Effects of commercial fishing on local abundance of Pacific cod (*Gadus macrocephalus*) in the Bering Sea

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Abstract—Groundfish fisheries in the southeast Bering Sea in Alaska have been constrained in recent years by management measures to protect the endangered Steller sea lion (*Eumetopias jubatus*). There is concern that the present commercial harvest may produce a localized depletion of groundfish that would affect the foraging success of Steller sea lions or other predators. A three-year field experiment was conducted to determine whether an intensive trawl fishery in the southeast Bering Sea created a localized depletion in the abundance of Pacific cod (*Gadus macrocephalus*). This experiment produced strongly negative results; no difference was found in the rate of seasonal change in Pacific cod abundance between stations within a regulatory no-trawl zone and stations in an immediately adjacent trawled area. Corollary studies showed that Pacific cod in the study area were highly mobile and indicated that the geographic scale of Pacific cod movement was larger than the spatial scale used as the basis for current no-trawl zones. The idea of localized depletion is strongly dependent on assumed spatial and temporal scales and contains an implicit assumption that there is a closed local population. The scale of movement of target organisms is critical in determining regional effects of fishery removals.

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As fishery management in the United States moves toward an ecosystem approach, both the direct and indirect effects of commercial harvests on marine food webs are being considered (Schoener, 1993; Murawski, 2000). Localized depletion is the hypothesis that intense fishing pressure may cause small-scale effects on local densities of the target fish—effects that are disproportionate to the managed overall harvest mortality rate. The possibility of localized depletion has been considered in developing and implementing regulations to reduce the jeopardy of mortality of Steller sea lions (*Eumetopias jubatus*) due to fishing in the Bering Sea. In 1997, the western stock of Steller sea lions was listed as endangered under the U.S. Endangered Species Act. Because the period of decline in sea lion numbers coincides with the period of rapid expansion of U.S. domestic fisheries in Alaska (Braham et al., 1980; Hiatt, 2005), there has been concern that commercial fisheries may indirectly affect sea lion abundance through competition for available prey (Alverson, 1992; Fritz et al., 1995).

During their consultations regarding the U.S. Endangered Species Act, scientists of the National Marine Fisheries Service (NMFS) cited the federally managed fishery for Pacific cod (*Gadus macrocephalus*) as one with a potential to adversely affect Steller sea lions. Pacific cod is the third-most valuable commercial fish species in the United States; the value of the 2006 harvest was estimated at $197 million. Approximately 40% of Pacific cod catch is taken by trawling in the southeastern portion of the Bering Sea during the winter "A" season, from 20 January through 31 March (Thompson and Dorn, 2005). The trawl fishery has historically been concentrated on an area of the continental shelf north of Unimak Island, where Pacific cod form dense spawning aggregations during the winter season.

Although the Pacific cod population in the eastern Bering Sea is managed at sustainable overall harvest levels, intensive trawl fishing in a smaller area has been suspected of causing short-term, small-scale impacts on fish abundance (localized depletion) that are disproportionate to the overall harvest rate. Particularly worrisome is the possibility that fishing mortality rates in the heavily trawled area may be much higher than those for the total region, and that this disproportionate mortality may cause reduced availability of Pacific cod as prey for Steller sea lions (Fritz et al., 1995). Evidence indicating such a local effect has been seen in commercial catch data in the eastern Bering Sea (Fritz and Brown, 2005). Under the assumption of reduced prey availability from localized fishing, trawl exclusion zones have been placed around Steller sea lion rookeries and haulouts in western Alaska, and seasonal and spatial allocation of catch quotas have been used to disperse fishing effort. Our goal was to test for effects of localized depletion of Pacific cod caused by the Pacific cod winter trawl fishery.

In order to test for the presence of localized depletion, the temporal and spatial scales of the presumed effects must be specified. Localized depletion is a general term that could encompass several types of interactions. Short-term movement rates of the target species in relation to the scale of the fishery are a critical factor in determining fishing effects. To illustrate, we offer three conjectures on fishery interaction, where the dynamics of harvest and fish movement result in different effects on fish abundance.

For the first conjecture, harvest results in a localized reduction in fish abundance in the immediate vicinity of fishing. This reduction remains geographically stable for some period of time. We refer to this effect as stationary localized depletion. This form of depletion may be envisioned as the action of a dipper to remove certain amount of mud from a bucket; a hole or depression would remain where the mud was removed, eventually filling in but persisting long enough to be observable. Implicit in such stationary localized depletion is the notion that movement by the fish is on a scale smaller than that of the fishery; therefore it does not obscure the geographic imprint of the removal.

For the second conjecture, the movement of the fish interacts with a locally intense harvest. In this case, short-term fish movement occurs on a geographic scale greater than that of the fishery and the effect of the removal would quickly dissipate over the area occupied by the fish. This form of depletion would more closely resemble the action of ladle in dipping water out of a bucket, with no persistent depression left behind by the ladle. On the scale of the ladle, the effect is transitory and there is no apparent localized depletion, even though there is a measurable removal on the scale of the bucket.

For the third conjecture, the short-term fish movement includes a net flow in one direction. In this scenario, fishing effects would show as a change to the flow of fish or as an area of reduced abundance that is displaced downstream. This effect would be similar to intercepting part of a flowing stream with a dip net. Combinations of random and directed short-term movement may also produce effects that are both dispersed and spatially displaced from the location of harvest.

In the specific case of Bering Sea Pacific cod, the scale of fishery harvest is known from commercial fishing data, but the scale of Pacific cod movement is poorly understood. From an early tagging study (Shimada and Kimura, 1994), it was found that Pacific cod make large-scale movements over the eastern Bering Sea on a seasonal basis. Short-term movement dynamics of Pacific cod, on the other hand, are only beginning to be studied (Nichol and Chilton, 2006). Assumed scales of Steller sea lion foraging are based largely on satellite tagging studies of adult female and juvenile Steller sea lions (Merrick and Loughlin, 1997). Measures enacted to protect Steller sea lions include trawl exclusion zones 18.5 or 37.0 km in diameter around Steller sea lion haulouts and rookeries. Use of trawl exclusion zones to reduce competition between Steller sea lions and trawlers implies an assumption of stationary localized depletion at this scale. Thus, under the current regulatory framework, the general question of whether fishing causes some form of localized depletion becomes much more specific, namely that of whether or not trawling causes a stationary localized depletion on the geographic scale of the trawl exclusion zones. Our experiment was therefore designed to address the specific mechanism that causes stationary localized depletion, and we assumed that this type of depletion would have the greatest potential for negatively affecting Steller sea lion abundance.

