

Using Acoustics to Evaluate the Effect of Fishing on School Characteristics of Walleye Pollock

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Abstract

Walleye pollock (*Theragra chalcogramma*) is the target of one of the world's largest fisheries and is an important prey species in the eastern Bering Sea (EBS) ecosystem. Little is known about the potential effects of fishing on the school characteristics and spatial distribution of walleye pollock. Few dedicated research surveys have been conducted during pollock fishing seasons, so analysis of fishery data is the only feasible approach to study these potential effects. We used acoustic data collected continuously by one fishing vessel in January-February 2003, which operated north of Unimak Island. Results from comparisons between two fishing periods showed significant changes of pollock distribution at different scales. The schools were smaller and denser during the second period. Furthermore, the spatial distribution of schools became sparser, as evidenced by the lower frequency of schools per elementary distance sampling unit and the increase in average

next-neighbor distances (NNDs). However, the average NND between schools within a cluster and the average abundance of clusters did not change significantly. Variography was used to investigate the changes at scales larger than 1 nm. The increased range, nugget effect, and sill in the second period indicated changes of pollock spatial distribution; however, it is unclear whether these changes are attributable to fishing or ecological processes.

Introduction

Pelagic species usually form dense aggregations, or schools, during daytime and disperse at night. Walleye pollock (*Theragra chalcogramma*), which is semi-pelagic, forms persistent mid-water and near-bottom schools during the spawning season. For schooling species, the pattern of aggregation may have a large effect on fishery catchability (Castillo and Robotham 2004). Harvesters are skilled at finding fish aggregations using search strategies aided by technology (echosounders, oceanographic sensors, satellite imagery, etc.). Consequently, strong interactions would be expected between the distribution and behavior of both fish and harvesters (Potier et al. 1997, Wilson et al. 2003, Bertrand et al. 2004). Wilson et al. (2003) studied how fishing activities affected the pollock distribution in Barnabas Trough in 2002, but did not find strong impacts. This paper focuses on changes in pollock schooling during a one-month fishing season in the eastern Bering Sea (EBS) using acoustic data collected aboard a commercial fishing vessel.

The commercial fishery for walleye pollock in the EBS is one of the largest fisheries in the world. This species is also an important component of the EBS ecosystem as a major prey species. Recently there has been great interest in the potential biological interaction between Steller sea lions (*Eumetopias jubatus*) and commercial fishing, following the classification in 1997 of the western population of Steller sea lions as endangered under the Endangered Species Act. It remains unknown whether fishing causes significant decreases in pollock abundance or changes in their spatial distribution that in turn adversely affect the foraging success of sea lions (Zeppelin et al. 2004).

Acoustic survey methods have been widely used for assessment because of their high temporal and spatial resolution (Simmonds and MacLennan 2005). Commercial vessels can be good platforms for collecting scientific acoustic data (Melvin et al. 1998, 2002; Wyeth et al. 2000; Mackinson and Kooij 2006), and are particularly useful for in-season monitoring of stock trends (Stephenson et al. 1999, Melvin et al. 2001). Pollock is the main sound scatterer at 38 kHz during the winter spawning season in the EBS (Dorn et al. 2002). Since 1979, acoustics have been used to estimate pollock abundance in mid-water during the echo-integration trawl (EIT) surveys of the EBS (Barbeaux and Dorn 2003).

However, these surveys are mainly conducted in the summer, except for several winter surveys conducted in 2001 and 2002 (Honkalehto et al. 2002). The first major fishing season (called the “A” season opening on January 20) occurs in winter. Consequently, surveys do not provide adequate information about interactions between fishing and pollock aggregations (Barbeaux and Dorn 2003).

