Short-term effects of commercial fishing on the distribution and abundance of walleye pollock (*Theragra chalcogramma*)

Paul D. Walline, Christopher D. Wilson, Anne B. Hollowed, and Sarah C. Stienessen

Abstract: Replicate acoustic surveys conducted near Kodiak Island, Alaska, USA, during summers 2001, 2004, and 2006 showed that the short-term effect of commercial fishing activities on walleye pollock (*Theragra chalcogramma*) during this period was small, in most cases too small to detect. An area with commercial fishing and a nearby comparison area where commercial fishing was prohibited were surveyed before and during the fishery. Acoustic data were used to assess changes in the abundance, geographical and vertical distributions, and small-scale spatial patterns of walleye pollock, which may have occurred after the fishery commenced. A decrease in biomass after fishing began was detected only in 2004. No changes were detected in geographical or vertical distributions that could be attributed to the fishery in any year. Adults did not appear to aggregate or disperse in response to the fishery. Juvenile aggregations did differ between the prefishery and fishery surveys in 1 of the 2 years when juveniles were present. These data suggest that changes in walleye pollock abundance and distribution caused by the fishery are likely quite small compared with natural fluctuations.

Résumé : Des inventaires acoustiques répétés en double réalisés près de l'île de Kodiak, Alaska, É.-U., durant les étés 2001, 2004 et 2006, ont montré que l'effet à court terme des activités de pêche commerciale sur la goberge de l'Alaska (*Theragra chalcogramma*) durant cette période est faible, dans la plupart des cas sous le seuil de détection. Nous avons inventorié une zone de pêche commerciale et une zone avoisinante de comparaison dans laquelle la pêche commerciale était interdite avant et durant la pêche. Les données acoustiques ont servi à évaluer les changements dans l'abondance, les répartitions géographiques et verticales et les patrons spatiaux à petite échelle qui ont pu se produire chez la goberge après le début de la pêche. Nous avons décelé une réduction de la biomasse après le début de la pêche seulement en 2004. Aucun changement n'a été observé dans les répartitions géographiques ou verticales qui aurait pu être attribué à la pêche durant ces trois années. Les adultes ne semblent pas se rassembler ou se disperser en réaction à la pêche. Les rassemblements de jeunes différaient dans les inventaires avant et durant la pêche lors de l'une des deux années pendant laquelle les jeunes étaient présents. Nos données laissent croire que les changements causés par la pêche dans l'abondance et la répartition de la goberge sont vraisemblablement petits par comparaison aux fluctuations naturelles.

[Traduit par la Rédaction]

Introduction

A multiyear study of the interactions between commercial fishing and walleye pollock (*Theragra chalcogramma*) was conducted near Kodiak Island in the Gulf of Alaska (GOA) in 2000–2006. The goal of the work was to examine the effect of the commercial fishery on the distribution and abundance of walleye pollock, a major prey item in the diet of Steller sea lions (*Eumetopias jubatus*; SSL). The work was undertaken as one of a number of investigations designed to understand processes that have contributed to the decline in the western SSL population since the 1970s (Merrick et al. 1987; Loughlin 1998). In response to the decline, the western SSL population was listed as threatened in 1990 and as endangered in 1997 under provisions of the US Endangered Species Act.

When the study was initiated in August 2000, one of many possible explanations for the decline was that competition with fisheries had caused nutritional stress with negative consequences for survival of SSL (Loughlin and Merrick 1989). More recent studies have attributed the steep decline in SSL abundance from the late 1970s to the early 1990s to a combination of factors, one of which was a shift in prey availability and composition associated with the 1976–1977 climate regime shift (Hare and Mantua 2000; Benson and Trites 2002; Trites et al. 2007). Predation by killer whales (*Orcinus orca*) has also been suggested as a potential cause for the SSL decline (Springer et al. 2008).

In the period after adoption of SSL protection measures, such as institution of no trawl zones near rookeries (Hennen 2006), the population has stabilized in most subregions, but declines in some subregions are still observed (Fritz and

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Stinchcomb 2005). Demographic studies suggest that declines in natality may be contributing to the lack of recovery in some subregions (Holmes et al. 2007). Although anthropogenic causes may have played a role in the decline, bycatch during commercial fishing, legal and illegal shooting, commercial hunts, subsistence hunting, and mortality incidental to research have since been greatly reduced, if not eliminated entirely, leaving competition with fisheries as one of two anthropogenic factors that could be delaying recovery of western SSL populations (Atkinson et al. 2008*b*). The other potential anthropogenic cause not ruled out by Atkinson et al. (2008*b*) was the effect of contaminants on SSL fecundity.

Steller sea lions are opportunistic feeders and can survive on a variety of different prey, provided abundance is adequate (Logerwell and Schaufler 2005; Atkinson et al. 2008*a*; Sigler et al. 2009). Walleye pollock are among the most common prey of SSL throughout the Aleutian Islands; in GOA, including the Kodiak region, the diet of SSL is mostly walleye pollock (Merrick et al. 1997; McKenzie and Wynne 2008). Thus, competition with the commercial fishery for walleye pollock could potentially affect SSL survival, either through reducing the amount of food available overall or through localized depletion at important feeding sites (Bez et al. 2006; Dillingham et al. 2006). Over longer time periods indirect effects of fishing in combination with climate regime shifts could have affected the composition of fish communities, altering unfavorably the prey field of SSL (Anderson and Piatt 1999; Litzow et al. 2006).

Analysis of bottom trawl survey data from GOA showed a decrease in mean density of walleye pollock between 1984 and 1996 (Shima et al. 2002). Over this time period the proportion of stations where walleye pollock were caught increased, indicating an expansion of their distribution. The authors suggested that the changes may have contributed to decreased foraging efficiency by SSL. They hypothesized that an increase in the suitability of habitats for walleye pollock was responsible for the wider distribution, perhaps because of expansion in the walleye pollock prey distribution. Alternatively, they suggested that the activity of multiple vessels that make up commercial fisheries could cause long-term redistribution of walleye pollock.

Disturbance of the SSL prey field by commercial fishing operations may be responsible for nutritional stress and may have contributed to the failure of the SSL populations to recover (Sinclair and Zeppelin 2002; Hennen 2006). Disturbance of semidemersal fish distribution has been reported by Ona and Godo (1990), who found that haddock (*Melanogrammus aeglefinus*) reacted to a vessel towing a trawl, but the observed distributions returned to the predisturbance pattern in less than 10 min. Such short-term changes are important for acoustic surveys, but would presumably have negligible effect on SSL foraging. Walleye pollock respond to trawling vessels, but the nature and duration of that response is not known (De Robertis and Wilson 2006). The present study was designed to detect changes in the distribution of juvenile and adult walleye pollock that persist for at least several days, including localized depletion and changes in small-scale vertical and horizontal distribution, which could affect SSL foraging success. Juvenile walleye pollock, although not targeted by the fishery, constitute the dominant size group in the diet of SSL near Kodiak Island (McKenzie and Wynne 2008). Long-term effects of fishing on walleye pollock distribution, such as those hypothesized by Shima et al. (2002) and Anderson et al. (2008), were not addressed.

The effect of commercial trawling operations on walleye pollock was assessed by comparing acoustic survey estimates of their vertical and horizontal distribution, abundance, and schooling patterns before commercial trawling operations began with those made during the commercial fishery in Barnabas Trough (also known as Kiluda Trough) near Kodiak Island. A similar nearby area, Chiniak Trough, where fishing was prohibited during the years of the study, was used as a comparison site. The relative merit of this paired-comparison design will also be evaluated and discussed, as its implementation is being considered for studies in other areas and for other species.

The goal of the study was to determine whether changes in abundance or spatial distribution or both are associated with commercial fishing on time scales of days to weeks. Data from the first 2 years of the study and some preliminary results were reported earlier (Wilson et al. 2003). A commercial fishery took place in only 1 of the 2 years in that study. The authors did not find evidence for an effect of the fishery on walleye pollock distribution. Here, data from additional years with different walleye pollock size distributions are analyzed, and improved methods for analyzing horizontal spatial distributions are applied.

Materials and methods

Field methods and design

Barnabas and Chiniak troughs on the east side of Kodiak Island, Alaska, USA, were chosen for study because they had similar bathymetric features, were close to each other, and had similar populations of walleye pollock that were commercially fished prior to the study (Wilson et al. 2003). Haulout sites (but not rookeries) for SSL were also located nearby. Although the walleye pollock populations are free to move within the troughs, the shallow depths between them restrict movement, effectively confining the local populations to the troughs themselves.

