Observations of Seasonal Movement from a Single Tag Release Group of Pacific Cod in the Eastern Bering Sea

Author: Rand, Kimberly M.

Source: Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science, 6(6) : 287-296

Published By: American Fisheries Society

URL: https://doi.org/10.1080/19425120.2014.976680

Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 6:287–296, 2014
American Fisheries Society 2014
ISSN: 1942-5120 online
DOI: 10.1080/19425120.2014.976680

ARTICLE

Observations of Seasonal Movement from a Single Tag Release Group of Pacific Cod in the Eastern Bering Sea

Kimberly M. Rand*
National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Alaska Fisheries Science Center, Resource Ecology and Fishery Management Division, 7600 Sand Point Way Northeast, Seattle, Washington 98115, USA

Peter Munro
National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Alaska Fisheries Science Center, Resource Assessment Conservation and Engineering Division, 7600 Sand Point Way Northeast, Seattle, Washington 98115, USA

Sandra K. Neidetcher
National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Alaska Fisheries Science Center, Resource Ecology and Fishery Management Division, 7600 Sand Point Way Northeast, Seattle, Washington 98115, USA

Daniel G. Nichol
National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Alaska Fisheries Science Center, Resource Assessment Conservation and Engineering Division, 7600 Sand Point Way Northeast, Seattle, Washington 98115, USA

Abstract
The Pacific Cod *Gadus macrocephalus* in the eastern Bering Sea is the target of one of the most lucrative fisheries in Alaska; however, relatively little is known about the movement of Pacific Cod and how this interacts with intense fishing on local spawning aggregations of cod every spring (January–April). This study aimed to draw inferences on Pacific Cod movement using a single tag release group of fish and the fishery as a representative for movement by qualitatively examining both temporal and spatial patterns of tag recoveries. Based on the tag recoveries in this study and past genetic studies, there is evidence that Pacific Cod show both homing tendencies and site fidelity during the spring when large aggregations of cod form to spawn. This study also supports results from an earlier study on Pacific Cod movement in this region and presents new insights into cod movement patterns. The cod in this tag release group were widely distributed across the Bering Sea during the summer and fall months and returned to the vicinity of the release site in the spring, presumably to spawn. Understanding the movement of cod and their interactions with the fishery is essential to the successful management of the Pacific Cod stock.

The Pacific Cod *Gadus macrocephalus* in the eastern Bering Sea has, until 2013, been managed as a single population that has no geographic or temporal substructure (Thompson and Lauth 2012). Assessment models have treated cod harvests from different parts of the Bering Sea, or in different seasons, as being uniformly imposed on the entire population. Tagging studies (Shimada and Kimura 1994) and spawning location studies (Neidetcher et al. 2014) suggest that Pacific

Subject editor: Ana Parma, Centro Nacional Patagonica, Puerto Madryn, Chubut, Argentina

*Corresponding author: kimberly.rand@noaa.gov
Received May 12, 2014; accepted October 7, 2014

Cod undertake seasonal migrations in the Bering Sea, traveling great distances between spawning and nonspawning areas. Such movements and distributions may be highly patterned, resulting in demographic substructures within the greater cod population, which may experience differential fishing mortality. However, possible differences in fishing mortality among components of the population cannot be accounted for because there is insufficient understanding to confirm or define demographic groupings of Pacific Cod.

Knowledge of small- or large-scale fish movement is fundamentally important to managing commercially fished stocks, especially when fisheries are spatially or temporally managed (Cadrin and Secor 2009; Cardinale et al. 2011). Fish population distributions are rarely considered homogenous; however, stock delineations for management purposes are often defined to serve political or administrative functions with no biological basis. Because we often lack the basic understanding of fish movement, the long-term effects of targeted fishing on aggregations of spawning fish or on habitat essential for reproduction and feeding are unknown. Studies have shown potentially adverse results from fishing on spawning aggregations of less migratory species, such as Orange Roughy *Hoplostethus atlanticus* and the Nassau Grouper *Epinephelus striatus* (Sadovy and Domeier 2005). In the short term, catch is reduced and aggregations become more difficult to locate in regions where they previously occurred. In the long term, recovery is slow and the effects of targeting spawning aggregations and spawning habitat remain unclear.

Large-scale fish movement has come under increased study in recent years. Movement of the Atlantic Cod *G. morhua* has been studied extensively. Researchers now believe that overfishing on spawning aggregations may have reduced the reproductive potential of western Atlantic Cod, prompting an increase in research on both movement and life history within the cod population (Rose et al. 2008). Even though western Atlantic Cod are highly migratory, they show fidelity to distinct spawning grounds year after year (Siceloff and Howell 2013). Although, in general, most western Atlantic Cod spawning grounds are now closed to fishing, identification of spawning areas and seasonal migrations have been and continue to be studied (Holland 2003; Siceloff and Howell 2013). In lieu of a complete spawning ground closure, small-scale fishery closures on spawning aggregations have been implemented with some success in the management of the Gulf of Maine Atlantic Cod (Armstrong et al. 2013). Movement of Plaice *Pleuronectes platessa* in the North Sea has been studied with results that have potential implications on management decisions. North Sea Plaice undergo seasonal migrations and show strong homing capabilities with complete spawning site fidelity (Hunter et al. 2003). These behaviors make it challenging to manage Plaice in the North Sea, as a portion of the stock moves out of the management area to spawn (Hunter et al. 2003). Understanding the timing of stock movement and behavior of the fishery is an important consideration as stock analysts develop a more holistic ecosystem-based approach to fisheries management (Cardinale et al. 2011).

In the eastern Bering Sea, few studies have focused on the movement of Pacific Cod, even though it is one of the largest commercial fisheries (by volume) in the United States and the fourth largest in Alaska (NOAA Fisheries 2013). Two prominent studies on Pacific Cod movement are one by Nichol et al. (2013), who investigated vertical movement of cod, and one by Shimada and Kimura (1994), who reported, among other things, that Pacific Cod exhibit seasonal movement patterns that are related, but not limited to, spawning and feeding. A third study by Conners and Munro (2008), although not addressing movement specifically, suggested that movement of Pacific Cod obscures possible localized fishery effects and consideration of large-scale, seasonal movements is integral to defining the nature of a localized fishery effect.

