ICES Journal of Marine Science, 60: 860–871. 2003
doi:10.1016/S1054–3139(03)00068-7

The diel vertical distribution and characteristics of pre-spawning aggregations of pollock (*Pollachius virens*) as inferred from hydroacoustic observations: the implications for survey design

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Neilson, J. D., Clark, D., Melvin, G. D., Perley, P., and Stevens, C. 2003. The diel vertical distribution and characteristics of pre-spawning aggregations of pollock (*Pollachius virens*) as inferred from hydroacoustic observations: the implications for survey design. – ICES Journal of Marine Science, 60: 860–871.

The characteristics of pollock (the synonymous European common name is saithe) pre-spawning aggregations were described at two locations with contrasting bathymetric features on the Scotian Shelf, off the Canadian Maritimes. The data were collected using a split-beam echosounder onboard a research vessel, augmented with periodic, bottom-trawl samples. Pollock form aggregations each fall that persist at the same location over time. Such aggregations appeared to be associated with spawning. Hydroacoustic information indicates that pollock become more densely aggregated at night. This could reflect movement away from the study area during the day, or changes in the proportion of pollock in the acoustic dead zone over the 24-h period. The hydroacoustic information indicates that while pollock can occur up to 30 m off bottom, the greatest proportion remains within 1–5 m off bottom during both day and night. The length composition of the pollock aggregations differed between the two sites, with larger fish found at the site further offshore. Within an aggregation, there was spatial heterogeneity with respect to fish size, with larger fish found primarily within the core area of aggregation as shown by the hydroacoustics. An appropriate survey design for obtaining an index of abundance for pollock would reflect both the contagious (patchy) distribution as they prepare to spawn, and the diel differences in the availability of the fish to the hydroacoustic-sampling gear.

Keywords: acoustic surveys, groundfish, aggregations, diel, bathymetry.

Received 29 July 2002; accepted 3 March 2003.

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Introduction

Pollock (*Pollachius virens*) is an abundant member of the Gadidae family in the Canadian Maritime waters and supports significant fisheries. However, despite its prominence in the demersal-fish community, little is known of its biology compared with other gadids such as cod (*Gadus morhua*) or haddock (*Melanogrammus aeglefinus*). The life history of pollock involves an offshore-spawning and larval phase, recruitment to the coastal environment for a period of 1–2 years, and then an offshore migration (Clay *et al.*, 1989). As adults in the offshore environment, they are generally found in schools of fish of about the same size. For example, within the Bay of Fundy (Figure 1) smaller (45–60 cm) fish were found off Brier Island at the mouth of the Bay of Fundy, off southwest Nova Scotia and larger (65–85 cm) fish were found off the western side of the bay (Steele, 1963). On the basis of a laboratory study of the internal structure and shape of fish schools, pollock were considered to be strongly facultative schoolers (Partridge *et al.*, 1980) and maintain consistent position in relation to neighbouring fish. It is also known that pollock spend less

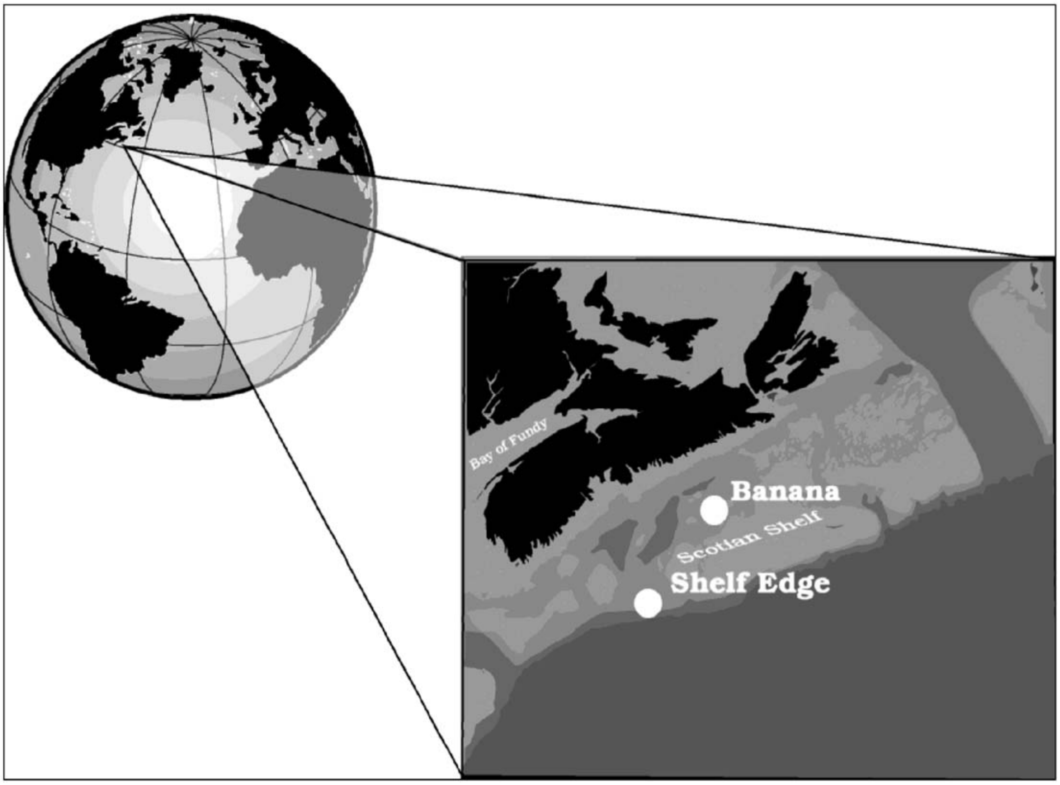

Figure 1. The positions of the two study sites located on the Scotian Shelf, Northwest Atlantic. The study area shown on a representation of the globe is also provided.

time on the bottom and more time moving freely through the water column (Scott and Scott, 1988) compared with other gadids.

The schooling, semi-pelagic, life-history characteristics of pollock make them ill-suited for the derivation of estimates of abundance from conventional bottom-trawl surveys. Neilson *et al.* (2002) noted that there has been interest in developing alternative indicators of the abundance of pollock. Elsewhere in the Atlantic range of the species, countries such as Norway (Nedreaas, 1997) have employed acoustic techniques for the evaluation of pollock abundance. The same life-history characteristics that make pollock ill-suited for conventional bottom-trawl surveys may enhance the prospects for using hydroacoustic approaches that have been more typically used for pelagic species such as herring. Prior to the implementation of such approaches, however, we wished to investigate the biological characteristics of pollock aggregations that might influence the survey design and evaluate the potential utility of hydroacoustic methods for assessing pollock abundance.