Commercial fishing took place in Barnabas Trough but was prohibited in Chiniak Trough during the study. Multiple replicate acoustic surveys were conducted in each trough over a period of several weeks during daylight hours in late August through early September in 2001, 2004, and 2006. Each replicate acoustic survey (pass) collected data along the same set of parallel transects (spaced at 5.6 km intervals) crossing perpendicular to the axis of the troughs (Fig. 1). The same survey design and the same transects were used for all passes. Passes were timed so that some occurred prior to fishing and the remainder after fishing began (Table 1). There was no attempt to control when or where fishing occurred in Barnabas Trough. Commercial fishing operations in Barnabas Trough did not begin immediately after the fishery opening, so acoustic surveys meant to assess conditions during commercial fishing were also delayed several days to allow trawling activities to get underway. The study was conducted in late summer, in part because postweaning SSL juveniles (1-year-olds) were considered especially vulnerable to nutritional stress in late summer and fall.

A measure of fishing pressure in Barnabas Trough during

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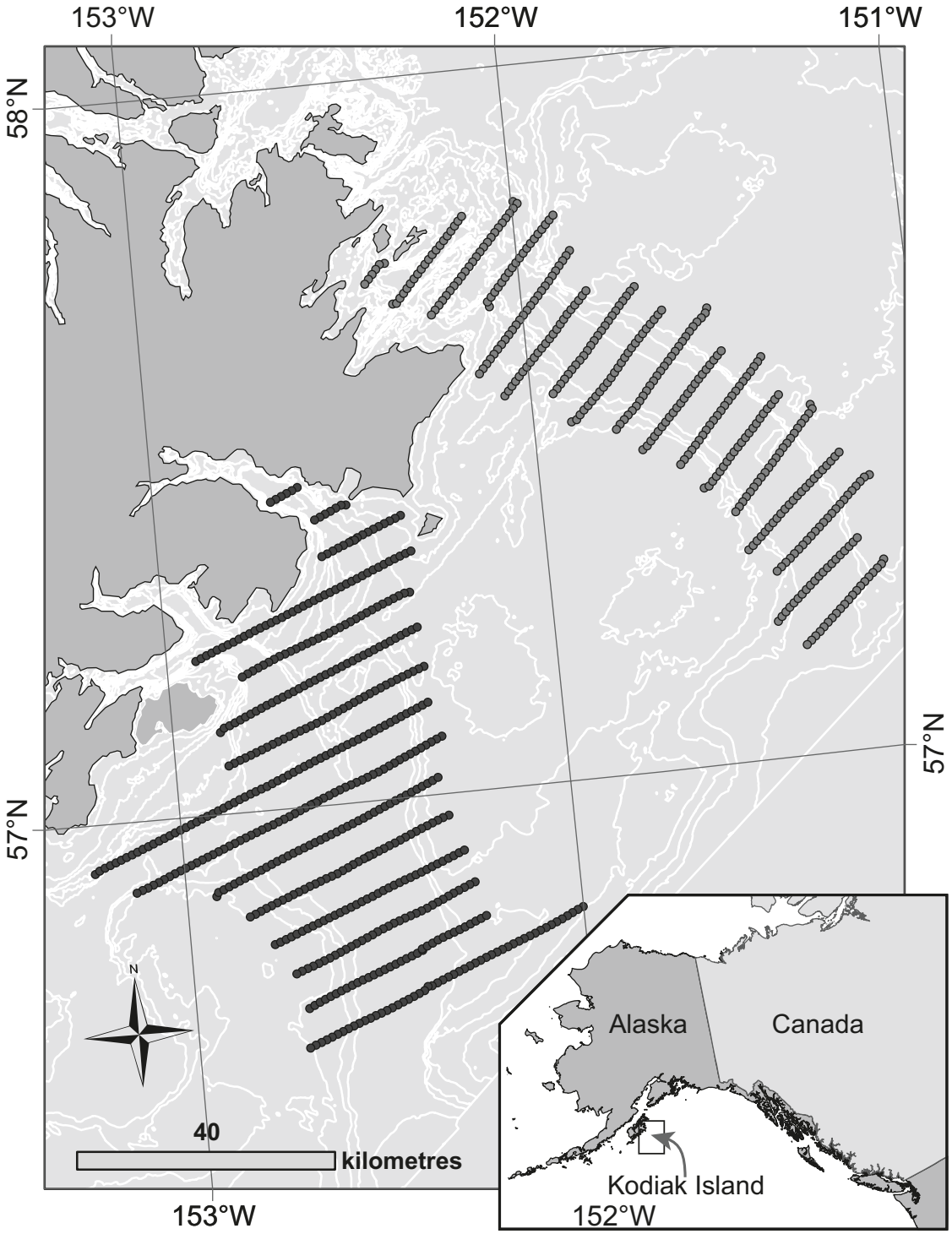
Fig. 1. Survey transects in Barnabas Trough (dark grey circles) and in the comparison area, Chiniak Trough (light grey circles), which was closed to fishing during the study. The study area was on the eastern side of Kodiak Island (Alaska, USA) in the northern Gulf of Alaska as shown in the inset. The same transects were used in all years.



the study period each year was made from catch data compiled from the National Marine Fisheries Service logbook data and shoreside database (National Marine Fisheries Service (NMFS), Alaska Region, P.O. Box 21668, Juneau, AK 99802–1668, USA) as described in Wilson et al. (2003). Vessel monitoring system data and trawl notebook data were used to determine the presence of fishing vessels in Barnabas Trough as well as the location where reported catches were taken. Number of hauls and total hours trawling were determined from logbook entries. Missing data were estimated using logbook averages for catch·haul^{-1} and hours·haul^{-1} combined with landings data, which was available for all vessels. Trawling hours for vessels that did not target walleye pollock but caught walleye pollock as bycatch (those with

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Table 1. Walleye pollock biomass estimates in thousands of tonnes for Barnabas and Chiniak Troughs from the fishery interaction study off the east side of Kodiak Island.

	Chiniak Trough			Barnabas Trough		
Survey pass	Date	Adult	Juvenile	Date	Adult	Juvenile
2001						
1 (prefishery)	**9–11 Aug.**	**3.5 (2.7, 4.9)**	**17.2 (13.9, 21.3)**	**11–14 Aug.**	**12.7 (9.5, 16.7)**	**7.8 (5.8, 10.6)**
2 (prefishery)	**14–16 Aug.**	**2.9 (2.5, 3.4)**	**19.7 (15.7, 24.3)**	**16–19 Aug.**	**4.8 (4.0, 5.7)**	**9.3 (7.3, 12.0)**
3 (fishery)	23–26 Aug.	3.7 (3.2, 4.2)	18.7 (14.0, 24.9)	26–29 Aug.	7.6 (6.2, 9.2)	10.7 (8.4, 13.9)
4 (fishery)				29–30 Aug.	4.6 (3.7, 5.7)	10.9 (7.6, 15.4)
2004						
1 (prefishery)	**13–15 Aug.**	**6.5 (4.9, 8.4)**		**15–17 Aug.**	**25.7 (20.8, 38.8)**	
2 (prefishery)	**18–21 Aug.**	**7.3 (5.9, 9.0)**		**21–24 Aug.**	**30.8 (23.9, 38.8)**	
3 (fishery)	30 Aug. – 2 Sept.	10.1 (8.2, 12.5)		26–30 Aug.	19.4 (14.5, 25.2)	
4 (fishery)				2–4 Sept.	22.7 (18.2, 28.3)	
2006						
1 (prefishery)	**13–15 Aug.**	**5.6 (4.7, 6.5)**	**2.5 (1.7, 3.1)**	**15–18 Aug.**	**6.8 (5.7, 8.2)**	**3.6 (1.5, 4.9)**
2 (prefishery)	**18–21 Aug.**	**6.9 (5.7, 8.1)**	**5.1 (2.9, 6.8)**	**21–24 Aug.**	**8.4 (6.7, 10.5)**	**5.4 (4.1, 6.5)**
3 (prefishery)	**24–26 Aug.**	**6.7 (5.6, 7.8)**	**5.0 (3.7, 6.0)**	**26–28 Aug.**	**9.3 (7.6, 11.4)**	**6.0 (4.9, 6.9)**
4 (fishery)	28–29 Aug.	5.8 (4.8, 7.0)	4.3 (3.1, 5.3)	29–31 Aug.	7.7 (6.2, 9.4)	4.9 (3.9, 5.9)
5 (fishery)	1–3 Sept.	4.9 (4.1, 5.8)	3.6 (2.5, 4.5)	4–5 Sept.	6.9 (5.5, 8.5)	4.4 (3.5, 5.3)

Note: Whether a survey pass was conducted prior to (bold font) or during (normal font) the commercial fishery is indicated. Juveniles consisted of mainly 1- and 2-year-old fish and were not found in 2004. Error bounds are shown in parentheses.

zero or nearly zero walleye pollock catch) were included in the totals, because these trawling operations may have also had an effect on walleye pollock distribution.