Every spring in the Bering Sea, Pacific Cod form large aggregations at specific locations to spawn and then disperse afterwards (Shimada and Kimura 1994; Neidetcher et al. 2014). However, not until recently have the spawning aggregation processes (e.g., timing, location) and dispersal following spawning been studied directly. Neidetcher et al. (2014) used gross maturity data collected by North Pacific groundfish observers during the cod fishery to document winter spawning aggregations in and near Unimak Pass and along the Bering Sea shelf. Because spawning aggregations are commonly targeted by the fishing industry, the fleet's dispersal by the end of March likely indicates when cod disperse. For example, within this study's time frame in 2005, 40% of the eastern Bering Sea bottom-trawl catch for Pacific Cod occurred between January and the end of March in a concentrated area near Unimak Pass (Thompson and Dorn 2005) (Figure 1). In general, this remains true today. Pacific Cod form dense spawning aggregations from Unimak Pass to Amak Island, Alaska, which have historically been the preferred fishing grounds during the spawning season. Shimada and Kimura (1994) described Pacific Cod movement patterns and attempted to estimate movement rates; however, their data were characterized by opportunistic tag releases that were scattered both temporally and spatially. There were no identifiable or discrete release groups of cod that could be associated with specific time periods or specific geographic strata. Therefore, estimating geographic-specific fishing mortality proved difficult and was not estimated. In addition, their estimates of movement required assumptions that could not be tested. Their data did permit them to support a qualitative understanding that Pacific Cod make large seasonal movements to form spawning aggregations and then make large movements following spawning. Further, they suggested the nature of some of those movements, but the data were not sufficient to allow their estimates of movement to be more than suggestions.

The present study describes observations of synoptic tag recoveries of a single, large, release group of Pacific Cod that were caught, tagged, and released between Unimak Pass and

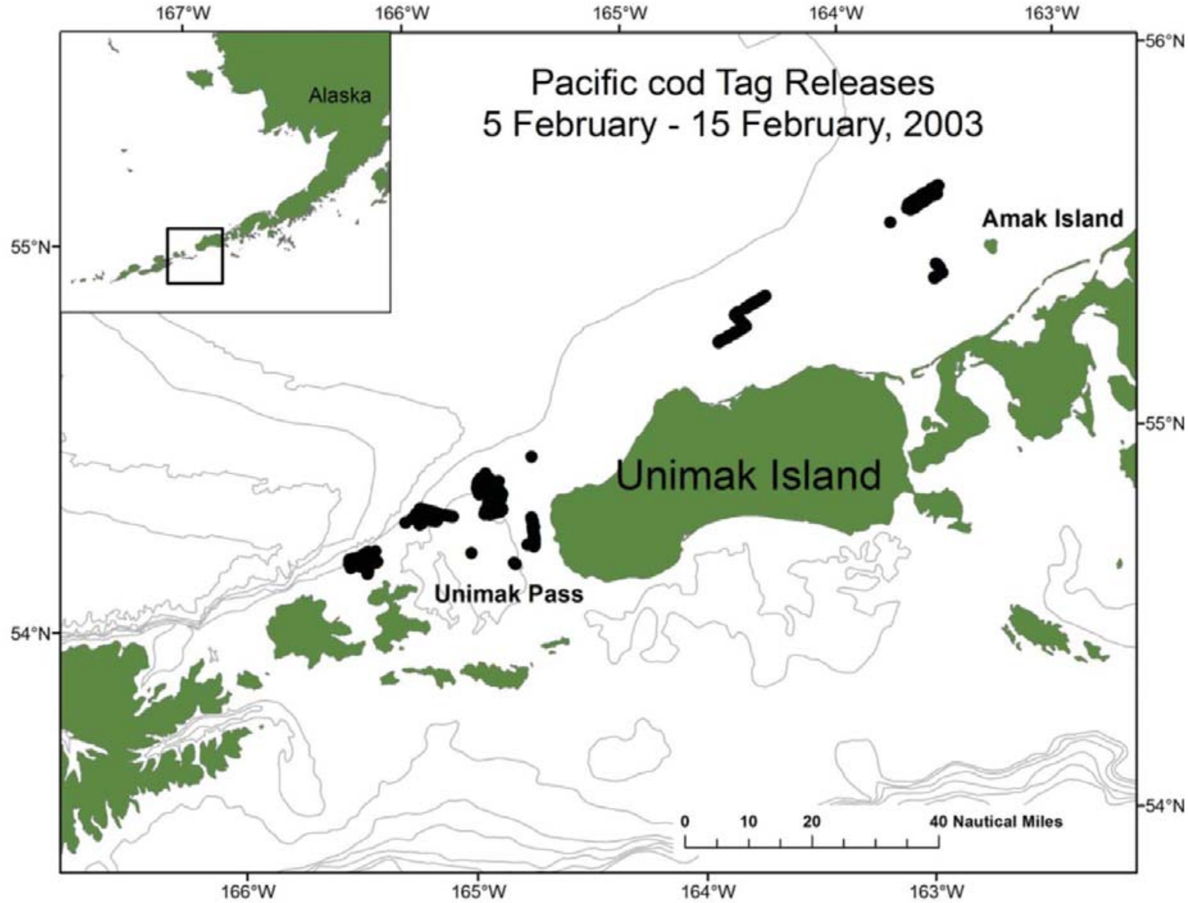

FIGURE 1. Location of Pacific Cod tag releases (black dots) in 2003, Unimak Pass, Alaska.

Amak Island. The tagging period occurred during a time associated with Pacific Cod spawning and in a region known to contain spawning grounds. Therefore, the fish tagged in this study were most likely captured before, during, or after spawning, but no attempt was made to specifically target spawners since this work was ancillary to other research. The primary goal of this study was to suggest patterns of seasonal movement by Pacific Cod over a 1-year time period, based on tracking the recoveries of tags by the commercial fishery. This tag release group was released over a 10-d time period over a span of 200 km, which prevented the estimation of movement rates among some predefined strata (i.e., movement between Unimak Pass and Amak Island).

Commercial fishing provided tag recoveries that were synoptic seasonally, though not all areas of the eastern Bering Sea were covered by all fisheries. The commercial fishing fleet for Pacific Cod in the Bering Sea consists of bottom trawlers (both catcher boats and factory processors) and pot and longline vessels. In general, bottom trawling for Pacific Cod occurs in the spring when cod are aggregated for spawning. Pot fishing often occurs just after fishing for opilio crab (snow crab) *Chionoecetes opilio* in the spring and generally within 100 km of Unimak Pass, and it is often limited by a 3-d trip limit because of concerns for product freshness and fuel consumption. Longline fishing occurs across the Bering Sea from Unimak Pass to as far north as the ice edge, and the fishery is generally active year round. To date, the only knowledge of Pacific Cod distribution across the entire Bering Sea comes from the annual bottom-trawl survey conducted by the National Marine Fisheries Service (NMFS), Alaska Fishery Science Center (AFSC) that occurs every year during the summer months. Therefore, in addition to qualitatively examining movement patterns over the course of 1 year, this paper discusses possible underlying mechanisms of movement and shows how these results may guide future Pacific Cod tagging research efforts.