Scientists from the Alaska Fisheries Science Center (AFSC) and University of Alaska Fairbanks developed a prototype data logger to interface with 38 kHz echosounders onboard fishing vessels and capture the acoustic backscatter returns in 2001 (Dorn et al. 2002). Since 2002, the joint opportunistic acoustic data (OAD) program has been collecting, processing, and storing acoustic data from selected factory trawlers participating in the eastern Bering Sea pollock fishery (Dorn et al. 2002). Seven fishing vessels collected acoustic data during normal fishing operations in the “A” season when the fish form pre-spawning aggregations. These data make it possible to study the relationship between pollock aggregations and fishing activities. However, due to difficult weather conditions and equipment breakdowns, much of the opportunistic data cannot be utilized. Here, only the acoustic data collected by one vessel in 2003, which had fewer missing pings and was generally of higher quality than data from other vessels, were used to examine pollock aggregation patterns in the area north of Unimak Island.

Materials and methods

Data collection and study area

The vessel is a large factory trawler that mainly operated north of Unimak Island (near 54°46'N, 164°08'W) in the eastern Bering Sea from January to February 2003 (Fig. 1). The vessel operated in the same area during the early and late periods of the fishing season. Acoustic data were logged with an uncalibrated 38 kHz Simrad ES60 split-beam echosounder with 1 ms nominal pulse length and 7.1° beam width. Uncalibrated acoustic data are of course not suitable for absolute fish density estimation; however, the purpose of this study was the analysis of school morphology characteristics, spatial patterns, and relative changes in school density, which should be robust to the lack of calibration.

Data analysis

Echoview 3.30 software (SonarData 2005) was used to process raw data and classify the echo trace from 15 m below the surface to 0.5 m above the bottom. Walleye pollock schools were detected and characterized using the school module in Echoview. We used only data collected dur-

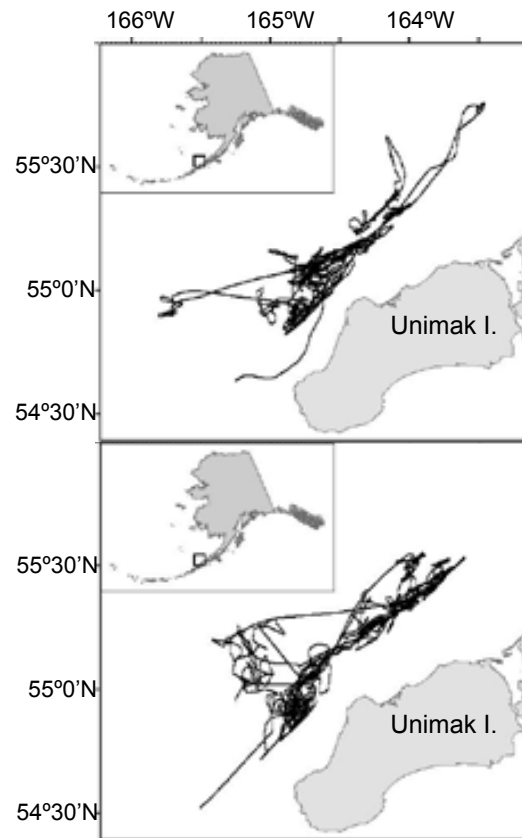


Figure 1. Area of operation of the fishing vessel in January-February 2003. The upper and lower panels display the fishing tracks from Jan. 22 to Feb. 5, and from Feb. 14 to Feb. 24, respectively.

ing daylight hours, when pollock show schooling behavior. Criteria from Wilson et al. (2003) were used to classify the pollock aggregations as follows. The threshold for detecting schools was set to -70 dB at 1 m. The other six input parameters for the school algorithm were minimum school length (40 m); minimum school height (5 m); minimum candidate length, i.e., minimum length allowed for a single school candidate (5 m); minimum candidate height, i.e., minimum height allowed for a single school candidate (2 m); maximum vertical linking distance, i.e., maximum vertical distance allowed between two school candidates being linked to form a school (5 m); and maximum horizontal linking distance (20 m) (SonarData 2005). A representative echogram showing walleye pollock schools is shown in Fig. 2.