Routine acoustic survey protocols were employed in the collection and analysis of acoustic and trawl data (Simmonds and MacLennan 2005; Honkalehto et al. 2008). Acoustic data were collected with a calibrated Simrad EK 500 echosounder operating at 38 kHz. Data were collected at a horizontal resolution of about 5 m (depending on boat speed) and vertical resolution of 0.1 to 0.5 m. Data were binned into 0.1 nmi (185 m) horizontal and 5 m vertical bins for analysis. The vertical bin size was reduced to 1 m for analysis of near-bottom vertical distributions. Echoview software (Myriax, Tasmania, Australia) was used for binning, export, and analysis of acoustic data, including identification of aggregations.

Walleye pollock backscatter was identified based on information from trawl hauls that targeted strong echosign. Age-0 walleye pollock occurred in mixtures with capelin (*Mallotus villosus*). The proportions of age-0 walleye pollock and capelin in the hauls that targeted these aggregations could not be used to partition the backscatter because the net selectivity for these two groups is unknown. For this reason, age-0 walleye pollock were not included in the juvenile walleye pollock category. Only age-1 and age-2 walleye pollock were found in catches from trawls targeted on aggregations identified on the echograms as juvenile walleye pollock. The acoustic backscatter (nautical area scattering coefficient, s_A, in units of $m^2 \cdot nmi^{-2}$; MacLennan et al. 2002) data were converted to fish numbers and biomass using fish length–mass information from the trawl catches and the standard target strength to length relationship for walleye pollock (Traynor 1996; Simmonds and MacLennan 2005; Honkalehto et al. 2008). Because walleye pollock length data were similar among passes within a trough in a given year, walleye pollock acoustic data were proportional to biomass and served as a proxy for biomass in geostatistical simulations for estimating error bounds on abundance estimates. A single length frequency based on trawls for all passes of a trough in a given year was used to convert the acoustic data to numbers and biomass.

Precision by geostatistical simulation

The spatial distribution of s_A was modeled using conditional (includes the original data points) geostatistical simulations to evaluate the precision of the abundance estimates (Walline 2007). Presence–absence of walleye pollock was simulated using a sequential indicator (SI) geostatistical method (Goovaerts 1997). Each realization of the SI simulation was used as a mask in a conditional sequential Gaussian (SG) simulation, so that the SG simulations were made only at grid nodes where walleye pollock were present (Goovaerts 1997; Deutsch and Journel 1998; Gimona and Fernandes 2003).

Geostatistical simulations are based on variogram models. In this study, empirical variograms were calculated for normal score-transformed s_A values (with zeros removed) for each survey, as required for the Gaussian simulations. An exponential and a spherical model with nugget were fit to each empirical variogram using a weighted least squares objective function (Cressie 1993), and the best fitting of the two was used in the simulations. The same procedure was used to fit models to the empirical indicator variograms for the presence–absence data sets.

The domain over which simulations were made was chosen as the area bounded by the transect endpoints. The domain was divided into 1 km × 1 km blocks, with the points at the center of these blocks composing the grid matrix used to represent the survey area. For each grid point (node) in the domain, a simulated or original data value was obtained for s_A. For the SG simulations, a newly simulated value at a node was chosen at random from a Gaussian con-

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ditional cumulative distribution function generated by kriging the input data values and any nearby previously simulated values. A similar procedure was followed for the SI simulations, using full indicator kriging (simple kriging) at each grid location to establish the conditional cumulative distribution function from which simulated values (1 for presence of walleye pollock, 0 for absence) were randomly drawn. The nodes were visited in random order, so a variable number of previously simulated nodes was available to be used in estimating the cumulative distribution function at a given node. Total abundance (sum of s_A) for each realization was obtained by summing the values for all grid points. This procedure was repeated to produce 1000 equally probable realizations of s_A spatial distribution. Confidence intervals were then determined empirically from the frequency distribution of the total abundance estimates.

Vertical distribution

Average depth and distance off bottom were calculated using s_A data as a proxy for biomass. Data were averaged over three nautical mile segments (i.e., distance equal to transect spacing). A check of the variograms showed that this procedure eliminated most of the spatial autocorrelation in the data set, allowing calculation of associated 95% confidence intervals by bootstrapping (Efron and Tibshirani 1993).

Fish close to the seafloor are not detected by acoustic methods (Mello and Rose 2009, Scalabrin et al. 2009), so if fish move closer to the bottom in response to trawling, biomass estimates could be affected. Changes among survey passes in vertical distribution near the bottom were observed by comparing high resolution (1 m) near-bottom vertical profiles. The proportion of the biomass (s_A) in the layer closest to the bottom was taken as an indicator of the density of fish in the acoustic dead zone. An increase in the proportion of fish in the layers closest to the bottom accompanied by a decrease in overall abundance could indicate movement of fish into the acoustic dead zone rather than a change in biomass.

Geographical distribution

Changes in horizontal location were analyzed using spatial indices (Woillez et al. 2007). The center of gravity (COG), which is the average position of abundance, was calculated for each pass in each year. It was calculated separately for latitude and longitude (converted to distance in kilometres from a reference location) from the following equation:

$$\mathrm{COG} = \sum (x \cdot s_A) \left(\sum s_A \right)^{-1}$$

where x is the location in kilometres from a reference point, and s_A is the water column integrated acoustic backscatter, used as a proxy for biomass. Inertia, the dispersion of biomass (s_A) about the COG, equivalent to variance (Bez et al. 1997), was calculated as

$$\mathrm{inertia} = \left[\sum (x - \mathrm{COG})^2 \cdot s_A \right] \left(\sum s_A \right)^{-1}$$

These calculations were made for each realization of a simulation (described earlier). Thus, the variability of these measures could be evaluated in a manner analogous to that used to determine confidence intervals for abundance estimates.

These statistics were combined to form a global index of collocation (Bez and Rivoirard 2000), which indicates the degree of overlap between the spatial distributions of two populations. The index was originally designed to examine the co-occurrence of two species, but in the present case, two passes of a trough were compared. The index (I_g) is then a measure of the degree of movement between the two passes:

$$I_g = 1 - \left[\Delta\mathrm{COG}^2 \cdot (\Delta\mathrm{COG}^2 + I_{P1} + I_{P2})^{-1} \right]$$

where I_{P1} and I_{P2} are the inertia for the first and second pass to be compared. The index varies from 1 (complete overlap, COGs are identical) to 0 (complete separation).

Small-scale spatial patterns

Adult and juvenile walleye pollock aggregated primarily in layers and not in discrete schools as they sometimes do in other areas and seasons. The layers were classified using school recognition algorithms. Estimates of various descriptive attributes that delineate the walleye pollock layers and aggregations observed on the echograms were generated using Echoview software (Myriax). Size and shape descriptors for this purpose included aggregation length, height, mean volume backscattering coefficient S_v (which is a measure of density), and fractal dimension (D), which relates perimeter (P) to area (A; $D = 2\ln(P/4)\cdot\ln(A)^{-1}$) and is a measure of aggregation convolution (Nero and Magnuson 1989; Barange 1994).

The criteria that were chosen to define an aggregation were examined over a range of values to determine which best reproduced the patterns observed on the original echograms. The values selected were S_v threshold (–70), minimum length (40 m), minimum height (5 m), minimum connected length (5 m), minimum connected height (2 m), maximum vertical linking distance (5 m), and maximum horizontal linking distance (20 m). These values were used for analyses of all passes and are consistent with those used in Wilson et al. (2003).

Principal component analysis (PCA) was used to compare aggregations of adult and juvenile walleye pollock based on the size and shape descriptors. The data were log-transformed prior to the analysis. All PCAs were based on a secondary correlation matrix. The mean values along the first and second principal components (i.e., along the first and second axes) were calculated for each trough–pass combination, and the significance of eigenvalues was determined using a randomization test in which the p value for an axis was $(n + 1)\cdot(N + 1)^{-1}$, where n is the number of randomizations with an eigenvalue for that axis that is equal to or larger than the observed eigenvalue for that axis, and N is the total number of randomizations ($N = 999$). PCA was chosen for these data because it is an ordination process that accounts for redundancy in the original data set and summarizes the variation using the fewest possible gradients. The relative position of the objects along the gradients defines the relationship between objects.