METHODS

Tag releases and recoveries.—Pacific Cod were tagged and released during a dedicated research cruise near Unimak Pass, Alaska, from February 5 to 15, 2003 (Figure 1). Operations were conducted aboard the FV *Pacific Star*, a 55-m (182 ft) vessel configured to launch and retrieve pot gear. The fish were captured in baited pots deployed on the seafloor. Approximately 40 pots were set in a string and were soaked for 12 h or less to attract fish, and all pots were retrieved within 12 h by the crew at the slowest possible vertical speed to reduce barotrauma to the fish. A single group of 3,442 Pacific Cod were captured, tagged, and released during the 10-d period. However, this analysis only used the tags recovered during 2003 and early 2004 in an effort to capture one complete seasonal cycle of cod movement.

We defined five recovery periods: spring 2003 (February through April), summer 2003 (May through July), fall 2003 (August through October), winter 2003–2004 (November through January), and spring 2004 (February through April). These seasons correspond to identifiable periods of commercial fishing activity as well as to different seasonal periods and to cod spawning and nonspawning periods.

This study limited consideration of tags recovered to freezer longliners and freezer bottom trawlers because these two fleets provided widest coverage of both seasons and areas. The tag recoveries and total cod catches from these two fleets were combined. Commercial catch data in each of each season defined above were provided by North Pacific Groundfish Observer Program, Alaska Fisheries Science Center, Seattle, Washington. Tag recoveries from fisheries that were narrowly focused in time and space (catcher only trawlers and pots) were not used due to the spatial limitations of the fishery (e.g., only fished within 50 km of the release site or port).

A total of 693 tag recoveries were used: 360 tags were recovered during spring 2003, 69 during summer 2003, 121 during fall 2003, 59 during winter 2003–2004, and 84 during spring 2004 (Table 1). The average length of a tagged Pacific Cod was 64 cm (range, 40–100 cm), and the length at 50% maturity for female Pacific Cod in the Bering Sea is 58 cm (Stark 2007). Based on this fact, we assumed that most of the tagged cod in this study were reproductively mature. For ease of discussion, tag recoveries were also characterized as either less than 100 km from the release site or greater than 100 km from the release site (Table 1).

Tag recovery rates and geographic distribution.—The tags recovered were spatially organized by the same 20 × 20-km grid that defines the survey design of the NMFS bottom-trawl surveys conducted annually during summer months by the AFSC (Lauth and Nichol 2013). Locations of commercial catches were also assigned to the NMFS bottom-trawl 20 × 20-km grid. For each grid cell, in each season, the total number of tagged fish recovered was divided by the total number of cod captured by the two fleets (freezer trawlers and freezer longliners). In the tables, plots, maps, and discussion that follow, we express this standardized tag recovery rate as the number of recovered tags per 10,000 cod captured within the 20 × 20-km grid cell. Commercial Pacific Cod catches were taken as proxies for cod population distributions in all the seasonal recovery periods.

For the summer 2003 recovery period, an alternative observation of Pacific Cod distribution was provided by the NMFS bottom-trawl survey (Acuna and Kotwicki 2004). In addition, temperatures collected during the 2003 and 2004 surveys were examined to assess whether differing annual temperatures may have had some influence on cod distributions during those 2 years. Because there was not a major shift in average bottom temperatures between the summers of 2003 and 2004, no further analysis was done (S. Kotwicki, AFSC, personal communication).

Patterns of Pacific Cod movement were qualitatively discerned by using maps that showed geographic distributions of capture rates by season. The distance (km) between the tag release and tag recovery locations were calculated for each recovered tag as a linear distance using ArcGIS 10.0 software (ESRI). A nonparametric Kolmogorov–Smirnov test (Zar 1999) was used to determine whether the cumulative distribution of the distance (km) between the release and recovery locations was different between the fall 2003 and spring 2004 time periods. A smaller distance between tag release and recovery during spring 2004 compared with fall 2003 would indicate movement towards the release site, presumably for spawning in spring. In addition, the fall 2003 period is considered the most representative time period for Pacific Cod distribution during a nonspawning season due to a strong fishing effort and therefore a large number of tag recoveries.

TABLE 1. Numbers (and percent) of tagged Pacific Cod in the eastern Bering Sea recovered by season and spatial category.

Recovery or spatial category	Spring 2003	Summer 2003	Fall 2003	Winter 2003–2004	Spring 2004
All recoveries (number of tagged cod)	360	69	121	59	84
Recoveries < 100 km from release site	353 (98%)	62 (90%)	68 (56%)	36 (61%)	71 (85%)
Recoveries > 100 km from release site	7 (2%)	7 (10%)	53 (44%)	23 (39%)	13 (15%)
Mean distance (km) between release and recovery (<100 km)	58	26	42	79	80
Mean distance (km) between release and recovery (>100 km)	424	425	403	471	290
Mean distance (km) between release and recovery (all)	65	66	201	232	112

