Identifying Seasonal Spatial Scale for the Ecological Analysis of Herring and Other Forage Fish in Prince William Sound, Alaska

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Extended Abstract

Recently there has been increasing interest in the distribution, abundance, and ecology of forage fish populations because of the crucial role they play in nearshore and pelagic ecosystems. However, relatively little is known about the ecology of forage fishes in Alaska. From 1995 to 1997 extensive ecosystem studies were conducted in response to the *Exxon Valdez* oil spill in 1989. Monthly broadscale aerial surveys were included in those studies for the purpose of determining distribution and abundance of juvenile Pacific herring (*Clupea pallasi*) and other surface-schooling forage fishes (Brown and Norcross 1997). Many other types of physical and biological data were also available for the same area and dates that could be used for ecological analyses of forage fishes. In order to proceed with hypothesis-driven science, we recognized that basic descriptive life history parameters and the spatial overlap with other ecological parameters needed to be documented first. Therefore, a general research goal

was established to perform an ecological analysis of forage fish distribution and abundance using the appropriate spatial scale. The research objective for this effort was to identify and define the appropriate seasonal spatial scale. In order to address the objective we used geographic information system (GIS) methodology since it is a powerful tool for examining spatial processes. Because of the profusion of data available we focused on Prince William Sound (PWS), situated at the northern boundary of the Gulf of Alaska in southcentral Alaska.

A critical starting place for ecological analyses is to define the spatial scale at which processes affect the species of interest. Fish affected mainly by ocean conditions and zooplankton (bottom forced), such as herring, may be affected by one scale during spawning, yet another during the larval stage, and possibly a third during the juvenile stage. Therefore, seasonal effects on spatial scale should be defined first. In addition, traditional nested quadrat analyses may not truly reflect the scale of bottom forcing events. We therefore chose to start by looking at the spatial distribution of forcing events. For this examination of scale, we evaluated some of the available spatial data by season and removed interannual variability by pooling all years for which data were available. In order to gain a better understanding of the timing of physical and biological processes affecting forage fish, we plotted events along a linear time scale pooled over the years of data availability (Fig. 1).

Timing of Events

Most of the ecological activity associated with the timing of forage fish activities in the surface waters (upper 100 m) occurred during the spring and summer months from April to August. In addition, we found that biological processes affecting forage fish during this period were concentrated in the upper 20 m of the water column. The activity was initiated by the formation and strengthening of the stratified layer (data source CLAB [Continuous-Linked Automated Buoy] Buoy 1991-1997; Eslinger 1998; central PWS); this is accompanied by a steady increase of temperature in the upper 20 m of the water column (Fig. 1A).

The phytoplankton bloom peaked in April during the formation of the stratified layer at approximately 20 m at a temperature of approximately 5°C (chlorophyll *a*, CLAB Buoy and southwestern PWS, 1994-1997; Unpublished data, D.L. Eslinger, University of Alaska Fairbanks; McRoy et al. 1997; Eslinger 1998; Fig. 1B). The offshore zooplankton bloom began in April and peaked in June (mid-sound and southwestern PWS, 1981-1997; Cooney 1997, 1998; Unpublished data, R.T. Cooney, University of Alaska Fairbanks). The inshore zooplankton bloom (near the juvenile herring rearing sites; Stokesbury et al. 1997) followed similar timing to the offshore bloom but was apparently more highly concentrated (1996 data; Unpublished data, R.J. Foy, University of Alaska Fairbanks; Fig. 1B).

Pacific herring spawning commenced after temperatures started rising (above 4°C) and peaked when the stratified layer first formed (15 d

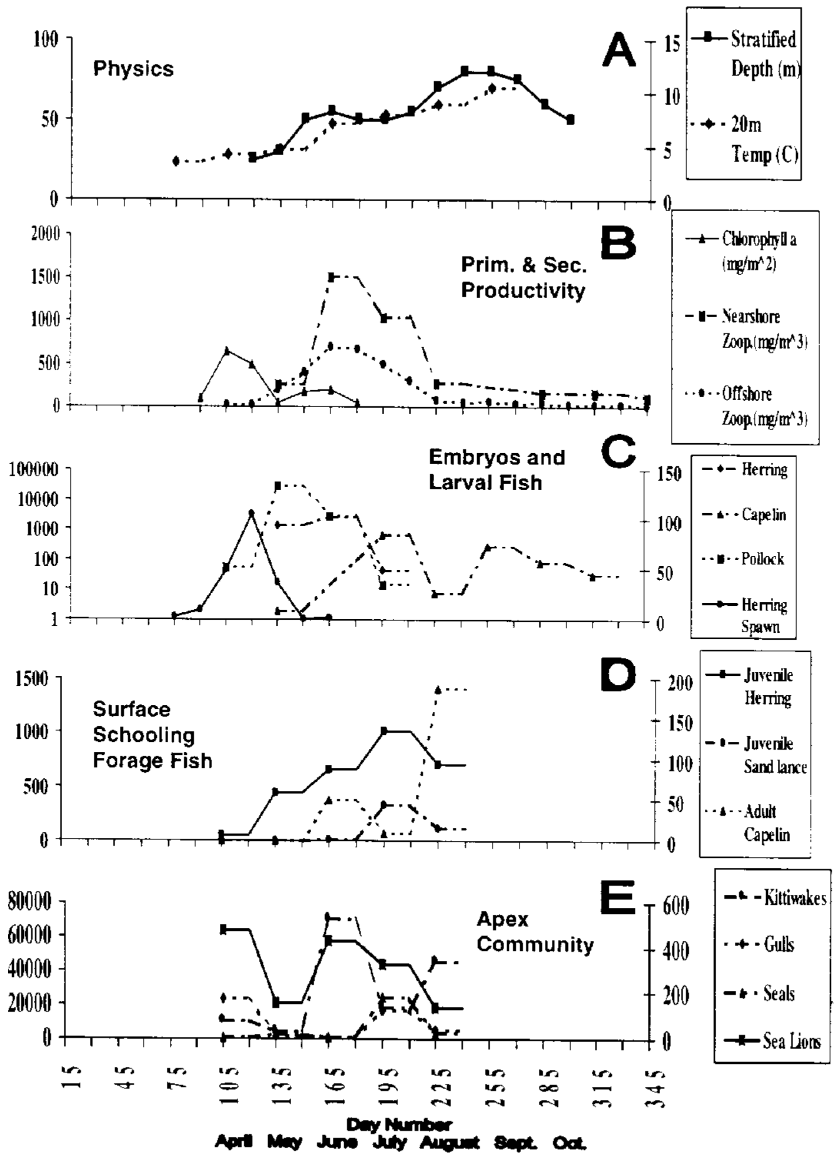

Figure 1. The timing of key ecological events in Prince William Sound, Alaska, including: (A) the formation of the stratified layer (depth in meters, left axis) and ocean temperatures at 20 m of depth (°C, right axis); (B) primary and secondary production (mg/m² or mg/m³); (C) herring spawning (cumulative miles of spawn, right axis) and larval fish (number of larvae/m³, left axis); (D) surface-schooling forage fish (total m² school surface areas; capelin on right axis, sand lance and herring on the left); and (E) apex predators (total number of individuals; kittiwakes and gulls on left axis, sea lions and seals on right).

cumulative estimates of miles of spawn, 1985-1997; Unpublished data, Alaska Department of Fish and Game, Cordova; Fig. 1C). From a single larval fish survey in 1989 (Norcross and Frandsen 1996), peak densities of larval pollock (*Theragra chalcogramma*) and Pacific herring (the second and fourth most abundant larval fish species found in PWS) roughly coincided with the peak of the zooplankton bloom (Fig. 1C). Capelin (*Mallotus villosus*; the third most abundant larval fish species) showed a bimodal trend in abundance, peaking later in July and then again in early fall, and remained abundant into October.

During the years 1995-1997, the most abundant surface-schooling forage fishes observed from the air were juvenile Pacific herring, juvenile sand lance (*Ammodytes hexapterus*), and prespawning adult capelin (Brown 1997) (Fig. 1D). Juvenile herring (mainly age 1; Unpublished data, E.D. Brown) appeared in the surface waters beginning in May after the stratified layer formed, temperatures had increased to at least 5°C, and coinciding with the onset of the zooplankton bloom. Their abundance steadily climbed, peaking in July and August after the age-0 herring joined the age-1 juveniles in the nursery bays. The appearance of sand lance in the surface waters coincided with a recruiting event (Unpublished data, E.D. Brown) of age-0 fish in the nearshore zone in July and August well after the peak of the bloom. The occurrence of large prespawn schools of capelin showed two peaks, one in June and one in August (Unpublished data, E.D. Brown) possibly indicating bimodal spawning events in PWS.