Neilson *et al.* (2002) described the seasonal component of pollock aggregations using information from the otter-trawler fleet operating on the Scotian Shelf off Canada's East Coast, and year-round, hydroacoustic data collected onboard a vessel specializing in the pollock fishery. These data were examined to assist with the design and evaluation of a potential survey of abundance for this species using hydroacoustic approaches. It was shown that the locations of aggregations do not change appreciably from month to month. However, the proportion of pollock weight compared with total-catch weight in individual sets tended to be higher from September to February. Standardized catch-rate analyses revealed that the highest catch rates occurred during the December–January period. Analysis of the hydroacoustic data showed that during this period pollock had least affinity with the seabed: a behavioural consideration for acoustic-survey design. Based on these observations, it was concluded that an acoustic survey during the December–January period might have the highest chance of success.

Having described aspects of the seasonality of pollock aggregations, we were interested in the finer-scale features that might be of consequence in survey design. In particular, we were interested in understanding day/night differences in the aggregations. This paper addresses these considerations.

Materials and methods

The data presented here were collected on board the CCGS "Teleost", from September 30 to October 4, 1999 at the location of two pollock aggregations on the Scotian Shelf (Figure 1). The first of these was located on a local bathymetric feature known to local fishermen as "The Banana" and it was sampled from September 30 to October 1, 1999, and also on October 4, 1999. The "Teleost" was joined on October 4 by the CFV "Cape John", a commercial otter trawler, as part of an industry–government joint effort to evaluate the acoustic approach for studying pollock aggregations. The second aggregation was located on the Scotian Shelf edge and it was sampled on October 2–3, 1999.

The acoustic equipment included a calibrated, Simrad EK 500 echosounder with a hull-mounted, split-beam, 38 kHz transducer and a personal computer. The performance of the EK500 was measured prior to the start of the trip while the vessel was moored in a deep-water cove by two bow and two stern anchors. A 38-mm tungsten-carbide sphere was suspended under the vessel by three monofilament lines at a range of approximately 27 m below the transducer. A vertical cast was made with a CTD to acquire data for calculation of the sound speed at the depth of the sphere. This value was used to determine a TS value for the sphere. The CTD data were used to compute the average sound speed for the range from the transducer face to the sphere also. This value was entered into the EK500 via the Sound-Speed Menu. The calibration was completed using the TS-measurement-, S_A-measurement- and LOBE-software procedures described in the "Calibration of the EK500/EY500 Section of the Simrad EK500 Manual". The TS and S_v Transducer Gains were estimated to be 26.13 and 26.11 dB, respectively. The values for beamwidth provided by the "FIT" procedure of the LOBE program were: 6.8° for the athwartships direction and 7.0 for the alongships direction. Using these beamwidth estimates, the equivalent two-way beam angle was computed to be −20.9 dB.

Acoustic data were collected on board the "Teleost" when the ship was steaming along transects at 6.0 knots, and during bottom trawls, typically conducted at 3.5 knots. The EK500 was configured with a ping interval of 1.0 s/pulse, a pulse length of 1.0 ms and a bandwidth setting of "Auto". The data-acquisition software known as CH1 (Simard *et al.*, 1998) was used to record volume-backscattering strength (S_v) data. On return to the laboratory, the S_v data were edited and integrated using the hydroacoustic data-analysis software known as CH2 (Simard *et al.*, 2000). The editing procedure involved removing ambient noise associated with the operation of the ship's acoustic-net, mensuration system, and identifying the bottom relative to fish concentrations. Backscattering-area coefficients (S_a, a unitless parameter (m2/m2), Anon., 2000) were obtained by integrating S_v data for six layers (1–5, 6–10, 11–15, 16–20, 21–25 and 26–30 m off bottom). The first metre off bottom was excluded from the integration because fish targets close to the bottom are generally undetectable using standard hydroacoustic techniques (Ona and Mitson, 1996).

The S_a data were averaged over six pings that, at a vessel speed of 6 knots, corresponded with a distance of about 18–30 m, depending on the speed over the bottom. To provide a graphic representation of the density of the fish as indicated by the hydroacoustic data, these average S_a values were contoured using kriging software (Anon., 2001). This approach takes irregularly spaced and geo-referenced data and interpolates it into an evenly spaced grid. The variogram, the function that describes the relationship between differences in pairs of measurements and the distance of adjacent points from each other, was assumed to be linear in form, and the search ellipse for the interpolation process was considered to be circular (isotrophic) at the Banana site, since physical features such as depth varied only slightly. However, at the aggregation located near the edge of the Scotian Shelf, where there was greater contrast in depth, examination of the echograms indicated that the long axis of the aggregation was located roughly parallel with the depth contours. As suggested by Kalikhman (2001) for situations such as this we relaxed the assumption that pollock were distributed isotrophically, and investigated the impact on the representation of the contoured acoustic data. However, even with the anisotrophy ratio, the ratio of the maximum range to the minimum range for the search to establish the interpolated grid, set as high as 3, the kriged representation of the results did not change appreciably. Therefore, we retained the assumption of isotrophy for both sites.

Periodic sets were made with a Campellen bottom trawl equipped with a 13-mm cod-end liner to confirm species identification. The tow speed was 3.5 knots, and the tow duration varied between 3 and 15 min. The average vertical opening of the trawl was 4.1 m, as indicated by an electronic, net-monitoring system, and thus included the near-bottom (up to 1 m off bottom) zone where fish were not detectable using hydroacoustic systems. The catch weights shown here are standardized to a towed distance of 0.75 nautical miles, equalling about 15 min at 3.5 knots. The catch was sorted by species and total weight, and a length–frequency sample was obtained in all cases. The bottom-trawl information was used to confirm the identity of the fish species comprising the aggregations located by the hydroacoustic system, and also to provide a qualitative comparison of the net catch to the acoustic signal.

Results

Overall, the total-catch weight of pollock was 59 241 kg during the study period, which represented about 88% of the total fish catch of 67 228 kg for the 28 sets made at the two sites. Other species co-occurring with pollock included scorpaenids (5% of the catch weight, mostly *Sebastes* sp. and blackbelly rosefish *Helicolenus dactylopterus*), silver hake *Merluccius bilinearis* and haddock *Melanogrammus aeglefinus*, each comprising 3% of the catch weight. The remaining 2% of the catch weight was comprised of more than 30 unique taxa. Typically, when the catch weight in a set exceeded 1000 kg, the proportion of pollock in the catch exceeded 95% (Figure 2).