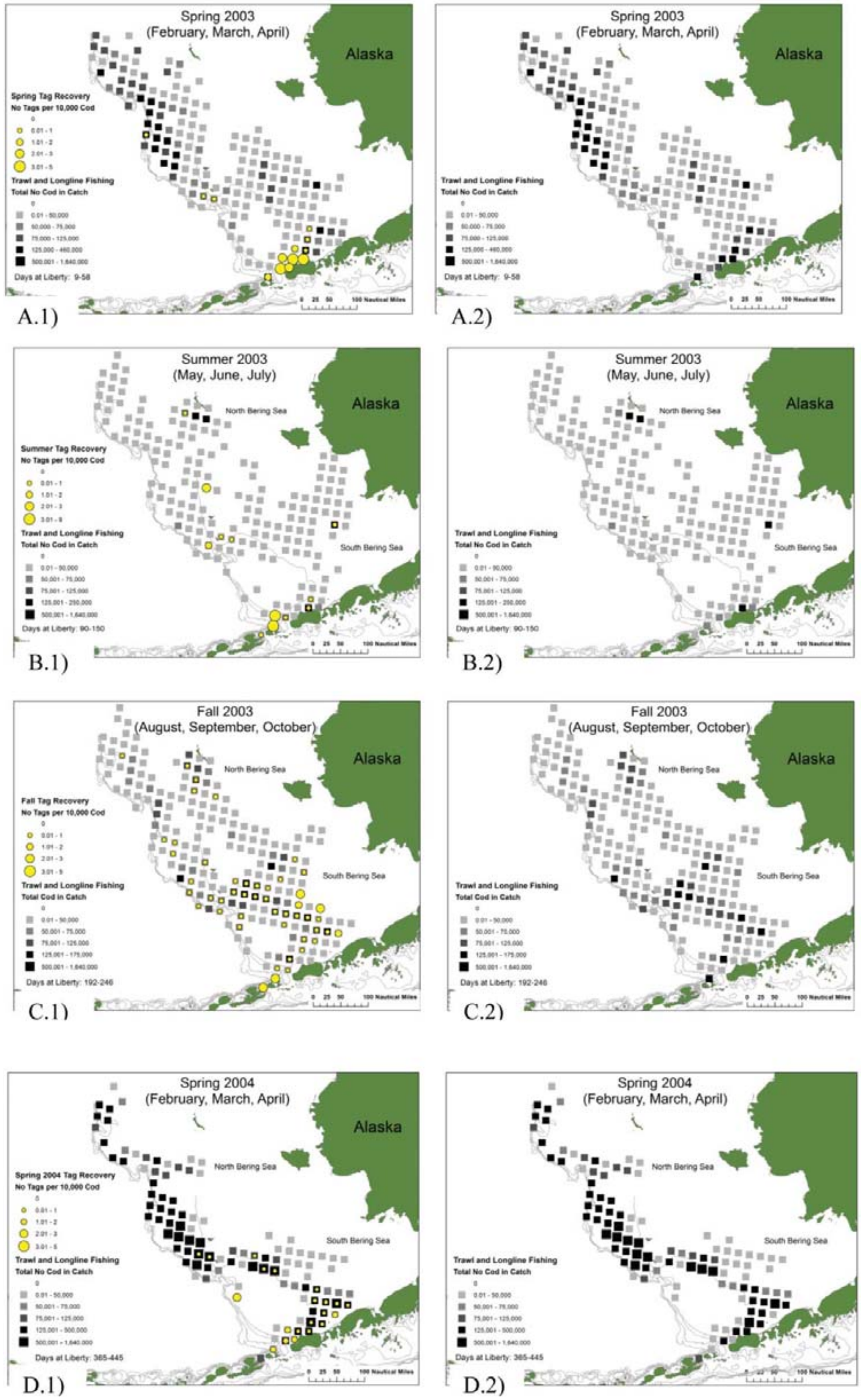

FIGURE 2. Pacific Cod tag recovery rates calculated by the total number of tags (yellow circles) per 10,000 cod captured (gray-scale grid cells), by season for 1 year. Each grid cell measures 20 × 20 km. Panels A.1, B.1, C.1, and D.1 are tag recovery rates over (yellow circles) total cod catch. Panels A.2, B.2, C.2, and D.2 illustrate only total cod catch.

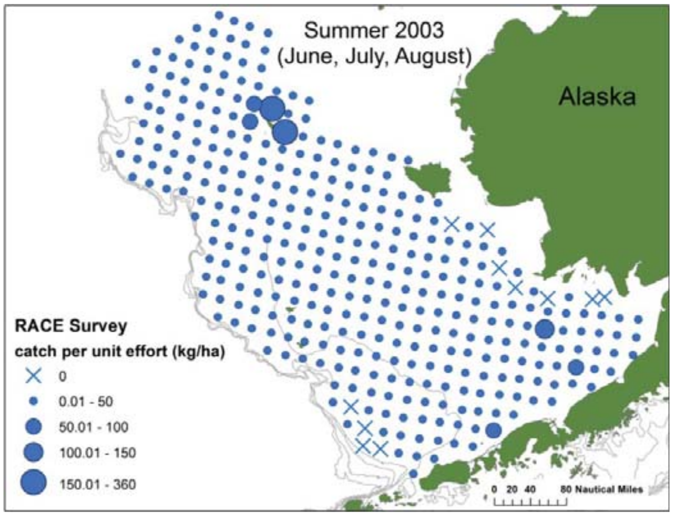

FIGURE 3. Pacific Cod CPUE (gray-scale grid cells) from the annual NMFS bottom-trawl survey, summer 2003. Each grid cell is 20 × 20 km and contains one station that is sampled.

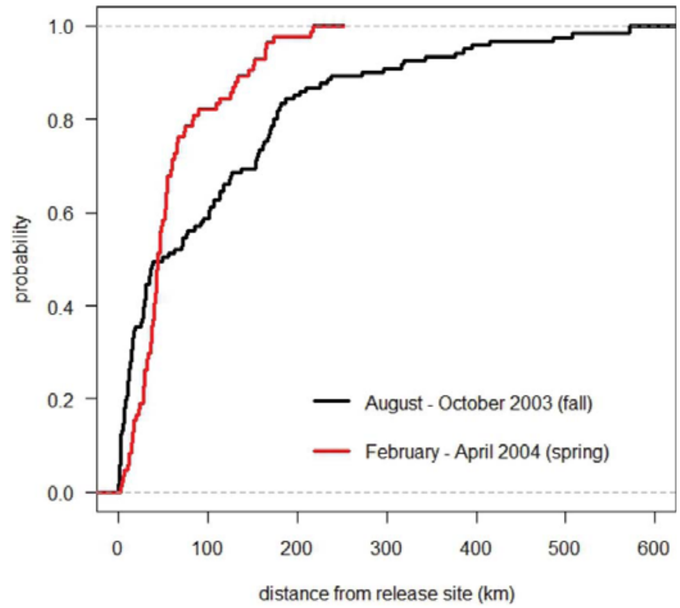

FIGURE 4. Cumulative probability distributions for the distance between Pacific Cod tag release and tag recovery locations for the fall 2003 and spring 2004 time periods. The curves represent the probability that 60% of the tags were recovered <100 km from the release site in the fall 2003 time period (black line) compared with the probability that over 80% of the tags were recovered <100 km from the release site in the spring 2004 time period (red line).