Information on aggregations of foraging predators was collected as auxiliary data during aerial surveys from 1995 to 1997. Those results indicated Steller sea lions and glacous-winged gulls were abundant in aggregations in April, coinciding with the herring-spawning event (Fig. 1E). Black-legged kittiwake and sea lion aggregations peaked in June, coinciding with the increase in surface schools of herring and capelin. The appearance of harbor seals peaked while sea lions continued to be abundant during July and August, most likely due to the return of large numbers of spawning salmon in PWS (not shown).

Spatial Overlays by Season

Monthly overlays from April through August of physical and biological data were produced using GIS. We show here only a few of the key figures.

In April, the stratified depth is at about 25 m in the central sound with a mean temperature of 4.2°C at a depth of 20 m. Over the 20-year hydrographic data set available (but not shown), the warmest regions occurred in northeast, north, and northwest PWS (up to 5.7°C); the coolest (2.9°C) occurred in the central sound associated with anti-cyclonic gyre and at the entrance and exit points to PWS from the Gulf of Alaska (GOA) (Fig. 2). The densest water was associated with the central gyre and the least dense water was associated with warmer regions and downstream from western glacial-filled fjords. The residual currents were generally low, ranging from 0.001 to 0.210 m/s with a mean flow of 0.04 m/s (Fig. 2). The flow into and out of

PWS during this month was minimal. Herring spawning regions occurring during the 1980s were generalized. Spawning regions occurred adjacent to, south, north, and east of the central gyre, but never west; all spawning occurred well inside the "oceanographic boundaries" of PWS. During this month all the surface-schooling fish (all herring), gulls, and aggregations of sea lions were associated with the herring spawn. Larval fish abundance was generally low and only pollock larvae were observed (Fig. 2).

In May, the stratified depth had increased to 30 m with an average temperature at 20 m of 5.5°C. The temperatures all over PWS showed a large increase from April (not shown), but the northeastern region of PWS remained the warmest (up to 6.9°C) and the regions associated with high flow and gyres the coolest (down to 4.2°C). Some of the "hot spots" in PWS were now associated with exchange of GOA water at the entrance and exits. The overall density of the water was lower during May with the least dense water still associated with higher temperatures. Ocean flow increased from April to a range of 0.004-0.284 m/s with a mean flow of 0.042 m/s (Fig. 3). The central gyre intensified, reversed direction (becoming anticyclonic), and extended farther north. In addition, the net flow into and out of PWS greatly increased during this month. Topography steered cross sound flow was also observed in the north region of PWS. Larval fish peaked in abundance during May and were broadly distributed (except capelin that was only observed in the northeast region) with and outside of the gyre-related currents. Note that herring larvae were as abundant west of the spawning regions as well as adjacent to them.

By June, temperatures at 20 m had risen significantly (mean at 7.3°C) with the stratified layer depth approaching 50 m. The temperatures during June were more uniform over the sound, with a range of 5.4-9.8°C; however, "hot spots" were still observed in the eastern sound and adjacent to the GOA. Density declined slightly from May, but apparently in response mainly to changes in salinity rather than temperature and salinity. Although the range of ocean flow lessened slightly from May (to 0.001-0.204 m/s), the mean flow was higher at 0.054 m/s. The flow into and out of the sound intensified from May with the formation of smaller topography-steered cyclonic gyres east and west of the inflow; overall, the exchange of surface water appeared to have increased over May. Larval fish were still relatively abundant and widespread (not shown), with an increase in the relative abundance of herring over pollock. No capelin larvae were observed. The most notable feature in June was the increase in appearance of surface-schooling forage fishes (Fig. 4). The most abundant species inside the sound was juvenile herring and outside the sound was prespawn adult capelin. A few sand lance schools were also observed inside the sound. Black-legged kittiwakes were highly associated with surface-schooling forage fishes, with notably large flocks associated with aggregations of spawning capelin. Gulls and sea lions (not shown) did not appear to be significantly associated with the juvenile herring; however, aggregations of both were observed near spawning capelin.

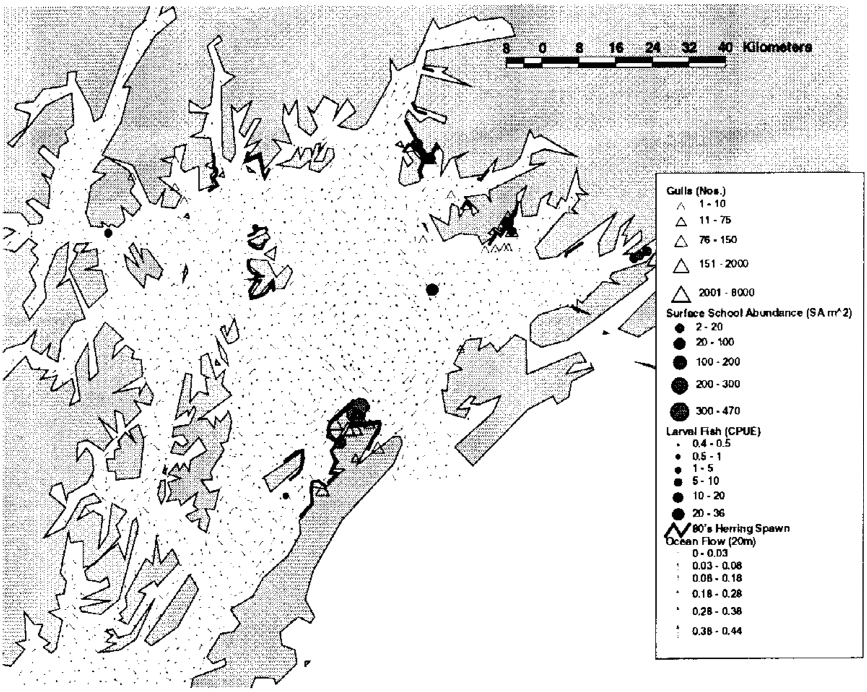

Figure 2. Ecological features within Prince William Sound, Alaska, during the month of April.

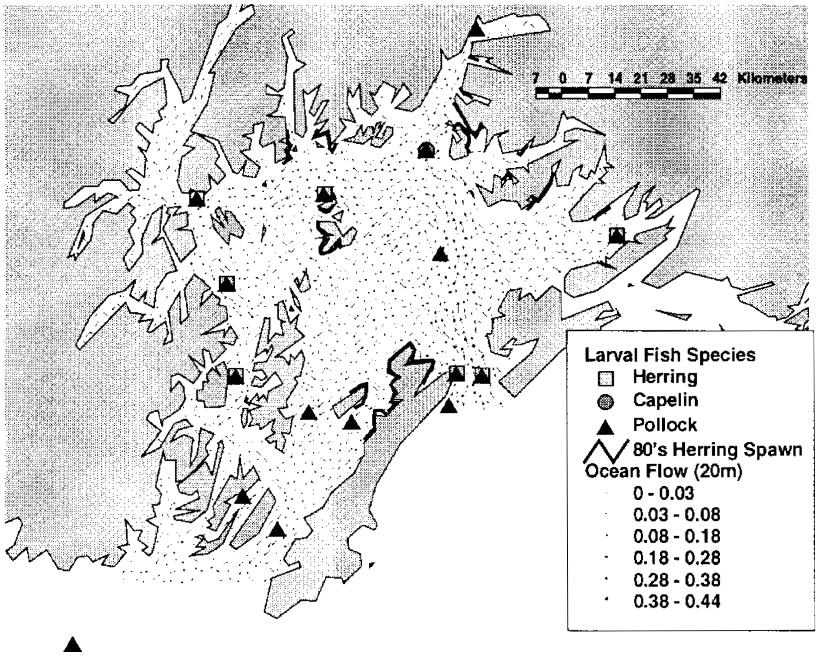

Figure 3. Ecological features within Prince William Sound, Alaska during the month of May.

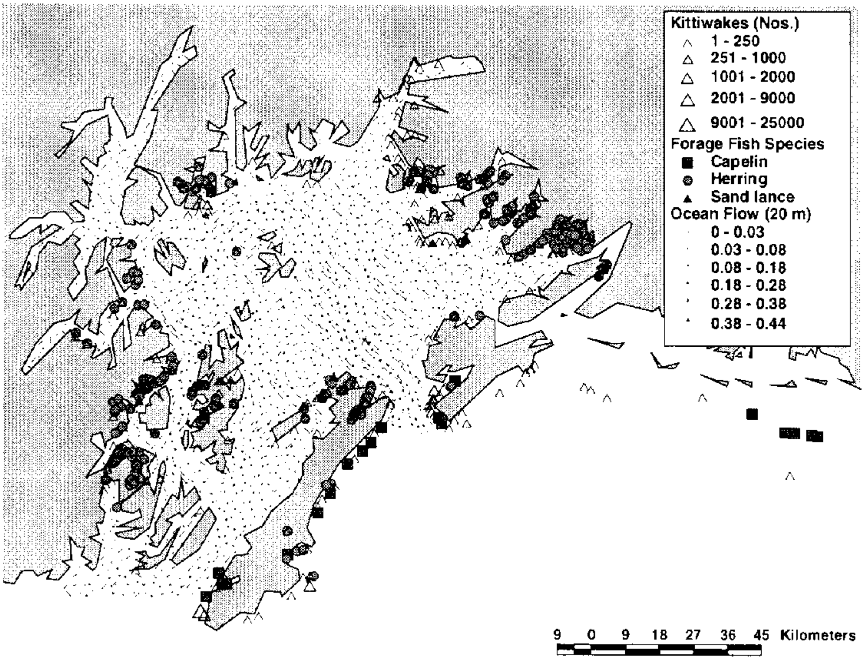

Figure 4. Ecological features within Prince William Sound, Alaska during the month of June.