The temperature profile obtained from the CTD casts indicated significant thermal stratification at both sites with a surface maximum of 18°C and a minimum of about 4°C within 50 m of the surface. The bottom temperature was about 10°C at both sites. The pollock aggregations identified at the sites were well below the thermocline, so that it did not appear to influence their distribution.

An aggregation of pollock was identified in the period September 30 to October 1, 1999 at the Banana site. When the research vessel returned on October 4, it was still present (Figure 3) at the same coordinates. Large net catches were made in the regions where high acoustic-backscatter values were observed, with some exceptions.

When the concentrations on the Banana were examined with respect to differences between day and night, contoured plots of S_a values showed that the aggregations were more apparent at night than during the day (Figure 4). At night, most of the pollock aggregation occurred shallower than the 175-m contour. The area of the concentration with S_a values equal to or greater than 0.8 was 3.05 km^2 at night, compared to 0.055 km^2 during the day. Example echograms obtained during both night and day are shown in Figure 5. As illustrated in that figure, the aggregations of pollock were sometimes so dense that they interfered with the ability of the hydroacoustic systems to discern the bottom.

In contrast to the hydroacoustic results, trawl catches of pollock made during day (number of sets = 14) were not significantly different from those made at night (number of sets = 7, Mann–Whitney U-test, $p = 0.067$). Large catches (standardized catch of >10 t per 15-min set) were made at both night and day.

The day–night differences in the representation of pollock aggregations found on the Banana appeared to be more pronounced at the Shelf Edge site, with well-defined aggregations present at night but virtually absent during the day (Figure 6). The aggregation at night appeared to be about 3 km in length (total area with S_a values equal to or greater than 0.5 was 2.14 km^2), and the aggregation was positioned between the 230 and 270 m contours. The long axis of the aggregation appeared to be parallel with the bottom-depth contours. Relatively few trawl sets were made at this location (N = 3 and 4 for day and night periods, respectively), thus reducing the potential to compare the catches during the two periods. However, a single large catch (>3 t per 15 min) was made both at day and at night.

We examined day–night differences in the backscattering-area coefficients (S_a) for the bottom-referenced depth layers defined previously using a two-way analysis of variance. At the Banana site, significantly ($p < 0.000$, $F = 10.680$) larger values of average S_a/transect were noted within the deepest layer (1–5 m off bottom) compared with the other layers. Significantly larger S_a values were also noted at night ($p < 0.004$, $F = 8.505$). At the Shelf Edge, a similar positive relationship of increasing signal strength with depth was revealed, with larger S_a values associated with the deepest layer ($p = 0.000$, $F = 4.609$) and at night ($p = 0.028$, $F = 4.906$). These data are displayed proportionately in Figure 7.

The length composition of the pollock catch differed between the two sites, with larger fish, on average, found at

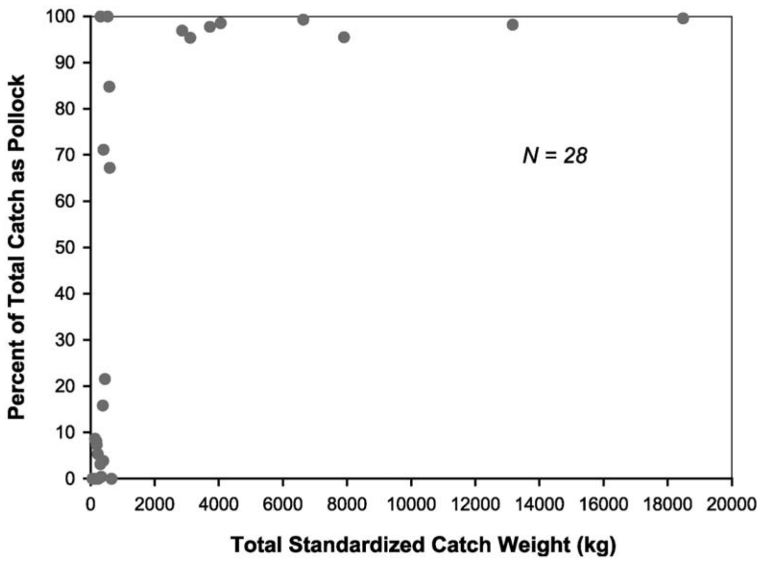

Figure 2. The relationship between total-catch weight standardized to a distance towed of 0.75 nautical miles, and the proportion of pollock comprising the total-catch weight, Scotian Shelf, 1999.