RESULTS

The geographic distributions of total Pacific Cod catches by the commercial fishery were overlaid by tag recovery rates for the four time periods (panels A.1, B.1, C.1, and D.1 in Figure 2); panels A.2, B.2, C.2, and and D.2 in Figure 2 show only the total cod catch and not the tag recoveries. During spring 2003, tags were primarily recovered within a short distance from the release site, and a few tags were recovered farther north along the Bering Sea shelf (A.1 in Figure 2). Several tags were recovered within a few days of the release, offering little chance for the cod to recuperate from the tagging process and mix into the population. During summer 2003, the cod catch was low, fewer tags were recovered, and no clear pattern in the recoveries was observed (B.1 in Figure 2). During fall 2003, tag recoveries were widely dispersed across the Bering Sea shelf, from the shelf break to well inside the 100-m bathymetric line and as far north as St. Matthew Island (C.1 in Figure 2). In spring 2004, most tags were recovered in the southern portion of the Bering Sea, north of Unimak Island and west of Amak Island, despite high cod catches along the entire shelf edge (D.1 and D.2 in Figure 2). Although most tags were recovered within 100 km of the release site during spring 2004, a few were caught at distances greater than 100 km from the release site (Table 1).

Results of the NMFS bottom-trawl survey indicated that during summer 2003, Pacific Cod were widely distributed at low densities, with few concentrations having a CPUE of greater than 50 kg/ha reported. The two highest observations came from near St. Matthews Island in the north, where CPUE ranged between 150 and 320 kg/ha (Figure 3). This result correlated with high concentrations of cod observed among some of the commercial fishing catches during the same time period (summer 2003) (B.2 in Figure 2).

Based on tag recoveries, Pacific Cod were found to have different geographic distributions during fall 2003 than in spring 2004 (Figure 4). During fall 2003, 56% of the tagged cod were more likely to be found less than 100 km from the release site (Table 1). During spring 2004, more than 80% of the cod were captured less than 100 km from the release site (Table 1). This finding is consistent with the Kolmogorov–Smirnov test to test the null hypothesis that distances between release and recapture locations come from a single probability distribution for tags recovered in both fall 2003 and spring 2004. The test produced a significant result ($P = 0.003$), allowing the null hypothesis to be rejected and the alternate hypothesis to be supported; the alternative hypothesis states that the two sets of distances followed different probability distributions, presumably because cod with tags recovered in spring 2004 were closer to the release site.

DISCUSSION

Interpretations of these data are predicted on the assumption that all the tagged Pacific Cod belonged to a single release group. What we call a single release group could be divided into three release groups (subsite): one east of Unimak Pass, one north of Unimak Island, and one to the north of Amak Island (Figure 1). These locations span a distance of approximately 140 km. Unfortunately we were unable to release a sufficient number of cod at each subsite to allow enough

TABLE 2. Categories of tags recovered from Pacific Cod with summary explanations.

Season	Recovered < 100 km from release site	Recovered > 100 km from release site
Spring 2003 (first spawning season; February, March, April)	Recovery rate artificially high because tagged fish were released into an active fishery.	Recoveries indicate cod traveled great distances in a short time period.
Summer 2003 (first nonspawning season; May, June, July)	Recoveries of fish that were never going to leave the area and fish that had not yet had a chance to leave.	Recoveries of fish that left the area of spawning aggregation to feed (or do other behaviors).
Fall 2003 (second nonspawning season; August, September, October)	Recoveries of fish that were never going to leave the area and fish that may have left and returned.	Recoveries of fish that left the area of spawning aggregation to feed (or do other behaviors).
Winter 2003–2004 (third nonspawning season; November, December, January)	Insufficient data to draw inference.	Insufficient data to draw inference.
Spring 2004 (second spawning season; February, March, April)	Recoveries of fish that never left the release site and those that left the release site and then returned to spawn.	Recoveries of fish that (1) were going to spawn in a different area than where originally captured and tagged, (2) were going to spawn in the area where originally captured and tagged but had not yet had a chance to return, (3) had spawned in the same location as where originally captured and tagged and then had moved away.

recoveries to discriminate among such fine divisions of release. The Bering Sea is large and the fisheries in which tagged cod were recovered are widespread and large in volume. A significant number of tag releases, well beyond those released in this study, would be required to allow anything other than coarse resolution in the recovery data. Even though our tag recovery data are unable to show spawning-site fidelity on a finer spatial scale, we cannot conclude that subpopulations of Pacific Cod do not exist within our study area.

There are limitations in drawing inferences about the movement of Pacific Cod from one tagrelease event, and there are limitations in using the fishing fleet as the only vehicle for tag recoveries. The most obvious limitation is that the fleet goes where the fish go, and it stands to reason that the fishing fleet will go to those areas considered most profitable (i.e., least effort with the highest payout) for catching fish. This is why trawl fishing on spawning cod aggregations is most profitable during January to March. After March, directed trawl fishing for cod decreases, both from allocation fulfillment and decreased cod aggregations, whereas longline fishing for Pacific Cod remains steady along the shelf throughout most of the year. Table 2 provides a summary of explanations for the categories of outcomes possible for recovered tags. At the bottom of the right-hand column of the table (i.e., as distance between release and recovery sites increases and time between release and recovery increases) it becomes apparent that movement-based explanations increase for how a tag came to be in the location where it was recovered.

In Table 2 we make no inference about the movement of Pacific Cod or their distribution for winter 2003–2004. Of the 59 tags recovered in that season, 40 were recovered very late, from mid to late January. This brief period may be better categorized as belonging to the 2004 spawning season, as it seemed a distinct possibility that the tagged cod recovered in late January may have been transitioning back to Unimak Pass for spawning. This concentration in time of recovered tags could also be explained by increased fishing effort, as the fishery opened in mid-January. Early fishing in January tends to concentrate on known spawning areas close to Dutch Harbor and may serve poorly as a proxy for overall cod distribution. The remaining 19 tags that were recovered during winter 2003–2004 were caught in November and December, a period for which fishing effort was fairly low. Due to this paucity of information, tags recovered during winter 2003–2004 are not discussed further.

Despite these limitations to inferences made on tag recoveries by the fishing fleet, we do have some supporting evidence that the fishing fleet as a proxy for Pacific Cod distribution is not entirely biased. For example, during summer 2003, the fishing effort for cod in the Bering Sea was small; however, there were a few locations where a higher cod catch coincided with a greater CPUE of cod during the annual NMFS bottom-trawl survey.