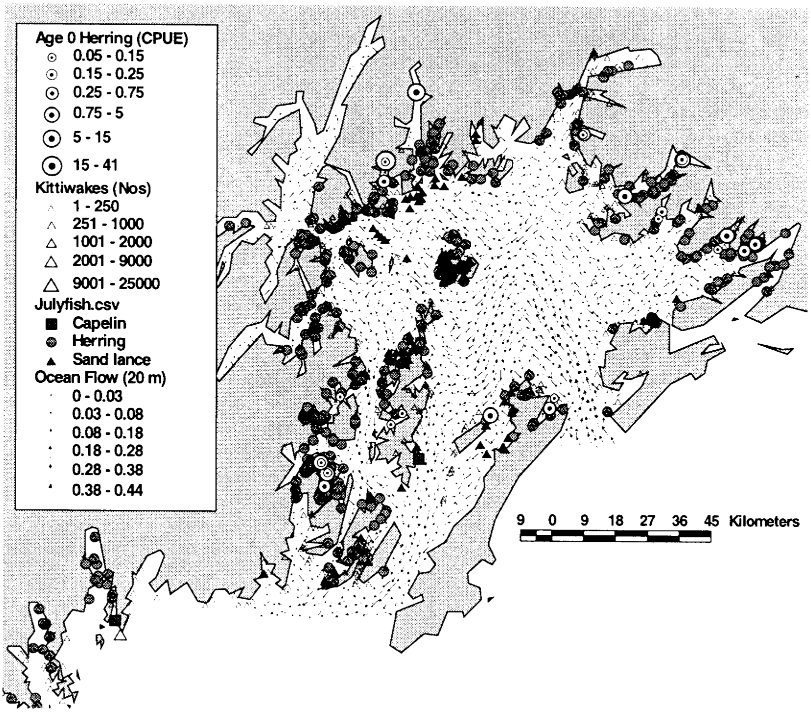

Figure 5. Ecological features within Prince William Sound, Alaska during the month of July.

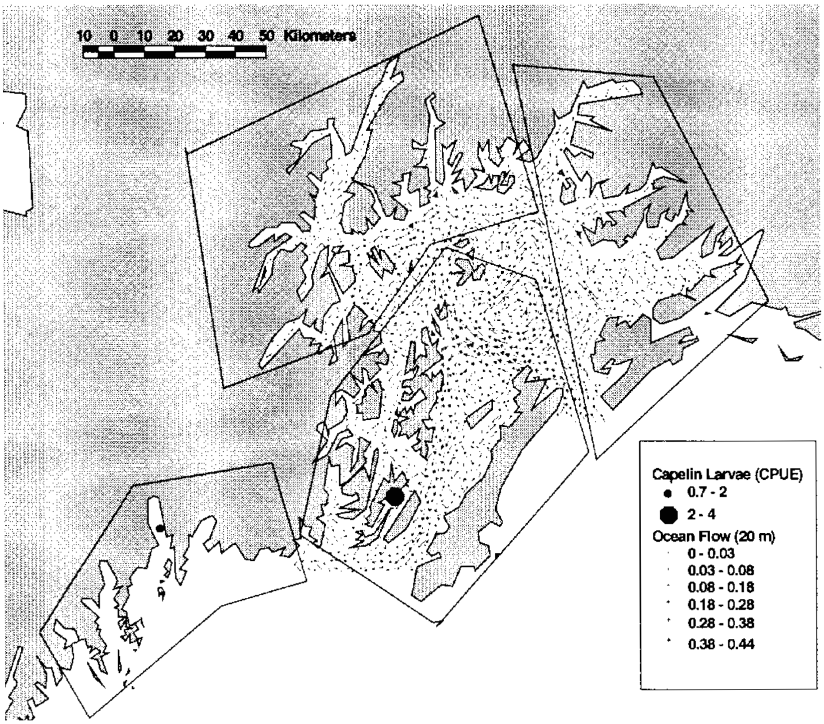

Figure 6. Ecological features within Prince William Sound, Alaska during the month of August and delineation of proposed ecological "regions."

In July, the temperatures at 20 m climbed to 10.1°C but the depth of the stratified layer was similar to its depth in June. The overall temperature range was 6.0-13.6°C, with the warmest regions occurring again in the eastern and, additionally, the northern sound. The coolest region remained in the central sound associated with strong currents. Densities were similar to those in June. Ocean flows were also similar to those in June, ranging from 0.0002 to 0.315 m/s with a mean flow of 0.054 m/s (Fig. 5). Larval fish were overall less abundant than in June but still widespread, with a decrease in the occurrence of both pollock and herring; the notable feature was the occurrence of large numbers of capelin broadly distributed within the sound (probably resulting from the spawning events observed in June; not shown). The numbers of surface-schooling fish increased significantly over June largely due to an increase in both herring and sand lance (Fig. 5). This distribution of herring and sand lance extended well west of PWS along the outer Kenai Peninsula. We believe this increase is due to recruiting events of age-0 fish for both species (based on unpublished data of E.D. Brown). As in June, kittiwakes were largely associated with the surface-schooling fishes while aggregations of associated gulls and sea lions were not observed.

In August, both the stratified depth (over 50 m) and temperatures at 20 m (mean 10.4°C) peaked over this 5-month period. Temperatures ranged from 4.3 to 12.7°C with the same pattern of higher temperatures around the “rim” of PWS but cooler temperatures associated with, presumably, ice-melt in the northern fjords (not shown). Ocean density and salinity remained very similar to those in July, although ocean flow peaked during this month (over the 5-month series) with a range of 0.0002-0.435 m/s and a mean of 0.082 m/s (Fig. 6). The flow into and out of the sound remained strong but the central gyre reversed direction to generally anticyclonic flow. Winds within PWS determined to a great degree the strength and directions of the gyres and surface currents. All the biological activity observed in the surface waters declined greatly during this month (not shown). Although capelin larvae were still present, they appeared to have migrated or advected out of PWS (Fig. 6).

The conclusion of this exercise is that there is variability in the seasonal spatial scale of bottom-driven forcing events in PWS. In an analysis of spatially explicit ecological processes in PWS, there appear to be three major regions to be considered (Fig. 6). The eastern portion of the sound is generally warmer, east of but influenced biologically by the central gyre and inflow, and seasonally highly variable. The northern and northwestern part of the sound is generally quieter, less variable, and less influenced by the inflow. The central region adjacent to the GOA is very dynamic, affected by the most intense flows, and is very likely responding to events outside of PWS to a much greater degree than the other two regions. This last region is also probably associated with greater losses of larval fish (advection of larvae out of PWS). The area off the outer Kenai Peninsula may be an “overflow” area for biological processes occurring within the sound.

References

Brown, E.D., and B.L. Norcross. 1997. Assessment of forage fish distribution and abundance using aerial surveys: Survey design and methodology. In: R.T. Cooney, Sound Ecosystem Assessment (SEA): An integrated science plan for the restoration of injured species in Prince William Sound, Appendix I, Chapter 11. FY96 Annual Report for the Exxon Valdez Trustee Council, Anchorage, Alaska, pp. 25-53.

Brown, E.D. 1997. Preliminary documentation of temporal and spatial variability of Pacific herring, other forage fish, and seabirds in Prince William Sound, Alaska. In: R.T. Cooney, Sound Ecosystem Assessment (SEA): An integrated science plan for the restoration of injured species in Prince William Sound, Appendix II, Chapter 10. FY96 Annual Report for the Exxon Valdez Trustee Council, Anchorage, Alaska, pp. 44-79.

Cooney, R.T. 1997. The role of zooplankton. Restoration Project 97320-H. In: R.T. Cooney, Sound Ecosystem Assessment (SEA): An integrated science plan for the restoration of injured species in Prince William Sound, Chapter 4. FY96 Annual Report for the Exxon Valdez Trustee Council, Anchorage, Alaska. 35 pp.

Cooney, R.T. 1998. The role of zooplankton. Restoration Project 97320-H. In: R.T. Cooney, Sound Ecosystem Assessment (SEA): An integrated science plan for the restoration of injured species in Prince William Sound, Chapter 4. FY97 Annual Report for the Exxon Valdez Trustee Council, Anchorage, Alaska. 22 pp.