Materials and methods

Study area

The study area was located in the southeast Bering Sea near the tip of the Alaska Peninsula (Fig. 1)—an area situated off Unimak Island at Cape Sarichef on the eastern side of Unimak Pass, at depths of approximately 70 to 110 m. This area is one of the most productive trawling grounds in the Bering Sea, where fisheries focus a great deal of trawling effort for Pacific cod. The trawl exclusion zone around the Steller sea lion haulout at Cape Sarichef intersects this preferred trawling ground and the two areas provided us an opportunity to use a spatially adjacent treatment zone and control zone. The spatial scale of the experiment was determined by the 18.5-km boundary of the Cape Sarichef trawl exclusion zone and the extent of preferred depths for trawl fishing. The temporal scale, the length of time an effect must persist to be observable, was taken to be approximately two weeks, which was the time required to conduct each phase of the research fishing.

Research pot gear

We used the catch of standardized pot gear as an index of local Pacific cod abundance. Pot gear is widely used in commercial fishing for both crab and Pacific cod in the eastern Bering Sea and Gulf of Alaska. Research catches were based on catch from pots, even though the fishery effect being tested for would have been due to trawling, because pots provide large sample sizes and can be deployed at a very high spatial resolution. Pot catches cannot be easily or reliably used to estimate absolute abundance of fish, but provide a consistent index of relative abundance that can be used to make statistical comparisons between different survey areas or times.

Commercial pots were used during initial feasibility and pilot studies for this project; a standardized research pot was then developed and used for the experiment. The research pots were slightly larger than most commercial pots, and had a smaller net mesh and modified tunnel openings: they were 2.3 m by 2.3 m by 1.2 m, and had 5-cm stretched mesh and two entrance tunnels, each with 68-cm by 23-cm tunnel openings.

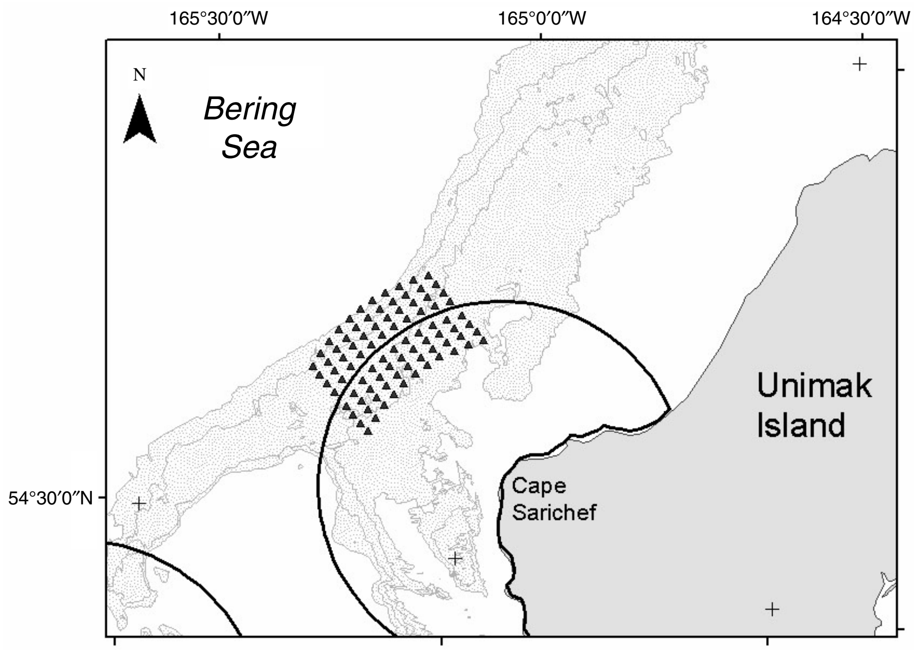

Figure 1

Location of the study to determine localized depletion of Pacific cod (*Gadus macrocephalus*) in the southeast Bering Sea. The large arc shows the regulatory notrawl zone around the Steller sea lion (*Eumetopias jubatus*) haulout at Cape Sarichef on Unimak Island. The small triangles indicate station locations for the experiment. Depth contour lines and light shading show the region of 70 to 100 m depth.

At the tunnel openings there was a modified Hilti-style stainless-steel trigger, a variation of a fish retention mechanism commonly used in cod-pot fishing. Research pots were fished individually with buoy lines, buoy configurations, and other tackle configured similarly to that deployed in commercial pot fishing.

Experimental design

We used an experimental design similar to the class of designs referred to as "before/after control/impact" (BACI). The capabilities and limitations of BACI study designs have been discussed extensively in the ecological literature (e.g., Osenberg and Schmitt, 1994; Hewitt et al., 2001). We used many of the components of a BACI design, but the final design differed substantially from the paired designs of Stewart-Oaten et al. (1992). In our study, the measured quantity was not the difference between treatment and control stations replicated over time, but the percentage difference over time at each station, replicated over space. In this sense, our design was similar to the ANOVA-type designs of Underwood (1994). Our design allowed for expected seasonal and small-scale spatial variability in fish abundance, and provided the necessary replication for hypothesis testing.

The experiment was conducted in 2003, 2004, and 2005. In each year, data were collected during two separate cruise legs: in early January (before the trawling season) and immediately after the main trawl harvest in late March. Sampling was balanced between a treatment area subject to intensive trawl fishing and a control area inside the Cape Sarichef notrawl zone. A total of 80 sampling stations were set along 10 parallel transects intersecting the notrawl zone boundary, and each transect contained four stations inside and four outside the boundary (Fig. 1). Although it was not possible to match treatment and control stations exactly with respect to depth, habitat, bottom currents, etc., this layout provided a similar range of habitats within the two zones.

