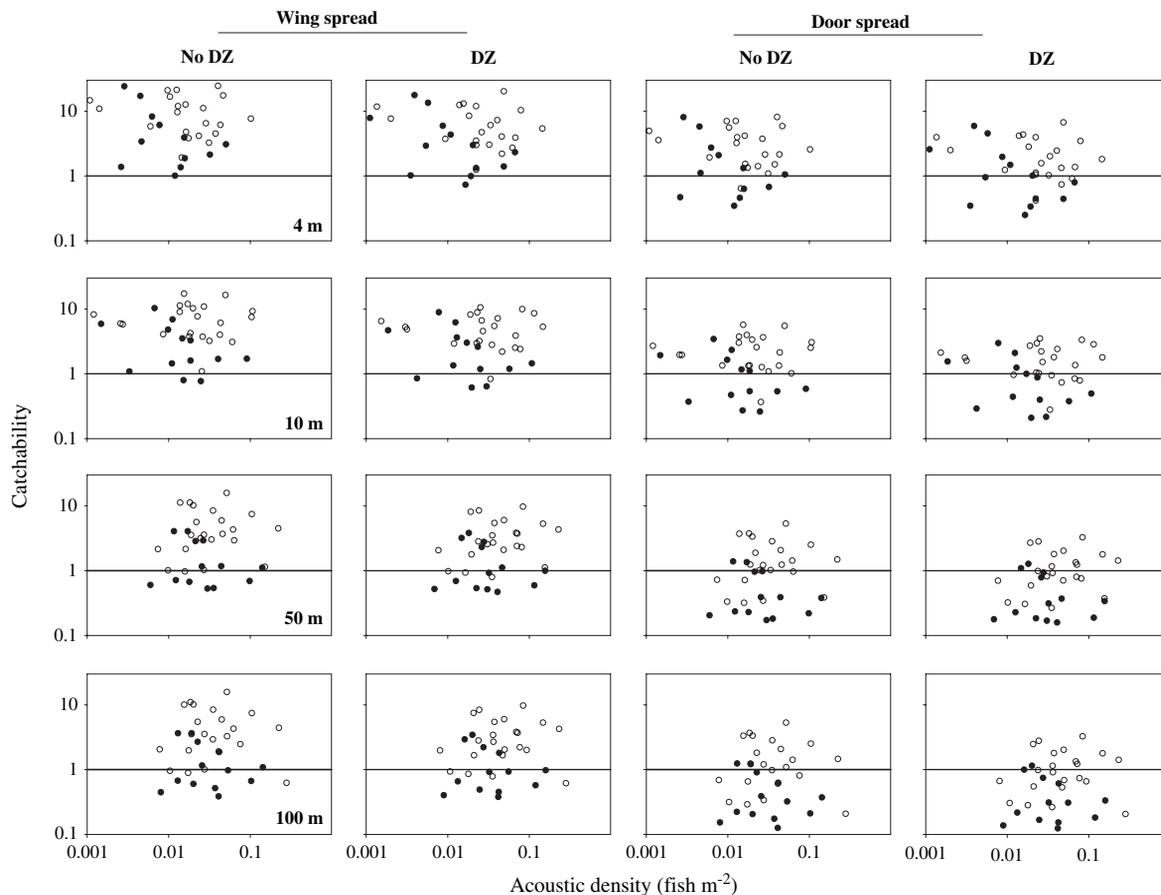


Figure 6. Relative catchability index ( $\rho^{\text{trawl}}$  divided by  $\rho^{\text{acoust}}$ ) as a function of acoustic density ( $\rho^{\text{acoust}}$ , fish  $\text{m}^{-2}$ ). Densities estimated from the trawl catch were estimated using the wing-spread and the door-spread method. Acoustic density estimates include different height intervals above the seafloor, and are with and without deadzone correction. Closed and open circles represent daytime and night-time results, respectively.

and Ona (1990) showed that, for gadoids, the herding process was equally efficient during day and night, but observed diel differences in the way fish entered and avoided the trawl opening.

Our results suggest that trawl surveys overestimate absolute redfish density. However, comparison of acoustic and trawl-area densities, respectively, depends greatly on the method used to estimate the width and height swept by the trawl. To our knowledge, no studies have addressed the issue of effective trawl width for *Sebastes*. We considered the door spread as the maximum effective trawl width, with wing spread as the minimum. The headrope of the Campelen trawl while fishing is approximately 4.2 m off the bottom. During the day, echo integration within this zone yielded lower estimates of density than was indicated by the trawl catch, even at the maximum fishing width. Hence, our data suggest that fish that were initially swimming above the trawl headrope were caught. The best prediction of catch was made by including fish up to 20 m off the bottom, but the high values of the regression

slopes suggest herding of fish at even greater heights. Yousif and Aglen (1999) reported that cod (*Gadus morhua*) up to 100 m above bottom might be scared down into the trawl. In another study on cod, saithe (*Pollachius virens*), redfish, and other demersal species, Aglen (1996) obtained significant correlations between acoustic and trawl density at heights of 30–40 m above the bottom, and higher for haddock *Melanogrammus aeglefinus*. Hjellvik *et al.* (2003) made similar observations on several species and noted strong variations between years and seasons. Such bias may result in overestimates of absolute redfish density but may be acceptable if densities are considered as relative estimates, based on a constant catchability.