Eslinger, D.L. 1998. Biophysical modeling and validation through remote sensing. In: R.T. Cooney, Sound Ecosystem Assessment (SEA): An integrated science plan for the restoration of injured species in Prince William Sound, Chapter 5. FY97 Annual Report for the Exxon Valdez Trustee Council, Anchorage, Alaska. 37 pp.

McRoy, C.P., A. Ward, E.P. Simpson, K. Tamburello, J. Cameron, S. McCullough, and P. Cassidy. 1998. Phytoplankton and nutrients. Restoration Project 97320G. In: R.T. Cooney, Sound Ecosystem Assessment (SEA): An integrated science plan for the restoration of injured species in Prince William Sound, Chapter 3. FY97 Annual Report for the Exxon Valdez Trustee Council, Anchorage, Alaska. 85 pp.

Norcross, B.L., and M. Frandsen. 1996. Distribution and abundance of larval fisheries in Prince William Sound, Alaska, during 1989 after the *Exxon Valdez* Oil Spill. American Fisheries Society Symposium 18:463-486.

Stokesbury, K.D.E., E.D. Brown, R.J. Foy, and B.L. Norcross. 1997. Juvenile herring growth and habitats. Restoration Project 95320T Annual Report. In: R.T. Cooney, Sound Ecosystem Assessment (SEA): An integrated science plan for the restoration of injured species in Prince William Sound, Chapter 11. FY96 Annual Report for the Exxon Valdez Trustee Council, Anchorage, Alaska. 75 pp.

Development of a Marine Habitat Protection Area in Bristol Bay, Alaska

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Abstract

An extensive area in Bristol Bay, Alaska, was proposed as a no-trawling zone to protect red king crab habitat from potential impacts. The Bristol Bay red king crab stock has remained at low abundance levels since a stock collapse in 1980. A literature review indicated that the proposed area encompassed all available habitat essential for red king crab juveniles of this stock. Published studies have shown that trawling could potentially degrade high-relief living habitat used extensively by red king crab juveniles, yet portions of the proposed area were also important and lucrative areas for trawl fisheries targeting yellowfin sole. Analysis indicated that a sub-area within the proposed closure area could be open to trawling on a seasonal basis and not severely impact crab habitat or increase crab bycatch. Closure of the remaining larger area to trawling could result in improved crab recruitment and subsequent benefits to crab fisheries.

Introduction

In January 1995, the North Pacific Fishery Management Council (NPFMC) reviewed a proposal to institute a trawl closure in the northeast and eastern sections of Bristol Bay. In combination with existing closures, all of Bristol Bay was proposed to be closed to trawling. It was felt that such a closure could reduce crab bycatch and protect red king crab (*Paralithodes camtschaticus*) habitat from potential degradation due to trawling. The directed red king crab pot fishery was closed in 1994 due to low abundance, and crab fishing representatives had requested that the NPFMC do what they could to rebuild this red king crab stock. Proponents of the closure believed that trawl closure areas would protect crabs from unobserved mortality by contact with passing gear and prevent habitat losses they believed were associated with trawl gear. Trawl fishing representatives agreed that actions should be taken to rebuild crab populations, but were concerned that a large-scale area closure could force them out of local areas in northern Bristol Bay where flatfish catch rates were reputed to be high and crab bycatch rates were low.

Several different fisheries occur in various areas of Bristol Bay. Pacific herring (*Clupea pallasi*) and Pacific salmon (*Oncorhynchus* sp.) gillnet fisheries take place in the spring and summer months within state waters (within 3 nautical miles from the coast). Commercial fisheries for red king and Tanner crabs (*Chionoecetes bairdi*) are prosecuted with pot gear largely during November in recent years. Trawl fisheries generally target yellowfin sole (*Pleuronectes asper*) in an area within the northern part of the bay after the ice cover melts (April-June). Large-scale trawl, longline, and pot fisheries directed at groundfish occur just outside Bristol Bay (west of 162°W). Prior to implementation of earlier area closures, some trawling was directed at Pacific cod (*Gadus macrocephalus*) and rock sole (*Pleuronectes bilineatus*) within the western part of Bristol Bay.

Area closures have been established in Bristol Bay for a number of reasons. In 1959, the Japanese prohibited their trawl vessels from fishing in a king crab pot sanctuary comprising the southern portion of Bristol Bay to minimize interaction with its crab pot and tanglenet fisheries. This area remained off-limits to trawling until 1983, when the NPFMC Bering Sea Groundfish Fishery Management Plan was amended to enhance a developing domestic trawl fishery by allowing fishing in this productive area. A crab protection zone was implemented by the NPFMC in 1987 to prevent the incidental catch of adult male and female red king crabs in the domestic trawl fisheries. This area, coincidental with the current National Marine Fisheries Service (NMFS) statistical area 512, was closed to trawling year-round and covered a substantial portion of the red king crab mating area (Fig. 1). In 1989, the current NMFS statistical area 516 was selected for closure during the period April 15-June 15 annually specifically to help protect mating and molting red king crabs. State waters bordering most of Bristol Bay were closed to trawling to protect mating and molting crabs. In 1967, much of Bristol Bay was declared a halibut nursery by the International Halibut Commission, and all commercial halibut longlining was prohibited from this area. In 1990, 12-mile buffer zones were established in NMFS regulations around three walrus haulouts in northern Bristol Bay. It was felt that prohibiting all vessels from entering these areas would minimize human interactions with these marine mammals.

Landings of red king crabs peaked at 60 million kg in 1980, followed by a stock collapse to very low abundance by 1983. No fishery occurred in 1983, but signs of improved abundance allowed fisheries to be prosecuted at low levels (roughly 2-7 million kg per year) through 1993 (Otto et al.

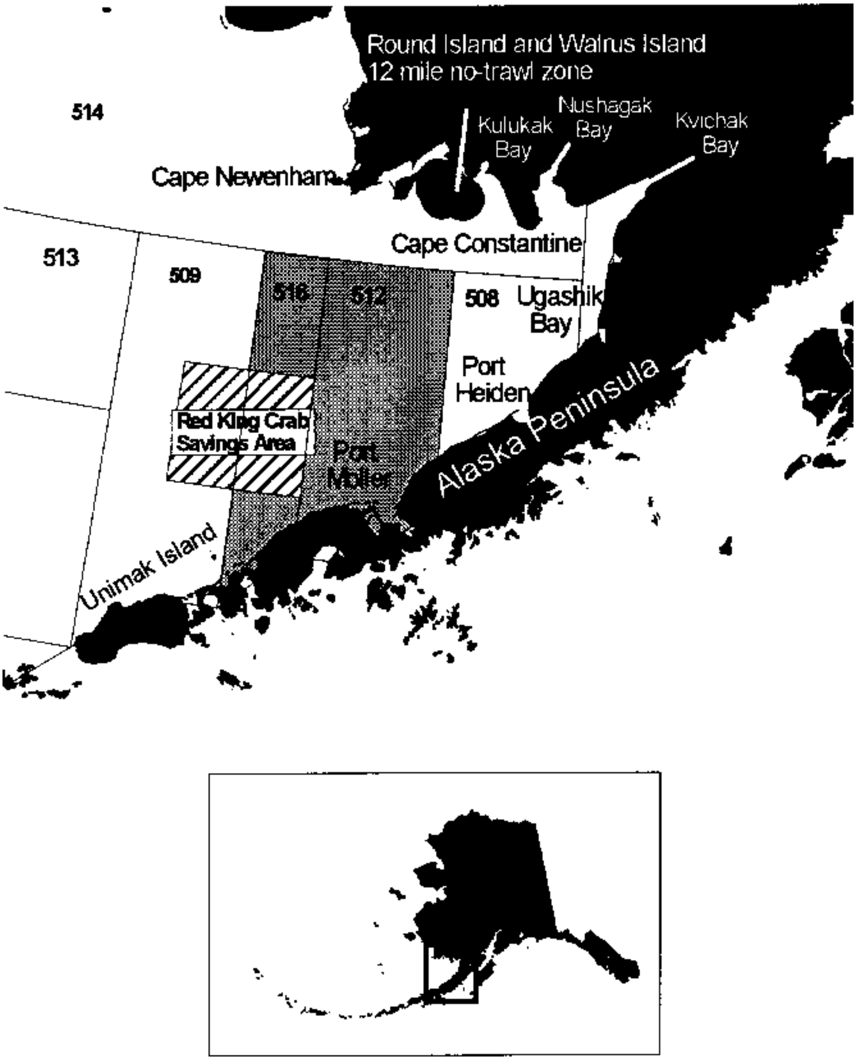


Figure 1. Map of Bristol Bay, Alaska, with NMFS three-digit statistical areas and place names. Trawl closure areas are variously shaded and include the Round Island no-trawl zone, areas 512 and 516, and the Red King Crab Savings Area. For reference the western edge of area 512 is 163°W.

