The evaluation of adverse impacts from fishing on crab essential fish habitat

NMFS and NPFMC staff discussion paper, March 2011

1 Introduction 1
2 Current EFH description for red king crab 2
3 Habitat needs for crab stocks 3
4 Evaluation of the effects of fishing in the 2005 EFH EIS 4
4.1 Red king crab habitat linkages 5
4.2 Conclusions about fishing impacts on crab EFH 5
5 How might a better methodology for evaluating adverse impacts of fishing on crab EFH be devised? 7
6 Distribution of the red king crab population and southwestern Bristol Bay 7
6.1 Importance of southwestern Bristol Bay 7
6.2 Changing distribution of red king crab throughout their range 8
7 Research questions 12
8 Options for Council action 13
9 Literature Cited 13

1 Introduction

In April 2010, the Council reviewed the summary report of the 5-year review of essential fish habitat (EFH) provisions. The report addresses new habitat information available since the last comprehensive review of EFH, documented in the 2005 EFH Environmental Impact Statement (EIS), and how it pertains to the EFH provisions of the Council's fishery management plans.

During the Crab Plan Team's review of EFH information pertaining to crab species, the Plan Team recommended that further analysis should be undertaken to evaluate fishing effects on crab stocks, and determine whether the conclusions reported in the FMP (and synthesized from the 2005 EFH EIS) are valid. Distribution of crab stocks, particularly red king crab, has changed since the analysis in the 2005 EFH EIS. Additionally, the Plan Team was concerned that the methodology used in the 2005 effects of fishing analysis may not adequately capture actual impacts of fishing on crab populations. Other parameters may need to be considered for crab stocks, such as the importance of spawning and larval distribution relative to oceanographic currents (pelagic habitat) for crab settlement. The conclusions in the 2005 EFH EIS may imply that more is known about the effects of fishing on the habitat needs and life history stages of crab (especially growth to maturity) than can be substantiated, based on research-to-date. Also, the Plan Team identified that recent shifts in the red king crab population distribution may mean that the spawning population is now present in an area in southwestern Bristol Bay that is also a location of intensive trawl fishing. Therefore the Crab Plan Team recommended further evaluation of the effects of fishing be undertaken.

Consequently, the Council asked staff to prepare a discussion paper to further examine the Crab Plan Team's recommendation to re-evaluate the effects of fishing on crab stocks. This discussion paper aims to provide clarification on the issues raised by the Plan Team with respect to the methodology that was used in the 2005 evaluation of fishing effects, and whether the appropriate parameters for crab stocks are included in that analysis (such as the importance of spawning and larval distribution relative to oceanographic currents for crab settlement). The paper focuses specifically on red king crab, as a case study, although a similar methodology is used for all crab species. The paper will also look at the importance of southwestern Bristol Bay for red king crab populations, and whether and how interactions with the trawl fisheries in that area may be impacting the crab stock. The paper evaluates existing crab protection areas in light of new information about shifting populations, and identifies some possible avenues for future Council action.

2 Current EFH description for red king crab

EFH descriptions are defined for by life history stage for managed species. The following information is available for defining EFH for red king crab:

BSAI Crab Species	Egg	Larvae	Early Juvenile	Late Juvenile	Adult
Red king crab	Inferred (from adult) – level 1	n/a	n/a	1	1

Level 1 means that distribution data are available for some or all portions of the geographic range of the species. At this level, only distribution data are available to describe the geographic range of a species (or life stage). Distribution data may be derived from systematic presence/absence sampling and/or may include information on species and life stages collected opportunistically. In the event that distribution data are available only for portions of the geographic area occupied by a particular life stage of a species, habitat use can be inferred on the basis of distributions among habitats where the species has been found and on information about its habitat requirements and behavior. Habitat use may also be inferred, if appropriate, based on information on a similar species or another life stage.