In the present study, the catchability of redfish at night was not constant but negatively correlated with the acoustic density measured in depths up to 4 and 10 m off bottom (upper panels of Figure 6). There also appeared to be a similar but non-significant trend in the daytime catchability. The reasons for density-dependence are not clear. It is possible, for example, that the escape response of redfish

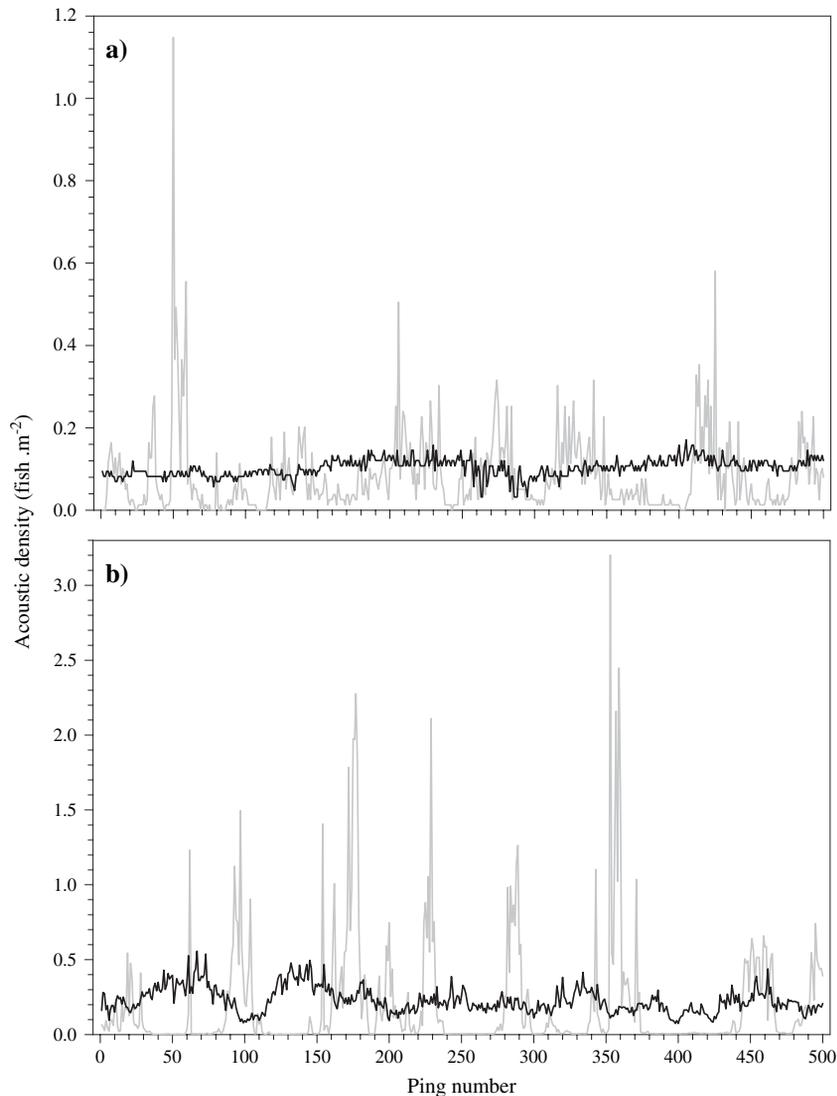


Figure 7. Distribution of acoustic density for the entire water column along two representative transects with 500 pings (ca. 1400 m) visited during day (grey line) and night (black line). Mean density, standard deviation and CV for (a) are: Day, 0.106, 0.125 and 118%; and Night, 0.128, 0.027 and 21% and for (b) are Day, 0.195, 0.384 and 196%; and Night, 0.227, 0.085 and 37%. No DZ corrections were applied to these data.

to the bottom trawl becomes more efficient as density increases, especially at night because of visual-threshold and herd-avoidance effects. Whatever the cause, density-dependence in catchability may be a serious problem for *Sebastes* trawl surveys.