1997). In 1994, the NMFS bottom trawl survey revealed low abundance of prerecruit red king crabs, indicating that poor year classes were being produced compared to the 1970s. The survey also detected that the female red king crab stock in Bristol Bay was below an established threshold of 8.4 million females >90 mm carapace length (CL), the mean size at 50% maturity. As a result, the fishery was closed in 1994. Similar survey estimates resulted in a closure in 1995. This situation prompted the Alaska Department of Fish and Game and the NPFMC to revise management strategies and develop comprehensive stock rebuilding plans. In addition, high trawl bycatch of red king crabs continued in spite of earlier closures of areas 512 and 516, and beginning with actions in 1994, the NPFMC created a closure area known as the Red King Crab Savings Area (Fig. 1), shown to have high red king crab bycatch and higher concentrations of adult female red king crabs.

A complete closure of Bristol Bay to trawling was proposed to the NPFMC in 1995 to help rebuild the red king crab stock in the area and revitalize the directed fishery. Due to the depressed state of the red king crab population, the NPFMC considered these additional measures to protect red king crabs across all life history stages. The closure of northern Bristol Bay and area 508 was proposed to reduce impacts on habitat favorable for juvenile crab survival. The proposed protection area would close all waters to trawling east of 163°W, the line extending from the western boundary of area 512 north to Cape Newenham.

This paper is a retrospective look at the information the NPFMC considered in 1995 and 1996, and the actions taken in response to continued low abundance of red king crabs in Bristol Bay, Alaska. The NPFMC had recently (1994-1996) acted to protect mature and spawning red king crabs. It had been hypothesized that juvenile red king crab settlement stages were the most important to survival, and the NPFMC wanted to provide as much protection as possible to juvenile crabs as well. Further ecosystem considerations were also part of the decision process. Bristol Bay is important to walrus, and no-trawl buffer zones had previously been established to afford minimum disturbance to haulouts and rookeries. The closure of all of Bristol Bay to trawling was seen as a means to broaden the areas of nondisturbance. Further, annual spawning of herring is concentrated in portions of the northern shore of Bristol Bay, and the perceived impacts that trawling could have on the migration paths and schools of herring were seen to be diminished by a closure. Bristol Bay is also important to migrating and nesting seabirds, and although the impacts of trawling on seabirds has been little studied, reducing the co-occurrence of seabirds and fishing activity was postulated as being a positive side-benefit.

The information presented to the NPFMC included a literature search on juvenile crab habitat requirements and effects of trawling on bottom habitat. An expanded literature search is provided in this paper. Where possible, data were analyzed that could verify or augment information from the literature and from public testimony. A Windows NT-based PC running ARC/INFO and ArcView geographic information system (GIS) programs was used to create the maps in this document and perform the spatial analyses for the NPFMC.

Area Description

Bristol Bay comprises the southeast corner of the Bering Sea shelf, including the waters north and east of Port Moller and south and east of Cape Newenham (Fig. 1). The shelf in this area is characterized by relatively smooth topology in waters <100 m. The shallow nearshore shelf deposits consist of gravel and coarse sand along the open shore, with clay and silt also found in some bays or coastal indentations including the shallow flat expanses near the mouths of the Kvichak and Nushagak rivers. The size of sediment decreases with distance from shore, moving from coarse sand through fine sand to mud as depth increases (Sharma 1979). Figure 2 provides a composite of the various bottom sediments graded on a sand-silt continuum as presented in Sharma (1979), and the general distribution of gravel coverage as presented in McDonald et al. (1981). The more coarse sediments are located to the north of the Alaska Peninsula and in the inner portion of Bristol Bay. Northern Bristol Bay, west and north of Cape Constantine, generally has finer sand and silt nearer the shoreline. Trawl locations in the commercial fishery for yellowfin sole overlap the areas of finer sand coverage (indicated in Fig. 2 and discussed below).

Crab Biology, Distribution, and Habitat Requirements

Bering Sea red king crab females bear an egg clutch for 11 months, and the eggs hatch prior to the female molting and extruding a new batch of eggs. Hatching generally occurs in April and May (Pereyra et al. 1976, Armstrong et al. 1981, McMurray et al. 1984). Larvae are subsequently in the water column for approximately 10 weeks (Pereyra et al. 1976, Wainwright et al. 1992) before settling to the bottom in July or August (Armstrong et al. 1981) and metamorphizing to a megalops stage and a subsequent benthic existence. The timing, locations, and movement of larval crabs have been studied in the Outer Continental Shelf Environmental Assessment Program (OCSEAP) which was undertaken to investigate possible impacts of oil exploration and drilling in the eastern Bering Sea and Bristol Bay. Armstrong et al. (1981) and McMurray et al. (1984) investigated larval and juvenile red king crab distributions and hypothesized on larval drift as part of this series of studies, and Hebard (1959) and Takeuchi (1962) reported on initial investigations into current and larval drift. In general, larval drift is with the current into Bristol Bay.

Habitat preferences for juvenile red king crabs were investigated by McMurray et al. (1984), Rice et al. (1988), and Rounds et al. (1990). In summary, juveniles prefer a solitary existence in high-relief habitat, pref-

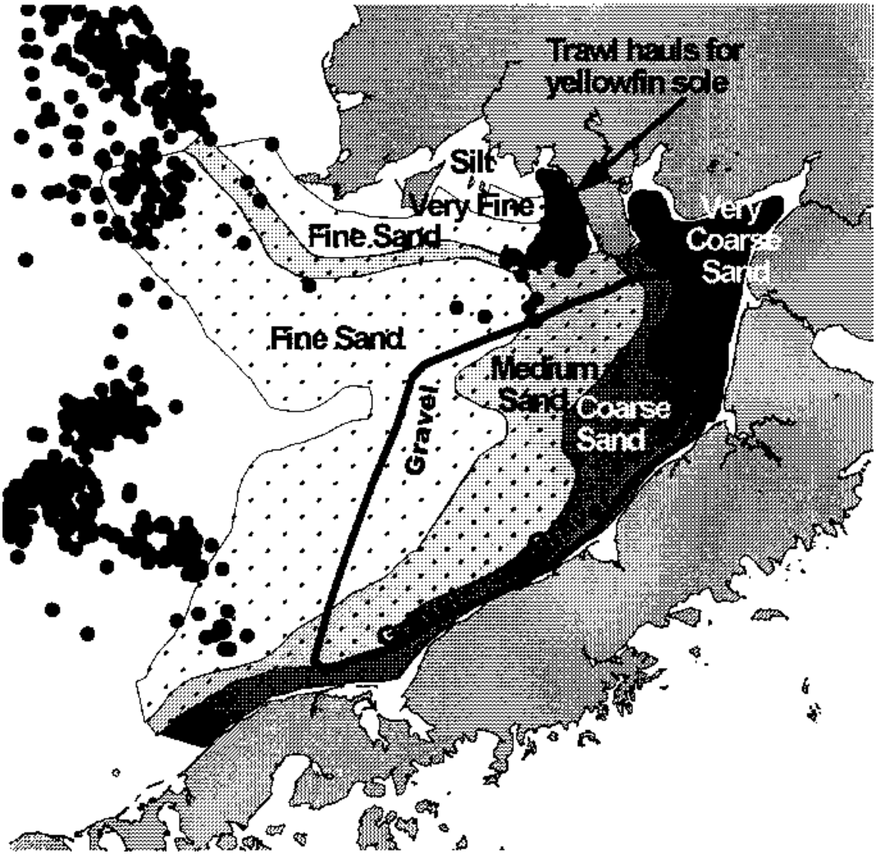


Figure 2. Bottom sediment gradations in Bristol Bay (shaded areas) as provided by Sharma (1979). The general distribution of gravel is as indicated by McDonald et al. (1981) and portrayed by a heavy dark line. The locations of trawl hauls targeting yellowfin sole in 1994 are indicated by large dots.

erably with abundant biota for protection and food. Specifically, juveniles are mainly found among biogenic assemblages, such as tube-building polychaete worms, sea onion (*Boltenia ovifera*), bryozoans, mussels, kelp, and ascidians (McMurray et al. 1984, NMFS 1991, Armstrong et al. 1993). If no epifaunal community exists, juveniles can be found on rocky or gravel substrate, but it is considered to be inferior habitat (McMurray et al. 1984). A shallow-water survey for juvenile red king crabs in Bristol Bay found most small crabs (4-11 mm CL) in stands of mussels, attached to bryozoans or hydroids at the base of sea onion stalks, among clumps of polychaete tubes, or in tows with abundant *Asterias* or *Evasterias* (NMFS 1991).

Juvenile red king crabs are found in shallow waters <30 m in depth and into the littoral zone (Pereyra et al. 1976), or in the eulittoral zone between 20 m and 60 m (Armstrong et al. 1993). In a review of NMFS annual survey data, Stevens (1990) found that most small crabs (<50 mm CL) were captured in depths <45 m and the major stations encountering crabs of this size were within 30 nautical miles of estuaries along the Alaska Peninsula. A survey of Port Moller specifically for red king crab juveniles (Wainwright et al. 1992) found few juveniles in either soft bottoms or in rock surveyed with a small rock dredge. Nearly all of the juveniles encountered were found in a foot survey of the intertidal area. There is a tendency of juveniles between 20 and 60 mm to form pods (Armstrong et al. 1993), and as red king crabs near adulthood, they join the adults in deeper waters. Adult crabs annually migrate to shallower nearshore waters to spawn in the winter and spring and back to deeper waters in summer and autumn (Takeshita et al. 1990).