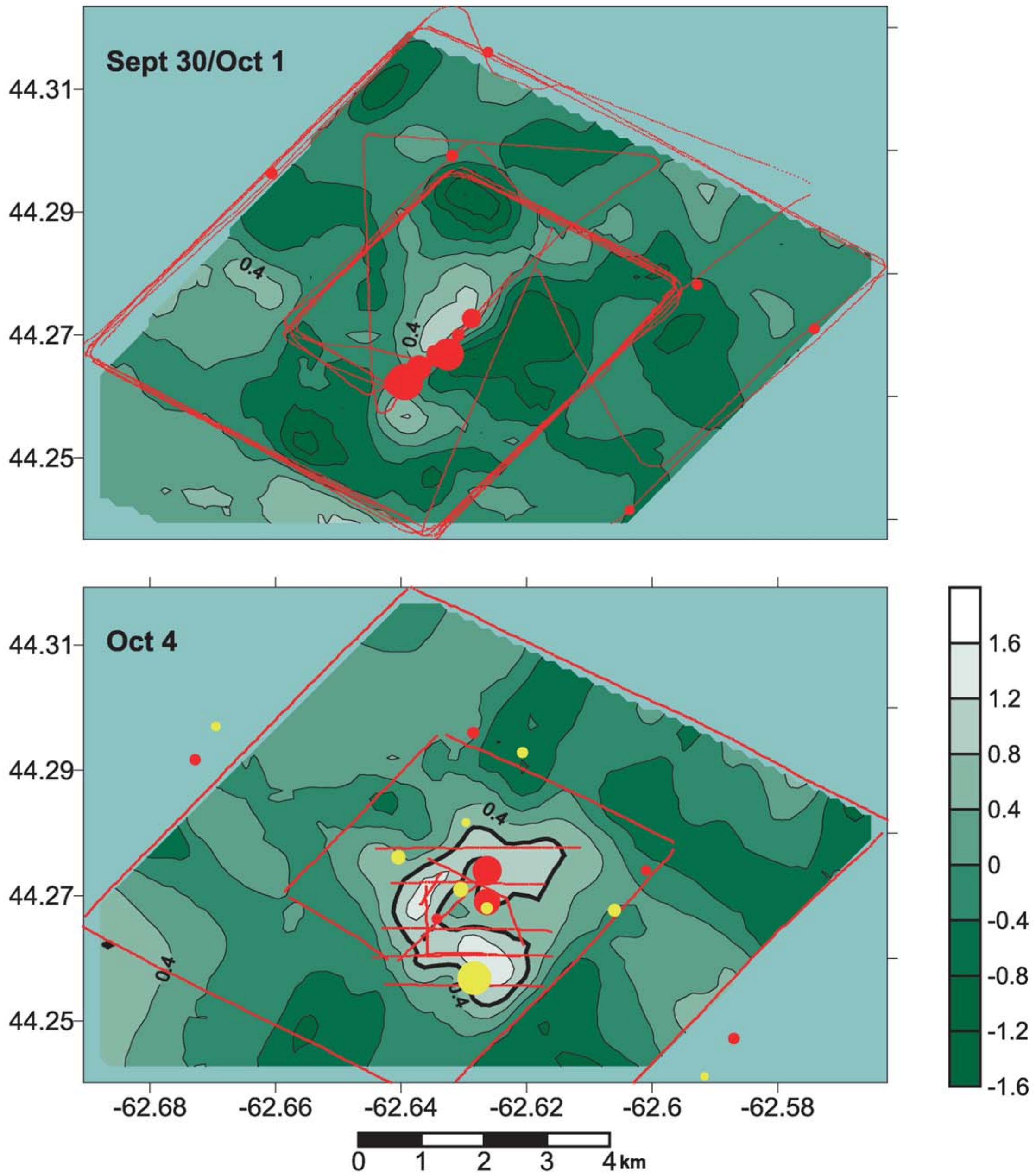

Figure 3. The distribution of pollock found at the Banana during the two periods September 30 to October 1 and October 4, 1999. The site was monitored for 48 and 24 h, respectively. The contours represent kriged, area-backscattering coefficients (S_a), with the lighter shades of green representing the higher values. The expanding red and yellow circles represent the standardized net catches by a research vessel and a commercial fishing vessel, respectively, scaled from a minimum of 0.001 mt to a maximum catch of 16 mt with all other catches between these two values proportionally scaled. The red lines represent the track of the research vessel. The heavy black contour defines the core area referred to in the analyses of length–frequency information.

the Shelf Edge site (Mann–Whitney U test, $p < 0.05$. However, no difference was found on a day–night basis at the Banana, (Figure 8). There were insufficient sets made at the Shelf Edge site to permit a comparison of length–frequencies on a day–night basis. When we grouped the length–frequency data for the sets made at the Banana, we found that the larger fish were found within the area of high concentration (Figure 9), as indicated from the hydroacoustic information (see Figure 3 for the outline of the area of high concentration).

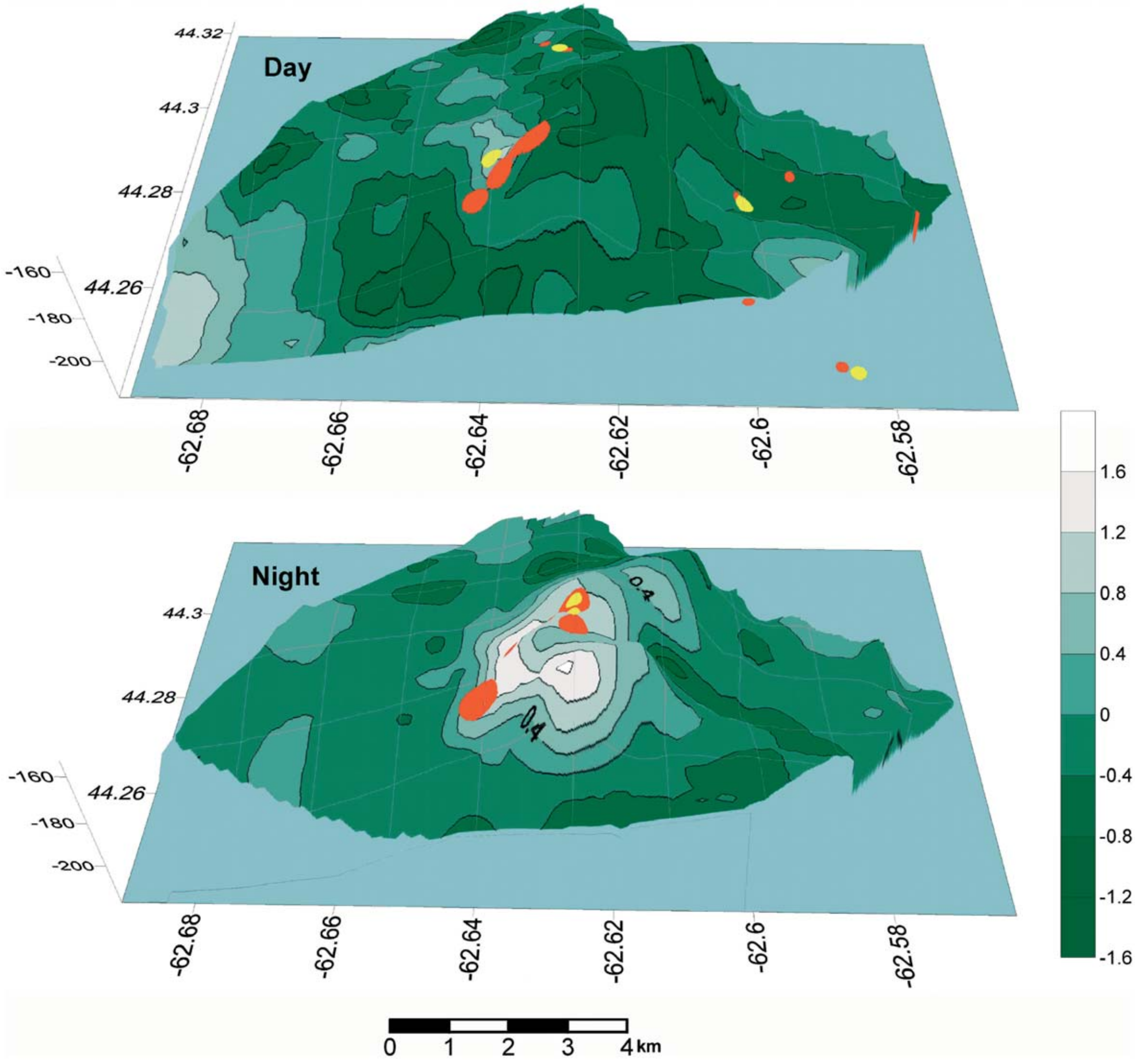

Figure 4. The night and day distribution of pollock found at the Banana during the two periods September 30 to October 1 and October 4, 1999. The contours represent kriged, area-backscattering coefficients (S_a), with the lightest shades of green representing the higher values. The expanding red and yellow circles represent the standardized net catches by a research vessel and a commercial fishing vessel, respectively, scaled from a minimum of 0.001 mt to a maximum catch of 16 mt with all other catches between these two values proportionally scaled. The z-axis represents depth (m), relative to the surface.