The quantity of interest for each station was the ratio of the mean pot catch (in numbers or weight of Pacific cod) at that station during the March survey ($\bar{X}_{After}$) to the average catch during the January survey ($\bar{X}_{Before}$). This ratio reflects the percentage change in abundance between the two surveys at a particular station. The seasonal percentage change is referred to as the delta (δ) for the station:

$$\delta = \left(\bar{X}_{After} - \bar{X}_{Before}\right) \Big/ \bar{X}_{Before} = \frac{\bar{X}_{After}}{\bar{X}_{Before}} - 1.$$

The ratio is expressed so that δ will be near zero if the catch is the same at a given station during both the before and after surveys, positive if the catch increases, and negative if catch decreases over the season. For example, a δ of –0.50 represents a 50% decrease in catch, and a δ of +1.00 represents a 100% increase.

Sampling considerations and gear deployment

There are two important concerns in using catch from fixed-gear such as pots as an index of fish abundance. The relationship between catch and abundance can break down at either very low or very high fish densities (Hubert, 1996). During our pilot studies, soak times and sampling procedures were developed to ensure that the research fishing did not result in either excessive numbers of empty pots or gear saturation (where the number of fish in the pot became so high that catchability of additional fish was reduced). To guard against gear saturation and to provide detail on the timing of fish catch within the soak period, instruments referred to as trigger timers were developed. These instruments involved a magnetic reed switch mounted on the triggers of the pot and an electronic event timer that recorded when the triggers were pushed open. A modular trigger assembly allowed instruments to be mounted and dismounted in pots without slowing down the pace of fishing.

In order to avoid gear saturation and to increase the number of observations, pot soak times were initially kept short (4–8 h), and fishing was conducted mainly during daylight hours. It was not feasible to fully standardize the soak time or the timing of the launch within the diel and tidal cycles over the 40–50 pots fished each day. In order to compensate for variation from these sources, each day's sampling included approximately equal numbers of stations inside and outside the notrawl zone. Difficulty in retrieving pots during strong tidal currents led to a change in procedure between 2004 and 2005. In 2005 a slightly longer overnight soak was used, with pots being launched at new locations in the afternoon or evening and retrieved the next morning.

Results of a pilot study conducted in 2002 showed short-term temporal variation (day-to-day variability in catch rates at a given station) as a larger component of variability than small-scale spatial variation (variability in catch between stations). In order to smooth over short-term temporal variation, we attempted to fish each station on at least three different days during each survey. Each day's fishing was balanced with stations in both the treatment and control areas, so that any short-term influences on abundance would affect both treatment and control groups. The goal was to apply fishing methods in such a way that variation in catch due to soak time, diel and tidal cycles, weather, and current patterns would be minimized and distributed evenly between trawled and untrawled areas.

Our pilot study results also indicated that pots located at least 0.11 km apart functioned as independent sampling units (no correlation between catch for pairs of pots at 0.11 km or further distances). Stations for the experiment were spaced 0.11 km apart within each zone (trawled or untrawled), and 1.8 km apart across the notrawl zone boundary. The same layout of study stations was used for all three years. Examination of both pilot study data and pot fishing data collected by fisheries observers indicated that there was not a strong relationship between length of pot soak and catch over a time span of 4–24 hours. For this reason, catch rates were expressed not as CPUE in fish/hour, but simply as total number or weight of Pacific cod caught per standardized pot deployment. The catch measure at each station was the average catch over all of the days that a station was fished during a survey. The use of an average over several days as the measure at each station provided smoothing over day-to-day variation and reduced the likelihood of zero catches in the final data set.

Pots were baited with chopped Pacific herring (*Clupea pallasi*) contained in meshed bait bags. Bait for each cruise was purchased as a bulk lot so that the same lot of bait was used for the entire cruise. Filled bait bags were weighed and the amount of bait adjusted to within 0.1 kg of the target weight of 5.0 kg. Procedures for securing bait bags and triggers, launching, and retrieving pots were consistent in all cruises.

Upon retrieval, all catch was sorted, identified, and weighed. A systematic subsample of pots (every second, third, or fourth pot retrieved) was selected with a random starting point each day; all Pacific cod from selected pots were processed for length frequency, by sex. The sampling interval was adjusted according to average catch rates so that at least 100 fish were measured each day. The condition of the gonad of measured fish was also examined visually and coded according to a 5-stage system, in order to record the approximate frequency of different stages of reproductive maturity of Pacific cod in the catch

Data analysis

After every study year, average catch rates for each station and cruise were calculated for all valid fishing days at a station. Average catches from the two cruises were used to compute the δ for each station. Spatial mapping of both raw catch data and δs was performed to look for spatial patterns and verify the assumption of independence between study stations. Distance-based correlograms (both anisotropic and isotropic) were plotted to check for spatial dependence in catch data.

Linear models were also used to look for patterns in untransformed catch data; effects of year, season, treatment versus control, station, and fishing day within each cruise were examined. After examination of the distributional characteristics and independence of the δ's, the nonparametric, rank-based Wilcoxon rank sum test (Ott, 1984) was used to test for a difference in distribution of δ between stations in the trawled and untrawled areas. The nonparametric test was selected over the parametric t-test because δ is a ratio of counts and may have a strongly non-normal statistical distribution. All modeling was conducted in S-Plus (Math Soft Inc., Seattle WA; Venables and Ripley, 2002).

Bootstrap methods (Manly, 1991) were used to evaluate the power of the experimental design to correctly identify the presence of a fishing effect. For each study year, daily catch data from all stations and days were pooled for use as a sampling population. Random samples the same size as those used in each year's experiment were drawn. Half of the simulated sample stations were randomly assigned to the treatment group, and the mean catch for these stations in the March cruise was decreased by a fixed percentage to simulate a known fishing effect. Percentage changes were then calculated for each station, and we used the Wilcoxon rank sum test to compare stations in treatment and control groups. This algorithm was repeated 1000 times for each level of fishing effect. The P-values computed for each sample were used to compute probabilities of rejecting the null hypothesis for $\alpha=0.05$, 0.1, and 0.2 for each of the levels of sampling effort.

