Schooling pattern of eastern Bering Sea walleye pollock and its effect on fishing behaviour

Haixue Shen, Martin W. Dorn, Vidar Wespestad, and Terrance J. Quinn


Walleye pollock (Theragra chalcogramma) form persistent midwater and near-bottom schools in the daytime during the winter spawning season in the eastern Bering Sea (EBS). Two spawning areas in the EBS, north of Unimak Island and near the Pribilof Islands, are the main fishing grounds. To study the schooling pattern of pollock and its effect on fishing behaviour on these two fishing grounds, a principal component analysis with instrumental variables was carried out using acoustic and observer data from 2003 and 2005. Significant differences between the school descriptors distinguished the schooling patterns among areas and years. The harvester, that is to say, the fishing vessel and its crew taken together, searched for fish aggregations, which were caught in a different manner when the schooling pattern changed. School density had a greater effect than school size on fishing behaviour. Aggregations were less dense in 2003 than in 2005, and the harvester tended to fish with longer tows, at higher speeds, when it encountered less dense aggregations.

Keywords: acoustic data, fishing behaviour, observer data, pollock, principal component analysis, schooling pattern.

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Introduction

Pelagic fish usually form different kinds of aggregations, such as schools, clusters of schools, clouds, and layers (Reid, 2000). As a semi-pelagic species, walleye pollock (Theragra chalcogramma) form persistent midwater and near-bottom schools during the spawning season. Knowledge of pollock schooling pattern provides information about fish behaviour essential to the management of the fishery (Marchal and Petitgas, 1993). In addition to being the main target of a fishery, walleye pollock is also an important component of the eastern Bering Sea (EBS) ecosystem as a major prey species (NRC, 1996). Its schooling pattern may affect the predation success of species in higher trophic levels, such as Steller sea lions (Wilson et al., 2003) and, therefore, it is important for ecological studies.

Acoustic methods have been used commonly in pelagic fisheries to explore the schooling behaviour of fish (Simmonds and MacLennan, 2005). Since 1979, such methods have been used to estimate the pollock abundance in midwater during the echo-integration and trawl surveys of the EBS, using research vessels (Ianelli et al., 2007). However, these surveys were usually conducted in summer, except for a few winter surveys in 2001 and 2002 (Honkalehto et al., 2002). Although their results may be less precise than those of dedicated scientific surveys, commercial vessels can be suitable platforms for collecting acoustic data for scientific purposes (Melvin et al., 2002; Mackinson and van der Kooij, 2006) and are particularly useful for in-season monitoring of stock trends (Melvin et al., 2001). Since 2002, a joint, opportunistic, acoustic-data programme has been collecting, processing, and storing acoustic data from selected factory trawlers participating in the EBS pollock fishery (Barbeaux et al., 2005).

Fish schools are formed when a number of fish aggregate. Many parameters are required to describe a fish school, inter alia morphometric, positional, and energetic descriptors; univariate analysis alone cannot adequately describe this complex entity. In this paper, the schooling pattern of pollock is examined by comparing observations in two fishing grounds (north of Unimak Island and around the Pribilof Islands) during two years (2003 and 2005), using a principal component analysis with instrumental variables (PCAIV) of the school descriptors. The concurrent fishing behaviour was also analysed using the PCAIV to study its relationship with the schooling pattern.

Material and methods

Acoustic data were collected using a large factory trawler that usually operated north of Unimak Island in the EBS from January to late February and around the Pribilof Islands from late February to March (Figure 1). There were no differences in the way the data were collected and logged in both areas and years. An uncalibrated, 38-kHz, Simrad ES60 split-beam echosounder with a 1 ms nominal pulse length and a 7.1° beam width was used. The data were corrected for the triangle-wave problem using the algorithm of Ryan and Kloser (2004). Although uncalibrated acoustic data are unsuitable for absolute fish-density estimation, the purpose of this study was to compare schooling patterns in different years and on different fishing grounds, but...
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Results

In all, 2405 schools were identified after removing 216 outliers among the four classes, namely U3 (936), P3 (470), U5 (433), and P5 (566). The acoustic data were generally of higher quality with less missing pings in north Unimak in 2003; therefore, there were a larger number of schools in the U3 class. Univariate analysis of school descriptors revealed significant differences between the two years in the two fishing grounds usually (Table 1). The main Unimak Island school descriptors were significantly different always, except for school length and perimeter. The Pribilof Islands schools were significantly different between years, except for school length. There was no clear difference in the observed schools between fishing and searching periods for both areas and years (K–S test, p > 0.05). Therefore, all schools were used to test for differences among the four classes using the PCAIV.

Figure 1. Tracks of the fishing vessel in January–March in 2003 and 2005. UI, Unimak Island; PI, Pribilof Islands.

detected by the same vessel, so this should therefore not be affected by the lack of calibration.