Results

Abundance, size composition, fishery removals

All surveys were conducted in late August to early September (Table 1). Size composition of walleye pollock as estimated from the midwater trawls (41 hauls in 2001, 59 hauls in 2004, and 47 hauls in 2006) and the bottom trawls (16 hauls in 2001, 10 hauls in 2004, and 13 hauls in 2006) differed among years, but much less so within years between

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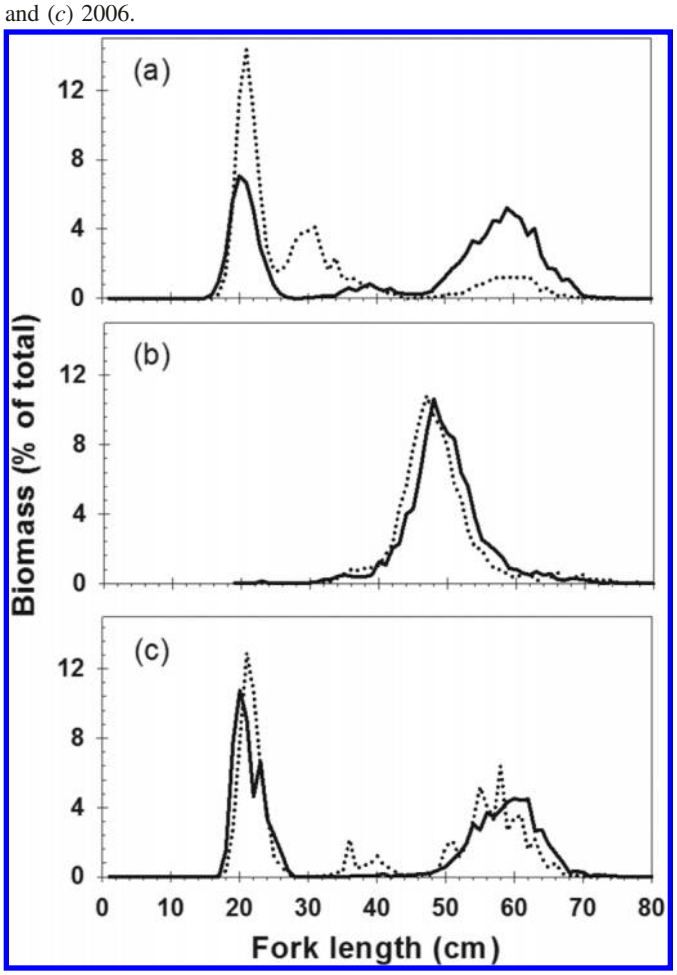
Fig. 2. Size composition of walleye pollock in Barnabas Trough (solid line) and Chiniak Trough (dotted line) in (*a*) 2001, (*b*) 2004, and (*c*) 2006.

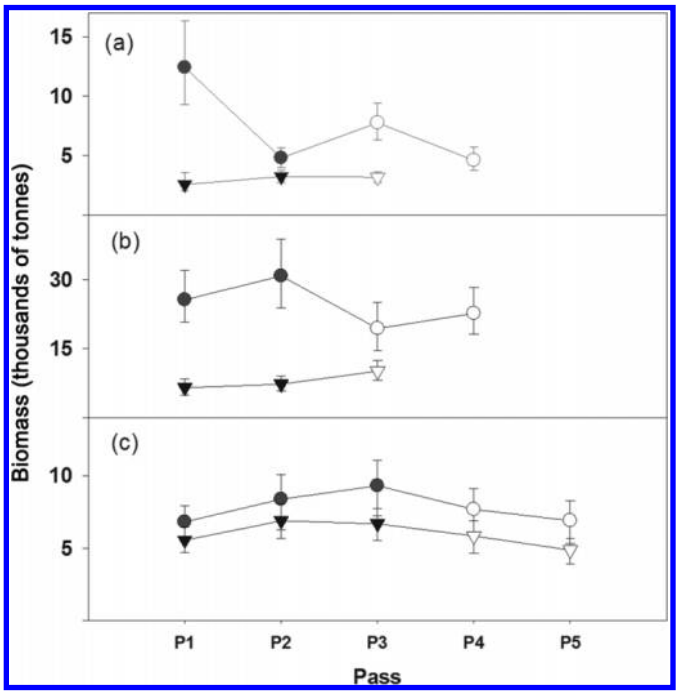


troughs (Fig. 2). Size compositions were nearly identical within troughs for a given year (not shown). Walleye pollock smaller than 30 cm were not observed in Chiniak or Barnabas troughs in 2004, but walleye pollock of this size were observed in both in 2001 and 2006.

Walleye pollock occurred in highest abundance in the inner half of both troughs and on the eastern side of Barnabas Trough. The greatest biomass of adult walleye pollock was observed in 2004 in both troughs. Average biomass for adults in Barnabas Trough for the prefishery surveys was 8.0, 28.2, and 7.6 thousand tonnes for 2001, 2004, and 2006, respectively. Adult biomass averaged over all passes within a year in Chiniak Trough was less: 3.4, 8.0, and 6.0 thousand tonnes for the 3 years (Table 1). Error bounds derived from simulations for biomass estimates for adult walleye pollock ranged from 31% to 14% for upper 95% confidence intervals (CIs) and from 25% to 13% for lower 95% CIs. Particularly wide CIs were observed for the first pass in Barnabas Trough in 2001. On that pass, a very high concentration of fish was encountered in a small area on the east side of the trough, accounting for the wide CI (Wilson et al. 2003).

Overlapping CIs were taken as indication that the corresponding abundance estimates did not differ. In some cases, such as in Barnabas Trough in 2001, large differences were observed between the two prefishery passes (Fig. 3). Only in

Fig. 3. Adult walleye pollock biomass estimates (thousands of tonnes) with 95% confidence intervals in Barnabas Trough (circles) and Chiniak Trough (triangles) in (*a*) 2001, (*b*) 2004, and (*c*) 2006. Solid symbols denote passes made before the fishery began.



2004 was there an indication of a possible effect of fishing on the abundance of walleye pollock; after fishing began, abundance decreased in Barnabas Trough but not in Chiniak Trough.

The catch of walleye pollock by the commercial fishery constituted a variable percentage of the estimated biomass. Catches in Barnabas Trough during the survey period were 2850 tonnes (t) in 2001, 954 t in 2004, and 1464 t in 2006, or 31%, 3.3%, and 19% of the estimated average prefishery biomass, respectively. Thus, removals by fishing were the smallest, and the estimated biomass was the largest in 2004, the only year when the biomass decreased in the fished trough and not in the unfished trough. The decrease in estimated biomass observed between Pass 2 and Pass 3 in 2004 was greater than the estimated catch taken during the study, as was the decrease in biomass between Passes 1 and 2 in 2001.

Fishing hours, number of hauls, and total catch were inversely related to abundance, with least effort made in 2004 when abundance was highest (Table 2). Fishing hours in 2001 were more than double those in 2004, while abundance in 2001 was less than half that in 2004. Catch per haul varied from 8 to 17 t, while catch per hour was less variable, from 2.1 to 3.0 $t \cdot h^{-1}$. Measures of $catch \cdot effort^{-1}$ (i.e., $catch \cdot haul^{-1}$ and $catch \cdot h^{-1}$) were not greater when abundance was greater. The presence and inclusion of fishing vessels not targeting walleye pollock could partially explain this result. For example, a trawl fishery for arrowtooth flounder (*Atheresthes stomias*) occurred in 2006, but not in the other 2 years. Thus, the catch per hour observed in 2006 ($10\ t \cdot h^{-1}$) was lower than that in 2001 ($17\ t \cdot h^{-1}$) despite greater abundance of walleye pollock in 2006. Some of the walleye pollock caught in 2006 were caught in trawls that targeted arrowtooth flounder,

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Table 2. Fishing effort in Barnabas Trough.

Year	No. of vessels	Dates	No. of hauls	Fishing hours	Removals (tonnes·haul^{-1})	Removals (tonnes·hour^{-1})	Removals (tonnes)
2001	28*	22–31 Aug.	167	1074	17	2.7	2850
2004	31	26 Aug. – 4 Sept.	124	450	8	2.1	954
2006	24	28 Aug. – 3 Sept.	147	496	10	3.0	1464

*Information for 2001 is from 27 of 28 vessels.

and therefore caught fewer walleye pollock per hour than trawls that targeted walleye pollock.

Vertical distribution

Adult walleye pollock were further off-bottom and exhibited more variability in distance off-bottom in Chiniak Trough than in Barnabas Trough (Fig. 4). In Barnabas Trough the distance off-bottom differed among years, but it did not change within a given year.

Adult walleye pollock were slightly deeper in Chiniak Trough than in Barnabas Trough (Fig. 4). Only slight differences were observed among years, and there was no indication of a change in mean depth after fishing began. There was a slight decrease in depth observed during the last pass in Barnabas Trough in 2006, but this was matched by a similar decrease in depth for the last pass in Chiniak Trough. Changes in the biomass of adult walleye pollock in the layer nearest the bottom were not related to biomass decreases nor to fishing activities.