If Pacific Cod movements were entirely random, we would expect the rate of tag recoveries to coincide with the catch rates of the fishing fleet, regardless of season. As supported statistically, there were a greater number of recoveries less than 100 km from the release site in spring 2004 than during fall 2003. If cod were distributed randomly, we would expect that tags would be recaptured farther away from the release site during spring 2004 because fishing effort was highest at a location greater than 100 km from the release site during this time period. Considering both the distance from tag release to tag recovery and the time between those two events, several types of seasonal cod movement can be hypothesized (Table 2). In the spring, cod form large dense aggregations in Unimak Pass that last from January to sometime late in March. After the cod spawn, tag recoveries suggest that a portion of the cod population disperses onto the Bering Sea shelf during summer for presumed feeding while another portion remains near the site of release (Table 2). Through the fall (August through October), many cod appear to remain dispersed while others remain near the release site. During the winter months, cod begin to move back to their spawning site (sometime in January) or remain to form large aggregations. Regardless of the season, some tagged cod were recovered near the original release site (panels A through D in Figure 2) suggesting that a portion of the population never leaves the area.

Based on the tag recovery data, there appear to be two different distributions of Pacific Cod: a more dense concentration during the spring and a more dispersed distribution during the fall. These distributions appeared stable over a period of months and seem consistent with expectations of dispersal during feeding periods and concentration during a period of spawning aggregation, as suggested by Shimada and Kimura (1994). There may have been transitional movement during the summer months, but a clear pattern could not be discerned owing to low fishing effort and the consequent low numbers of recoveries. The NMFS bottom-trawl survey does suggest that the summer distribution of Pacific Cod is greatly dispersed. Support for the notion that cod concentrate into spawning aggregations during the spring can be seen in the intense targeting by the trawl fishing fleet. This is realized in high catch rates in areas along the outer shelf and near the Pribilof Islands and Unimak Island during the spring spawning season.

Previous tagging studies suggest that Pacific Cod spawn in large aggregations over small spatial scales on the Bering Sea side of Unimak Pass, southwest of the Pribilof Islands, and in areas along the Bering Sea shelf edge (Shimada and Kimura 1994). Spawning and prespawning aggregations were identified by Russian trawl surveys along the northern Bering Sea outer shelf, extending from Russia to U.S. waters, in addition to areas in and around the Pribilof Islands and near Unimak Pass (Stepanenko 1995). Recently, Neidetcher et al. (2014) reported Pacific Cod spawning along the Bering Sea outer shelf (100–200-m depths) between the Pribilof Islands and the slope. Spawning cod were also found southeast of the Pribilof Islands along the 100-m isobath and along the north side of Unimak Island inside of the 100-m isobath.

Although our tag recovery observations in this study suggest movement patterns related to spawning aggregations, the mechanism for site selection by Pacific Cod for spawning remains unknown. It is possible that ecological conditions beneficial for early life survival, such as high concentration of prey (Leggett 1985) and the dispersal potential of eggs or larvae (Cushing 1969), drive the location and timing of spawning. A successful strategy for Pacific Cod larvae may involve maximizing the probability of encountering favorable feeding conditions and favorable currents that allow larvae to be transported to suitable nursery areas in the weeks following spawning, as suggested for Atlantic Cod (Brander 1994).

Research based on mark–recapture studies (Ruzzante et al. 1996; Morris and Green 2002) and genetics (Ruzzante et al. 1996) has reported both resident and transient populations of Atlantic Cod off the coast of Newfoundland. The inshore population of Atlantic Cod was considered resident and the offshore population was considered transient; this supports a high degree of spawning-site fidelity even though the two populations intermingle at certain times of the year (Ruzzante et al. 1996).

As noted earlier, Pacific Cod from our single release group were caught near the release area throughout the year. Persistent tag recoveries close to the release area suggests that some Pacific Cod also maintain a year-round residency, though we cannot be certain that some fish recovered with tags did not leave and come back. In contrast, other cod were found to be highly migratory based on the increased level of tag dispersion observed in summer and fall. That this dispersion decreased the following spring, coupled with more concentrated tag recoveries near Unimak Pass during spring, lends support to the idea that some migratory Pacific Cod returned to the tag release area, presumably for spawning. Such round-trip migrations indicative of spawning-site fidelity were also observed among Pacific Cod tagged with timed depth-recording tags (Nichol et. al 2013), where some individuals migrated from the Unimak area (~70 m) in spring to shallower water (~30–40 m) in summer–fall then back to the Unimak area in spring (D. G. Nichol, personal observation). These two observations of dispersion and return to the release site support spawning-site fidelity. However, further inference to site fidelity in this tag release group is not plausible for two reasons. We cannot assume that the tag release site and the spawning site are the same because we cannot be certain that we tagged spawning fish. Though we conducted operations in the same broad region and same general time frame as cod spawning in the southern Bering Sea, we cannot assign tagged fish to specific spawning events. For example, it is entirely possible that cod released at Unimak Pass were on their way to Amak Island to spawn, a distance of approximately 140 km. In addition, the assumption that a recovery location was also a spawning location is even harder to defend because the recovery time period was broad (3 months) and the gross maturity of the recovered fish was not estimated.

Discerning movement patterns of Pacific Cod in the Bering Sea is increasingly important as evidence of a spatial stock structure emerges. Shimada and Kimura (1994) concluded that emigration and immigration between the Bering Sea and Gulf of Alaska were on a scale large enough to assume a genetically homogeneous population of Pacific Cod. This result was supported by Grant et al. (1987). However, advances in molecular techniques have offered new insight into the population structure of cod. There is now strong evidence that Pacific Cod in the Aleutian Islands are genetically distinct from those in the Bering Sea (Cunningham et al. 2009; Spies 2012). Further, there is evidence of genetic differentiation between the north (Pribilof Islands) and south (Unimak Pass) Bering Sea cod (Spies 2012). This genetic differentiation is consistent with our observation of spawning-site fidelity. The genetic evidence suggests greater spawning-site fidelity than originally speculated (Shimada and Kimura 1994) since it takes several generations of very little exchange at a spawning site to detect genetic differentiation.

Consideration of Pacific Cod movement in the eastern Bering Sea is important to stock assessment. Two critical reasons for this are to (1) better estimate model parameters and (2) better understand the role of cod at the ecosystem level as stock assessment evolves toward ecosystem management as well as single-species management. The inclusion of spatial components in management strategies would improve our understanding of cod movement, and thus parameters in stock assessment models may also be improved. Mark–recapture data from a well-designed movement estimation experiment would, as a by-product, allow parameters such as natural mortality or size-dependent selectivity to be estimated.