To check that substantial removals of Pacific cod took place during the study, we evaluated the harvest in the study area using NMFS catch estimates and haul-specific data collected by the Alaska Fisheries Science Center observer program. Winter-season Pacific cod catch for trawl gear was summarized for each of the two federal reporting areas that intersect the study area. These totals included both catches in the study area and catches in other parts of the reporting area. Observer data did not cover all hauls on all vessels but were recorded with spatial precision to the nearest minute latitude and longitude. Records for all observed hauls within the two reporting areas were extracted, and hauls within a one-degree longitude by 30-minute latitude block around the study area were identified. The proportion of observed hauls and total fishing effort (duration of haul) in the study area as a proportion of observed hauls in each reporting area was calculated. The total catch of Pacific cod was determined from the smaller subset of observed hauls (for which there were catch composition data), and the proportion of Pacific cod catch coming from the study area was also estimated. This fraction was then applied to the total catch for the reporting area to obtain a rough estimate of Pacific cod harvested from the study area by gear type.

Tagging studies

In conjunction with the localized depletion study, we conducted studies on the feasibility of determining on Pacific cod movements through tagging. Partial results of these studies are reported here to explain the results of the main experiment. Tagging work included development of methods 1) for capturing and handling Pacific cod with pot gear, 2) for tagging fish and determining data formats, 3) for releasing Pacific cod tagged with archival data-storage tags and standard spaghetti tags, and 4) for studying preliminary tag-induced mortality. The goal of this effort was to collect information on both seasonal migration patterns and small-scale movements of Pacific cod during the spawning season.

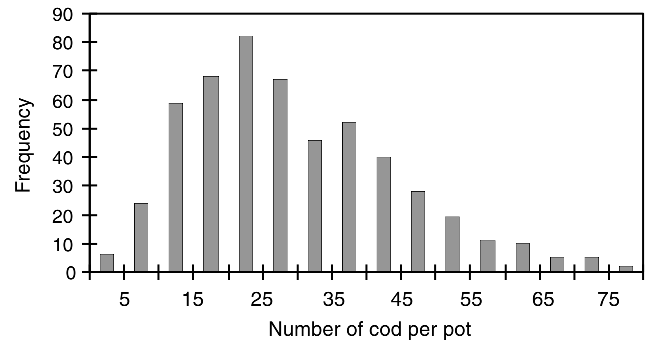

Figure 2

Example of the frequency distribution of pot catch data for Pacific cod (*Gadus macrocephalus*). Catch data are in numbers of fish per pot from all stations during the March 2004 cruise.

An understanding of these movements is important for the interpretation of the local abundance study. During a special tagging cruise in February 2003, tagged fish were released at a series of locations, including within the notrawl zone off Cape Sarichef. Tag recapture was conducted entirely by the fishing industry. Date and location of the recaptures were provided by fishermen and fishery observers. In total, 295 archival tags and over 6000 spaghetti tags were released between 2002 and 2004. Approximately 35% of both types of tags were returned over the five years after tag release. Full results of these tagging studies will be presented in a separate publication.

Results

Field data confirmed that assumptions for the experimental design were met. The frequency distribution of the raw catch data (Fig. 2) illustrated the properties of pot catch. Similar results were obtained with either numbers or weight of Pacific cod per pot as the measured quantity. Zero catches (empty pots) were rare, and there was no evidence of gear saturation at high catches (the upper tail of Fig. 2 declines gradually without a sharp cutoff). Although the distribution of pot catch data was slightly skewed, the skewness and heteroscedasticity were much smaller than is typical for many types of fishery data.

The level of Pacific cod catch varied strongly between study years and seasons but was fairly consistent within each study cruise. Average catch ranged from 8.8 Pacific cod per pot (27.7 kg) in March 2003 to 31.7 cod per pot (105.5 kg) in March 2004. Coefficients of variation for the raw catch data ranged from 64% for January 2004 to 42% for March 2005. Coefficients of variation for cruise averages at individual stations ranged from 14% to 43%. The average catch rate changed substantially between January and March in each year of the study,

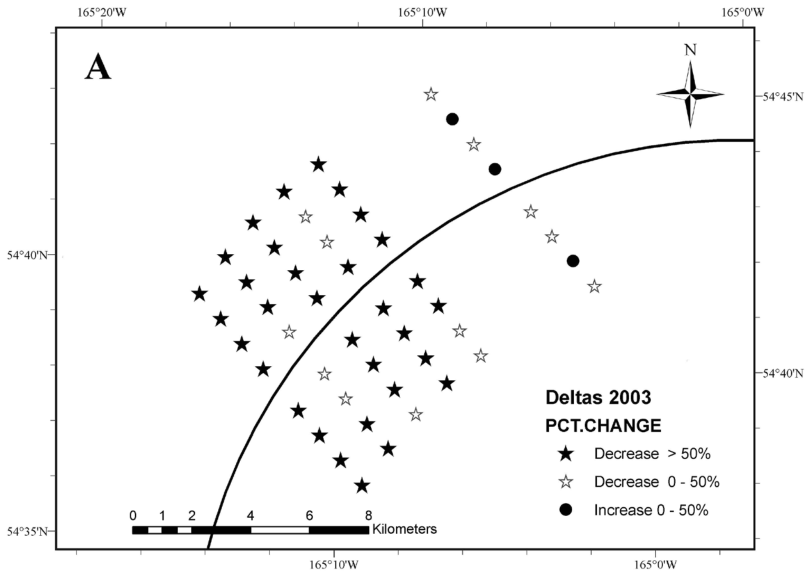

Figure 3

Spatial pattern in seasonal percent change (δ) for the three study years. Refer to Figure 1 for general location of the study area. Symbols show study stations. The arc in the middle of the stations is the Cape Sarichef notrawl zone boundary. Symbol shape and size indicate the size of the percent change in Pacific cod (*Gadus macrocephalus*) catch between "before" (early January) and "after" (immediately after the main trawl harvest in late March) surveys in each year: (**A**) 2003, (**B**) 2004, and (**C**) 2005.

but not always in the same direction. In 2003, the average catch rate decreased 55% from January to March, and nearly all of the individual station changes (δ) were less than 1.0. In 2004 and 2005, the average catch rate increased by 73% and 26%, respectively, from January to March. These differences were presumably the result of interannual differences in the timing of seasonal migration and spawning aggregation

A check of spatial pattern in the raw data and final δ's verified the independence of the experimental study stations and the absence of any strong spatial patterns. There was no consistent spatial pattern in raw catch data, either between trawled and untrawled areas or from southwest to northeast within the study area. There was some evidence of serial correlation between adjacent pots within each fishing day; we believe this correlation to be a result of similarities in timing of pot launches within tidal and diel cycles rather than spatial correlation in fish abundance. There was no spatial correlation in the calculated average catch at each station over a cruise. Although there was some evidence of serial correlation between days within a cruise, averaging the catch at each station over the days within a cruise eliminates this correlation. Maps of percentage change values (δ) also showed no discernible spatial pattern (Fig. 3). Distance-based variograms (both isotropic or anisotropic) were reviewed for the final δ's and we found no significant spatial correlation as a function of distance between pots. Correlation of pairs of δ's at all distances of 0.11 km or more were not significant, verifying the assumption of independence between stations.