Discussion

Based on our observations at the Banana in September–October, 1999, pollock in the Northwest Atlantic form aggregations that persist over a period of at least 5 days. Information from the fishery indicates that the aggregations persist considerably longer, with reports of significant catches from the Banana up until February 2000. Based on observations of gonad maturity made during this study and in a subsequent survey in September 2000, both the males and females larger than 40 cm had developing gonads but had not yet reached the stage of maturation associated with the imminent release of reproductive products. Information from ichthyoplankton surveys indicates a peak abundance of early stages of pollock eggs on the Scotian Shelf around December–January (Neilson and Perley, 1996). Given the timing of peak spawning, the developing nature of the gonads observed during our survey and the information from the fishery, we consider the observed aggregations in September and October to be pre-spawning in nature, and it is likely that such concentrations persist over a period of several months as the fish mature and spawn.

Given recent concerns that fishing activity could disrupt spawning aggregations the persistence of the aggregations

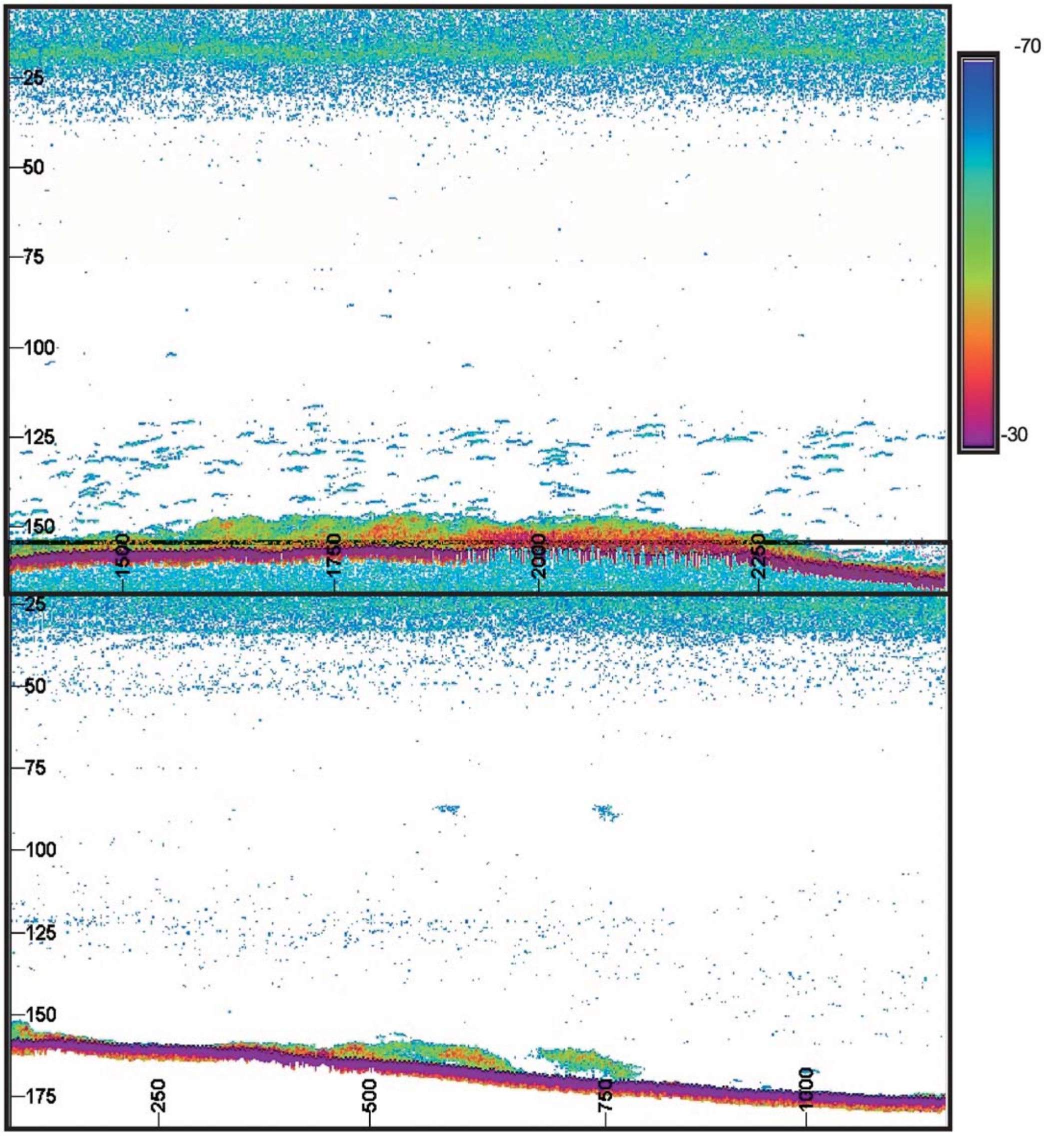

Figure 5. Example echograms of pollock aggregations obtained at night (top panel) and day (bottom panel) at the Banana site (September 30, 1999). The colour scale indicates the dB values, with red indicating relatively high values, and blue representing low values. The night aggregation was sufficiently dense to interfere with the detection of the bottom. The vertical scale is depth in metres and the horizontal scale indicates distance in metres.

in the face of considerable fishing activity is noteworthy. Morgan *et al.* (1997) used hydroacoustic observations to demonstrate that the passage of a 65-m wide, as measured from door to door, trawl through an aggregation of spawning cod (*G. morhua*) affected cod density in a swath extending 200–400 m on either side of the trawl. They did not comment on the duration of the disturbance effect. Ona and Godo (1990) detected horizontal movement of pre-spawning cod and haddock away from an oncoming trawl but the original spatial structure of the aggregation reformed 6 or 7 min after its passage. Our data may allow an evaluation of this kind for pollock in the future given the density of transects and trawling in a comparatively small area. However, experience with other species such as cod suggests that the translation of observed disturbances into quantifiable impacts on the success of reproduction may be difficult, even with considerable additional study.