School descriptors were generated by the Echoview software, including morphometric descriptors (length, thickness and area of schools, Fig. 2), positional descriptors (longitude, latitude, school depth, bottom

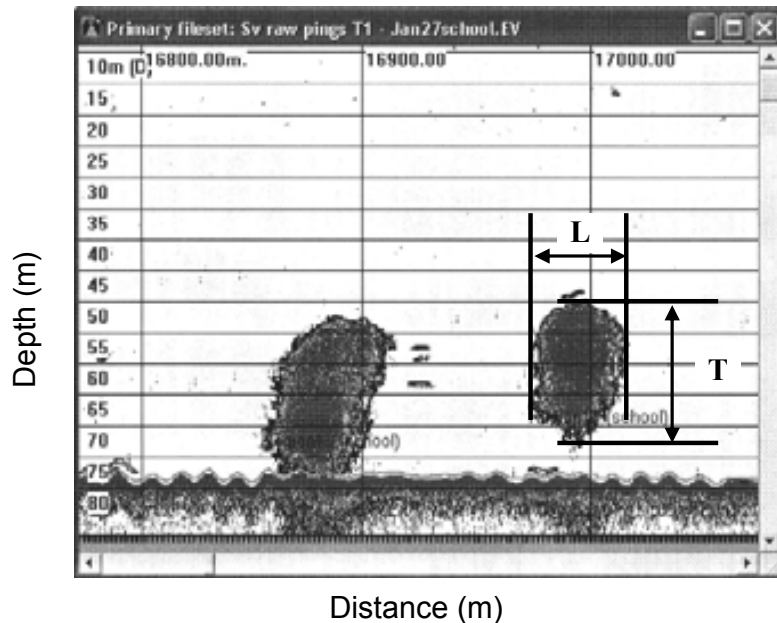


Figure 2. Representative echogram of walleye pollock schools. L is the length and T is the thickness of a school.

depth), and energetic descriptors (S_v , volume backscattering strength; $NASC$, nautical area scattering coefficient) (Simmonds and MacLennan 2005). Based on the above descriptors, some relational descriptors were also determined as follows. Fractal dimension of a school is an index of shape complexity and is a function of school perimeter related to school area (Nero and Magnuson 1989). The line backscattering coefficient, s_L , is a measure of a school's total backscatter and is calculated by integrating the volume backscattering coefficient (s_v) over the sectional area of aggregation (MacLennan et al. 2002). An abundance index, I_{abun} , was obtained by multiplying $NASC$ by school area. The vertical distribution of a school, V_D , is the distance between school depth and bottom depth.

To examine pollock schooling changes during fishing, two separate fishing periods were used to investigate the changes at the school scale and larger scales. Based on the available data and the track of the fishing vessel, the first period was set from January 22 to February 5, and the second period was set from February 14 to February 24. The vessel operated in roughly the same area in both periods, allowing comparisons to be made between periods (Fig. 1). For hypothesis testing, the detected schools during the two periods were pooled and the statistical significance was determined by Student t -tests (Zar 1999).

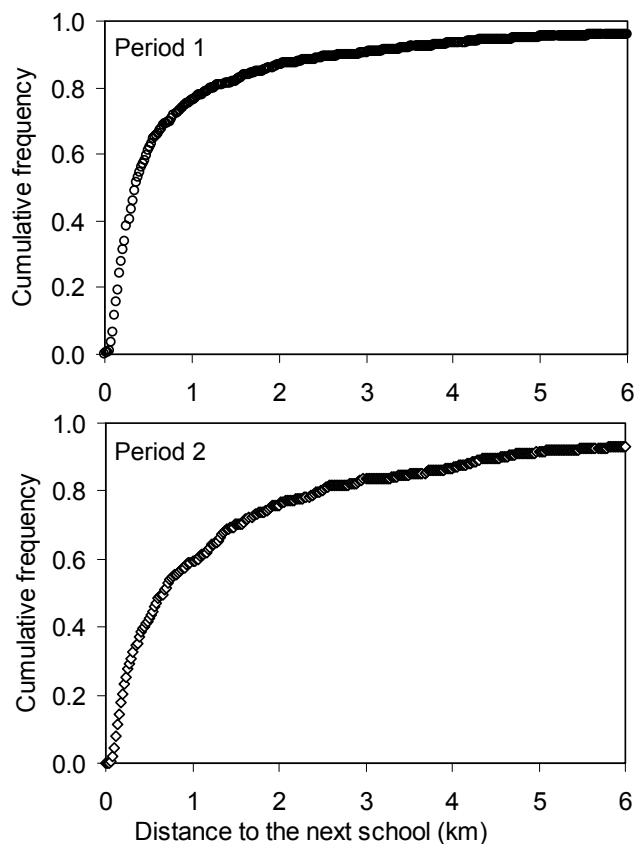


Figure 3. The cumulative distribution of the distance to the next school along the fishing track in the two periods.