Methodology for existing EFH descriptions for crab stocks

EFH is described as 95 percent of the population where the species' life stage has been recruited to the survey, investigated through research, officially observed, or reported in a vessel catch log.
In addition to scientific information sources the description is based upon two significant fishery geographic information data resources: survey (Resource Assessment and Conservation Engineering Division [RACE]) and observer (NORPAC). For eggs and larvae, the EFH description was based on presence/absence data from surveys (AFSC RACE Matarese 2003). Under this methodology, for crab species, no EFH description was possible for these life history stages. An EFH description for eggs was inferred from the EFH description for egg-bearing female crab.

For adult and late juvenile life stages, each data set was analyzed for 95 percent of the total accumulated population for the species using GIS. EFH shape files were developed based on these data sets.
Fishery catch per unit of effort (CPUE) data from the NMFS observer database (NORPAC, 1990 to 2001), NMFS trawl survey data from RACE, 1987 to 2002, and, where appropriate, ADF&G survey data were analyzed to estimate the population distribution of each species. Where this information exists, the area described by these data is identified as EFH. The analyzed EFH data and area were further reviewed by scientific stock assessment authors for accuracy. Stock expert review ensures any outlying habitat areas not captured by the CPUE data are included and errors in the data or described EFH area.

Red king crab EFH description

The following is the EFH text description for red king crab, by life history stage:

Eggs
Essential fish habitat of the red king crab eggs is inferred from the general distribution of egg-bearing female crab. (See also Adults.)

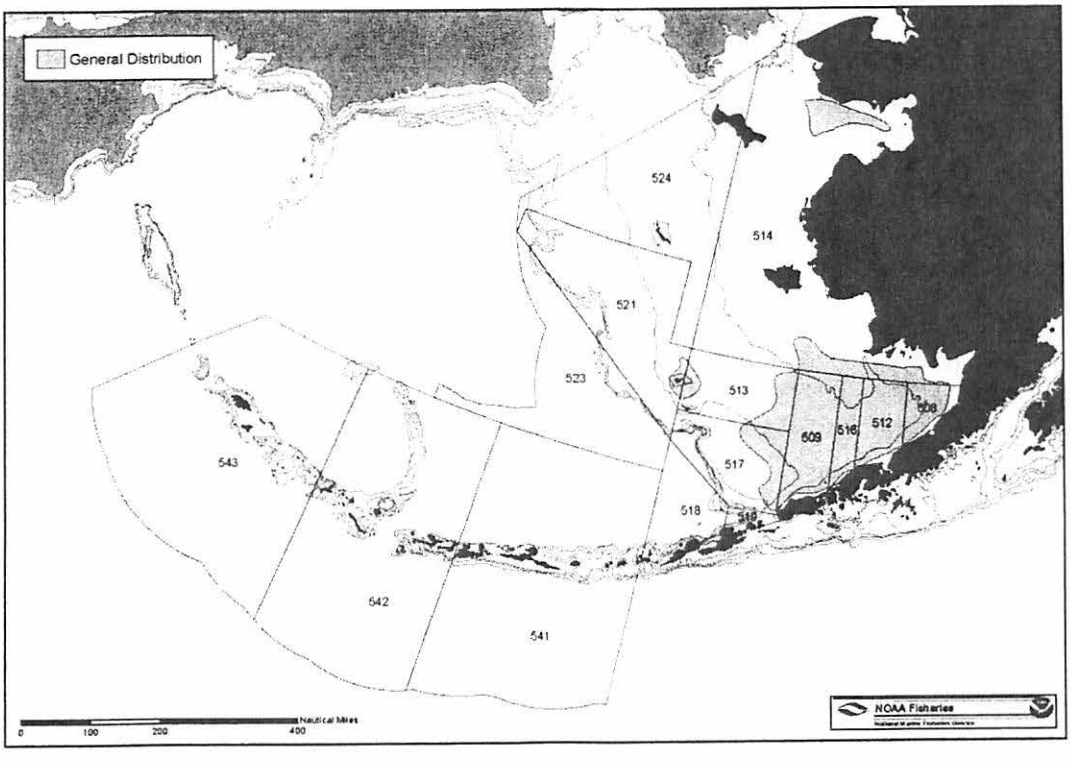
Larvae—No EFH Description Determined
Insufficient information is available.

Early Juveniles—No EFH Description Determined
Insufficient information is available.

