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ABSTRACT: Results from the first two years of a multiyear fishery interaction study near Kodiak Island in the Gulf of Alaska are presented. Findings from acoustic surveys, which were conducted in August 2000 and 2001, provide important information that begins to address the question of whether the abundance and spatial patterns of various species, including walleye pollock *Theragra chalcogramma* are impacted by commercial fishing activities over short spatio-temporal scales. The biomass and distribution of walleye pollock were stable over periods of days to weeks although during the second year an unusual, extremely dense, small-scale walleye pollock aggregation was detected during one of several survey passes. Several morphological descriptors of the walleye pollock echosign layers were evaluated to better understand whether differences at the scale of the fish aggregations occurred in response to fishing. Variography was also used to quantify walleye pollock spatial patterns. Results from the second year, when the commercial fishery took place within the study area, do not suggest a significant link between fishing activities and changes in estimates of juvenile and adult walleye pollock geographical distribution, biomass, or vertical distribution. It will be important, however, to evaluate whether these trends persist during subsequent years.

INTRODUCTION

A multiyear field experiment was initiated in August 2000 near Kodiak Island in the Gulf of Alaska. The aim of this research was to characterize the effects of commercial fishing activity on the distribution and abundance of walleye pollock *Theragra chalcogramma* over short temporal scales of days to weeks. The work forms part of a larger research effort designed to determine whether commercial fishing activities impact the prey availability of walleye pollock and other forage fish species (e.g., capelin *Mallotus villosus*) to endangered Steller sea lions *Eumetopias jubatus* (Fadely et al. 2003).

The impetus for this work was the need to understand mechanisms that contributed to the precipitous decline in the western stock of Steller sea lions which began in the 1970s (Loughlin 1998). One of several explanations that have been offered to account for this decline is that large-scale commercial fisheries, such as those for walleye pollock and Atka mackerel *Pleurogrammus monopterygius*, compete with Steller sea lion populations by reducing the availability of potential prey in localized areas (Loughlin and Merrick 1989; Merrick et al. 1987). The home range of a foraging Steller sea lion could be considered a localized area. A reduction in prey availability may result from a reduction in prey abundance and/or a disruption in the spatial patterns of the Steller sea lion prey. The spatio-temporal extent of the perturbation to the prey field could determine the impact on the foraging success of the Steller sea lion predator. For example, fishing removals may cause a decline in the abundance of a prey species within a localized area, but recovery to pre-fishery levels may be so quick that impacts to predator foraging success would be negligible. Alternatively, disturbances from fishing operations may elicit longer-term behavioral responses by prey species that might affect spatial patterns and impact Steller sea lion foraging behaviors. Disturbed fish might move deeper in the water column to form smaller, denser aggregations, which may adversely impact the foraging behavior of Steller sea lions. Unfortunately, no data exist to answer two important questions regarding interactions among commercial fishing, Steller sea lions, and their prey. Firstly, do commercial fishing activities affect the distribution and abundance of Steller sea lion

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prey species significantly? And secondly, if the fishery induces perturbations in prey spatial patterns and/or abundance, how do these perturbations impact Steller sea lion foraging success?

The primary goal of this study was to investigate whether measurable changes in spatial patterns (i.e., vertical distribution, fish school characteristics) and abundance occurred in walleye pollock at scales relevant to Steller sea lion foraging (Merrick and Loughlin 1997). This paper reports results from the first two years of the field study to examine the spatio-temporal characteristics of walleye pollock before and during a commercial fishing season. Although results for capelin are briefly discussed, complete results for this species will be reported elsewhere. Future directions for this type of fishery-interaction research are also discussed.

METHODS

Study Area and Season

The east side of Kodiak Island in the Gulf of Alaska was chosen as the study area for the fishery interaction work for several reasons (Figure 1). Two adjacent submarine troughs with similar topographical features characterized the area. Barnabas Trough served as a treatment site where commercial fishing was allowed and Chiniak Trough served as a control site where fishing was prohibited. The proximity of the two troughs minimized vessel travel time and enabled a more synoptic sampling schedule. Additionally, a commercial trawl fishery for walleye pollock occurs within the area so that implementation of an experimental fishery perturbation was relatively easy. Although not a requirement for the experiment, the area along the east side of Kodiak Island is also characterized by at least six haulout sites for Steller seal lions where 508 animals were counted in June–July 2002 (Sease and Gudmundson 2002; Figure 1). Thus, other closely associated research efforts have been initiated in the area, which focus directly on the behavior of the Steller sea lions in relation to their prey distributions (Fadely et al. 2003; Shima et al. 2003).