Fishermen in the Canadian Maritimes have often observed that pollock aggregations tend to form in association with bottom-topographic features such as rises or mounds. The

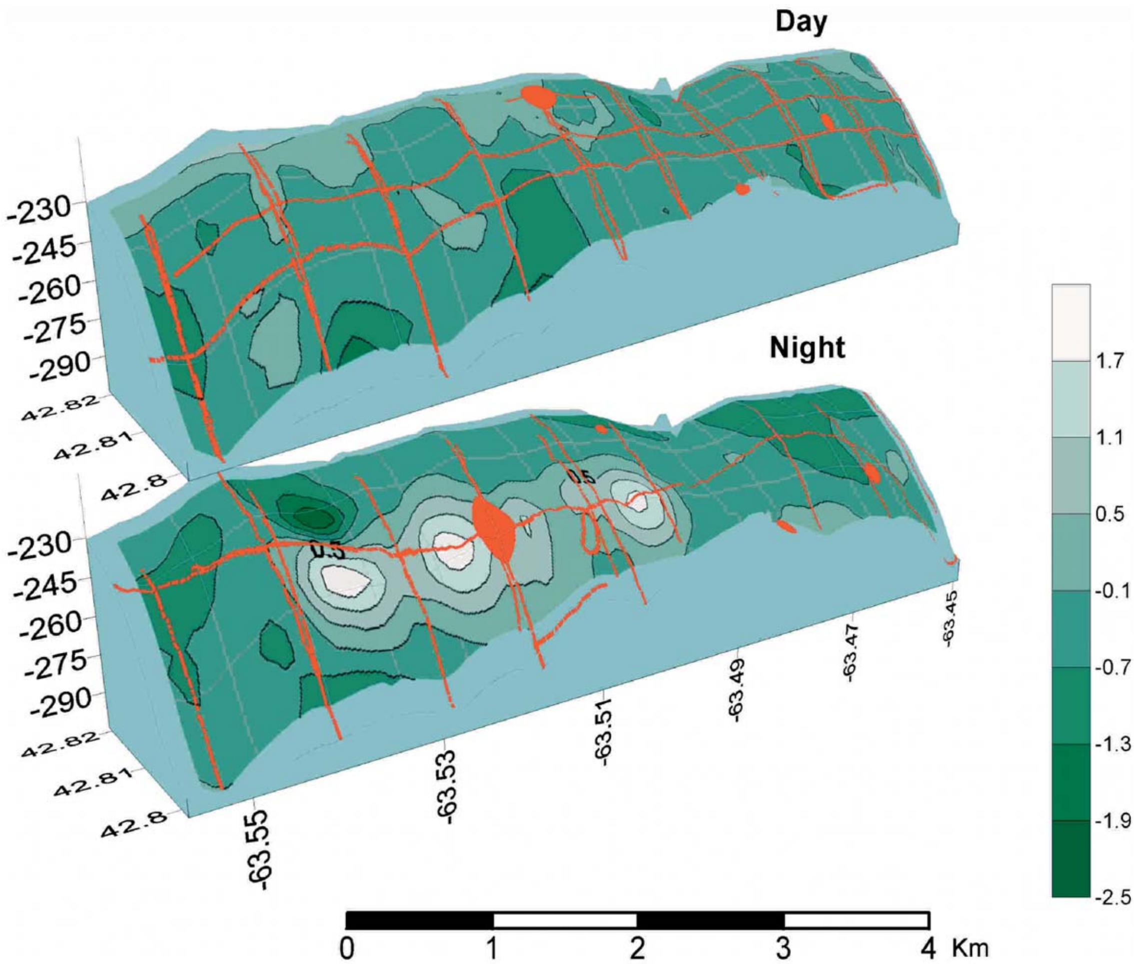

Figure 6. The night and day distribution of pollock at the Shelf Edge (October 2–3, 1999). The contours represent kriged, area-backscattering coefficients (S_a), with the lightest shades of green representing the higher values. The expanding red circles represent the standardized net catches by a research vessel, scaled from a minimum of 0.001 mt to a maximum catch of 4 mt with all other catches between these two values proportionally scaled. The red lines represent the track of the research vessel. The bottom panel depicts the bottom depth contours in metres. The z-axis represents depth (m), relative to the surface.

Banana site is an example of this as the densest part of the night aggregation was associated with the shallowest part of the rise (Figure 4). Sarno *et al.* (1994) has also described how pollock aggregations are frequently associated with a temperate reef within a Scottish sealoch. They also noted that pollock undertook periodic excursions away from the reef during daytime but returned to the reef and formed schools at night. Such observations appear consistent with our hydroacoustic observations. The reasons why pollock appear to be associated with bottom topographic features, however, remain unclear at present.

The reduction of significant concentrations of pollock during the day, as indicated by the hydroacoustic data, could be accounted for by two mechanisms operating singly or in concert. The first possibility is that pollock become more closely associated with the "acoustic dead zone" (ADZ) (Ona and Mitson, 1996) during daylight hours. The ADZ is the region where fish are indistinguishable from the bottom, and in our study, we considered it to be within 1 m of the bottom. In a study of the diel vertical distribution of Atlantic cod (*G. morhua*) off western Newfoundland, McQuinn *et al.* (1999) inferred that a higher proportion of the acoustic signal occurred within the ADZ during the day. In making this observation, the authors assumed that the density of fish within the ADZ was the same as in the 2-m layer immediately above it. If a similar phenomenon occurred in pollock, we would predict that net catches of pollock would remain high during daylight, since the net samples the volume that includes the ADZ. This prediction is supported by our observations at the Banana site and at the Shelf Edge,