Detailed analysis of acoustic area densities indicated that redfish horizontal distributions were more heterogeneous during the day than at night. Daytime patches were found on a relatively small spatial scale (tens to hundreds of m), while night-time aggregations were more continuous (over several km). Small-scale patchiness suggests that even small differences in the assigned position of the acoustic data relative to the trawl path could result in large

differences in density estimates. In keeping with this suggestion, mean acoustic area densities measured in consecutive passes over the same transect showed much higher variability during the day than at night, probably as a result of small differences in the position of repeated transects or movements of fish schools. Hence, surveying at night is likely to result in a reduction of bias attributable to spatial variability in fish distribution, an important source of error in both trawl and acoustic redfish surveys (Atkinson, 1989; Rose *et al.*, 2000).

In summary, the most reliable estimates of redfish area density are likely to be achieved using acoustic methods at night, supported by research trawling. We make the

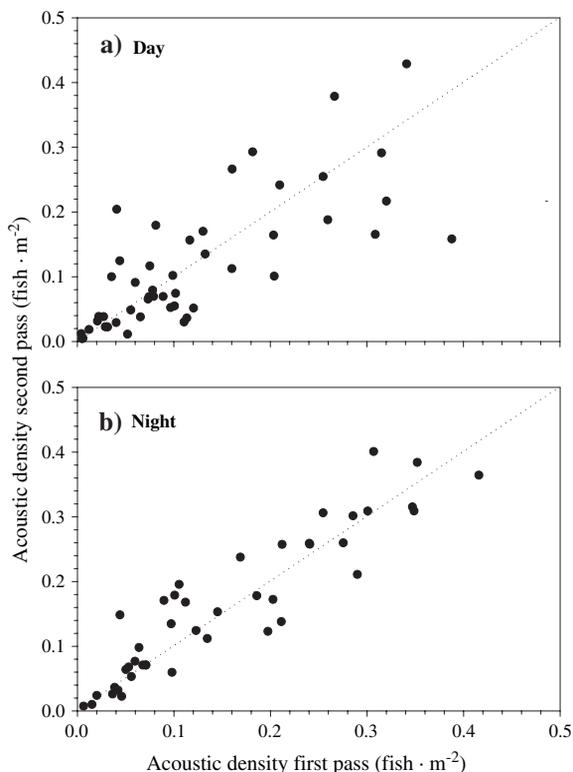


Figure 8. The relationship between acoustic density from two consecutive passes over several transects. (a) Daytime and (b) night-time transects. The dotted line represents a slope of 1.

following recommendations: (i) acoustic surveys should be conducted at night to decrease biases attributable to behaviourally-mediated dynamics of detectability (Lawson and Rose, 1999) and horizontal aggregation, (ii) a relatively simple TS-length model is likely to adequately scale backscatter to absolute density (e.g. Gauthier and Rose, 2002b), (iii) dead-zone correction is necessary (Ona and Mitson, 1999, this paper), (iv) accept small biases from inclusion of invertebrate backscatter, (v) survey design to further reduce horizontal density differences attributable to habitat preferences and schooling needs attention in any survey.

Bottom-trawl surveys for *Sebastes* can produce relative indices of abundance, but our results suggest the following cautions: (i) Trawling overestimates true density because of herding. (ii) Assumptions of constant catchability over a wide range of redfish densities may be invalid, especially at night. (iii) Bottom-trawl surveys are likely to produce lower and least variable catch at night than during the day, and mixes of day and night trawling may introduce bias into a survey design.

In conclusion, neither the acoustic nor the trawl methodologies are without significant bias. An optimized survey design will undoubtedly require both methods.