Surveys for the fishery interaction experiment occurred in August when recently weaned Steller sea lion juveniles (1-year-olds) were considered vulnerable to nutritional stress due to their high caloric needs per unit body weight and inexperience at capturing prey (Winship et al. 2002; Loughlin et al. *In press*). A commercial walleye pollock fishery was also scheduled to open in the area during August. The study was designed to extend over several years because natural shifts in ocean conditions and/or variations in the age composition of the walleye pollock stock might influence responses to fishing activities.

Field Methods

Multiple surveys of the control and treatment troughs were conducted during daylight hours (about 15 hours/day) over several weeks in August 2000 and August 2001 using acoustic survey methods routinely employed by Alaska Fisheries Science Center scientists (Karp and Walters 1994; Traynor 1997). The surveys consisted of a series of uniformly-spaced (3 nmi) parallel transects (Figure 1). A complete sampling of all transects within a trough was considered a survey pass.

The work during the first year was completed in the absence of the August fishery and during the second year was conducted before and during the fishery. The work during the first year served two purposes. First, the area had not been previously surveyed with acoustic methods during summer, so it was important to evaluate the feasibility of this approach in the study location in August. Second, it was important to characterize the natural variability in the temporal and spatial patterns of the walleye pollock distribution and abundance over the 2–4 week field season. Two survey passes were conducted within each trough in August 2000. During the second year of the study, two survey passes were conducted within each trough before the fishery commenced in Barnabas Trough. These were followed by one pass in Chiniak Trough and two passes in Barnabas Trough *during* the fishery in Barnabas Trough to investigate whether fishery-induced changes occurred in the fish distribution. The fourth, partial pass in Barnabas Trough was only conducted over the area where walleye pollock had been encountered during earlier passes. Thus, no commercial fishing was allowed in either Barnabas or Chiniak Troughs during survey passes 1–2 in either year, and commercial fishing operations occurred in Barnabas Trough during passes 3–4 in 2001. A similar number of days elapsed between repeated surveys in each trough during both years (Table 1).

The acoustic data for this study were collected with a calibrated Simrad[1] EK 500 echosounder operating at 38 kHz. The nominal pulse length was 1 ms, beam width was 6.9°, and ping rate was 1 s^{-1}. Echo-integration data from the sounder were initially logged

[1] Reference to product names does not imply endorsement by the National Marine Fisheries Service, NOAA.