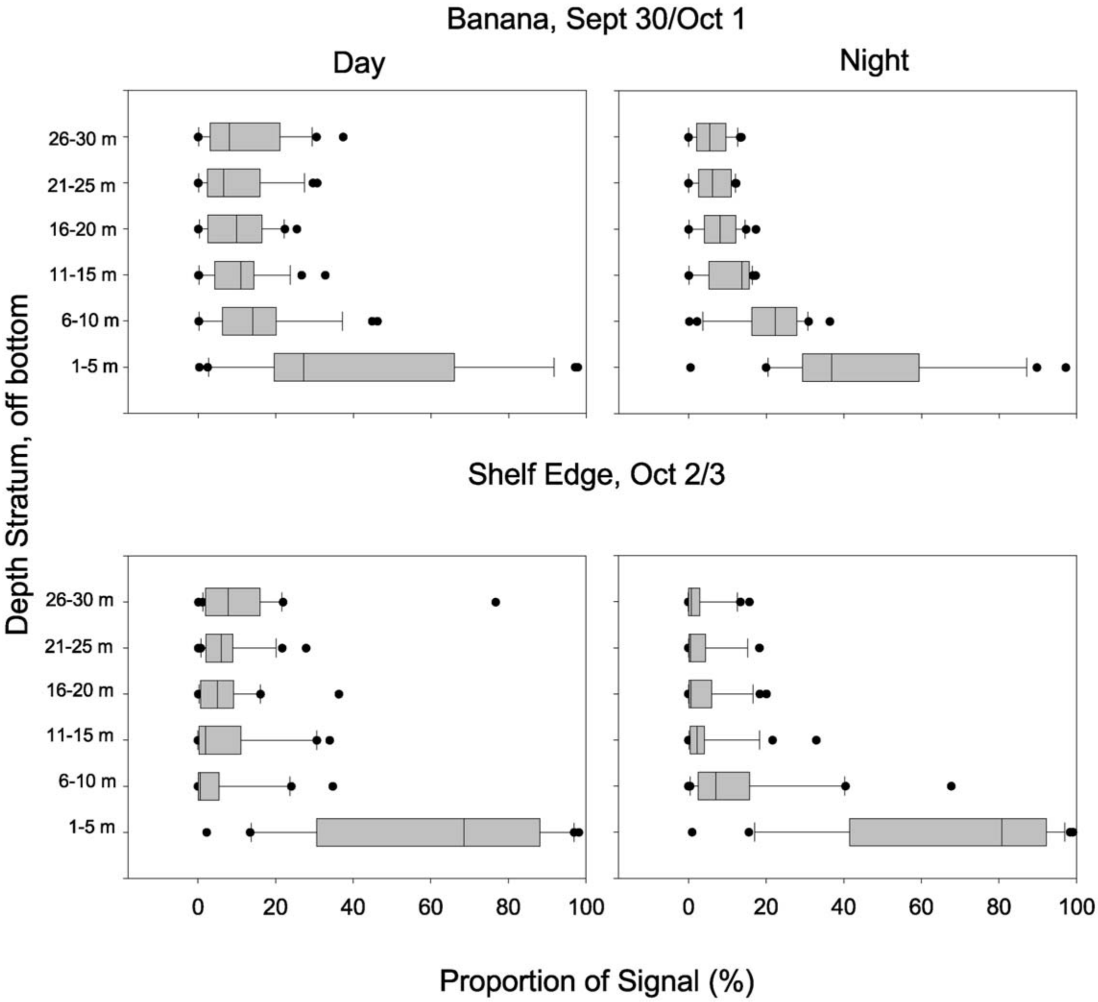

Figure 7. Box plots of total-backscatter coefficients (S_a) in bottom-referenced depth ranges, shown by day and night. The vertical line within the box plots represent the medians and the box ranges over the 25th and 75th percentiles. The whiskers represent the 10th and 90th percentiles, respectively, with any points outside the 10th and 90th percentiles considered to be outliers. Banana site, September 30 to October 1, 1999 (top) and Shelf-Edge site October 2–3, 1999 (bottom).

where large catches were made during both day and night. A second prediction is that the proportion of the acoustic signal within the 1–5 m layer, i.e., immediately above the ADZ, would be higher during the day than at night, since fish are assumed to be more closely associated with the bottom during the day. This is not supported by our study (Figure 7). Thus, the evidence supporting the hypothesis of changes in the day–night occurrence of pollock within the ADZ is equivocal.

Support for the alternative hypothesis that pollock move horizontally on a day–night basis is provided by a study of saithe using acoustic transmitters referenced earlier (Sarno *et al.*, 1994). Differences in the day–night movement of the fish in relation to a small, underwater reef in the loch were reported in that case. Consistent with other underwater observations made by Wyche (1984) in the same locale, Sarno *et al.* (1994) found that saithe made most of their longer-distance movements during the day. At night, the saithe remained in close association with the reef, and swimming speeds were reduced.

Our interpretation of the available data on day–night differences in pollock aggregations is that the aggregations become larger and denser at night but daytime aggregations persist, albeit more scattered than those at night (see Figure 5 for examples). Such differences appear more pronounced at the Shelf Edge site than at the Banana site. Knowledge of these day–night differences in aggregations of pollock has implications for the design of a survey of abundance. It may be necessary to include considerations of the day–night changes in the availability of pollock in the survey design

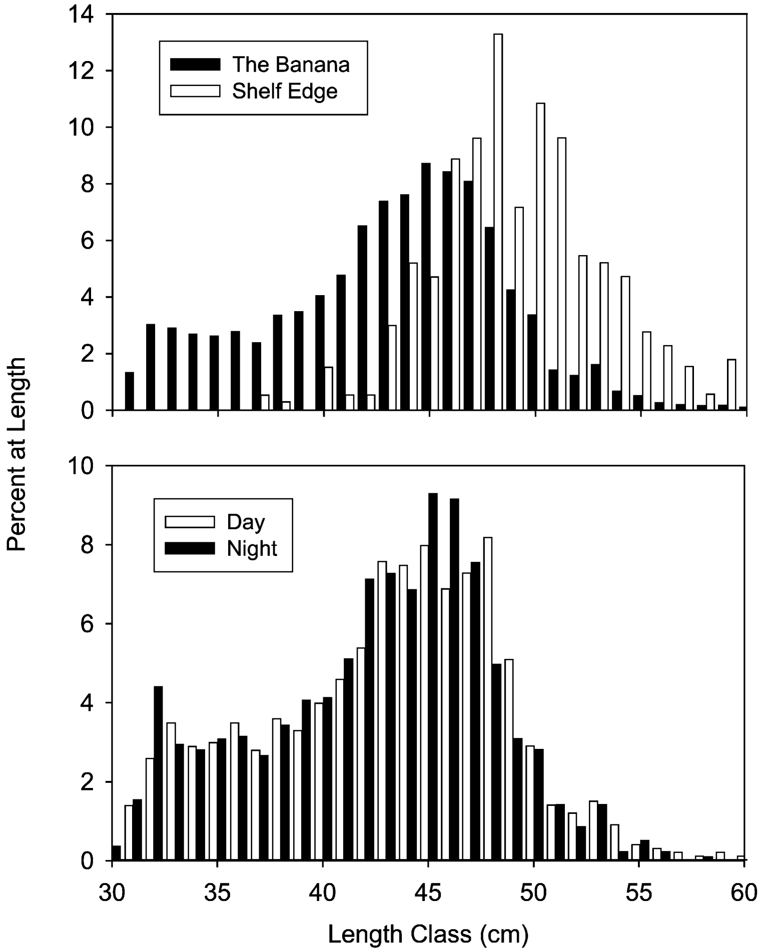

Figure 8. A comparison of length–frequency distributions of pollock caught at the Banana and Shelf-Edge sites (top). The lower panel shows the length–frequency distribution of pollock caught during day and night sets on the Banana. Sampling took place at the Banana from September 30 to October 1 and on October 4, 1999. The sampling took place at Shelf Edge October 2–3, 1999.

and analyses of the data. Aglen *et al.* (1999) also observed diel variations for demersal species in the Barents Sea, with different patterns of vertical migrations for small and large redfish (*Sebastes* spp.) and haddock (*M. aeglefinus*). In our case, we did not find any differences in the size composition of the bottom-trawl catches of pollock between the periods of night or day.