It is common for schools of pelagic species to group together in larger scale aggregations, called clusters (Swartzman 1997, Petitgas 2003). To test if there was clustering of schools, the school data for each day were binned into 1 nm elementary distance sampling units (EDSUs) along the fishing track; this distance is commonly used in acoustic analysis (Reid 2000). Statistical significance was tested by the Pearson χ^2 criterion:

$$\chi^2 = \sum_{i=1}^m (n_i - \bar{n})^2 / \bar{n}$$

which has a χ^2 distribution with $m-1$ degree of freedom (Swartzman 1997), where m is the number of EDSUs, n_i is the number of schools of the i th EDSU, and \bar{n} is the average number of schools in an EDSU.

If there was evidence of clustering, the patterns in school clusters were studied. To define a cluster, the next-neighbor distance (NND) was computed for each school along the fishing track. A 1 km thresh-

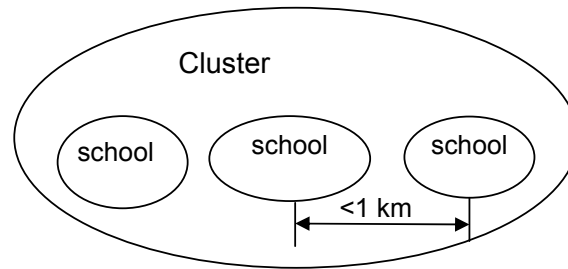


Figure 4. Schematic figure showing the relationship between cluster and schools.

old NND was used to group schools into different clusters because it is near the leveling-off point of most NND-cumulative distributions (Fig. 3) (Petitgas 2003). This point is used as the threshold because the curvature of the distribution curve is related to the repetition rate of the process and hence to the scale of the clustering. Fig. 4 shows the schematic relationship between a cluster and schools. After clustering, some additional variables were recorded: the number of clusters (N_{clus}), the length of each cluster (L_{clus}), the number of solitary schools (N_{soli}) (schools not in clusters), the number of schools per cluster (N_s), and the number of schools per unit cluster length (ρ_{clus}). The abundance index was also calculated for clusters (I_{clus}) and solitary schools (I_{soli}). To test if the threshold is appropriate, a linear regression was conducted for the number of schools in cluster versus the cluster length (Petitgas 2003).

Variography was used to examine changes in the spatial structure between the two fishing periods. Based on the detected schools, we calculated the arithmetic average of the school volume backscattering coefficient (s_v) within each 1 nm EDSU for constructing one-dimensional variograms. Acoustic survey data are characterized by a few large values with a majority of rather low values. This may cause severe problems in structural analysis based on the semi-variogram and its parameters. Consequently a robust version of the experimental semi-variogram (Cressie and Hawkins 1980) is used:

$$\gamma^*(h) = \frac{1}{2} \frac{\left\{ \frac{1}{|N(h)|} \sum_{i=1}^{N(h)} |z(s_i) - z(s_i + h)|^{1/2} \right\}^4}{0.457 + 0.494/|N(h)|}$$

where $z(s_i)$ is the value of the school descriptor s_v at location s_i , $z(s_i + h)$ is the value of s_v at a distance h from s_i , and $N(h)$ is the number of pairs with a distance h apart.