Survey Information on Crab Abundance and Distribution

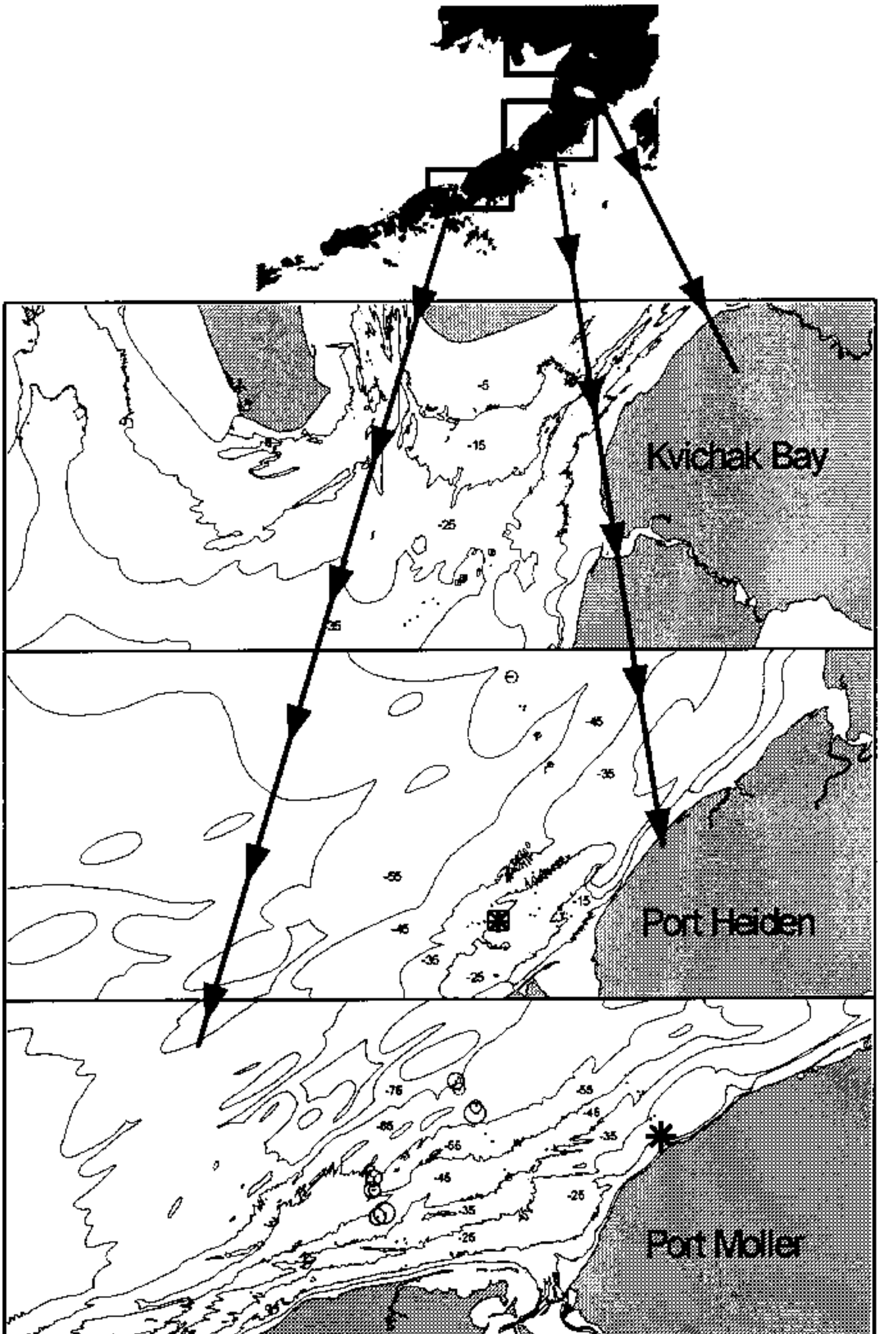
Data from the annual summer NMFS Bering Sea trawl survey (in this case, 1975-1997) was used to examine locations of crab abundance. The annual trawl survey covers the intersection points of a 20 × 20 mile grid throughout lower Bristol Bay and along the Bering Sea shelf. Crabs are identified by sex, measured for carapace length and other biological data are collected. Surveys to assess king crab stocks in the Bering Sea began in 1955 (Hayes 1983) and annual assessments of the red king crab stock in Bristol Bay have been conducted since 1968 (e.g., Otto et al. 1997). In addition to overall abundance estimates, the NMFS survey reports estimates for three size groups of male crabs (juveniles <110 mm CL, prerecruits ≥110 mm CL and <35 mm CL, and legals ≥135 mm CL) and two size groups of female crabs (small females <90 mm CL and large females ≥90 mm CL). While the annual trawl survey is capable of assessing larger crabs, the trawls are generally unable to retain small (<30 mm CL) crabs (Reeves and Marasco 1980, Armstrong et al. 1981), and the survey does not occur in the shallow waters believed to be the principal habitat for young crabs (Armstrong et al. 1981, Armstrong et al. 1993).

A supplementary survey cruise was conducted prior to the annual survey in 1991 to specifically sample for juvenile red king crabs and juvenile flatfish (Stevens and MacIntosh 1991). Seven transects were conducted in waters shallower or with rougher bottom type than is normally included in the annual trawl survey. Haul locations, numbers, and sizes of juvenile crabs encountered in the survey were contained in the cruise report. Similarly, in 1995 a supplementary cruise was made of shallow-water locations in Togiak and Kulukak bays in northern Bristol Bay to assess yellowfin sole and other flatfish in the area (NMFS 1995).

Although representing only seven transects along the northern Alaska Peninsula and into Kvichak Bay, the survey for juvenile red king crabs in 1991 (Stevens and MacIntosh 1991) yielded some interesting information which helps to confirm the location and habitat preferences of juvenile crabs. The station data provided in the cruise report are reproduced in Fig. 3. The station furthest into Kvichak Bay was located over very rough substrate, and even a modified scallop dredge met with limited success. The results of the survey do confirm, however, that the smallest crabs (4-11 mm CL in this case) are located in the shallower stations, and in the vicinity of estuaries as had been reported in Stevens (1990). A large portion of these small crabs were found to be in close association with the biota in the area as discussed above. Crabs in the middle size group (15-49 mm CL) appeared to be distributed similarly to the small size class. However, a haul nearest the shore in the vicinity of Port Moller at a depth of 20 m had a high catch of small crabs with no crabs from larger size categories (Fig. 3). The larger crabs (>49 mm CL) were strongly segregated from the smaller size groups and found in deeper water (Stevens and MacIntosh 1991).

McMurray et al. (1984) reported juvenile red king crabs (age 0+) within Togiak Bay. Additional NMFS survey hauls were made into these shallow waters in 1989 and 1991 because of the trawl fishing activity, and no red king crabs were found in the hauls within Togiak Bay (Stevens and MacIntosh 1989, Stevens et al. 1991). A cruise to sample the shallow waters of Togiak and Kulukak bays specifically to assess abundant flatfish such as yellowfin sole was conducted in May of 1995 (NMFS 1995). This survey found

Figure 3. (Facing page.) Catch of crab in a supplemental NMFS trawl survey (NMFS 1991) specifically to locate juvenile crab near Port Moller, Port Heiden, and Kvichak Bay in Bristol Bay. Size of symbols is proportional to the catch in the tow. Three size groups are presented as follows: small juvenile red king crab (4-14 mm) as an asterisk; medium juvenile crab (15-49 mm) as a box; and large juvenile crab (>49 mm) as a circle.


Kvichak Bay
Port Heiden
Port Moller

resident juvenile yellowfin sole and mature adults in spawning condition, verifying that yellowfin sole spawn in the area. Among the dominant 22 species identified in the hauls, there were no red king crabs reported, although these could have been recorded in the miscellaneous category. The mesh of the net was fine enough (4.0 mm) to retain juvenile crabs.