Movement estimates are not generally incorporated into stock assessments currently conducted at the AFSC. There are 22 federally managed stocks or stock assemblages in the eastern Bering Sea. Seasonal movement is considered only when area-specific catch allocations are made (Jim Ianelli, AFSC, personal communication). Such allocations are typically based on survey data and, in a few instances, information on movement rates as determined from tagging (e.g., Pacific Cod and Sablefish *Anoplopoma fimbria*) (Hanselman et al. 2012; Thompson and Lauth 2012). Specifically, the Pacific Cod stock assessment considers availability and selectivity from the NMFS bottom-trawl survey in its estimates of catchability and selectivity (Nichol et al. 2007). For lack of adequate data, movement of cod within the Bering Sea is acknowledged but not formally incorporated into the models, and possible movement between the Bering Sea and Aleutian Islands or the Gulf of Alaska is assumed to be negligible.

In addition to single-species stock assessment, estimating Pacific Cod movement within the framework of life history strategies can further identify the role of cod in the ecosystem. The importance of understanding Pacific Cod movement patterns is pronounced in the debate over impacts of commercial fishing on other predators, including the endangered Steller sea lion *Eumetopius jubatus* (NRC 2003). While the overall rate of Pacific Cod harvest from the Bering Sea is believed to be low enough not to cause reductions in sea lion foraging success, concerns have been raised about transient local effects on prey density in the immediate vicinity of sea lion rookeries (Ferrero and Fritz 1994). A recent study showed an increase in the frequency of occurrence of Pacific Cod in the diets of Steller sea lions between the eastern Aleutian Islands and western Gulf of Alaska over the last decade, especially in the winter diets (Sinclair et al. 2013). The effect of fishery removals on local prey densities cannot be evaluated without some knowledge of the temporal and spatial scales of fish movement. The large movements of tagged Pacific Cod seen in this study indicate that, while cod may form dense, small-scale, spatial aggregations during the spawning season, not all cod disperse across the Bering Sea or remain in the spawning area.

Proper estimation of seasonal movement of Pacific Cod in the Bering Sea seems both important but lacking. Simple mark–recapture techniques may be applicable to this species in this large marine ecosystem, because the assumption of a closed population may well be defensible. A well-designed mark–recapture study will require properly defined geographic strata, properly defined seasons, seasonally synoptic releases of tag groups throughout all strata, and seasonally synoptic recovery events (Anganuzzi et al. 1994). Definitions of "proper" strata and seasons must incorporate biological processes (e.g., spawning, foraging, and moving) and be tractable under logistical constraints on research activities. Patterns of seasonal movement would be integral to defining strata and seasons. Currently, Pacific Cod are considered to be successfully managed as a single stock in the Bering Sea, but it is also true that we know little about many aspects of cod life history, including movement. Our research suggests that the incorporation of seasonal distribution, seasonal movement patterns, biological processes, and the interaction with the local, intense fishery on a population of spawning fish is important and should be considered in the management of this species.

ACKNOWLEDGMENTS

We thank the North Pacific Research Board for providing the funding for this research paper (NPRB Project 815, Publication 508). We thank Stan Kotwicki at the AFSC for providing input on bottom temperatures in the Bering Sea. We also thank the crew members of the FV *Pacific Star* for providing the platform for the tag release of Pacific Cod in the Bering Sea. Thanks are extended to the AFSC scientists, including Terry Sample and Olav Ormseth, who participated in the cruise. Finally, thank you to the three AFSC reviewers, in particular Libby Logerwell, the Fisheries Interaction Team leader. The findings and conclusions in the paper are those of the authors and do not necessarily represent the views of the

NMFS, NOAA. Reference to trade names does not imply endorsement by the NMFS.

REFERENCES

Acuna, E., and S. Kotwicki. 2004. 2003 Bottom trawl survey of the eastern Bering Sea Continental Shelf. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Alaska Fisheries Science Center, processed report 2004-02, Seattle.

Anganuzzi, A., R. Hilborn, and J. R. Skalski. 1994. Estimation of size selectivity and movement rates from mark-recovery data. Canadian Journal of Fisheries and Aquatic Sciences 51:734–742.

Armstrong, M. P., M. J. Dean, W. S. Hoffman, D. R. Zemeckis, T. A. Nies, D. E. Pierce, P. J. Diodati, and D. J. McKiernan. 2013. The application of small scale fishery closures to protect Atlantic Cod spawning aggregation in the inshore Gulf of Maine. Fisheries Research 141:62–69.

Brander, K. M. 1994. Spawning and life history information for North Atlantic cod stocks. ICES (International council for the Exploration of the Sea) Cooperative Research Report 205.

Cadrin, S. X., and D. H. Secor. 2009. Accounting for spatial population structure in stock assessment: past, present and future. Pages 405–426 *in* R. J. Beamish and B. J. Rothschild, editors. The future of fisheries science in North America. Springer-Verlag, New York.

Cardinale, M., V. Bartolino, M. Llope, L. Maiorano, M. Sköld, and J. Hagberg. 2011. Historical spatial baselines in conservation and management of marine resources. Fish and Fisheries 12:289–298.

Conners, M. E., and P. Munro. 2008. Effects of commercial fishing on local abundance of Pacific Cod (*Gadus macrocephalus*) in the Bering Sea. U.S. National Marine Fisheries Service Fishery Bulletin 106:281–292.

Cunningham, K. M., M. F. Canino, I. B. Spies, and L. Hauser. 2009. Genetic isolation by distance and localized fjord population structure in Pacific Cod (*Gadus macrocephalus*): limited effective dispersal in the northeastern Pacific Ocean. Canadian Journal of Fisheries and Aquatic Sciences 66:153–166.

Cushing, D. H. 1969. The regularity of spawning season of some fishes. ICES Journal of Marine Science 33:81–97.

Ferrero, R. C., and L. W. Fritz. 1994. Comparisons of Walleye Pollock, *Theragra chalcogramma*, harvest to Steller sea lion, *Eumetopias jubatus*, abundance in the Bering Sea and Gulf of Alaska. NOAA Technical Memorandum NMFS-AFSC-43.