A spherical model was used to fit semi-variograms (Cressie 1993). The range, sill, and nugget characterize the spatial structure of pollock

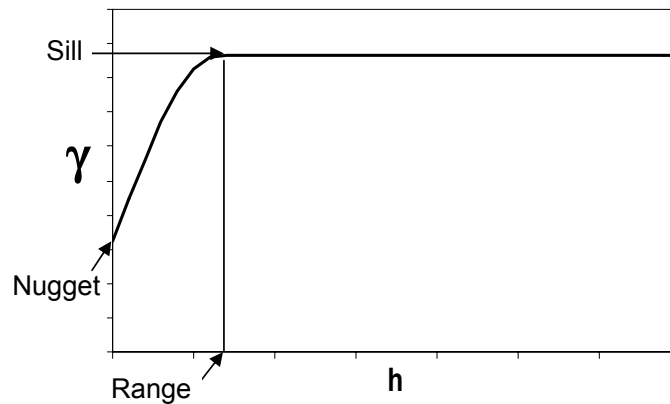


Figure 5. Parameters of the model variogram.

at a scale larger than 1 nm. The range is the distance where the semi-variogram levels off at the sill (Fig. 5). The discontinuity at the origin is the nugget effect caused by measurement error and variation at scales smaller than the lag size.

Results

Echo trace classification

There were 808 schools identified in the first period and 474 schools identified in the second period. Several school characteristics exhibited significant differences between the two periods (Table 1). School density was significantly higher in the second period, as evidenced by higher $NASC$ and s_L ($P < 0.001$). The density almost doubled but the school size became smaller in the second period, as evidenced by the decrease in all morphometric descriptors (school length, thickness, and area in Table 1, $P < 0.01$). Despite the smaller size in the second period, the abundance index was higher ($P < 0.05$). Fractal dimension was significantly different between the two periods ($P < 0.001$); the schools became smoother in the second period as indicated by their smaller fractal dimensions. Unlike the differences in morphometric and energetic descriptors, the vertical distribution of schools (approximately 7.5 m above bottom, Table 1) was similar for the two periods ($P = 0.74$).

NND-clustering

The average number of schools per EDSU for each day, \bar{n} , was higher in the first fishing period than in the second period (Table 2). A non-parametric test was used to test the difference of the daily \bar{n} in the two periods and the results demonstrated that they are statistically different (Wilcoxon rank test, $P < 0.05$). The clustering of schools was apparent for

Table 1. The school descriptors generated by Echoview and some relational descriptors.

	Period 1		Period 2		P-value
	Average	SE	Average	SE	
Length (m)	114.46	7.80	80.75	6.31	0.003
Thickness (m)	15.26	0.26	11.27	0.28	<0.001
Area (m ²)	899.39	73.50	580.77	85.21	0.006
NASC (m ² /nmi ²)	22630	2015	44569	3144	<0.001
Fractal	1.478	0.004	1.429	0.004	<0.001
s_L (m)	0.048	0.004	0.079	0.009	<0.001
I_{abun}	5.80	0.65	8.91	1.46	0.03
V_D (m)	7.42	0.22	7.56	0.40	0.74

s_L = the line backscattering coefficient; I_{abun} = the abundance index of school; and V_D = the distance between the school depth and bottom depth. A Student t-test was used to test for significant differences between the two periods.

most days (Table 2). It is not surprising that the average NND increased in the second period ($P < 0.001$, Table 3), because the number of schools per EDSU was smaller (Table 2).

With a fixed 1 km threshold to identify clusters, 723 schools were grouped into 115 clusters with 85 solitary schools in the first period. In the second period, 349 schools were grouped into 80 clusters with 125 solitary schools. The coefficients of determination (R^2) from the linear regression of the number of schools in a cluster on cluster length are high in the two periods (0.92 and 0.88, respectively).

Although the average NND between schools increased in the second period, the distances between schools within the clusters did not differ in the two periods, because there was similar number of schools per unit cluster length (i.e., ρ_{clus} , Table 3). The larger NND is due to the larger distance between clusters ($P = 0.04$) and between solitary schools ($P = 0.10$). In contrast, there are more schools in each cluster in the first period ($P < 0.05$), which resulted in the cluster length being significantly higher in the first period ($P < 0.05$). Also, the number of schools per km significantly decreased and the ratio of solitary schools to total schools significantly increased in the second fishing period (Wilcoxon rank test, $P < 0.05$) (Fig. 6). However the decrease of the number of clusters per km was not significant (Wilcoxon rank test, $P = 0.098$) (Fig. 6). The Wilcoxon rank test was used here because these ratios were calculated for each day and sample sizes were small. Cluster abundance was similar for the two periods ($P = 0.96$) although on average clusters were of smaller size with fewer schools in the second period. Similarly, abundance of solitary schools did not differ between the two periods.