Implementation of the study design was generally successful, and good replication was obtained. The exception was the January cruise in the first year of the experiment (2003), where severe weather and mechanical problems severely curtailed the field effort. Sample size from this cruise (160 pots fished) was small (Table 1). The March "after" cruise in 2003 was, however, successful; a total of 475 pots were fished and full replication at all 80 experimental stations was obtained. Both before and after cruises in 2004 and 2005 achieved full coverage of the 80 stations and good replication. Because of the very low sample size in January 2003, δ's could be calculated for only 48 of the study stations, and some before values were based on only a single measurement. In 2004 and 2005, δ's at all 80 study stations were calculated from the averages for over three to five replicate fishing days within each cruise. The resulting values ranged from negative numbers, representing a net seasonal decrease at a station, to fairly large positive values, indicating a substantial seasonal increase. In 2004, there was a particularly large outlier (δ>4) at one station which had very low catches in January. The shift to overnight soaks in 2005 resulted in not only smaller variance of the raw catch data but in smaller

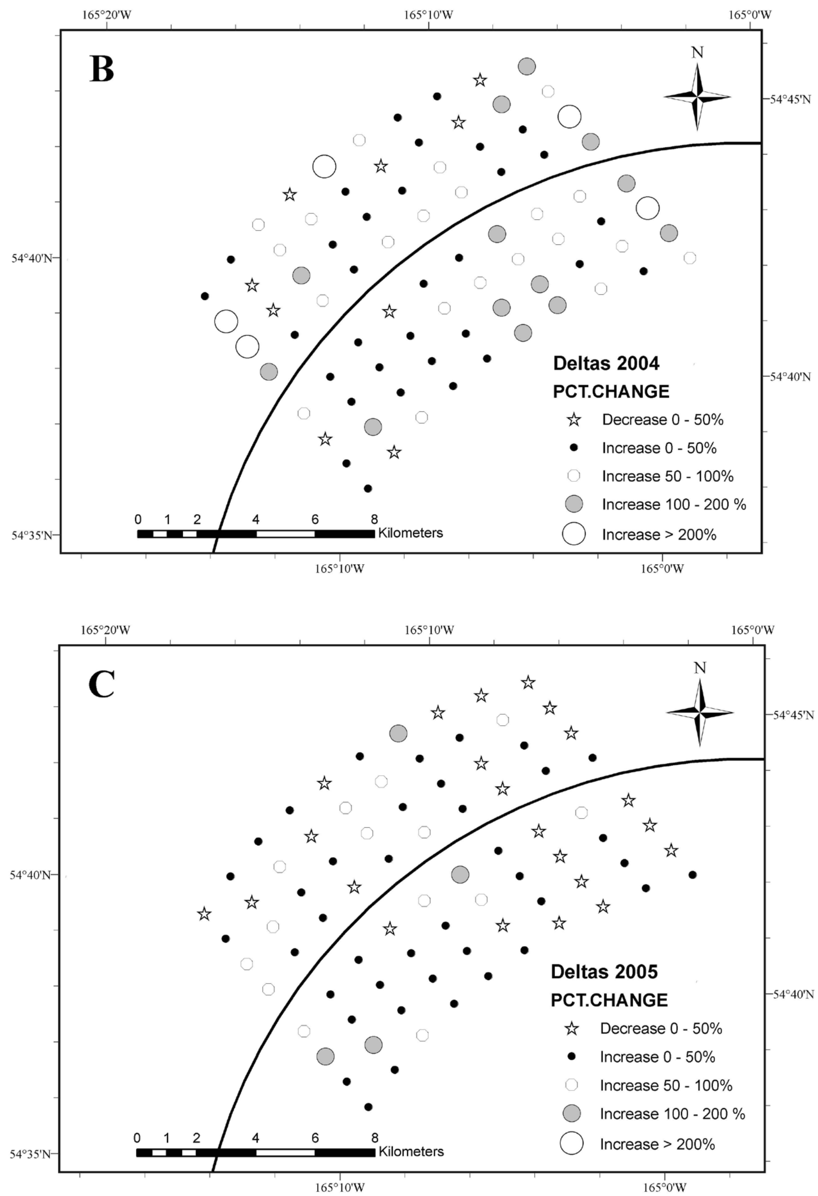

Figure 3 (continued)

variance of the δ's. Although the small sample size in January 2003 limited the power of statistical testing in this year, the overall consistency of the results persuaded us to include the 2003 data set in final analyses.

Analysis of the raw data foreshadowed the overall results of the study. We examined the catch data from individual pots, using standard linear model analysis. The best-fit linear model accounted for only 30% of the variability in the data, reflecting the importance of other sources of variability not included in the model. The treatment effect (trawled vs. untrawled zone) was not significant for the raw data, indicating only slight differences in baseline abundance between the two zones. The interaction term for treatment and season (which is the term that would reflect a substantial localized depletion in the trawled zone) was strongly not significant. As pointed out in discussions of simple BACI analysis (Hurlbert, 1984; Stewart-Oaten et al., 1986; Underwood, 1991), the interaction term from the standard ANOVA does not provide the correct error term for a true test of impact; for testing the presence or absence of localized depletion we used the analysis of δ's.