The vertical distribution of juvenile walleye pollock differed between the troughs. In both troughs juvenile depths and distance off-bottom were more variable in 2006 than in 2001 (Fig. 4). In Barnabas Trough distance off-bottom and depth in the water column were almost constant for juvenile walleye pollock except for the last pass in 2006 when fish were slightly further off-bottom. In Chiniak Trough fish generally reduced their distance off-bottom and increased their depth in the water column over the course of the survey in 2001, whereas fish moved further off-bottom and shallower in the water column between the first and last passes in 2006.

Geographical distribution

Relatively large-scale movement of adult walleye pollock within the troughs varied among years, based on changes in the COG (Fig. 5) and the global index of collocation (I_g; Table 3). The first pass in Barnabas Trough in 2001 differed from all other passes in all years of the study. As mentioned earlier, a single, very dense, compact school was observed near bottom on the east side of the trough, which caused the COG displacement. This unique distribution (such a school was never observed again during the study in either Barnabas or Chiniak troughs) was reflected by a low I_g between the first pass and the other passes (Table 3). Adult COG estimates showed there was very little movement in either Barnabas or Chiniak troughs in 2004, and all the indices of collocation were greater than 0.97. Differences in I_g were detected in Barnabas Trough in 2006. For example, the I_g for Passes 1 and 4 was 0.45. However, this movement was not related to fishing activity, as the I_g for the comparison of Pass 1 (prefishery) to the last pass (fishery) was the greatest observed (0.96). Similar variations in I_g were observed in Chiniak Trough. For example, the I_g for the comparison of Pass 1 (prefishery) and Pass 4 (fishery) was 0.59 and that of Pass 1 and Pass 5 (fishery) was 0.99.

The distributions of juvenile walleye pollock were more variable than those of the adults (Fig. 6). COG estimates differed among years, and they changed within years, indicating movement. However, movement appeared to be unrelated to fishing activities. In 2001, the COG in Barnabas Trough differed between prefishery Pass 1 and fishery Pass 3 (I_g = 0.34), but the fish were in nearly the same location during prefishery Pass 2 and fishery Pass 4 (I_g = 0.99). In Chiniak Trough there appeared to be movement to the northwest from Pass 1 to Pass 3 in 2001. In Barnabas Trough juveniles were in a different location during Pass 1 than during the other four passes in 2006, while in Chiniak Trough the fish were in a different location during the fishery than before.

Small-scale spatial patterns

The range for models fit to the empirical variograms used in the geostatistical simulations is a measure of the walleye pollock spatial distribution and can be compared between passes and troughs. The range is the distance at which two measurements (e.g., walleye pollock s_A) are no longer correlated. Thus, a longer range indicates larger patch sizes, while shorter ranges indicate smaller patches and a distribution closer to random. Ranges of variograms for normal score-transformed adult data varied between 4.7 and 14 km (mean 10.0 km) in Barnabas Trough and between 5.5 and 33 km (mean 13.9 km) in Chiniak Trough. Ranges for juveniles were smaller and less variable than those for adults in both troughs, varying between 5.0 and 9.0 km (mean = 7.5 km) in Barnabas Trough and between 2.7 and 8.0 km (mean = 5.4 km) in Chiniak Trough.

The range for the normal score variograms used in the simulations did not show consistent differences between the prefishery and fishery periods for juveniles or adults. In some cases the range increased after fishing began (juveniles in both troughs 2001; adults in Chiniak 2004; juveniles in Barnabas 2006), and in other cases the range decreased (adults in both troughs 2001 and 2006). The largest difference between troughs (~2 km) was observed in 2004, but the range changed only in the unfished Chiniak Trough. Only for juvenile walleye pollock in 2006 did the range change in Barnabas Trough after fishing began but remain unchanged in Chiniak Trough, the pattern that was expected if fishing caused the changes.

Models fit to the experimental variograms for juvenile walleye pollock exhibited shorter ranges in the prefishery period compared with the fishery period in Barnabas Trough in 2001 and 2006. Chiniak Trough showed a greater difference than Barnabas Trough in 2001, but a smaller one in 2006.

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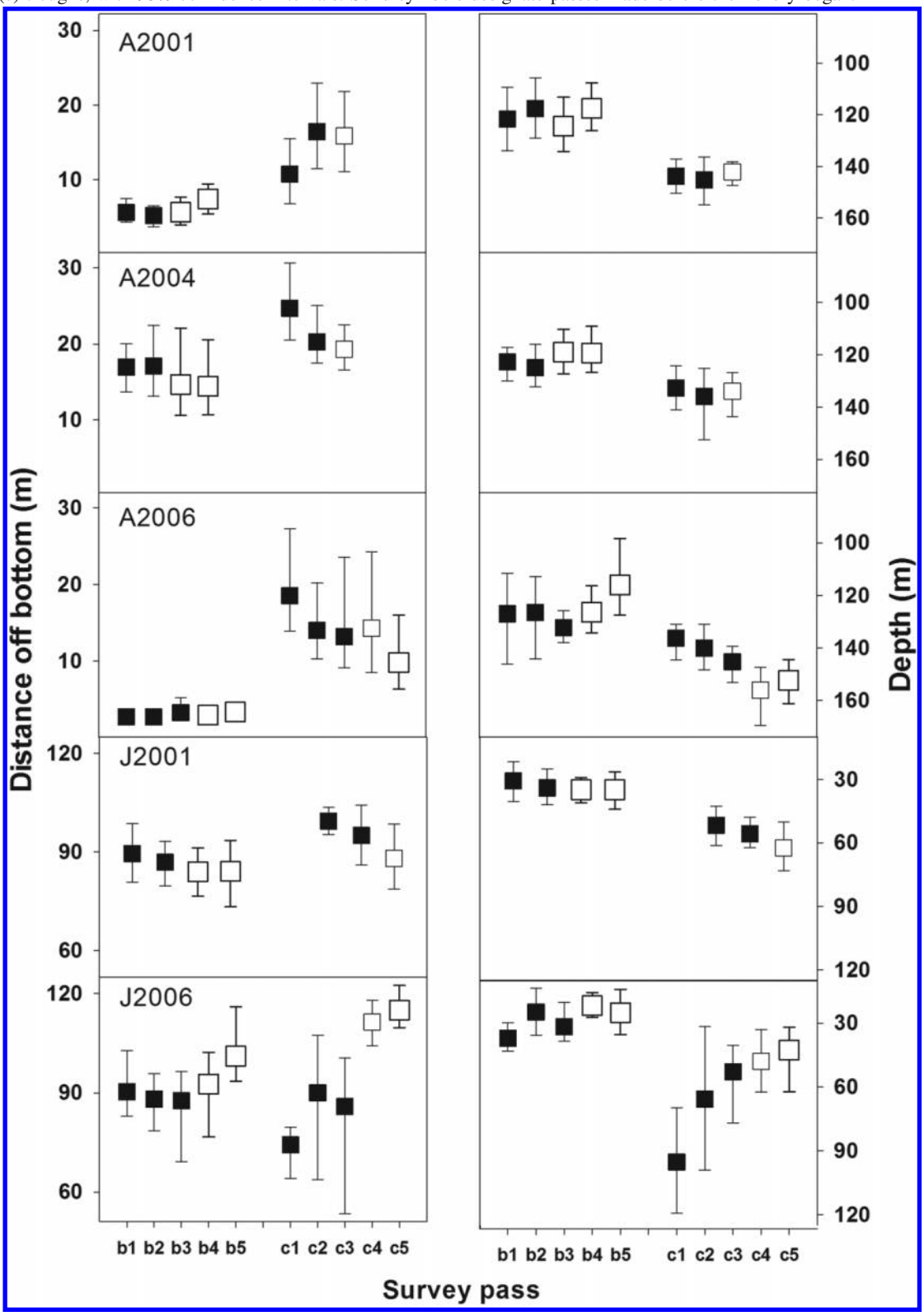
Fig. 4. Adult (A) and juvenile (J) walleye pollock distance (m) off the bottom and mean depth (m) by year and survey pass in Barnabas (b) and Chiniak (c) troughs, with 95% confidence intervals. Solid symbols designate passes made before the fishery began.