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## References

- Aglen, A. 1996. Impact of fish distribution and species composition on the relationship between acoustic and swept-area estimates of fish density. *ICES Journal of Marine Science*, 53: 501–506.
- Aglen, A., Engås, A., Huse, I., Michalsen, K., and Stenholt, B. K. 1999. How vertical fish distribution may affect survey results. *ICES Journal of Marine Science*, 56: 345–360.
- Atkinson, D. B. 1989. Diel movements of beaked redfish and the implications of these to stratified, random bottom-trawl estimates of biomass and abundance. *North American Journal of Fisheries Management*, 9: 163–170.
- Beamish, F. W. H. 1966. Vertical migration by demersal fish in the Northwest Atlantic. *Journal of the Fisheries Research Board of Canada*, 23: 109–139.
- Casey, J. M., and Myers, R. A. 1998. Diel variation in trawl catchability: is it as clear as day and night? *Canadian Journal of Fisheries and Aquatic Sciences*, 55: 2329–2340.
- Engaas, A., and Ona, E. 1990. Day and night fish-distribution pattern in the net-mouth area of the Norwegian bottom-sampling trawl. *Rapport et Procès-verbaux des Réunions du Conseil International pour l'Exploration de la Mer*, 189: 123–127.
- Footo, K. G. 1999. Extinction cross-section of Norwegian spring-spawning herring. *ICES Journal of Marine Science*, 56: 606–612.
- Footo, K. G., Knudsen, H. P., Vestnes, G., MacLennan, D. N., and Simmonds, E. J. 1987. Calibration of acoustic instruments for fish-density estimation: a practical guide. *International Council for the Exploration of the Sea Cooperative Research Report*, 144: 57 pp.
- Footo, K. G., Ona, E., and Tóresen, R. 1992. Determining the extinction cross-section of aggregating fish. *Journal of the Acoustical Society of America*, 91: 1983–1989.
- Furusawa, M., Ishii, K., and Miyanoana, Y. 1992. Attenuation of sound by schooling fish. *Journal of the Acoustical Society of America*, 92: 987–994.
- Gauthier, S., and Rose, G. A. 2001. The target strength of encaged Atlantic redfish (*Sebastes* spp.). *ICES Journal of Marine Science*, 58: 562–568.
- Gauthier, S., and Rose, G. A. 2002a. Acoustic observation of diel vertical migration and shoaling behaviour in Atlantic redfishes. *Journal of Fish Biology*, 61: 1135–1153.
- Gauthier, S., and Rose, G. A. 2002b. *In situ* target-strength studies on Atlantic redfish (*Sebastes* spp.). *ICES Journal of Marine Science*, 59: 805–815.
- Hjellvik, V., Godø, O. R., and Tjøstheim, D. 2002. Diurnal variations in bottom-trawl survey catches: does it pay to adjust? *Canadian Journal of Fisheries and Aquatic Sciences*, 59: 33–48.
- Hjellvik, V., Michalsen, K., Aglen, A., and Nakken, O. 2003. An attempt at estimating the effective fishing height of the bottom trawl using acoustic-survey recordings. *ICES Journal of Marine Science*, 60: 967–979.
- Konstantinov, K. G., and Shcherbino, M. N. 1958. The diurnal vertical migrations of redfish. *Rybnoe Khoziaistvo*, 39: 11–13.

- 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.
- Michalsen, K., Godø, O. R., and Fernø, A. 1996. Diel variation in the catchability of gadoids and its influence on the reliability of abundance indices. *ICES Journal of Marine Science*, 53: 389–395.
- Mitson, R. B. 1983. *Fisheries Sonar*. Fishing News Book, England.
- Olsen, K. 1990. Fish behaviour and acoustic sampling. Rapport et Procès-verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 189: 147–158.
- Ona, E., and Mitson, R. B. 1999. Acoustic sampling and signal processing near the seabed: the deadzone revisited. *ICES Journal of Marine Science*, 53: 677–690.
- Pálsson, O. K., Jónsson, E., Schpka, S. A., Steinarsson, B. Æ., and Thorsteinsson, G. 1985. Icelandic groundfish survey, 1985. NAFO Scientific Council Research Document 85/79.
- Parsons, L. S., and Parsons, D. G. 1976. Effects of diurnal variation in availability upon estimation of redfish numbers and biomass from stratified, random trawl surveys. *International Commission for the Northwest Atlantic Fisheries Selected Papers*, 1: 19–29.
- Petitgas, P., and Levenez, J. J. 1996. Spatial organization of pelagic fish: echogram structure, spatio-temporal condition, and biomass in Senegalese waters. *ICES Journal of Marine Science*, 53: 147–153.
- Reynisson, P. 1996. Evaluation of threshold-induced bias in the integration of single-fish echoes. *ICES Journal of Marine Science*, 53: 345–350.
- Reynisson, P., Sigurdsson, Th., Magnusson, J., and Magnusson, J. V. 1995. Diurnal variations of the echo intensity and some biological observations on redfish in the Irminger Sea. *ICES CM 1995/G:44*.
- Rose, G. A., Gauthier, S., and Lawson, G. L. 2000. Acoustic surveys in the full monte: estimating uncertainty. *Aquatic Living Resources*, 13: 1–6.
- Simmonds, E. J., Williamson, N. J., Gerlotto, F., and Aglen, A. 1992. Acoustic-survey design and analysis procedure: a comprehensive review of current practice. *ICES Cooperative Research Report*, 187: 127 pp.
- Sokal, R. R., and Rohlf, F. J. 1981. *Biometry*. W. H. Freeman and Company, New York.
- Vaskov, A. A., Mamylov, V. S., and Ratushny, S. V. 1998. Review of 1983–1996 Russian trawl and acoustic surveys to assess redfish stock on the Flemish Cap Bank. Science Council Research Document, NAFO, 98/15.
- Wardle, C. S. 1993. Fish behaviour and fishing gear. *In The Behaviour of Teleost Fishes*, 2nd ed. Ed. by T. J. Pitcher. Fish and Fisheries Series 7. Chapman and Hall, London.
- Yousif, A., and Aglen, A. 1999. Availability of pelagic-distributed cod (*Gadus morhua* L.) to bottom trawls in the Barents Sea. *Fisheries Research*, 44: 47–57.