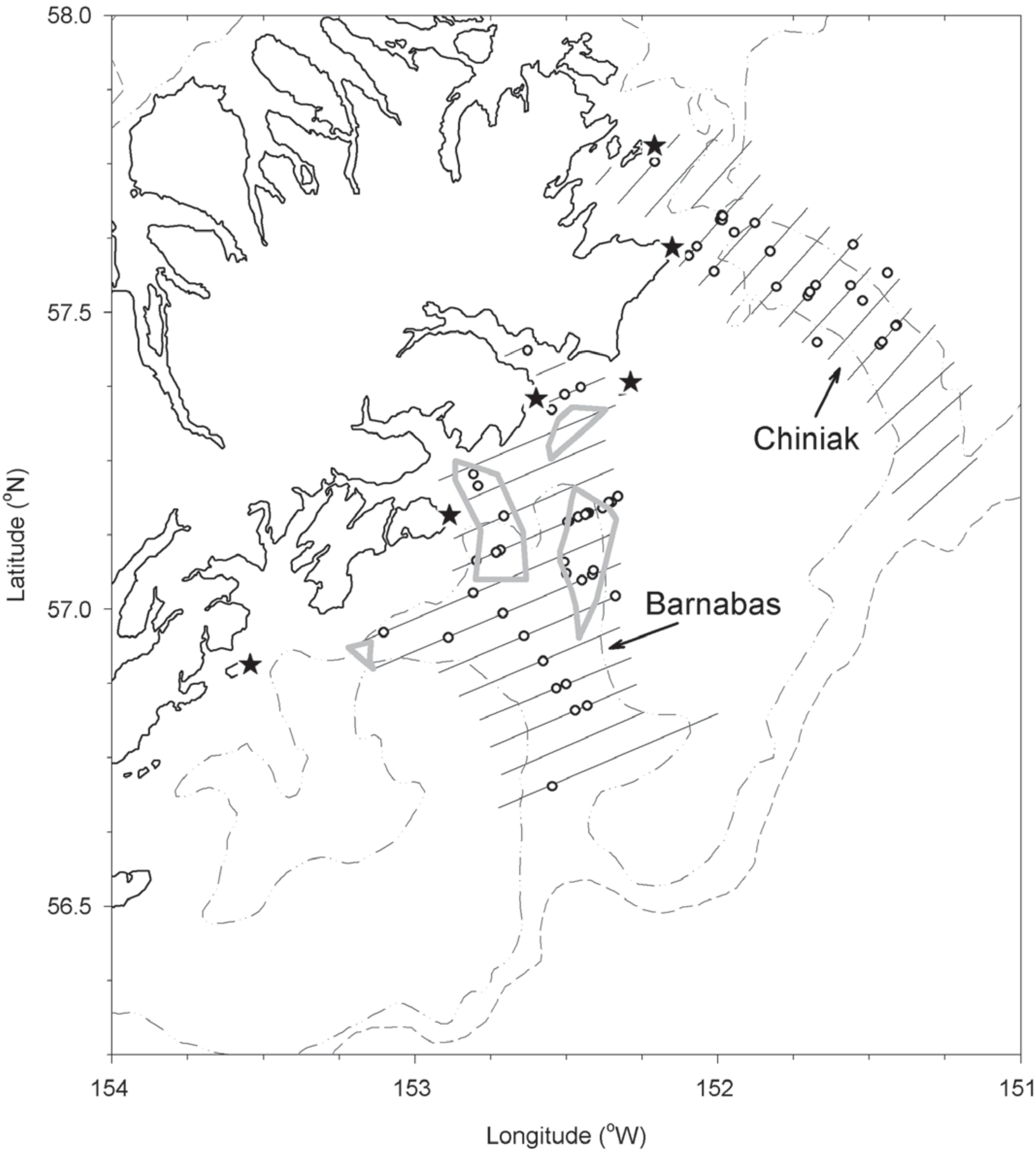

Figure 1. Fishery interaction study area off the east side of Kodiak Island showing survey transects used for all passes during August 2000 and 2001, and survey trawl locations (open circles) for August 2001. Similar numbers of trawl hauls were conducted during August 2000. Polygons (gray lines) in Barnabas Trough represent areas where commercial trawl hauls were made in August 2001. Stars represent locations of six Steller sea lion haulout sites.

Table 1. Walleye pollock biomass estimates (thousands of t) for Barnabas and Chiniak Troughs from the fishery interaction study off the east side of Kodiak Island. Error bounds are shown in parentheses (see text for explanation). Whether a survey pass was conducted prior to or during the August commercial fishery is indicated.

	Chiniak Trough			Barnabas Trough		
Survey Pass	Date	Adult	Juvenile	Date	Adult	Juvenile
Study year 2000						
1 (pre-fishery)	8–11 Aug	6.7 (5.9, 7.5)	5.9 (4.3, 7.5)	11–14 Aug	13.1 (10.7, 15.5)	0
2 (pre-fishery)	14–17 Aug	6.2 (5.4, 7.0)	8.0 (5.8, 10.2)	17–19 Aug	10.8 (8.2, 13.4)	0
Study year 2001						
1 (pre-fishery)	9–11Aug	3.5 (2.9, 4.0)	17.2 (14.5, 20.0)	11–14 Aug	12.7 (9.7, 15.8)	7.8 (4.9, 10.6)
2 (pre-fishery)	14–16 Aug	2.9 (2.3, 3.5)	19.7 (16.2, 23. 2)	16–19 Aug	4.8 (4.1, 5.5)	9.3 (8.2, 10.4)
3 (fishery)	23–26 Aug	3.7 (3.2, 4.1)	18.7 (14.8, 22.6)	26–29 Aug	7.6 (5.9, 9.2)	10.7 (9.1, 12.2)
4 (fishery)				29–30 Aug	4.6 (3.7, 5.5)	10.9 (8.0, 13.8)

with a horizontal resolution of about 5–6 m (dependent on vessel speed which averaged 5–6 m s^{-1}) and a vertical resolution of 0.1–0.5 m. These data were processed with the Echoview software (SonarData 2002) for the echo trace classification analysis. The Simrad BI500 software (Knudsen 1990) was used to log the data and to classify the echosign into different groups based on taxonomic or size-group considerations (see below and Results). The classified data were binned into cells with a vertical resolution of 5 m and horizontal resolution of 185 m (0.1 nmi) for subsequent analyses.