Echoview 3.30 software (SonarData, 2005) was used to process the raw data and classify the echotrace from 15 m below the surface to 0.5 m above the seabed. Pollock within the near-bottom zone were not included in this analysis. This problem was unimportant in the study, because all the schools were compared using the same methods. Schools of walleye pollock were detected and characterized using the school module in Echoview. The data were collected only during daylight, when pollock displayed schooling behaviour. To detect the schools, a volume-scattering strength (Sv) threshold of −70 dB re 1 m−1 was applied, with the other criteria for the school algorithm being the minima of school length (40 m), school height (5 m), candidate length (5 m), and candidate height (2 m), and the maxima of vertical (5 m) and horizontal (20 m) linking distances (Wilson et al., 2003; SonarData, 2005).

The school descriptors generated by the Echoview software included morphometric (length, L; thickness, T; perimeter, P; and area of schools, A), positional (latitude, longitude, school depth D), and energetic descriptors (Sv, and Sv, the nautical-area-scattering coefficient; Simmonds and MacLennan, 2005). Based on these descriptors, two others, namely school fractal dimension and school elongation, were determined. The fractal dimension (F) of a school is an index of shape complexity, which depends on the relationship between the school perimeter and area (Nero and Magnuson, 1989). The elongation (E) is the ratio of the school length to the school thickness (Weill et al., 1993). A Kolmogorov–Smirnov test (K–S test; Zar, 1999) was done to test for significant differences at the confidence level α = 0.05 between the two years in the two fishing grounds. The confidence level was not adjusted for the multiple tests, because there were few descriptors, and the aim was not to specify the significance level for the entire testing procedure, as might be done in a multiple-comparisons procedure.

To evaluate the effects of area and year, a PCAIV of the fish-school descriptors was done using the statistical software “R” (http://cran.r-project.org). The PCA was based on eight non-redundant variables as defined above: L, T, P, A, D, S, F, and E. The schools were divided into four classes: U3 (Unimak Island; 2003), P3 (Pribilof Islands; 2003), U5 (Unimak Island; 2005), and P5 (Pribilof Islands; 2005). Before the PCA, outliers were identified by the multivariate method in “R” (Filzmoser et al., 2008), which computes the Mahalanobis distances based on robust principal components. The Mahalanobis distances were transformed so that a critical value from a Chi-squared distribution could be used to remove the outliers. To examine differences in the schooling pattern between classes, a between-class PCA was done; this is a particular case of the PCAIV with one qualitative instrumental variable (Doledec and Chessel, 1994; Pélissier et al., 2003). In this case, class was used as the instrumental variable, so the analysis focused on the differences that best distinguished the classes. This was done by minimizing the between-class inertia, which is the variance of the class determinations (Akhisar and Bener, 2002). A Monte Carlo test was done to examine the significance of differences between the classes (Romesburg, 1985).

Data collected simultaneously by a fishery observer on the vessel were used to investigate how fishing behaviour changed in response to the schooling pattern. The vessel track was separated into search and fishing paths, by combining the observer-recorded deployment and retrieval times of the net with the acoustic data. In winter, the backscatter emanated mainly from pollock aggregations on both fishing grounds. Therefore, the school density could also be indexed by the sv for the whole water column, averaged over 1 km, as the elementary sampling distance unit for both search and fishing time. Similarly, the observer data were divided into four classes: U3, P3, U5, and P5. Seven variables were chosen for the PCA: fishing depth (fd), fish density during search (ssA), fish density during fishing (fsA), searching duration (sD), fishing duration (fD), searching speed (sS), and fishing speed (fS). The PCAIV and Monte Carlo tests were also done to examine the differences in fishing behaviour between the school classes.
Most fishing-behaviour variables differed significantly between the two years for both fishing grounds (Table 2). The results from the PCAIV for fishing behaviour are displayed in Figure 4. The first axis accounted for 49% of the between-class inertia and was mainly a function of fishing depth and ssA (on the left) and searching speed (on the right). An inverse relationship between ssA and each of the descriptors fishing duration, searching, and fishing speed was observed with both principal components (Figure 4), because the harvester tended to decrease the searching and fishing speeds and hauling time when denser fish aggregations were encountered. Search duration had a weaker relationship with searching speed and fishing duration. The second axis accounted for 43% of the between-class inertia and was mainly defined by fishing duration and searching speed. The third axis accounted for only a small percentage of the between-class inertia and can be ignored.

The Monte Carlo test also confirmed a significant difference in fishing behaviour between classes (\( p < 0.001 \)). Fishing behaviour in 2003 was distinguished from that in 2005 by longer fishing duration and higher searching speed (Figures 4 and 5). In 2003, the fishing behaviour in the two areas differed in fishing speed and search duration (Figure 4). The Pribilof tracks in 2003 exhibited the highest fishing speed and fishing duration, and the shortest search duration, among the four classes (Figure 5). There was no significant difference between areas as regards fishing behaviour in 2005, although the fishing and searching speeds were slightly higher at Unimak Island (Table 2).