Table 2. Statistics of schools per elementary distance sampling units (EDSU).

Date	1/22	1/23	1/24	1/25	1/26	1/27	1/28	1/29	2/1	2/2	2/3	2/4	2/5
\bar{n}	3.18	3.67	4.05	2.21	0.52	1.03	1.76	2.36	2.71	0.56	1.78	1.69	3.39
χ^2	364*	220*	168*	174*	89*	258*	280*	402*	259*	64	136*	79*	412*
Date	2/14	2/15	2/16	2/17	2/18	2/19	2/20	2/21	2/22	2/23	2/24		
\bar{n}	1.69	2.14	1.38	2.24	2.48	0.50	1.17	1.65	1.20	0.35	0.35		
χ^2	107*	248*	183*	169*	319*	102	157*	378*	185*	101*	131*		

\bar{n} is the average number of schools in the EDSU. The asterisk means the chi-square test is statistically significant at a $P < 0.05$ level.

Table 3. Parameters estimated by next neighbor distances (NND) clustering procedure.

	Period 1		Period 2		P value
	Average	SE	Average	SE	
NND (m)	1,232.2	104.8	2,399.7	251.5	<0.001
D_{soli} (m)	4,149.4	368.7	5,225.5	538.3	0.10
D_{clus} (m)	6,467.3	886.4	10,298.7	1,832.1	0.04
L_{clus} (m)	1,724.7	200.9	1,203.0	148.6	0.04
N_s	6.28	0.64	4.36	0.47	0.02
ρ_{clus} (#/km)	5.65	0.42	5.43	0.47	0.74
I_{clus}	34.04	5.81	33.52	9.15	0.96
I_{soli}	8.93	3.27	12.09	3.53	0.53

NND = average next-neighbor distance among all schools; D_{soli} = average next-neighbor distance among solitary schools; D_{clus} = average distance to the next cluster; L_{clus} = average length of clusters; N_s = average number of schools per cluster; ρ_{clus} = average number of schools per unit cluster length; I_{clus} = average abundance index of clusters; I_{soli} = average abundance index of solitary schools. The Student t -test was used for the statistical significance.

Variography

Variograms for the average s_v showed significant structure in the two periods (Fig. 7). The nugget effect only contributed a small part of the variance (42% for the first period and 25% for the second period). The variograms for the two periods were different, indicating that the spatial structure of walleye pollock changed between the two periods. The estimated nugget, sill, and range (0.12, 0.29, 5.9, respectively) in the first period were smaller than those (0.66, 2.61, 16.8, respectively) in the second period, which indicates an increase in variability of pollock schools at all spatial scales and that the spatial structure of pollock schools was more extended after fishing.