Juvenile red king crabs live among epifaunal communities, which are associated with gravel and cobble substrate. Much of this habitat type is too rough or too shallow for trawl assessment. Juvenile distribution in Bristol Bay can be interpreted from published maps showing the distribution of associated substrate (gravel and cobble) and areas sampled for young crabs (McMurray et al. 1984, Stevens and MacIntosh 1991, Wainwright et al. 1992, Armstrong et al. 1993). Suitable juvenile habitat is "extremely patchy" in Bristol Bay (McMurray et al. 1984, Jewett and Onuf 1988). Areas shown by surveys to contain age 0-2 juvenile crabs do not adequately describe their actual distribution because: (1) the entire area has not been sampled; and (2) young crabs are difficult to catch with sampling gear, particularly in cobble habitats (Stevens and MacIntosh 1991). Furthermore, distribution of juvenile red king crabs may be affected by year-class strength. Juvenile surveys were conducted in 1984 and 1991, which were years of low stock abundance. The abundance and distribution of juveniles might have been more encompassing and conclusive had the surveys occurred in the early 1970s when overall population abundance was high and the distribution covered a greater area. Sample areas with low abundance could nonetheless be viable habitat in times of high abundance. It is therefore not possible from the existing survey data to determine the exact distribution of juveniles in any given year. Studies have combined juvenile survey data with substrate information to create a general map of juvenile red king crab habitat (Hsu 1986, Armstrong et al. 1993).

Trawl Impacts on Habitat

Trawling and dredging can negatively impact crab habitat, particularly living substrate on which young red king crabs depend for food and protection from predators. Juvenile red king crabs in the Bering Sea depend on both physical substrate and biogenic assemblages for settlement, food, and protection from predators (McMurray et al. 1984, Stevens and MacIntosh 1991). Both the physical substrate (cobble, shell) and biogenic assemblages (such as ascidians and tube-building polychaete worms) are vulnerable to trawling. Studies have shown that trawling and dredging impact the seabed through scraping and ploughing, sediment resuspension, and physical destruction, removal, or scattering of nontarget benthos (Messieh et al. 1991, Jones 1992). In the Wadden Sea, scientists have observed destruction and elimination of erect epifaunal species (Reise 1982). If habitat is impacted by trawling and dredging, crab settlement and survival could be reduced, thereby lowering recruitment.

Armstrong et al. (1993) and Cassano et al. (1995) proposed more extensive trawl closures to protect both spawning females and juvenile habitat from impacts of trawling. They conjectured that the lack of suitable habitat could be a population constraint, and habitat protection should be considered as a means to increase red king crab populations.

Groundfish Fisheries

Trawling was fairly limited in the proposed area with the exception of a yellowfin sole trawl fishery in April and May which targeted the flatfish when they migrated to the shallower waters of northern Bristol Bay to spawn. This fishery is prosecuted in Kulukak and Togiak bays (the vicinity of Walrus Island, Fig. 1) on a fine sand substrate in shallow waters (Fig. 2). The fishery is typically located in a confined area as represented by observed hauls in 1994 (Fig. 2), and occurs in mid-April to mid-June. Trawlers argued, and an analysis of the observer data confirmed, that few crabs were taken as bycatch in the fairly confined area this fishery utilized. An area proposed to remain open for this fishery was between 159ºW and 160°W and between 58ºN and 58°43′N (Fig. 4).

Data from individual fishing vessel trawl hauls were obtained from the NMFS observer program. Observers collect specific catch information from randomly selected hauls on vessels requiring an observer. A comparison of the directed yellowfin sole catch and red king crab bycatch in this area with the catch and bycatch in the rest of the Bering Sea for the yellowfin sole fleet indicated that a high of 13% of the red king crab bycatch from the yellowfin sole fishery was taken in this area in 1991. Similarly, 12% was taken in 1993. However, in most years, this percentage ranged between 1% and 5%. An analysis of the observer data indicated that most of the crab bycatch is from tows along the southern boundary of the area to remain open, or along the northern edge of area 512. In contrast, between 10% and 40% of the directed yellowfin sole catch came from this area in any given year.

Discussion and Conclusion

Fishery managers usually must focus upon measures that will monitor and/or control the portions of the exploited population affected by fishing gear. Setting seasons, catch limits, or the size or sex to be taken are examples of management options which can control total fishing mortality. Also, fishery managers must assure that critical nursery habitat is protected and that all sources of mortality (including bycatch) are taken into account. Specifically, red king crabs in the Bering Sea have been at low population levels since the early 1980s, and at the time of this action mature female crabs had declined in numbers to a level below an established threshold believed to be necessary to the continuing health of the population. In addition, recruitment to the population is variable and has

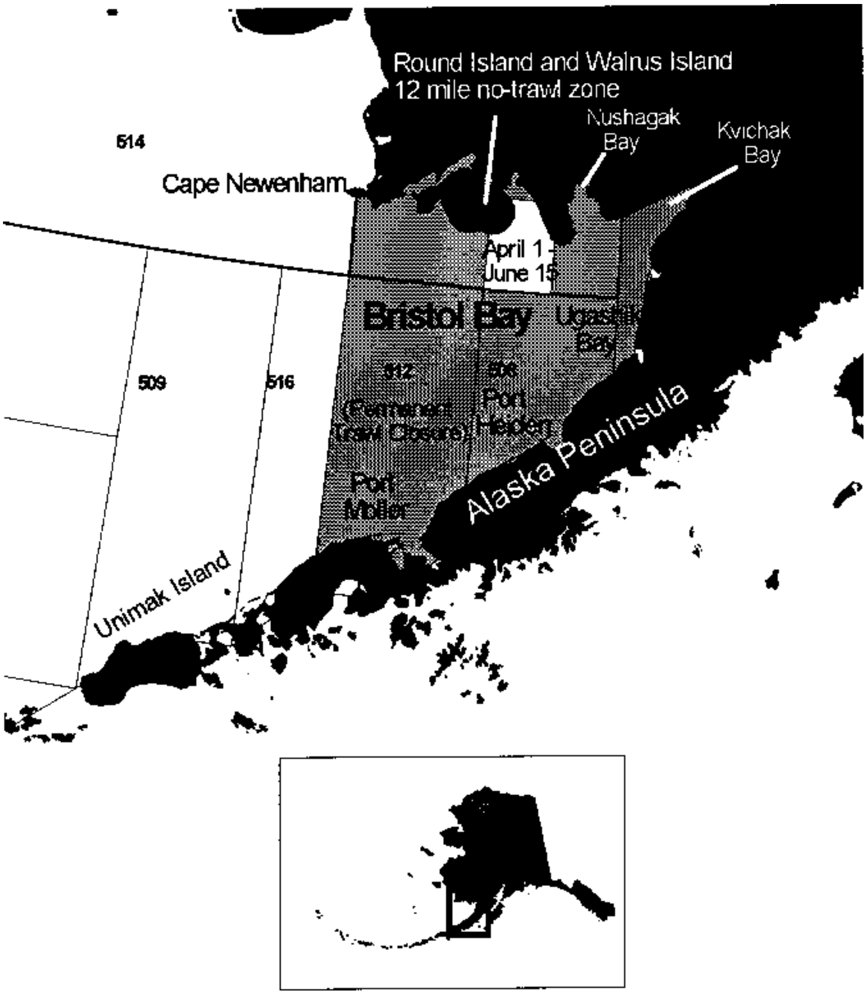


Figure 4. Map of the Bristol Bay trawl closure area. The unshaded area within Bristol Bay is an area open to trawling for yellowfin sole from April 1 to June 15 annually.

mostly been low in recent years. With the closure of Bristol Bay and the Red King Crab Savings Area to trawling, managers and policy makers have moved to increase protection to include all possible life-history stages.

The effectiveness of any trawl/dredge closure designed to protect juvenile red king crabs hinges on our understanding of recruitment dynamics and the distribution of juveniles and their habitat. Red king crab year-class strength depends both on the number of spawners and on environmental conditions such as temperature and currents (Tyler and Kruse 1995). It has been hypothesized that the availability of appropriate red king crab habitat at the settlement and juvenile stages constrains juvenile abundance, in turn affecting year-class strength and recruitment (McMurray et al. 1984, Armstrong et al. 1993, Cassano et al. 1995). Larvae drift with the current before settling to begin life on the benthos. Larval settlement and survival patterns vary according to ocean currents and availability of appropriate substrate. If the current transports the larvae to an area without suitable habitat, the chances of survival are slim (McMurray et al. 1984, Jewett and Onuf 1988).

In his analysis of the life history of major red king crab stocks, Rodin (1990) established the following four basic habitat components for a viable population: (1) conditions experienced by hatching larvae in the coastal zone must be combined with transport of larvae to favorable habitats for survival; (2) a well-developed sessile community (dense concentration and large areas of hydroids, bryozoans, and sponges) is needed for refuge from predators, and a food base is necessary where the massive settlements of larvae occur; (3) a broad continental shelf is necessary with a rich food base for adults; and (4) no physical barriers to the movement of juvenile crabs into the adult spawning population and no barriers to the migration of adults into or out of spawning areas should exist. Rodin (1990) concluded the list with the following observation: "The most important, judging from everything, is the presence of favorable habitat conditions for the post larval stages."