Biological samples were collected with trawls during all surveys to identify the species and size compositions of selected echosign and to collect other information needed to estimate abundance and distribution patterns (Wilson and Guttormsen 1997). A large midwater Aleutian wing trawl and smaller midwater Marinovich trawl were used to target midwater echosign, and a poly Nor'eastern bottom trawl (poly Nor'eastern) was used to target near-bottom echosign. The codends of the Aleutian wing trawl and poly Nor'eastern were fitted with 32 mm (1 1/4 in) mesh codend liners and the Marinovich trawl with a 3.2 mm (1/8 in) mesh liner except in August 2001, when a 9.5 mm (3/8 in) mesh liner was used in the Aleutian wing trawl. The smaller liner was used the second year to improve the retention of smaller capelin. Walleye pollock were sampled to determine sex, fork length (to nearest cm), body weight (to nearest 2 g), age, maturity, and ovary weight of selected females.

Walleye pollock biomass estimates were derived by partitioning the echogram and catch data into geographic areas within each trough so that the areas were characterized by similar walleye pollock echo signatures and fish length distributions. An estimate of the acoustic backscattering or nautical area scattering coefficient (s_A; defined in MacLennan et al. 2002) attributed to walleye pollock was calculated for each geographic area based on the average of all s_A values from within that area. The s_A estimate for each geographic area was then scaled to length-specific fish numbers and biomass using walleye pollock length distributions, a length-weight relationship derived from trawl catches, and a standard target strength to walleye pollock length relationship (Traynor 1996). Estimates of length-specific biomass were then summed across fish lengths and geographic strata to provide total estimates for each trough. Because the acoustic data were only collected from a nominal depth of 14 m to within about 0.5 m of the bottom echo, the resulting biomass estimates may not represent the total biomass within the troughs.

Data Analysis

To evaluate whether significant large-scale differences existed between the walleye pollock geographical distributions between the pre-fishing and fishing periods, a statistical test was used which is based on a modified Cramer-von Mises (CvM) statistic (Syrjala 1996). This test is dependent on the spatial scale selected. This procedure calculates a test statistic as the sum of the squares of the differences between the cumulative distribution functions of walleye pollock density (i.e., s_A) from the two samples. Observations were normalized to remove the effect of differing population sizes between passes. Significance of the test statistic was determined with a randomization test. To test for differences between the pre-fishing and fishing periods in the treatment and control troughs, the acoustic data were initially block-averaged into 3 nmi sections (i.e., distance equal to transect spacing) along transects for each survey pass. Because differences between passes were slight within the pre-fishing or fishing periods for either trough, means at each 3 nmi location were calculated using the block-averaged passes within each period when multiple passes were conducted within the period (i.e., both Chiniak and Barnabas Troughs for pre-fishery, Barnabas Trough for fishery period). For the fishery period in Barnabas Trough, observations at similar locations during pass 3 and the partial pass 4 were averaged and inserted into the pass 3 data set. These means of the block-averaged data were tested for differences using the modified CvM test.

To determine whether differences occurred between estimates of walleye pollock abundance for each period, relative estimation errors were generated using a model-based one-dimensional geostatistical procedure (Petitgas 1993a; Williamson and Traynor 1996). The estimation variance obtained from geostatistical analysis is an indicator of the precision of the biomass estimate (Rivoirard et al. 2000). Error bounds or intervals were constructed by adding or subtracting twice the relative estimation error from the mean. In this study, mean estimates of biomass were considered significantly different when intervals constructed in this way did not overlap.

To evaluate whether the walleye pollock changed position in the water column between the pre-fishing and fishing periods, estimates were calculated of the mean fish depth and the mean fish depth above the bottom. Ninety-five percent confidence intervals were generated using bootstrapping methods (Mooney and Duval 1993), and estimates were compared with a z-test (Zar 1984).

Two analytical procedures were used to describe the structure of the walleye pollock distribution in August 2001 at different spatial scales, and to evaluate whether the scale of patchiness changed between the pre-fishery and fishery periods. These included an echo trace classification (Reid 2000) and variographic analysis (Petitgas 2001) of the walleye pollock echosign, which are described below.