Grant, W. S., C. I. Zhang, T. Kobayashi, and G. Stahl. 1987. Lack of genetic stock discretion in Pacific Cod (*Gadus macrocephalus*). Canadian Journal of Fisheries and Aquatic Sciences 44:490–498.

Hanselman, D. H., C. R. Lunsford, and C. J. Rodgeveller. 2012. Assessment of the Sablefish stock Alaska. Pages 509–618 *in* Stock assessment and fishery evaluation report for the groundfish fisheries of the Gulf of Alaska and Bering Sea/Aleutian Islands area. North Pacific Fishery Management Council, Bering Sea and Aleutian Islands Stock Assessment and Fishery Evaluation, Anchorage, Alaska.

Holland, D. S. 2003. Integrating spatial management measures into traditional fishery management systems: the case of the Georges Bank multispecies groundfish fishery. ICES Journal of Marine Science 60:915–929.

Hunter, E., J. D. Metcalfe, and J. D. Reynolds. 2003. Migration route and spawning area fidelity by North Sea plaice. Proceedings of the Royal Society London B 270:2097–2013.

Lauth, R. R., and D. G. Nichol. 2013. Results of the 2012 eastern Bering Sea continental shelf bottom trawl survey of groundfish and invertebrate resources. NOAA Technical Memorandum NMFS-AFSC-256.

Leggett, W. C. 1985. The role of migrations in the life history evolution of fish. Contributions in Marine Science 27(Supplement):277–295.

Morris, C. J., and J. M. Green. 2002. Biological characteristics of a resident population of Atlantic Cod (*Gadus morhua* L.) in southern Labrador. ICES Journal of Marine Science 59:666–678.

Neidetcher, S. K., T. P. Hurst, L. Ciannelli, and E. A. Logerwell. 2014. Spawning phenology and geography of Aleutian Islands and eastern Bering Sea Pacific Cod (*Gadus macrocephalus*). Deep Sea Research Part II Topical Studies in Oceanography 109:204–214.

Nichol, D. G., T. Honkalehto, and G. G. Thompson. 2007. Proximity of Pacific Cod to the sea floor: using archival tags to estimate fish availability to research bottom trawls. Fisheries Research 86:129–135.

Nichol, D. G., S. Kotwicki, and M. Zimmerman. 2013. Diel vertical migration of adult Pacific Cod *Gadus macrocephalus* in Alaska. Journal of Fish Biology 83:170–189.

NOAA (National Oceanic and Atmospheric Administration) Fisheries. 2013. Fisheries of the United States 2013: statistical highlights. NOAA Fisheries, Silver Spring, Maryland. Available: http://www.st.nmfs.noaa.gov/Assets/commercial/fus/fus13/FUS2013.pdf. (November 2014).

NRC (National Research Council). 2003. The decline of the Steller sea lion in Alaska waters: untangling food webs and fishing nets. National Research Council, Washington, D.C.

Rose, G. A., I. R. Bradbury, B. deYoung, S. B. Fudge, G. L. Lawson, L. G. S. Mello, D. Robichaud, G. Sherwood, P. V. R. Snelgrove, and M. J. S. Windle. 2008. Rebuilding Atlantic Cod: lessons from a spawning ground in coastal Newfoundland. Pages 197–219 *in* G. H. Kruse, K. Drinkwater, J. N. Ianelli, J. S. Link, D. L. Stram, V. Wespestad, and D. Woodby, editors. Proceedings of a symposium on the resiliency of gadid stocks to fishing and climate change. University of Alaska Fairbanks, Alaska Sea Grant College Program, AK-SG-08-01, Fairbanks.

Ruzzante, D. E., C. T. Taggart, D. Cook, and S. Goddard. 1996. Genetic differences between inshore and offshore Atlantic Cod (*Gadus morhua*) off Newfoundland: mircorsatellite DNA variation and antifreeze level. Canadian Journal of Fisheries and Aquatic Sciences 53:634–645.

Sadovy, Y., and M. Domeier. 2005. Are aggregation-fisheries sustainable? Reef fish fisheries as a case study. Coral Reefs 24:254–262.

Shimada, A. M., and D. K. Kimura. 1994. Seasonal movements of Pacific Cod, *Gadus macrocephalus*, in the eastern Bering Sea and adjacent waters based on tag-recapture data. U.S. National Marine Fisheries Service Fishery Bulletin 92:800–816.

Siceloff, L., and W. H. Howell. 2013. Fine-scale temporal and spatial distributions of Atlantic Cod (*Gadus morhua*) on a western Gulf of Maine spawning ground. Fisheries Research 141:31–43.

Sinclair, E. H., D. S. Johnson, T. K. Zeppelin, and T. S. Gelatt. 2013. Decadal variation in the diet of western stock Steller sea lions (*Eumetopias jubatus*). NOAA Technical Memorandum NMFS AFSC-248.

Spies, I. 2012. Landscape genetics reveals population subdivision in Bering Sea and Aleutian Islands Pacific Cod. Transactions of the American Fisheries Society 141:1557–1573.

Stark, J. W. 2007. Geographic and seasonal variations in maturation and growth of female Pacific Cod (*Gadus macrocephalus*) in the Gulf of Alaska and Bering Sea. U.S. National Marine Fisheries Service Fishery Bulletin 105:396–407.

Stepanenko, M. K. 1995. Distribution, behavior and abundance of Pacific Cod, *Gadus macrocephalus*, in the Bering Sea. Journal of Ichthyology 35:17–27.

Thompson, G. G., and M. W. Dorn. 2005. Assessment of the Pacific Cod stock in the eastern Bering Sea and Aleutian Islands area. Pages 219–330 *in* Stock assessment and fishery evaluation report for the groundfish fisheries of the Gulf of Alaska and Bering Sea/Aleutian Islands area. North Pacific Fishery Management Council, Bering Sea and Aleutian Islands Stock Assessment and Fishery Evaluation, Anchorage, Alaska.

Thompson, G. G., and R. Lauth. 2012. Assessment of the Pacific Cod stock in the eastern Bering Sea and Aleutian Islands area. Pages 245–544 *in* Stock assessment and fishery evaluation report for the groundfish fisheries of the Gulf of Alaska and Bering Sea/Aleutian Islands. North Pacific Fishery Management Council, Bering Sea and Aleutian Islands Stock Assessment and Fishery Evaluation, Anchorage, Alaska.

Zar, J. H. 1999. Biostatistical analysis. Prentice-Hall, Englewood Cliffs, New Jersey.