Crab stocks will rebuild only when recruitment increases. Managers can affect recruitment by addressing the following three components: (1) ensure there are adequate numbers of spawners, (2) provide adequate habitat available for settlement, and (3) reduce fishing-related impacts on juvenile crabs. The closure of Bristol Bay to trawling should provide measures to reduce impacts on all three components necessary to recruitment. Mature adults, although protected by previous closure measures such as areas 512 and 516, and the Red King Crab Savings Area, should enjoy further protection, especially along the northern section of Bristol Bay. Cessation of trawling in the nearshore areas of Bristol Bay is expected to allow sessile benthic fauna to thrive. And, although not readily retained by trawl gear, juveniles in the closure area will not experience injuries or mortality from the passing trawl gear.

An area within northern Bristol Bay to seasonally permit trawling for yellowfin sole was established at the same time the larger Bristol Bay closure was implemented. An analysis of NMFS observer data indicated this was a highly productive area for yellowfin sole, and relatively low bycatch of red king crabs. The substrate within this subarea is relatively fine sand and silt, and does not appear to have the high relief habitat and biota necessary to juvenile king crabs. Surveys in the area were not able to locate red king crabs. The NPFMC determined that the area could be opened during the spawning season of yellowfin sole without appreciable effects on king crab juveniles or their habitat. In summary, the closure of Bristol Bay, with a sub-area available for yellowfin sole trawling, ensures that the possible impacts by trawl gear on the benthos are minimized.

Further benefits can be expected for marine mammals that inhabit Bristol Bay and already have had no-trawl zones established around rookeries and haulouts to minimize trawl and marine mammal interactions. Bristol Bay is also an important area for migrating and nesting seabirds to which disturbances would be reduced. Finally, the northern border of the area open to yellowfin sole trawling was purposefully established south of the inner reaches of Kulukak Bay to minimize trawl interactions with spawning herring which utilize the first few hundred meters from the shore for spawning.

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References

Armstrong, D.A., L.S. Incze, D.L. Wencker, and J.L. Armstrong. 1981. Distribution and abundance of decapod crustacean larvae in the southeastern Bering Sea with emphasis on commercial species. NOAA, Office of Marine Pollution Assessment. OCSEAP Final Report, Research Unit 609.

Armstrong, D.A., T.C. Wainwright, G.C. Jensen, P.A. Dinnel, and H.B. Andersen. 1993. Taking refuge from bycatch issues: Red king crab (*Paralithodes camtschaticus*) and trawl fisheries in the eastern Bering Sea. Can. J. Fish. Aquat. Sci. 50:1993-1999.

Cassano, E., G. Harrington, P.S. Hill, and T. Loher. 1995. Management of Bristol Bay red king crab: A critical intersections approach to fisheries management. SMA/FRI-UW-9510. University of Washington, Seattle.

Hayes, M.L. 1983. Variation in the abundance of crab and shrimp with some hypotheses on its relationship to environmental causes. In: W.S. Wooster (ed.), From year to year: Interannual variability of the environment and fisheries of the Gulf of Alaska and the eastern Bering Sea. Washington Sea Grant Program, University of Washington, Seattle, pp. 86-101.

Hebard, J.F. 1959. Currents in southeastern Bering Sea and possible effects on king crab larvae. NOAA Tech. Rep. NMFS SSRF 293.

Hsu, C.C. 1986. Spatial and temporal distribution patterns of female red king crabs in the southeastern Bering Sea. Ph.D. thesis, University of Washington, Seattle. 298 pp.

Jewett, S.C., and C.P. Onuf. 1988. Habitat suitability index models: Red king crab. U.S. Fish Wildl. Serv. Biol. Rep. 82(10.153).

Jones, J.B. 1992. Environmental impact of trawling on the seabed: A review. N. Z. J. Mar. Freshwater Res. 26:59-67.

McDonald, J., H.M. Feder, and M. Hoberg. 1981. Bivalve mollusks of the southeast Bering Sea. In: D. W. Hood and J.A. Calder (eds.), The eastern Bering Sea shelf: Oceanography and resources. Vol. 2. National Oceanic and Atmospheric Administration, Office of Marine Pollution Assessment. University of Washington Press, Seattle.

McMurray, G., A.H. Vogel, P.A. Fishman, D.A. Armstrong, and S.C. Jewett. 1984. Distribution of larval and juvenile red king crabs (*Paralithodes camtschatica*) in Bristol Bay. NOAA OCSEAP Final Rep. 53(1986):267-477.

Messieh, S.N., T.W. Rowell, D.L. Peer, and P.J. Cranford. 1991. The effects of trawling, dredging and ocean dumping on the eastern Canadian continental shelf seabed. Continental Shelf Res. 2:1237-1263.

NMFS (National Marine Fisheries Service). 1995. Cruise results. Cruise 95-1 Crawdad, 1995 Togiak nearshore beam-trawl survey, May 18-May 29, 1995. NMFS, Alaska Fisheries Science Center, Resource Assessment and Conservation Engineering Division, Seattle, Washington.

Otto, R.A., J.A. Haaga, and R.A.MacIntosh. 1997. Report to industry on the 1996 eastern Bering Sea survey. NMFS, Alaska Fisheries Science Center, Processed Rep. 97-02. Seattle, Washington.

Pereyra, W.T., J.E. Reeves, and R.G. Bakkala. 1976. Demersal fish and shellfish resources of the eastern Bering Sea in the baseline year 1975. NMFS, Northwest Fisheries Center, Processed Rep. Seattle, Washington.

Reeves, J.E., and R. Marasco. 1980. An evaluation of alternative management options for the southeastern Bering Sea king crab fishery. NMFS, Northwest and Alaska Fisheries Center, Processed Rep. 80-6. Seattle, Washington.

Reise, K. 1982. Long-term changes in the macrobenthos invertebrate fauna of the Wadden Sea: Are polychaetes about to take over? Netherlands J. Sea Res. 16:29-63.

Rice, S.D., T.C. Shirley, and S.M. Shirley. 1988. Coastal fisheries oceanography of the southern Bering Sea and north Aleutian Basin: Habitat requirements of red king crab larvae and juveniles. NOAA, National Ocean Service, Ocean Assessments Division, Alaska Office. Interim Final Report, OCSEAP Research Unit 693.

Rodin, V.E. 1990. Population biology of the king crab *Paralithodes camtschatica* Tilesius in the north Pacific Ocean. In: Proceedings of the International Symposium on King and Tanner Crabs. University of Alaska Sea Grant, AK-SG-90-04, Fairbanks, pp. 133-144.

Rounds, P.M., C. Brodersen, and M.M. Babcock. 1989. Effects of cohort density and habitat on survival and growth of juvenile red king crab, *Paralithodes camtschatica*. In: Proceedings of the International Symposium on King and Tanner Crabs. University of Alaska Sea Grant, AK-SG-90-04, Fairbanks, pp. 209-218.

Sharma, D.S. 1979. The Alaska shelf: Hydrographic, sedimentary, and geochemical environment. Springer-Verlag, New York.

Stevens, B.G. 1990. Temperature-dependent growth of juvenile red king crab (*Paralithodes camtschatica*), and its effects on the size-at-age and subsequent recruitment in the eastern Bering Sea. Can. J. Fish. Aquat. Sci. 47:1307-1317.

Stevens, B.G., and R.A. MacIntosh. 1989. Report to the industry on the 1989 Eastern Bering Sea crab survey. NMFS, Alaska Fisheries Science Center, Processed Rep. 89-18, Seattle, Washington.

Stevens, B.G., and R.A. MacIntosh. 1991. A survey of juvenile red king crabs with dredge and beam trawl in Bristol Bay, Alaska. Cruise results supplement OH-91-1 (Ocean Hope 3). Available from National Marine Fisheries Service, P.O. Box 1638, Kodiak, AK 99615.

Stevens, B.G., R.A. MacIntosh, and J.A. Haaga. 1991. Report to the industry on the 1991 Eastern Bering Sea crab survey. NMFS, Alaska Fisheries Science Center, Processed Rep. 91-17, Seattle, Washington.

Takeshita, J., H. Fugita, and S. Matsuura. 1990. A note on population structure in the eastern Bering Sea adult red king crab, *Paralithodes camtschaticus.*In: Proceedings of the International Symposium on King and Tanner Crabs. University of Alaska Sea Grant, AK-SG-90-04, Fairbanks, pp. 427-434.

Takeuchi, I. 1962. On the distribution of zoea larvae of king crab, *Paralithodes camtschatica*, in the southeastern Bering Sea. Bull. Hokkaido Reg. Fish. Res. Lab. 24:163–170.

Tyler, A.L., and G.H. Kruse. 1995. Report of the modeling workshop on year-class strength formation of red king crab. Regional Information Rep. 5J95-11. Alaska Department of Fish and Game, Commercial Fisheries Division, Juneau, Alaska.

Wainwright, T.C., D.A. Armstrong, H.B. Andersen, P.A. Dinnel, D.W. Herren, G.C. Jensen, J.M. Orensanz, and J.A. Shaffer. 1992. Coastal fisheries oceanography of the southern Bering Sea and northern Aleutian Basin: Port Moller king crab studies. Minerals Management Service, Alaska OCS Region, OCS Study MMS 92-0040.