Walleye pollock echo traces were classified using the Echoview software (SonarData 2002), which included school or patch recognition algorithms, and also generated estimates of various descriptive parameters of the aggregations. Most of the walleye pollock echosign was distributed in pelagic and demersal layers (Reid 2000; Swartzman et al. 1994) rather than aggregations more typically chararcterized as schools (Partridge et al. 1980). For the purposes of this study, these finite walleye pollock layers are referred to as aggregations or patches. Several mean volume backscattering strength (S_v) thresholds (-70 to -60 dB) and a range of values for other criteria used to define an aggregation were evaluated before the final values were chosen. An S_v threshold of -70 dB in conjunction with other criteria values (i.e., minimum school length (40 m), minimum height (5 m), minimum connected length (5 m), minimum connected height (2 m), maximum vertical linking distance (5 m), maximum horizontal linking distance (20 m)) provided the best definition of the walleye pollock aggregations when compared to the original echograms. These final values were used in the analysis of all survey passes. As emphasized by Reid (2000) and Freon et al. (1996), the criterion values will likely contain substantial and unknown biases in defining aggregations, but if kept constant (as in the present study), they should provide useful information about the variability of the aggregation structure. Caution is needed, however, in making inferences about the exact dimensions of fish aggregations with these types of data (Reid 2000). A few areas were excluded from the present analysis, where substantial backscattering from unidentified organisms overlapped with that from walleye pollock.

Several of the aggregation-size and -shape descriptors generated by the Echoview software (SonarData 2002) were used to evaluate whether differences existed in the walleye pollock aggregations between the pre-fishery and fishery periods during the second year. Descriptors used in this analysis, which are defined in Nero and Magnuson (1989), included aggregation height, length, area, perimeter, and mean volume backscattering coefficient (S_v). Fractal dimensions of the aggregations, which relate school perimeter to school area, were also generated (Nero and Magnuson 1989; Barange 1994). An increase in the fractal value, which indicates a more complex aggregation shape, may be indicative of a redistribution process of the fish aggregation (e.g., potential indicator of disruption of walleye pollock layer into smaller groups). Where various descriptors were highly correlated (i.e., length, area, perimeter), a representative morphological variable is presented (i.e., length). Statistical significance among the descriptor estimates was based on analysis of variance results and the Student's t statistic with Bonferroni adjustment (Zar 1984). A log transform of some of the variables was needed to stabilize the variance. Statistical test results were considered significant at $P < 0.05$. Ninety-five percent confidence intervals were based on traditional sample-based methods.

Variography was used to examine the spatial structure of walleye pollock distributions. Experimental semi-variograms were constructed for the adult and juvenile walleye pollock for each pass and trough using the 0.1 nmi echo integration data (i.e., s_A). A 2-parameter (range and nugget) spherical model was fitted to each semi-variogram using a weighted least squares algorithm (Johnston et al. 2001). The range corresponds to the distance at which the semi-variogram reaches its asymptote. The sill defines the asymptotic height of the variogram (i.e., the maximum variability in the data). The two components of the sill are the nugget and partial sill. The nugget is the fitted semi-variance at a lag of zero. It is composed of measurement error and variation at scales smaller than the lag size (about 1 km in the present study). The partial sill is the difference between the sill and the nugget and is the part of the semi-variance due to autocorrelation. Model estimates for the range, nugget, and partial sill are reported to characterize walleye pollock spatial structure between the pre-fishery and fishery periods. Isotropy was assumed because data were not available to evaluate differences in the spatial structure as a function of direction at scales smaller than the inter-transect distance (3 nmi).

RESULTS

The survey for the first year of the study was conducted between 8–20 August 2000. Two survey passes were completed within each trough, along with 35 hauls conducted with the Aleutian wing trawl, 5 hauls with the poly Nor'eastern, and 5 hauls with the Marinovich trawl. The echo integration-trawl survey for the second year of the study was conducted between 9–31 August 2001. Multiple survey passes were completed within each trough prior to the fishery along with 41 hauls conducted with the Aleutian wing trawl and 16 hauls with the poly Nor'eastern.