Final results of the study clearly indicated very similar values of seasonal change in Pacific cod abundance (δ) in both the trawled and untrawled portions of the study area. We did not see the differences in slope that we would have expected to result from strong localized depletion in the trawled zone. When we used the rank-based Wilcoxon test to look for differences in mean δ between the trawled and untrawled regions, *P*-values

Table 1

Dates and summary statistics for cruises conducted during the Bering Sea localized depletion experiment for Pacific cod (*Gadus macrocephalus*). Each year's experiment included a "before" cruise in early January (before the trawling season) and an "after" cruise in late March immediately after the main trawl harvest.

Cruise dates	Cruise purpose	Number of days fishing	Number of pots fished	Average number of cod/pot	Average weight (kg) of cod/pot
30 Mar–25 Apr 2002	Pilot study and tagging	21	703	28.8	103.4
28 Dec 2002–8 Jan 2003	Abundance experiment—before	4	160	22.2	104.4
4–17 Feb 2003	Tagging	11	336	22.3	78.3
12–31 Mar 2003	Abundance experiment—after	14	475	8.8	27.7
2–10 Jan 2004	Abundance experiment—before	9	360	19.3	93.3
15–31Mar 2004	Abundance experiment—after	15	604	31.7	105.5
9–22 Mar 2005	Abundance experiment—before	14	481	21.2	85.3
16–29 Mar 2005	Abundance experiment—after	14	500	25.7	95.4

for the three study years were 0.70, 0.92, and 0.81, respectively. Although the range and mode of the observed δ's changed from year to year, in each year the distribution of δ's over stations within the two zones was very similar (Fig. 4).

Power simulations gave us confidence that the strong failure to reject the null hypothesis in 2004 and 2005 reflects a true absence of a treatment effect in the study area. Power was poor in 2003 because of the low sample size and higher variability of the data; only imposed fishing effects of 50% or more would have given a high probability of correctly detecting a difference between treatment and control groups. In 2004 and 2005, however, full replication of the experiment resulted in good power. We were able to detect differences at 25–30% fishing effects in the 2004 experiment and at as low as 20% fishing effects in 2005.

We verified that substantial fishing removals occurred within the trawled portion of the study area during our experiment. The reported January–March fish harvest data from the NMFS Alaska Regional Office indicated that the harvest of Pacific cod by bottom trawl gear in the two federal reporting areas around Cape Sarichef was on the order of 25,000 metric tons (t) per year. Based on observed hauls, approximately 45% of the total harvest in these two reporting areas came from the study area (Table 2).

Auxiliary biological and tagging data were useful for interpreting our results. Sex ratio and length–frequency data collected during each cruise indicated that the population of fish sampled sometimes changed substantially, even within the two-week duration of a study cruise. Sex and maturity class data from systematic subsamples of Pacific cod collected during the March 2004 cruise are shown in Figure 5. Although shifts from developing and prespawning stages to ripe and spent stages may reflect seasonal maturation of individual fish, differences in the proportion of mature to immature fish can only be explained by movement of fish into and out of the study area during the two-week period of the cruise. The overall sex ratio for the 15–22 March samples was 0.93 (males/female), whereas the sex ratio for 23–20 March was 0.75. This difference represents a significant change in sex ratio (P=0.0004) over the two-week period.

Table 2

Estimation of the Pacific cod (*Gadus macrocephalus*) harvest from the study area. Total Pacific cod catch during the winter trawl season in each year is shown for National Marine Fisheries Service reporting areas 509 and 517, which included the study area. Catch data from observed hauls were used to estimate the proportion of cod catch taken from a 1° latitude-longitude block around the study area; this proportion applied to the total harvest was used to show the approximate harvest (in metric tons) from the study area during the experiment.

	Estimated harvest (metric tons) taken with bottom trawl gear		
Year	Reporting areas	Study area	Proportion
2003	20,971	10,215	48.7%
2004	25,158	12,295	48.9%
2005	29,870	13,882	46.5%

Qualitative tagging studies were conducted concurrently with the localized depletion experiment. Although these studies are to be reported separately, some of their results help to explain the outcome of the localized depletion experiment. Partial results from the February 2003 tagging studies indicated substantial movement of Pacific cod, both over spans of several months and over shorter time scales (Table 3). Over 70% of the fish released in the study area in February 2003 and recovered within two weeks of release were recaptured more than 18.5 km (10 nmi, the radius of the notrawl zone) from their release location. The majority of fish recaptures took place east and slightly north of the release site within the Cape Sarichef notrawl zone, and only a few recaptures were documented for the study area immediately outside the notrawl zone.

Discussion

The results of our experiment were extremely clear. Although the direction and magnitude of the net seasonal change in abundance differed between study years, in each study year direction and magnitude of the percentage change (δ) were similar in the trawled and untrawled areas. Nonparametric tests used to compare δ's from the two zones consistently had P-values over 70%, indicating that there was no evidence that the distribution of the two groups differed—a conclusion that is evident without any statistical testing simply by comparing the frequency distributions of the δ's in the trawled and untrawled zones (Fig. 4). Analysis of the raw catch data with linear models leads to the same conclusion. Checks for more subtle indications of fishing effects, such as spatial patterns in catch within the study region or temporal trends within each two-week cruise, were also negative. These experimental results are inconsistent with the hypothesis of strong stationary localized depletion at the scale of the existing notrawl zones in Alaska.

Power simulations indicated that the failure to see a difference between trawled and untrawled areas was not simply due to a lack of resolution in the data. Although the sample size for 2003 was low, results for 2004 and 2005 showed that fishing removals that resulted in a 20–30% decline in catch rates in the trawled area would have been detected. There is little information on the size and duration of prey density decreases that would be necessary to impact Steller sea lion foraging success. It is possible that Pacific cod abundance in the study area was so high that even the substantial fishing removals resulted in a <20% change in local Pacific cod abundance. If this is the case, then the question becomes one of whether or not such small changes in prey availability would significantly affect Steller sea lion foraging.