A total of 4081 adult walleye pollock aggregations were analyzed (2468 in Chiniak Trough and 1613 in Barnabas Trough) and a total of 3188 juvenile walleye pollock aggregations were analyzed (1501 in Chiniak Trough and 1687 in Barnabas Trough) (Table 4). The PCA results indicate that prefishery and fishery aggregations of adult walleye pollock did not differ in Barnabas Trough. Although there was no difference between the prefishery and fishery periods, there was a difference between troughs in 2001 (plot not shown) and in 2006 (Fig. 7*a*). Aggregations in Barnabas Trough

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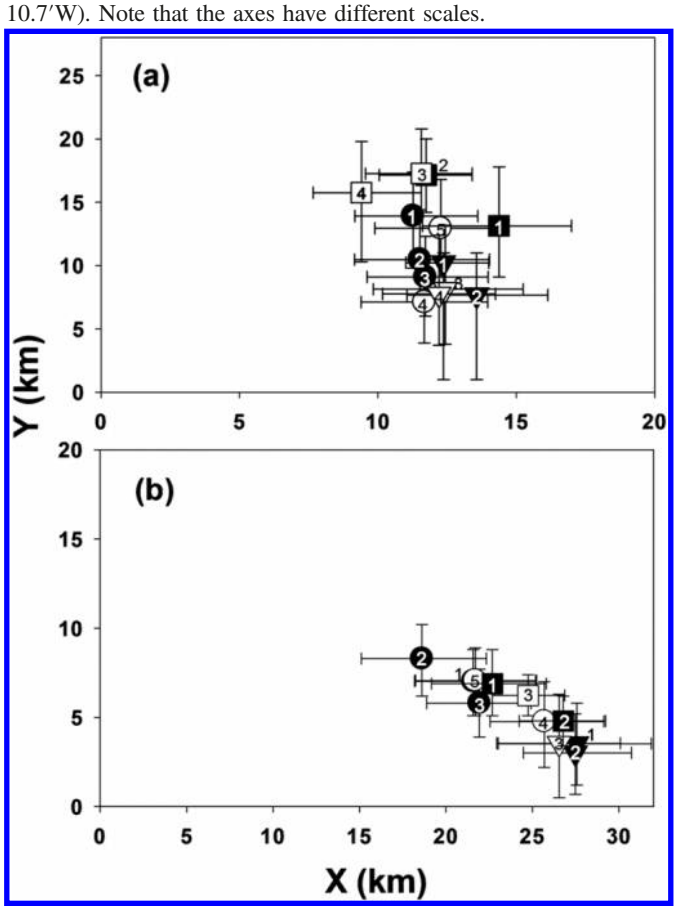
Fig. 5. Adult walleye pollock location of the center of gravity within (*a*) Barnabas Trough and (*b*) Chiniak Trough in 2001 (squares), 2004 (triangles), and 2006 (circles). Solid symbols denote passes made before the fishery began. Symbols are labeled with the pass number. Axes show distance in kilometres from the reference location (Barnabas 57°2′N, 152°50.9′W; Chiniak 57°32.3′N, 152° 10.7′W). Note that the axes have different scales.



were less dense than aggregations in Chiniak Trough in 2001, and there were more, less dense aggregations of adults in Chiniak Trough than in Barnabas Trough in 2006. The variability about the mean of the descriptors used was high (Table 4), so differences between troughs or between prefishery and fishery periods were not significant when non-log-transformed descriptors were considered individually.

The PCA analysis distinguished between prefishery and fishery school characteristics for juvenile walleye pollock in both troughs during 2001 (Fig. 7*b*) and in Barnabas Trough during 2006 (Fig. 7*c*). Mean fractal dimensions of juvenile aggregations were greater during the fishery for both troughs in 2001 and for Barnabas Trough in 2006. Additionally, the density of juvenile aggregations was lower during the fishery in Barnabas Trough in 2006. Because the changes in school characteristics between the prefishery and fishery period were similar in both troughs, only in 2006 was there a possible fishery effect on the characteristics of juvenile aggregations.

Discussion

Our study provides evidence that the effect of fishing on walleye pollock in Barnabas Trough over short time periods of several days during the late-summer fishery was small, in most cases too small to detect. The use of Chiniak Trough as a comparison area was helpful in preventing the identification of false positives when the same change between the prefishing and fishing periods was detected in both troughs. Based on the bootstrapping analysis, sufficient sampling intensity was used to allow detection of changes as small as 10 m in the vertical dimension. Simulation methods allowed the estimation of CIs about the COG estimates so that small changes on the order of a few kilometres could be detected. No large changes that could be attributed to a fishery effect were found in either vertical or geographical distributions.

Abundance

Fishing removals were not detectable because of relatively high variability in estimated biomass among replicate surveys when there was no fishing activity. This high natural variability could not be explained by fish movement into and out of the near-bottom zone where they could not be detected acoustically.

The removals made during the study probably were not large enough to have affected the nearby SSL populations, based on the following argument. In the absence of data showing the densities of fish necessary for successful SSL feeding, indirect evidence based on estimates of biomass in an area where SSL feed must be used. Using estimates from Winship et al. (2002) for SSL prey consumption averaged over the entire Alaskan population results in a requirement of 3818 t of prey per year for 500 SSL consuming a diet of 50% gadids and 50% forage fish. The capture efficiency of Steller sea lions is unknown; therefore, it is not possible to estimate how much prey is needed to satisfy this forage demand. Sease and Gudmundson (2002) counted 508 SSL at haulouts on the east side of Kodiak Island in 2002, and there were 703 juveniles and adults and around 500 pups at the nearby Marmot Island rookery in 2004 when the last survey was made there (Fritz and Stinchcomb 2005). Sigler et al. (2009) found that 500–1700 t of prey was enough to attract up to 500 sea lions in nonbreeding areas in southeastern Alaska. The biomass of adult walleye pollock in Barnabas Trough, even after the fishery removals, was never lower than 4600 t. This could be an underestimate of the biomass present if there was a substantial biomass of walleye pollock not detected because of avoidance reaction to the vessel or because they were within the acoustic dead zone. Although the densities of walleye pollock (abundance·m^{-3}) were not indicated by Sigler et al. (2009) for the area in the inside waters of southeast Alaska they surveyed, the areal densities presented are similar to those found in Barnabas Trough. In both locations fish were aggregated, not spread out over the entire surveyed area, so their abundance in the vicinity of Barnabas and Chiniak troughs was probably sufficient to attract SSLs, especially if in addition to the walleye pollock, there were other nutritious prey available (Sigler et al. 2009). Thus, removals made during this study were not likely to have adversely affected SSL populations.

Vertical distribution

Neither the estimated mean distance off-bottom nor the estimated mean depth differed between the prefishery and fishery periods for adult or juvenile walleye pollock for any of

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Table 3. Global index of collocation for comparing location of adult and juvenile walleye pollock between passes within years for Barnabas and Chiniak troughs.

	Barnabas					Chiniak				
Year	Pass	B2	B3	B4	B5	Pass	C2	C3	C4	C5
Adult										
2001	B1	0.60	0.59	0.52		C1	0.97	0.99		
	B2		1.00	0.82		C2		0.98		
	B3			0.83						
2004	B1	0.97	0.98	0.97		C1	0.99	0.98		
	B2		0.99	0.99		C2		1.00		
	B3			1.00						
2006	B1	0.78	0.62	0.45	0.96	C1	0.89	0.92	0.59	0.99
	B2		0.94	0.75	0.88	C2		0.71	0.41	0.81
	B3			0.89	0.71	C3			0.73	0.95
	B4				0.52	C4				0.65
Juvenile										
2001	B1	0.64	0.34	0.75		C1	0.75	0.58		
	B2		0.65	0.99		C2		0.86		
	B3			0.67						
2006	B1	0.46	0.44	0.46	0.49	C1	0.95	0.93	0.44	0.41
	B2		0.98	0.99	0.94	C2		0.97	0.48	0.45
	B3			0.99	0.98	C3			0.58	0.54
	B4				0.97	C4				0.99

Note: Passes are identified with B for Barnabas, C for Chiniak, and 1 to 5 for the pass number within a year. Passes 1 and 2 in 2001 and 2004 and Passes 1, 2, and 3 in 2006 were prefishery.

the 3 years in the Barnabas Trough. Differences on the order of 10–15 m in average depth distribution could have been detected based on the magnitude of estimated CIs. More intense sampling (for example, by closer transect spacing) might have allowed detection of smaller changes by narrowing the CIs, but it is uncertain that smaller differences would be consequential to SSL. Juvenile SSL quickly attain the ability to dive to depths where walleye pollock were observed. Juvenile SSL can dive to 200 m by 1 year of age and can reach 400 m by 3 years of age, although most dives are much shallower (Pitcher et al. 2005). Adult walleye pollock in Barnabas Trough were found on average in water depths less than 135 m and in Chiniak Trough at depths of less than 160 m. Thus, even the adult walleye pollock population close to the bottom was potentially available to 1-year-old SSL. However, juvenile SSL have higher mass-specific metabolic demands, less foraging experience, and can spend less time at depth than adults, so the effect of changes in prey depth could affect juveniles more than adults (Loughlin et al. 2003; Pitcher et al. 2005).