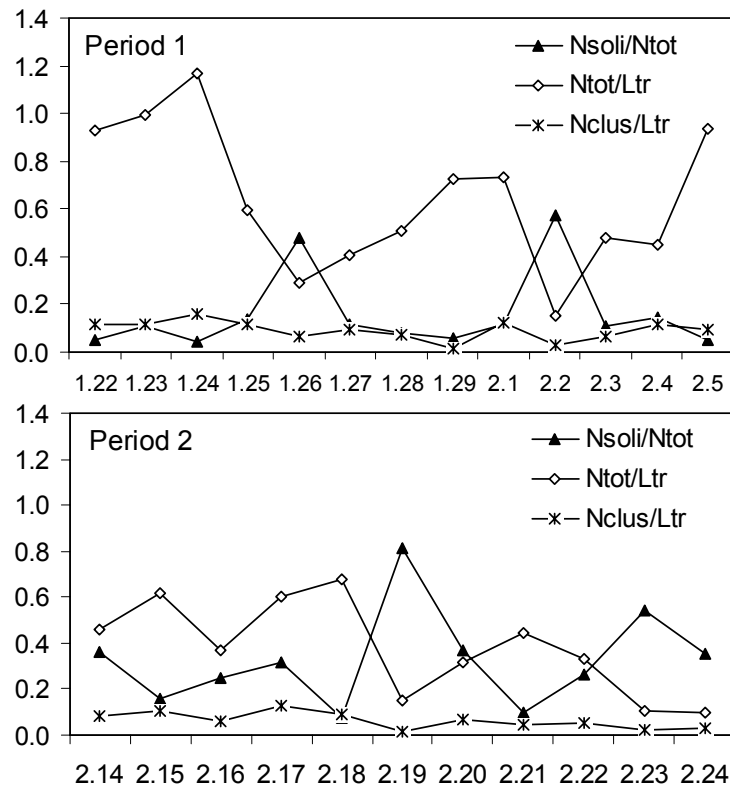


Figure 6. Results of the next neighbor distances (NND) clustering procedure for the two fishing periods: ratio of solitary schools (N_{sol}) to total number of schools (N_{tot}), ratio of N_{tot} to track length (L_{tr}), and ratio of number of clusters (N_{clus}) to L_{tr} .

Discussion

Walleye pollock is one of the main prey species of Steller sea lions. The decline in the sea lion abundance has caused concerns about potential competition between commercial fishing and sea lions. Wilson et al. (2003) described two kinds of fishing effects on pollock. First, fishing removal may cause the decline of the stock abundance in a local area. However, Battaile and Quinn (2006) found evidence pollock recover from this impact in about one week, so this effect may not be strong. Second, fishing may affect long-term pollock behavior that may cause changes in pollock spatial structure. The fish may dive deeper after fishing or form smaller but denser aggregations. The spatial coverage of fish may decrease after disturbance. Both of these effects may impact the foraging behavior of predators on pollock.

To study the effects of fishing on a fish population, one method is to observe the exploited population over a short period, such as the

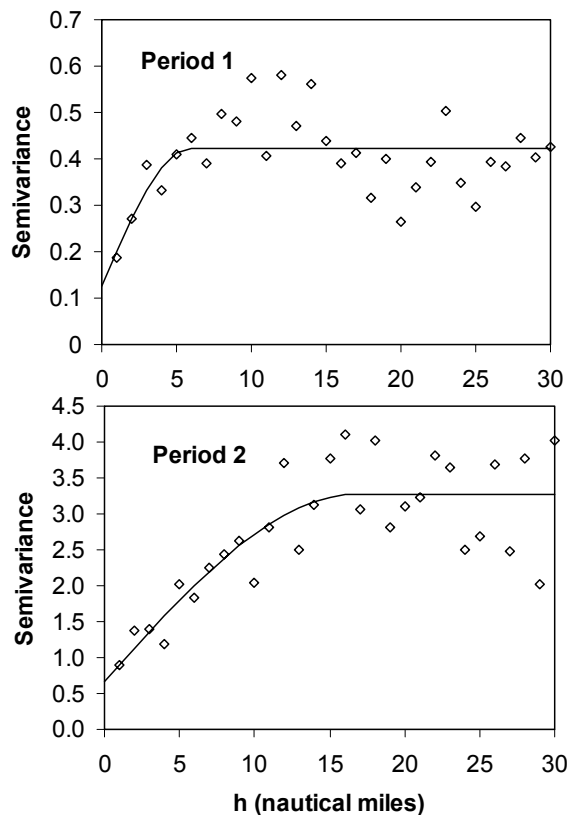


Figure 7. Variograms for two fishing periods. Lag interval was 1 nm and a total of 30 lags were used.

Wilson et al. (2003) study on the interaction between pollock and fishing in the Gulf of Alaska east of Kodiak Island. The study area was surveyed before, during, and after fishing activities. Pollock spatial distribution, biomass and vertical distribution were compared to investigate the effect of fishing. They were unable to detect significant links between fishing and pollock distribution and biomass.

We used two fishing periods because nearly the same areas were fished in both (Fig. 1). Although the fishing tracks were not exactly the same in the two periods as in a scientific survey, the fishing tracks were highly overlapped in the study area. Most of the areas traversed in the second period had been traversed during the first period. Therefore, we considered it reasonable to compare the pollock distribution during the two periods.