Acoustic backscattering attributed to walleye pollock and capelin was easily recognized from other backscattering in Barnabas and Chiniak Troughs each year (Figure 2). Most of the backscattering was assigned to 4 types of fish echosign: 1) adult walleye pollock, 2) juvenile (mostly age-1) walleye pollock, 3)

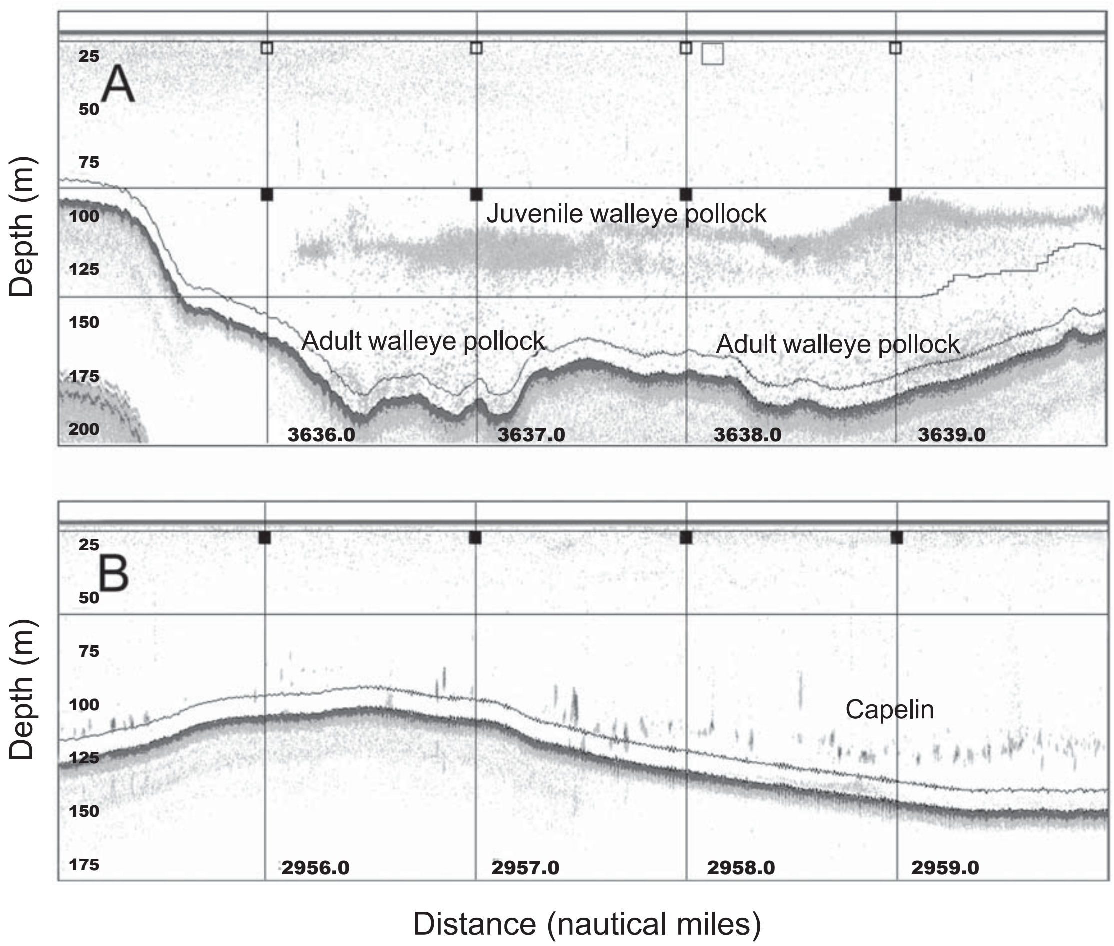

Figure 2. Example echograms illustrating echosign layers attributed to walleye pollock (A) and capelin (B) during August 2001. Distance refers to cumulative distance traveled by the vessel during the survey.

a mixture of capelin/age-0 walleye pollock in August 2000 or capelin in August 2001, and 4) other fishes.

The size composition of adult walleye pollock was similar between years and troughs whereas the juvenile walleye pollock were largely absent in Barnabas Trough during the first year (Figure 3). Juveniles were present in both troughs during the second year, although the size composition indicated that some age-2 fish (about 30 cm modal fork length) were present in Chiniak Trough but not Barnabas Trough.