Geographical distribution

The pattern exhibited by juvenile walleye pollock in the unfished trough in 2006 was what one would expect if fishing activities caused walleye pollock to move to a different location after fishing began. That is, COGs for all the prefishery passes were located near each other, and the two for the fishery period were together in a different place. This illustrates the importance of the unfished comparison trough in avoiding incorrect interpretations of the survey results. Because no change in location was detected after fishing began in any of the 3 years in the fished trough for either adult or juvenile walleye pollock, the 2006 finding that juvenile walleye pollock in the unfished trough moved to a new location in the trough after fishing began can be interpreted in two ways. Either juvenile walleye pollock movements were not related to fishing, or fishing in Barnabas Trough prevented movements of juvenile walleye pollock like those that occurred in Chiniak Trough, where there were no fishing activities. It is not possible to determine which explanation is correct, but the pattern was not consistent among years, so the second possibility seems unlikely. In short, there was no indication from these surveys that fish moved in response to fishing. Instead, patterns of walleye pollock distribution within the troughs appear to be related to oceanographic conditions (Hollowed et al. 2007). At least some of the changes in horizontal distribution that were observed have been related to storms that pass through the area and cause pulses in the Alaska Coastal Current (Wilson et al. 2003; Logerwell et al. 2007). In the absence of wind-driven events, the distribution of adults and juvenile walleye pollock is stable, located inshore of a front in warm, low-salinity water, where primary production is high and presumably the abundance of euphausiids, a preferred food, is also high (Hollowed et al. 2007; Logerwell et al. 2007).

SSLs may target dense, compact schools, such as the one observed in the first prefishery pass in 2001 in our study (Sigler et al. 2009). However, as mentioned earlier, such an aggregation was not observed again during any of the other 23 passes made in the 3 years of the study, so that it appeared to be a rare event. In addition, the aggregation had moved or dispersed before fishing began, as it was not seen on the second prefishery pass. These observations do not rule out the possibility that such aggregations may occur more frequently and predictably in other areas. Although our study suggests that such high-density patches may be rare and can disperse

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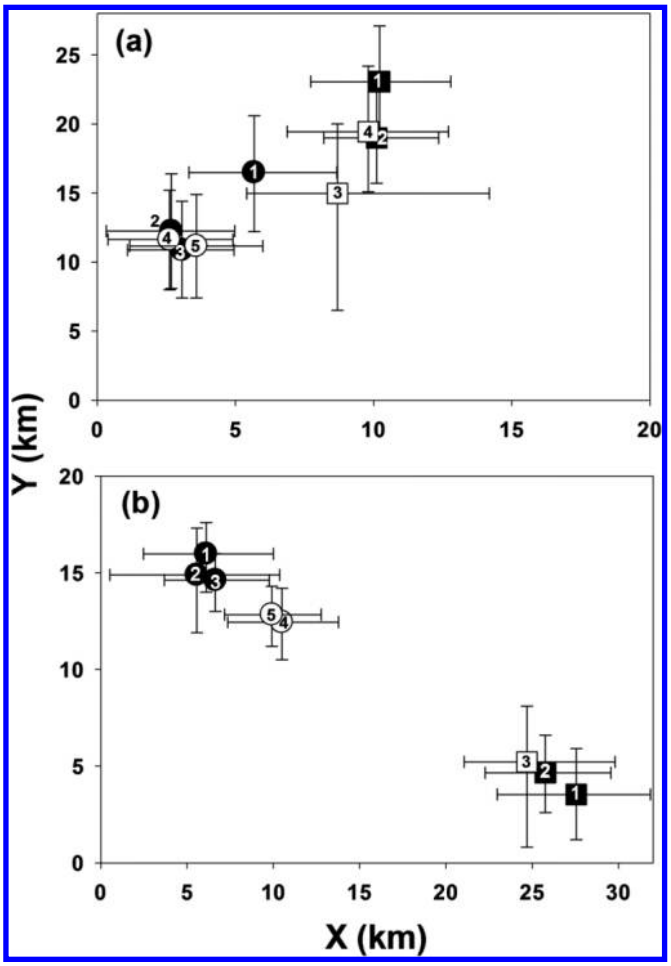
Fig. 6. Juvenile walleye pollock location of the center of gravity within (*a*) Barnabas Trough and (*b*) Chiniak Trough in 2001 (squares) and 2006 (circles). Solid symbols denote passes made before the fishery began. Symbols are labeled with the pass number. Axes show distance in kilometres from the reference location (Barnabas 57°2′N, 152°50.9′W; Chiniak 57°32.3′N, 152°10.7′W). Note that axes have different scales.



without regard to commercial fishing activity, it does not provide any evidence as to what the effect of fishing would be if such schools were present during fishing operations.

Small-scale spatial patterns

The PCA and variogram methods used to analyze changes in the characteristics of adult walleye pollock aggregations and layers that may have occurred in response to fishing produced similar results; adult walleye pollock do not appear to aggregate nor disperse in reaction to the fishery in Barnabas Trough. Although related to the size of fish aggregations, the range and nugget from variogram models are dependent on the choice of lag size (scale) and so measure aggregations on a larger scale (km) than that analyzed with the school recognition algorithms (m) in the PCA analysis. Thus, the use of these complementary methods allowed analysis of changes in more characteristics and at a wider range of scales than use of either alone, strengthening the conclusion that there were no effects of fishing activities on the aggregations of adults.

Conclusions were somewhat different for juvenile walleye pollock. The changes in the aggregations observed in 2001 in both troughs were explained by Wilson et al. (2003) as possibly caused by an intense storm that passed through the area between the prefishery and fishery survey passes. In 2006, the Barnabas Trough juvenile aggregations during the fishery were more numerous, had a higher fractal dimension, and were less dense than prefishery aggregations. These changes were not observed in Chiniak Trough and were consistent with an interpretation that fishing activities in the area caused a break up or redistribution of juvenile aggregations into less cohesive groups, although juvenile walleye pollock are not the target of the fishery. The response was not the predator avoidance reaction typically exhibited by many pelagic fish, which is to reduce nearest-neighbor distances of school members, resulting in smaller, denser schools (Pitcher and Parrish 1993; Ryer and Olla 1998). Changes like those observed for aggregations of juvenile walleye pollock in 2006 may make it easier for SSL to locate them, but the reduced densities within the patches might negatively affect SSL feeding success.

Critique of method and possible improvements

The difficulty in interpreting changes in abundance detected between the prefishery and fishery periods illustrates the problems caused by not being able to assign the fishing randomly to the troughs and not having replicates of the treatment (fishing) or comparison site (Hurlbert 1984, 1993; Heffner et al. 1996). The study design, although a substantial improvement over a design without a comparison area, does not allow testing for the significance of a fishing effect. The methods do allow for estimation of CIs and detection of statistically significant differences between passes, but the cause for detected differences cannot be assigned to fishing. Instead, interpretation of results must be made by inference. Oksanen (2004) postulated that valid conclusions can be drawn through logic and biological reasoning provided the perturbation applied is strong enough and the resulting differences are large enough. The results of our study imply that removing a larger proportion of the fish biomass would be helpful if the experimental design is based on a single paired comparison area. If it is not practical or allowable to catch a high percentage of the stock, a design employing several comparison areas (control sites) would be a possible alternative if logistically feasible (Underwood 1994; Conquest 2000). However, if the results are meant to apply to additional areas not studied, the treatment (fishing) and controls would still need to be randomly assigned to locations over time (years). It should be noted that finding two areas with geographic characteristics as similar as those in the present study would be extremely difficult.

Differences between troughs in geographical and vertical distributions and in small-scale spatial patterns, as well as in biomass, were usually much greater than differences observed within Barnabas Trough between the nonfishing and fishing periods. The problems that this caused in determining the effect of fishing could have been reduced by randomly assigning fishing effort to the two troughs each year. However, this would have been extremely difficult in our study because of the lead time needed to notify fishermen and other logistic hurdles involved in closing different areas to the fishery in a random manner.

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Table 4. Mean and standard deviation (SD) for aggregation descriptors of adult (A) and juvenile (J) walleye pollock in Chiniak (C) and Barnabas (B) troughs during summers 2001, 2004, and 2006, before (bold font, first row of pair) and during the fishery (normal font, second row of pair).