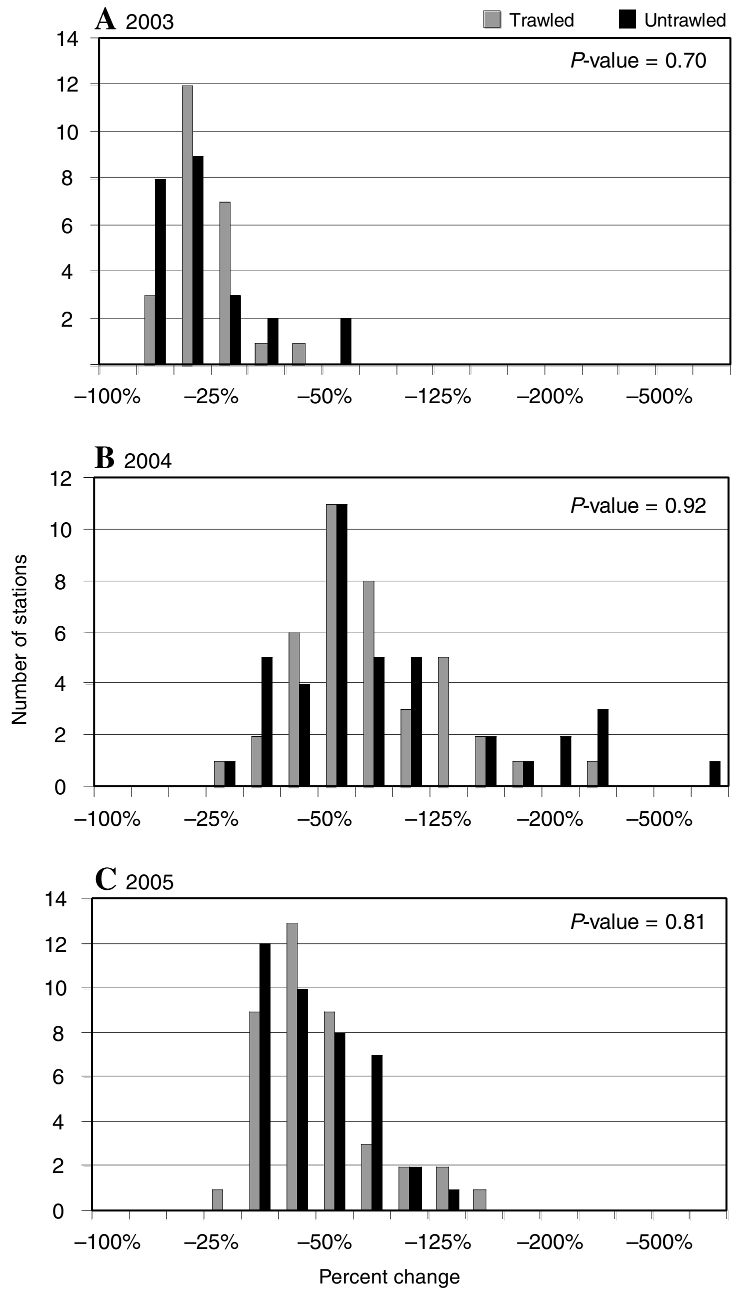

Figure 4

Frequency distribution of seasonal percent change in abundance (δ) for the Cape Sarichef localized depletion study. Dark bars are frequencies of δ for untrawled stations inside the notrawl zone, and hatched bars represent trawled stations outside the notrawl zone boundary: (**A**) 2003, (**B**) 2004, and (**C**) 2005. P-values for the nonparametric rank-sum test are shown in each figure.

Data from the auxiliary tagging and biological studies clearly indicated that Pacific cod in our study area were highly mobile over much shorter time scales than previously assumed. The stationary localized depletion scenario is based on the assumption of a closed local pool of fish that is reduced by local removals. Both the tagging data and the observed shifts in maturity and