Late Juveniles
EFH for late juvenile red king crab is the general distribution area for this life stage, located in bottom habitats along the inner (0 to 50 m), middle (50 to 100 m), and outer shelf (100 to 200 m) throughout the BSAI wherever there are substrates consisting of rock, cobble, and gravel and biogenic structures such as boltenia, bryozoans, ascidians, and shell hash, as depicted in Figure 1.

Adults
EFH for adult red king crab is the general distribution area for this life stage, located in bottom habitats along the nearshore (spawning aggregations) and the inner (0 to 50 m), middle (50 to 100 m), and outer shelf (100 to 200 m) throughout the BSAI wherever there are substrates consisting of sand, mud, cobble, and gravel, as depicted in Figure 1.

Figure 1 EFH Distribution map for BSAI red king crab, late juveniles/adults



3 Habitat needs for crab stocks

Crab species in the eastern Bering Sea have similar life history events. Females brood their embryos, which are released into the water column as larvae. Mature red king crab females migrate into relatively shallow waters (< 50 m) in nearshore areas where they aggregate and release larvae, molt, mate, and extrude eggs (Armstrong et al., 1987; Stone et al., 1992; Stone et al., 1993, Loher and Armstrong 2005). Egg extrusion and hatching is relatively synchronous in red king crab and occurs every year (unlike blue king crab; Somerton and MacIntosh 1985). Adults have a much lower predation risk, so the ability of habitat to provide a predation refuge becomes less important as crab mature. However, because the crab are densely aggregated in these habitats and because of their soft shell condition, they are vulnerable at this critical period in their life history. Since the larvae from these females spend an extended period in the plankton and are transported far from the release site, there may be particular areas, such as the western end of the Alaska Peninsula, that are disproportionately important, as larvae released there are more likely to end up in prime settling areas than are larvae released elsewhere, based on prevailing currents (Dew and McConnaughey, 2005). The spatial distribution of mature females prior to larval release and locations of crab larvae settlement may also be important for positive recruitment (Zheng and Kruse 2006). The benthic environment or habitat occupied by molting and mating crab differs from that occupied by mature crabs during the remainder of the year when they move offshore to soft substrates (Rodin 1989).

Larval stage survival is likely dependent on environmental conditions and is tied to successful settlement. Crab larvae spend several months feeding in the pelagic habitat, except for golden king crab larvae which are likely benthic and do not feed. The habitat for larvae of all the crab species except golden king crabs (Shirley and Zhou 1997) is the pelagic zone, generally close to the surface. Larval stages are distributed according to vertical swimming abilities, the oceanographic currents, and mixing or stratification of the water column. Larvae, like many other zooplanktonic species, exhibit a diel vertical migration, probably to minimize predation risk during the day and maximize feeding at night (Armstrong et al., 1987; McMurray et al., 1984). The habitat is primarily defined by the physical characteristics of the water column, such as temperature and salinity, and each species has a tolerance range for these parameters (e.g., Shirley and Shirley, 1989). Temperature, salinity, vertical mixing, and upwelling can also influence food availability for the larvae, which can influence recruitment (Rosenkranz et al., 1998; Rosenkranz et al., 2001; Zheng and Kruse, 2000). Finally, current structure is very important in transporting larvae to suitable settling habitat or retaining larvae within a region (Rosenkranz et al. 1998, Rosenkranz et al. 2001). Larvae molt two to three times before metamorphosizing into a settling stage (glaucothoe for king crabs, and megalops for the *Chionoecetes* spp.).

Defining the environmental conditions important for larval survival is difficult, while settlement habitat requirements are better understood. The settling stage seeks and settles in suitable benthic habitat where they molt into the first crab stage. Young of the year red king crab require nearshore shallow habitat with significant cover that offers protection (e.g., sea stars, anemones, macroalgae, shell hash, cobble, and shale).