			Length (m)		Height (m)		Fractal dimension		Density (fish·1000 m^{-3})	
	Year	No. of schools	Mean	SD	Mean	SD	Mean	SD	Mean	SD
AC	2001	**413**	**186**	**366**	**11.0**	**12.3**	**1.76**	**0.11**	**5**	**18**
		265	231	537	11.2	12.2	1.75	0.09	7	51
AB		**192**	**339**	**706**	**9.8**	**8.0**	**1.79**	**0.10**	**6**	**33**
		316	296	528	10.7	7.8	1.80	0.08	4	15
AC	2004	**530**	**217**	**452**	**10.9**	**9.5**	**1.73**	**0.13**	**5**	**25**
		152	330	606	12.3	10.8	1.72	0.12	4	6
AB		**331**	**417**	**967**	**10.2**	**7.6**	**1.71**	**0.16**	**19**	**38**
		301	390	965	9.4	7.1	1.74	0.02	14	57
AC	2006	**812**	**234**	**754**	**10.9**	**11.4**	**1.76**	**0.08**	**2**	**2**
		296	466	1767	12.2	17.5	1.76	0.09	2	2
AB		**315**	**352**	**736**	**8.9**	**8.9**	**1.76**	**0.08**	**5**	**6**
		158	382	500	9.2	6.3	1.77	0.08	5	12
JC	2001	**620**	**235**	**699**	**13.9**	**13.1**	**1.57**	**0.16**	**53**	**100**
		228	218	780	11.5	11.1	1.64	0.14	26	56
JB		**289**	**230**	**600**	**12.8**	**9.6**	**1.57**	**0.15**	**61**	**110**
		337	319	964	11.2	8.6	1.64	0.14	59	143
JC	2006	**406**	**196**	**615**	**11.8**	**9.5**	**1.64**	**0.13**	**36**	**84**
		247	310	886	13.0	12.2	1.63	0.13	28	66
JB		**483**	**164**	**430**	**12.2**	**8.2**	**1.55**	**0.14**	**76**	**145**
		578	154	371	10.6	7.8	1.62	0.14	60	138

Note: There were no juveniles present in 2004.

Potential short-term impacts of fishing on SSL

Hennen (2006) found that fishing activities near rookeries had a negative effect on SSL populations and that protections instituted in 1991 reduced the effect, possibly through reduction in direct kills by small trawl vessels. He also advanced an additional possible explanation that small trawlers may have caused localized depletions of fish populations critical to foraging success of females and juveniles near rookeries. Our study failed to find evidence for such localized depletions at current fishery levels in Barnabas Trough.

It is not known whether Barnabas Trough is heavily used by foraging SSL during the late-summer commercial fishing season. If SSL are not present when fishing takes place, the short-term impact is obviously negligible. If large numbers are present during the late-summer fishing season, the short-term effect on SLL is probably small based on the results of our study. Because this study took place in late summer, it provides no direct evidence concerning possible short-term effects of the commercial fishery on walleye pollock distribution during other fishing seasons, when the effects of nutritional stress on SSL would be different, but not necessarily more severe (Jeanniard du Dot et al. 2008).

The results of this work are consistent with several other studies that examined the potential competition between commercial fishing and SSL. Cornick et al. (2006) used simulations to calculate energy budgets for the GOA SSL population under various scenarios of groundfish harvest. They were unable to demonstrate competition between SSL and commercial fisheries and suggested that spatially explicit models might be more appropriate to examine interaction in critical foraging areas within 20 km of major rookeries. However, Dillingham et al. (2006), in a study of the fine-scale geographic interactions between SSL trends and local fisheries, concluded that neither groundfish abundance nor fishing effort could explain the historic decrease in SSL abundance. Furthermore, the analysis of Dillingham et al. (2006) indicated that complete cessation of trawl fishing would have had a negligible effect on the rate of SSL population change.

The changes in abundance and vertical or geographical distribution that the walleye pollock fishery in Barnabas Trough may have caused appear to be small compared with natural fluctuations that can occur. For example, the effect of the absence of juveniles in both troughs in 2004 on SSL is not known. However, it is safe to assume that if it had any effect at all, it was surely greater than that potentially caused by short-term, small-scale changes in the distribution of juveniles resulting from commercial fishing activities.

The lack of evidence of acute nutritional stress (Trites and Donnelly 2003; Atkinson et al. 2008*b*) and the increased survivorship of both adult and juvenile SSL in recent years (Holmes et al. 2007) are encouraging, although more long-term effects such as decreased fecundity, delayed weaning, or increased age when giving birth the first time are still issues of concern. Results from recent studies have also shown the importance of forage fish and salmon to the diet of SSL, so the abundance and distribution of species such as Pacific herring (*Clupea pallasii*), capelin, eulachon (*Thaleichthys pacificus*), and salmon (*Oncorhynchus* spp.) could be important to understand the role that fishing may have in impacting SSL population recovery rates (Donnelly et al. 2003; Womble and Sigler 2006; Womble et al. 2009). Our study did not

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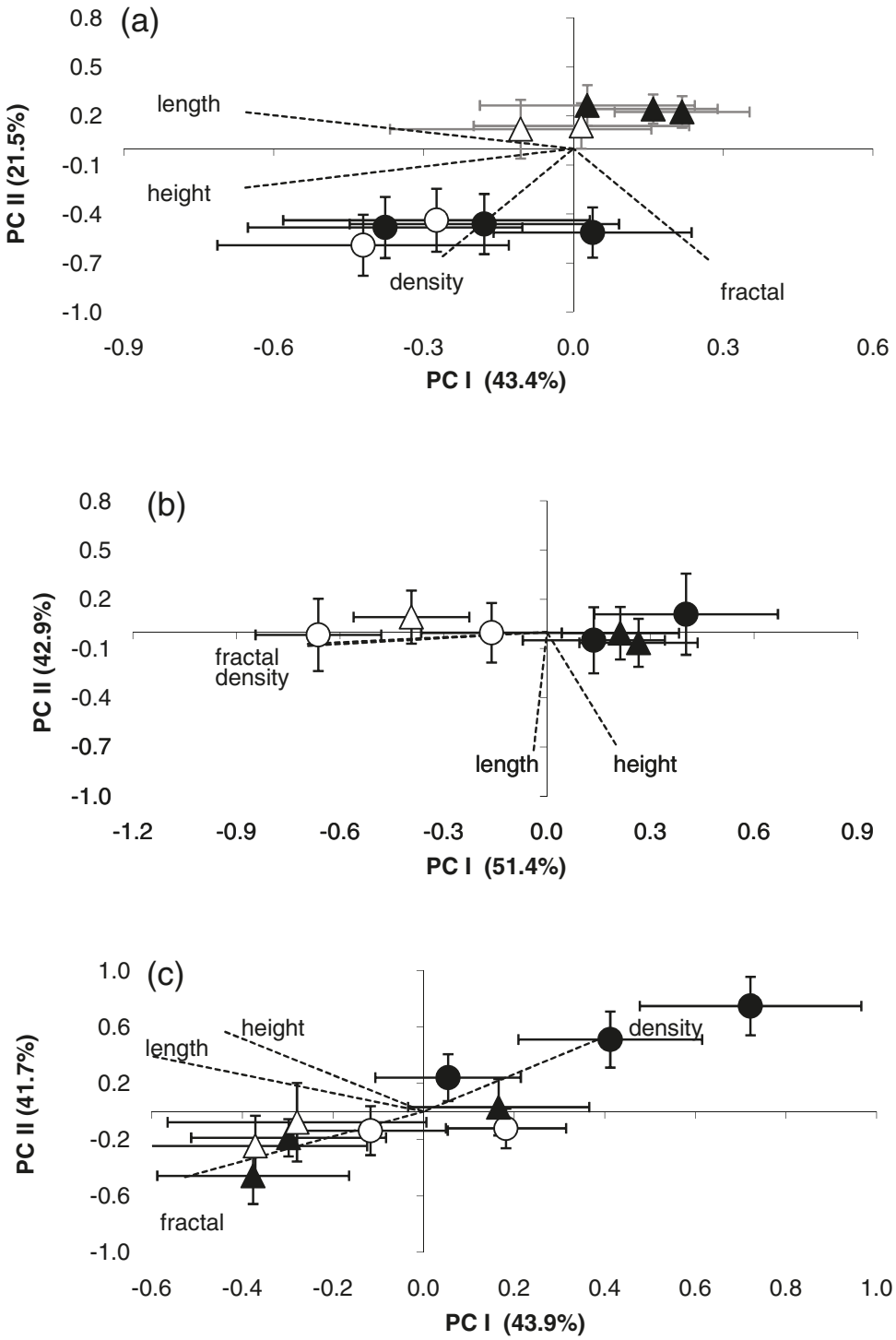
Fig. 7. Adult and juvenile walleye pollock ordinations derived from principal component analysis of aggregations of (*a*) adults in 2006, (*b*) juveniles in 2001, and (*c*) juveniles in 2006 in Barnabas Trough (circles) and Chiniak Trough (triangles). The solid symbols are for prefishery passes. The bars represent 95% confidence intervals of each trough–pass combination mean along PC1 and PC2, and the dashed lines represent the eigenvectors, a proxy for coordinates.



detect direct short-term fishing effects on prey fields, which suggests that investigation of the long-term effects of commercial fishing on the species composition and abundance of the fish communities that constitute the prey of SSL might provide more insight into the impact of fishing on the population dynamics of SSL in Alaska.

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