The study vessel headed northeast after February 6 and returned to the study area on February 14. The other fishing vessels exhibited similar fishing patterns based on our data. This exploitation pattern gave pollock in the study area about one week without fishing impacts.

The average abundance was similar in the two fishing periods, suggesting that any local depletion that may have occurred was apparently replenished by pollock moving in from other areas.

This paper mainly addressed the question of changes in pollock spatial distribution at different scales over a short time period (about one month). After some days of fishing, the pollock schools seemed to have significant changes at the small scale (school level). The schools became denser (increased $NASC$ and s_l), smaller (decreased morphometric descriptors), and smoother (decreased fractal dimension). Since total abundance did not change substantially between the two fishing periods, an increase in school density would be expected to result in a decrease in school frequency and an increase in the distance among schools. Unlike the significant changes in morphometric and energetic descriptors, the vertical distribution did not change significantly, suggesting that the fish did not dive deeper as has been hypothesized. The bottom depth is mostly less than 150 meters on the fishing grounds north of Unimak Island. Since most of the detected schools were just above the bottom, the ability of schools to dive deeper is restricted, so the vertical distribution of disturbed fish in deeper fishing areas cannot be inferred from our study.

Clustering of schools is a common phenomenon for schooling fish (Swartzman 1997, Petitgas 2003). Our study confirmed that there is clustering of eastern Bering Sea pollock schools. To identify the clusters, both fixed distance threshold (Swartzman 1997) and variable threshold (Petitgas 2003) methods have been used. For comparison of clusters in the two fishing periods, we chose the fixed threshold method, because of the short time period and small area covered in this study. The 1 km threshold value was chosen based on the cumulative frequency of NNDs. Our results established that this threshold worked well according to the criteria by Petitgas (2003). There are neither too many clusters nor solitary schools, and there is a high R^2 for the linear regression of the number of schools in a cluster on cluster length.

Similar to the results at the school level, there were also significant changes at the level of clusters of schools and 1 nm EDSU. A decrease of school numbers per EDSU and the increase in NNDs suggest that fishing may have had a short-term effect. One interesting result is that the NND between schools within clusters did not change. This suggests that there is some attraction/repulsion process that keeps NND within clusters the same while changing the number of schools in a cluster. The increased overall NND was caused by an increase in inter-cluster distance or perhaps distances between solitary schools (Table 3). In contrast, the cluster abundance was similar between the two periods despite the changes of school characteristics in clusters. Similarly, average abundance of solitary schools did not differ during the two periods. Pollock may find more places suitable for aggregation in the absence of fishing,

but then find fewer areas suitable after encountering fishing impacts. Once these preferred areas are chosen, pollock might form tighter and smaller schools or clusters of schools with high abundances.

Variograms display the spatial distribution pattern of pollock schools at a scale larger than 1 nm. The nuggets for the two periods contributed only a small portion of the variance, which suggests the presence of spatial correlation. From the increased sill and nugget, pollock schools became more variable in spatial distribution at all scales greater than 1 nm, which is also found at school level. In the second period, most of the school descriptors had higher variances (Table 1). The range in the second period is higher than that of the first period (Fig. 7), indicating that spatial correlation of pollock extends to greater distances.

In summary, our results suggest the following operative hypothesis of pollock schooling behavior during the A fishing season. Pollock aggregate into schools in the daytime and disperse at night during the spawning season. After about two weeks of fishing, the aggregation pattern changes both at the school scale and scales larger than 1 nm. Pollock aggregate in smaller but denser schools that have a patchier distribution in space. The changed aggregation pattern may be due to commercial fishing or to biological changes in behavior and movement. It is unknown whether the increased patchiness of pollock is a persistent feature of the A fishing season. This study is a first look at pollock schooling and the effects of fishing on pollock school distribution. The observations are somewhat limited, so it is difficult to draw strong conclusions. However, the results of this study suggest fishing may alter school distribution and density. We recommend further research be undertaken to better understand the relationship between fishing removals and the subsequent reduced spatial extent of the pollock and the possible effect on the foraging ability of Steller sea lions and other predator species dependent on pollock.

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