August 2001 Fishery

Catch data have been compiled for 27 of 28 vessels that were fishing in Barnabas Trough during the experiment in August 2001 (Figure 1). These data account for about 99% of the total catch removed from this trough based on the National Marine Fisheries Service logbook data and shoreside database (NMFS, Alaska Region, P.O. Box 21668, Juneau AK 99802-1668). The 27 vessels spent 1,074 hours fishing to complete 167 hauls during 22–31 August (i.e., during Chiniak Trough survey pass 3 (23–26 August) and Barnabas Trough passes 3 (26–29 August) and 4 (29–30 August)). Vessel deliveries during this period indicated 2,850 t of walleye pollock were removed from Barnabas Trough. Based on historical fishing trends, this did not appear to be an unusual level of effort.

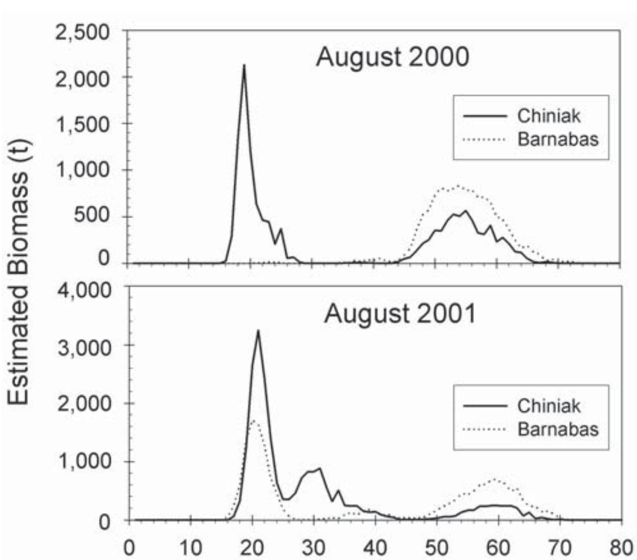

Figure 3. Walleye pollock size composition estimates for Chiniak and Barnabas Troughs during August 2000 and August 2001.

Geographical Distribution

The geographical distribution of walleye pollock and capelin within each trough exhibited similarities between years although some notable differences existed for juvenile walleye pollock. Adult walleye pollock were distributed throughout Chiniak Trough, and in Barnabas Trough they tended to concentrate more towards the northern half of the trough during both years (Figure 4). Juvenile walleye pollock were broadly distributed in Chiniak Trough but virtually absent in Barnabas Trough during the first year; they occurred in both troughs during the second year, with distributions similar to the adults (Figure 5). The mixture of age-0 walleye pollock and capelin was broadly distributed in both troughs during the August 2000 survey. The following year, age-0 walleye pollock were only detected at the east end of one transect in Chiniak Trough during the second survey pass. Capelin were often present over the shallower edges of Chiniak Trough, but were concentrated in the deeper waters within the southern half of Barnabas Trough during the second year. These basic geographical patterns for each group occurred during each pass each year. Thus, although the distributional patterns between the two troughs exhibited some intra- and interannual differences, they were similar enough to justify their use as treatment and control sites.

During the second year no significant difference was detected in the geographical distributions between the pre-fishery and fishery periods for juvenile walleye pollock in Barnabas Trough (CvM test, $P = 0.453$), although the difference was marginally significant for juveniles in Chiniak Trough ($P = 0.049$). Because no fishing was allowed in the control site, this difference suggested that the temporal variability in the juvenile distribution patterns differed between the troughs. No difference was detected between the periods for adults in Chiniak Trough ($P = 0.362$). Although a significant difference was detected between periods for adults in Barnabas Trough ($P = 0.017$), this result was due to the presence of a small, but extremely dense aggregation of adults that was only observed during one of the two pre-fishery passes (pass 1) along the east end of transects 6 and 7 (Figure 4). This dense adult aggregation also complicated biomass estimates (see below). However, when the single extreme observation along transect 6 was replaced with the pass 2 (pre-fishery) observation from the same location, no significant difference was detected between the pre-fishery and fishery periods for adults ($P = 0.108$). This illustrates that the statistical significance of the CvM test is sensitive to single large values. Thus, the statistical significance may not indicate that a fundamental difference exists in the underlying population represented in the pre-fishing and fishing periods.

Abundance

Biomass estimates for August 2000 indicated that adults were about twice as abundant in Barnabas Trough as Chiniak Trough (Table 1). Juvenile walleye pollock were scarce in Barnabas Trough but present in quantities similar to adults in Chiniak Trough. Differences in estimates between passes ranged between 7% and 36%. The results suggest that the biomass of adult walleye pollock was relatively stable over a period of 1–2 weeks in both troughs and offers support for using the two troughs as treatment and control sites.