Samples taken at the two sites indicate that the length frequencies of pollock differed significantly, with larger pollock found in the deeper water at the Shelf Edge. This is consistent with the observations of Steele (1963) that pollock generally form size-specific aggregations. Very few pollock were found at the Shelf Edge that were less than 45 cm, the size at 50% sexual maturity (Trippel *et al.*, 1997), while most pollock at the Banana site were <45 cm. Juvenile pollock throughout their range are found primarily in coastal waters, expanding their distribution farther offshore with age, as indicated by studies from both the Northwest (Clay *et al.*, 1989) and Northeast Atlantic (Jakobsen and Olsen, 1987).

Detailed sampling at the Banana site indicated finer-scale size segregation as well. Larger fish dominated the size composition in the core area, while smaller pollock were more abundant outside this area. Age–length keys developed from sampling the commercial fishery in the area indicate that the smaller mode in Figure 9 corresponds with the 1997 year-class (2-year-olds), while the second mode of larger fish comprises the 1995 and 1996 year-classes (3- and 4-year-olds). Segregation by size has been described for a number of fish species (Ranta *et al.*, 1992; Ward and Kraus, 2001). Smaller fish in an aggregation have been shown to be at a competitive disadvantage in feeding (Seppa *et al.*, 1999; Ward and Krause, 2001) and at a higher risk of predation because of their conspicuousness

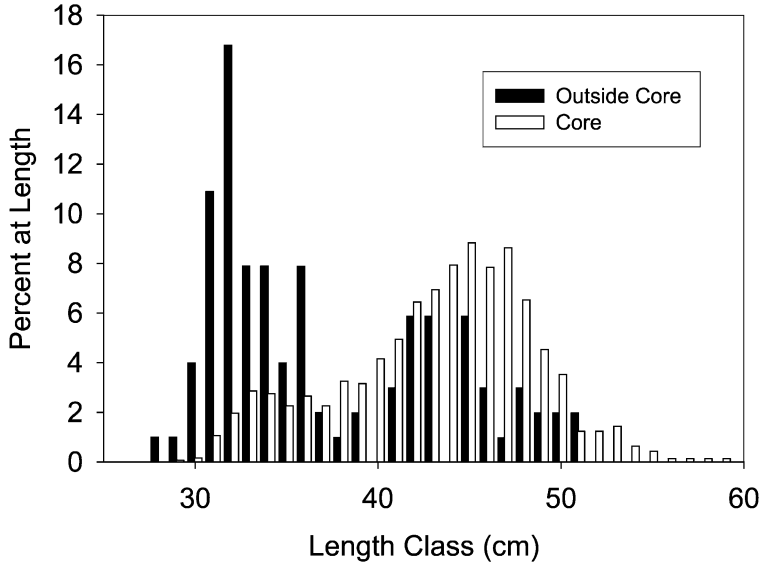

Figure 9. Length–frequency distributions of pollock taken from the core of the pollock aggregation at the Banana site (see Figure 2 for the boundary definition) compared with the length–frequency distribution of pollock outside the core area. The sampling took place from September 30 to October 1 and on October 4, 1999.

(Landeau and Terborgh, 1986). Joining the dense aggregation of larger pollock may, therefore, be disadvantageous for these smaller pollock. This has implications for sampling pollock for characterizing the length composition of acoustic records. Samples taken from outside the area of high aggregation may not be representative of the size composition of the aggregation.

Acoustic surveys of groundfish generally include periodic net sampling to determine species and size composition. In the present situation it will be necessary to identify and sample both the centre and edges of the aggregation to ensure that the samples accurately reflect the size structure of the entire population. Godø *et al.* (1998) describe the effect of sampling variability on the precision of the acoustic-abundance estimates of gadids and improved procedures for the allocation of trawl-sample information are discussed.

From the perspective of survey design, our study confirms the observations of Neilson *et al.* (2002) that pollock form aggregations associated with spawning that persist over several months but the more in-depth nature of the sampling reported here allows us to identify further considerations that have to be taken account of. For example, the day–night differences in the density of the aggregations demonstrated at the Banana site indicate that the relationship between an index of population abundance obtained from an acoustic survey and the population *per se* might differ on a diel basis. To account for this one possibility might be for the surveys to be conducted at night only when the aggregations appear to be more readily detected. Alternatively, the changes in the relationship between acoustic index and population could be described explicitly for both day and night and included in the calculation of the overall index of abundance. A description of how this could be done for bottom-trawl indices as well as an evaluation is given in Hjellvik *et al.* (2002). However, in the examples provided there, such adjustments for biases from diel effects often resulted in decreased precision of the estimates of abundance from the surveys.

Taken together, the results presented in the current paper and those presented in the study of Neilson *et al.* (2002) indicate that a combined acoustic survey and trawl approach could be the preferred design for a survey of pollock abundance. Pollock have been shown to be patchy in distribution but the patches appear to be persistent and generally predictable in location (Neilson *et al.*, 2002). Simmonds *et al.* (1992) suggest that for wide-shelf environments with a contagiously distributed stock such as the case here, a two-stage, adaptive design is appropriate. As noted in Neilson *et al.* (2002) this could include an initial outline survey covering the area where pollock aggregations have been located in the past, followed with more intensive sampling-reduced spacing between transects or reduced transect length to better define the extent of the aggregation. Such an approach is employed in the assessment of Northeast Arctic saithe, where the acoustic survey covers known saithe grounds rather than a systematic design involving regular survey transects (Nedreaas, 1997). These results also indicate that pollock form relatively monospecific aggregations that are best detected during the night. Given the finding that the size structure of the population varies within the aggregation, bottom-trawl samples will be required to verify both size and species composition.

Acknowledgements

We thank the captain and crew of the CGSS "Teleost" for their excellent cooperation in completing this study. We also appreciate the collaboration and contribution of data from the "Cape John", provided by Captain Charlie Croft and Mr Michael O'Connor of National Sea Products. We thank Mr Art Cosgrove for drafting Figure 1. Drs John Anderson and Ross Claytor and two anonymous reviewers provided many valuable comments on an earlier version of this manuscript. This work was supported by the Department of Fisheries and Oceans' Strategic Science Fund initiative.

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