**Discussion**

The aim of this study was to examine the schooling pattern of pollock and to evaluate the relationship between fishing behaviour and pollock-schooling patterns in the EBS. Acoustic data from a single factory trawler were used to avoid variability caused by using different acoustic systems and vessels. The skipper and fishing mate had been on this vessel for the past 10 years. There were no important changes in the acoustic equipment or the vessel machinery during the study period. Therefore, the observations describe real differences in schooling patterns and fishing behaviours. Further, the application of a volume-scattering strength threshold and exclusion of bad acoustic data ensured

![Figure 2](https://academic.oup.com/icesjms/article-abstract/66/6/1284/692357)
reliable results. The school descriptors are mostly relative indicators that should be robust to calibration changes. That is not the case for the energetic descriptors, and this means that apparent changes in fish density could be caused by calibration variability. Further, the presence or proximity of other fishing vessels may induce fish avoidance and thus result in a lower density of observed fish. Given the similar and consistent practices of the pollock fleet, however, this problem is not expected to have had any large effect on the present study. The results should be applicable to other fishing vessels operating in a similar manner in the EBS. Nevertheless, it would be wise to study different vessels in the same area to substantiate this conclusion.

The schools displayed different structures between years in both fishing grounds. This may have been because of changes in the physical environment, especially water temperature. There was a larger biomass in 2003 than in 2005 (Ianelli et al., 2007), which could have affected schooling patterns. Although the winter temperature at the seabed in the study area was not recorded directly, other sources could inform the winter conditions in 2003 and 2005. The mean sea surface temperature (SST) for January through April at 56°52'N 164°3'W, where a moored data buoy was maintained by the NOAA, was 2.44 and 1.95 °C in 2003 and 2005, respectively (http://www.beringclimate.noaa.gov). The winter SSTs at the Pribilof Islands were 2.46 and 1.78 °C, respectively, in the same years. Both datasets indicated a warmer winter in 2003 than in 2005.

A larger biomass of fish could result in larger and denser schools or an expanded range of the stock itself (Aukland and Reid, 1998). In the present study, a larger biomass resulted in either larger schools or a greater area occupied by the stock, but no increase in school density was observed (Table 1). The schools at Unimak Island were larger in 2003, with no increase in the occupied area, because the stock was constrained by ice cover. In the Pribilof Islands area, however, the stock occupied a larger area in 2003 (Figure 1), but the schools were smaller and of lower density. The lower density in that year was probably a consequence of the warmer winter. Although both the size and density of schools may affect fishing behaviour, the latter is primarily motivated by density changes. For both fishing grounds, the fish densities were lower in 2003, which resulted in longer fishing durations and higher fishing speeds. School density also affected fishing speed and fishing duration (Figure 4).

The PCAIV revealed that three morphometric descriptors, school fractal dimension, school thickness, and school elongation, were useful for identifying schools among the four classes distinguished. School fractal dimension is a smoothness measure of school boundary; a higher value indicates a school with a more complex shape. In 2005, the schools had higher fractal dimensions on both fishing grounds, suggesting that cool conditions resulted in more complex school shapes, especially for the large schools in the Pribilof Islands. There was an inverse relationship between school thickness and school elongation (Figure 2). Because

<table>
<thead>
<tr>
<th>Variable</th>
<th>U3</th>
<th>U5</th>
<th>p</th>
<th>P3</th>
<th>P5</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>fd</td>
<td>84.8</td>
<td>91.5</td>
<td>0.00</td>
<td>105.4</td>
<td>105.2</td>
<td>0.51</td>
</tr>
<tr>
<td>ssA</td>
<td>1 718.0</td>
<td>1 461.6</td>
<td>0.07</td>
<td>840.2</td>
<td>2 020.6</td>
<td>0.01</td>
</tr>
<tr>
<td>fsA</td>
<td>1 612.7</td>
<td>1 331.3</td>
<td>0.26</td>
<td>1 454.1</td>
<td>1 824.4</td>
<td>0.43</td>
</tr>
<tr>
<td>sD</td>
<td>219.2</td>
<td>1 665.5</td>
<td>0.03</td>
<td>167.5</td>
<td>182.5</td>
<td>0.00</td>
</tr>
<tr>
<td>fD</td>
<td>135.1</td>
<td>106.2</td>
<td>0.04</td>
<td>187.3</td>
<td>82.2</td>
<td>0.00</td>
</tr>
<tr>
<td>sS</td>
<td>6.3</td>
<td>5.6</td>
<td>0.00</td>
<td>6.7</td>
<td>5.2</td>
<td>0.00</td>
</tr>
<tr>
<td>fS</td>
<td>5.3</td>
<td>5.0</td>
<td>0.00</td>
<td>5.7</td>
<td>4.8</td>
<td>0.00</td>
</tr>
</tbody>
</table>

The variables were compared using the K–S test; p is the significance level of differences between the two years.
school length was similar in the two years, we conclude that pollock evidently form schools with different thickness, rather than length, in response to varying conditions. The water column is well mixed during winter in the EBS, and the homogeneous vertical conditions might have allowed fish to spread in depth more easily than they could have done in stratified water.

Data from a single vessel were used to compare schooling patterns, and their effect on fishing behaviour. Further studies are needed to examine the effect of different fishing practices among vessels and any interaction that might occur, dependent on the spatial-activity pattern of the fleet.

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References
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