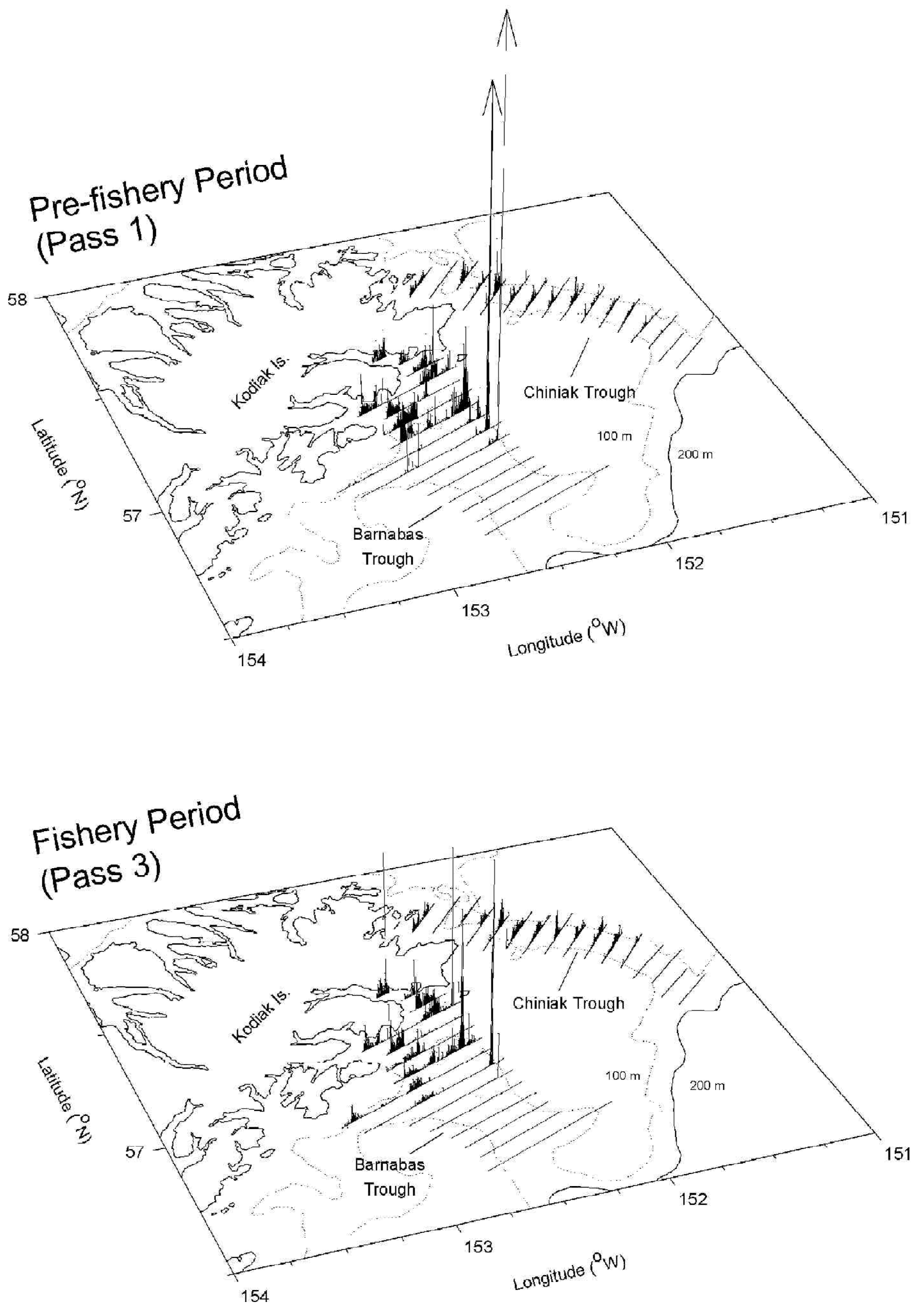

Figure 4. Acoustic backscatter attributed to adult walleye pollock along transects during a typical pass from the pre-fishery and fishery periods in August 2001. See text for explanation. Vertical (z -axis) scale is 0 to 12,000 m^2 nmi^{-2}.