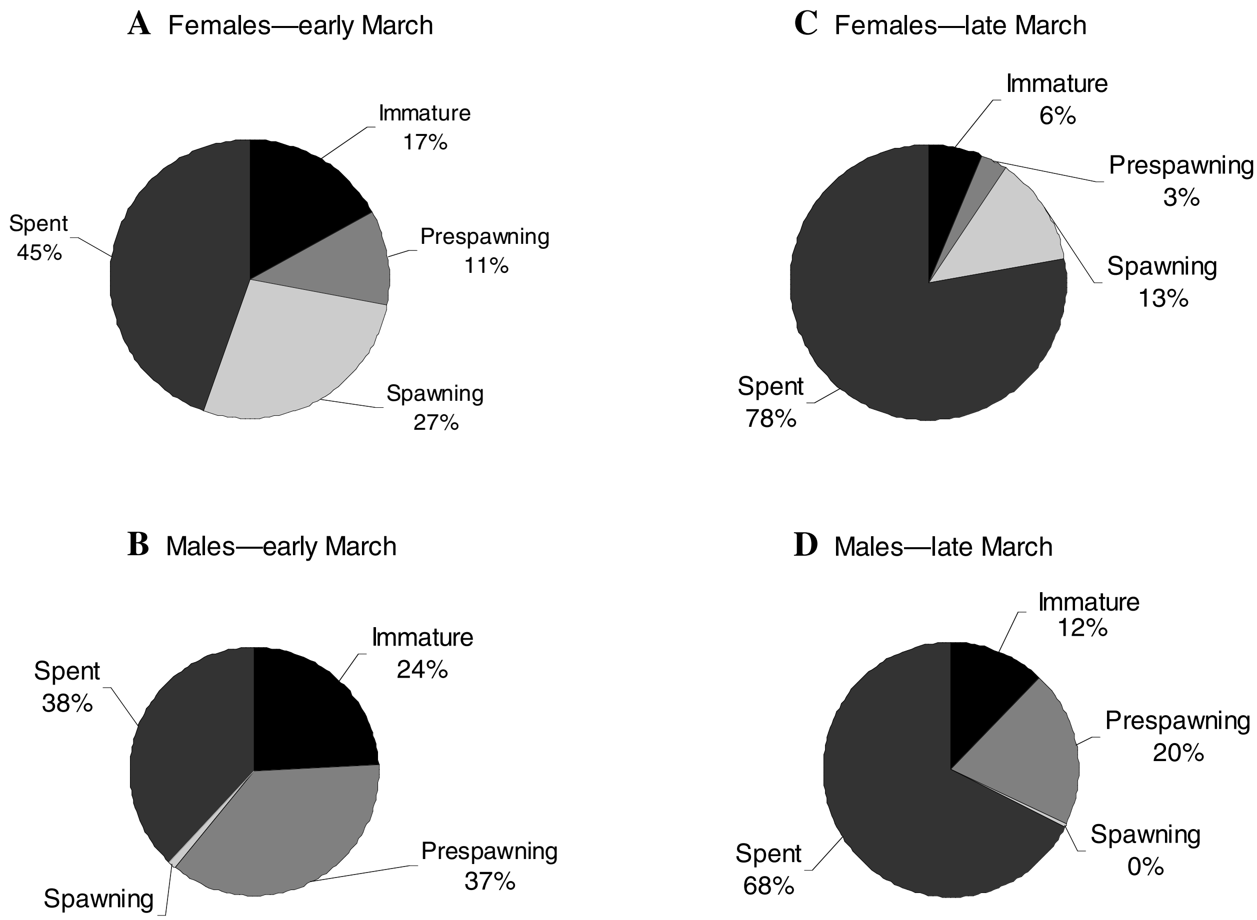

Figure 5

Gonad maturity stages for Pacific cod (*Gadus macrocephalus*) caught in March 2004. Fish were classified as immature, prespawning, spawning, or spent (immediately postspawning) based on visual inspection of the gonad. (**A**) females in randomly sampled catch from 15 through 22 March 2004, (**B**) males from this period, (**C**) females in randomly sampled catch from the same locations in 23–30 March 2004, and (**D**) males from this period.

sex ratio indicate that the local population of Pacific cod in our study area was not a closed, static pool of fish but a shifting, dynamic mix. In fact, the tagging data indicate that the short-term movement scale for Pacific cod in this region is substantially larger than the 10 nmi notrawl zone. Although fishing removal may have had an immediate localized effect on fish abundance, the effect was obscured by rapid fish movement (less than one week) over a geographic scale greater than that of the fishery removal. Thus, of the three localized depletion scenarios presented earlier (see *Introduction*), our results strongly disagree with conjecture one (stationary localized depletion). Because the experiment was limited in scale, our results do not eliminate the possibility of conjectures two and three (regional effects over larger spatial scales or displaced effects due to directed movement). Recent hydroacoustic studies of walleye pollock (*Theragra chalcogramma*) abundance in the same region (Barbeaux et al.[1]) also indicated attenuation of fishery-removal effects by rapid fish movement. Barbeaux et al. saw a visible pattern in echo sign during fishing, but diurnal fish movements eliminated the pattern within 12–24 hours.

The movement of Pacific cod, as qualitatively observed in the tagging data, could appear as a decline in catch rates for catch data measured on the same geographic scale. In a previous study of possible effects of commercial fishing on Pacific cod abundance (Fritz and Brown, 2005), commercial catch-per-unit-of-effort (CPUE) data were collected from a large region of the southeast Bering Sea, including our study area. Fritz and Brown interpreted a decreasing trend in fishery CPUE from

[1] Barbeaux, S. J., M. Dorn, J. Ianelli, and J. Horne. 2005. Visualizing Alaska pollock (*Theragra chalcogramma*) aggregation dynamics. ICES Council Meeting 2005/U:01.

Table 3

Partial results from tagged Pacific cod (*Gadus macrocephalus*) released near Cape Sarichef in February 2003, showing net movement of tagged fish. Table columns show distance travelled (km) between release and recapture points of a tagged fish. Table rows show weeks at liberty (the time elapsed between release and recapture dates). Table values show the percentage of recovered tags for which the distance travelled is within the specified range.

	Distance (km)						
Weeks at liberty	<9.3	9.3–18.5	18.5–37.0	37.0–74.1	74.1–148.2	>148.2	Number of tags recovered
<2	12.2%	15.1%	25.9%	18.0%	3.6%	25.2%	139
2–4	7.0%	2.3%	9.3%	34.9%	23.3%	23.3%	43
4–8	2.9%	5.9%	5.9%	26.5%	32.4%	26.5%	34
8–16	18.8%	12.5%	6.3%	25.0%	6.3%	31.3%	16

13 February through 24 March 2001 as localized depletion due to fishing removals. The models used in the Fritz and Brown study (the models of Leslie and Davis, 1939, and DeLury, 1947) are based on the assumptions of a closed population and constant catchability. These models are unable to distinguish between changes in abundance due to fishing removals and those due to fish dispersal or movement across the boundaries of the study area. If the assumption of a closed population is true, then declining CPUE would indicate a regional-scale effect (conjecture two). Given the high mobility indicated in Table 3, however, we doubt that the model assumptions are met for Pacific cod. Understanding patterns in Pacific cod abundance must take into account both substantial short-term movement and seasonal processes of migration and aggregation related to spawning.

The formal statistical inference presented in the present study applies only to the study area; extending this inference to other areas is reasonable but can only be considered a qualitative exercise. As with many comparative environmental studies, this project included only two experimental units, in the sense that the treatment (trawling) was applied to one region and the other region (notrawl zone) was used as a control. Hurlbert (1984) pointed out that, in an observational study with only one treatment and one control area, a statistical test constitutes evidence only for a difference between the two observed areas. The observation of an effect (or lack of effect) must be combined with biological knowledge of the system to extend inference from the observed areas to other parts of the system. In the case of Cape Sarichef, the experimental area was selected not as a representative location for the entire Bering Sea, but as the location where trawl fishing was most intensive and most likely to produce measurable local effects. Qualitative inference to other areas will require consideration of similarities in fishing pressure, Pacific cod behavior, and Pacific cod movement.

Localized depletion has not been widely discussed in the scientific literature. It has been proposed as a mechanism primarily in coral and sedentary benthic species (Gorfine et al., 2001; Jamieson, 2001; Harriott, 2003; Smith et al., 2004). Our results demonstrate that the mobility of the target organism must be considered in looking for localized spatial effects on groundfish. If localized depletion is to occur, it will result from the interaction of fishing pressure, fish abundance, and fish movement. To evaluate the impacts of fishery removals on other predators, such as Steller sea lions, the relevant scales of fishing, fish movement, and predator feeding must be clearly defined and understood. For Pacific cod, the very small spatial scale associated with the current regulatory notrawl zones appears to be smaller than the relevant scale of fish movement. Potential fishery effects at broader spatial and temporal scales may be more appropriately addressed by continuing to manage seasonal and spatial dispersal of the Pacific cod harvest.

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