Juvenile populations are most likely limited by predation; thus, their habitat requirements are defined by their anti-predator strategy. Juvenile red king crab have been shown to prefer nearshore habitats of high complexity (Loher and Armstrong 2000). Red king crab juveniles are associated with both biogenic structure, such as sea stars, bryozoans, or tube worms for feeding and refuge (Dew, 1990; McMurray et al., 1984; Sundberg and Clausen, 1977), and non-biogenic structure, such as cobble or shell hash (Loher and Armstrong, 2000). However, many of these studies occur offshore while the age-0 juvenile crab most likely representative of larval dispersion are located in shallow areas closer to shore than most surveys.

4 Evaluation of the effects of fishing in the 2005 EFH EIS

The EFH EIS draws conclusions about the effects of fishing on crab habitat essential for four requirements (spawning, rearing, feeding, and growth to maturity). The following subsections provide information directly from Appendix B of the 2005 EFH EIS that pertains to red king crab.

4.1 Red king crab habitat linkages

Habitat effects on crab concern effects on prey and on living and non-living structures on and in the ocean bottom. Effects on the population due to bycatch in trawl fisheries are not included as a habitat effect. Direct effects due to bycatch mortality in trawl fisheries on crab populations were addressed in the PSEIS (NMFS 2004). The focus of the EFH EIS is on the linkages to fishing-induced impacts on habitat and their subsequent effects on spawning/breeding, growth to maturity, or adult feeding of red king crab.

Spawning/Breeding

Spawning and breeding success of crab species depends upon high egg-fertilization rate, successful transport of pelagic larvae to nursery areas, good environmental conditions, and survival to the adult stage. Egg fertilization success depends upon the size and number of mature male crabs (and hence the amount of sperm) available. The eggs are attached to the underside of females and carried for nearly a year before hatching. Transport of larvae depends upon environmental conditions, and survival depends upon the quantity and quality of nursery habitat and the presence of predators.

Settlement and nursery areas are important components of spawning success for crab species. In the southeastern BS, females remain in relatively shallow nearshore waters most of the year, whereas males move offshore into deeper water during the summer and fall, then return to shallower water for breeding in the winter and early spring (Loher 2001). The location of females hatching eggs and prevailing currents determine the general area where larvae settle. Settling larvae have moderate swimming capability and have some ability to choose the micro-habitat where they settle (Loher 2000). Suitable substrates for survival of settling larvae appear to be largely rock or cobble bottoms, or mussel beds (Stevens and Kittaka 1998).

Adult Feeding

From settling larvae to senescence, crabs dwell on the bottom and depend on benthic feeding. Red king crabs are omnivorous. Bivalves, barnacles, polychaetes, snails, Tanner crab, echinoids, and hydroids have been found in stomachs of red king crab from shallow waters near Kodiak during May and June (Feder and Jewett 1981). Juvenile red king crab near Kodiak have been observed to eat sea stars, kelp, sea lettuce, red king crab molt exuvia, lettleneck clams, mussels, nudibranch egg masses, and barnacles (Dew 1990).

Growth to Maturity

Early stage red king crabs seek out biological cover in which to hide. Survival at this stage depends upon availability of cover. After they reach a size exceeding 25-millimeter (mm) carapace length, red king crabs form pods, which consist of similar sized crabs of both sexes, and may contain hundreds to thousands of crabs. Pods of juvenile crabs form during the daytime, but disperse at night for feeding. As crabs grow, they move to deeper water in Bristol Bay where the substrate is mostly sand, silt, and mud.

4.2 Conclusions about fishing impacts on crab EFH

For red king crab, the effects of fishing on EFH in the 2005 EFH EIS are summarized as follows:

Spawning/breeding	MT (Minimal, temporary, or no effect)
Feeding	U (Unknown effect)
Growth to maturity	MT (Minimal, temporary, or no effect)

Habitat Impacts Relative to Spawning/Breeding

There is only a small area of overlap between current female red king crab distribution and areas where trawling occurs. This overlap would only occur in the areas between about 162 and 163° W, where fishing effects are generally low. Male and female red king crabs migrate to nearshore waters generally less than 50 m deep to hatch their eggs and mate. North of Unimak Island, some of the high fishing effects area extends into waters less than 50 m deep; however, to the east, trawling generally occurs more than 50 m deep. The mating areas would experience little impact; however, trawling in deeper waters somewhat overlaps the migration route to mating areas.

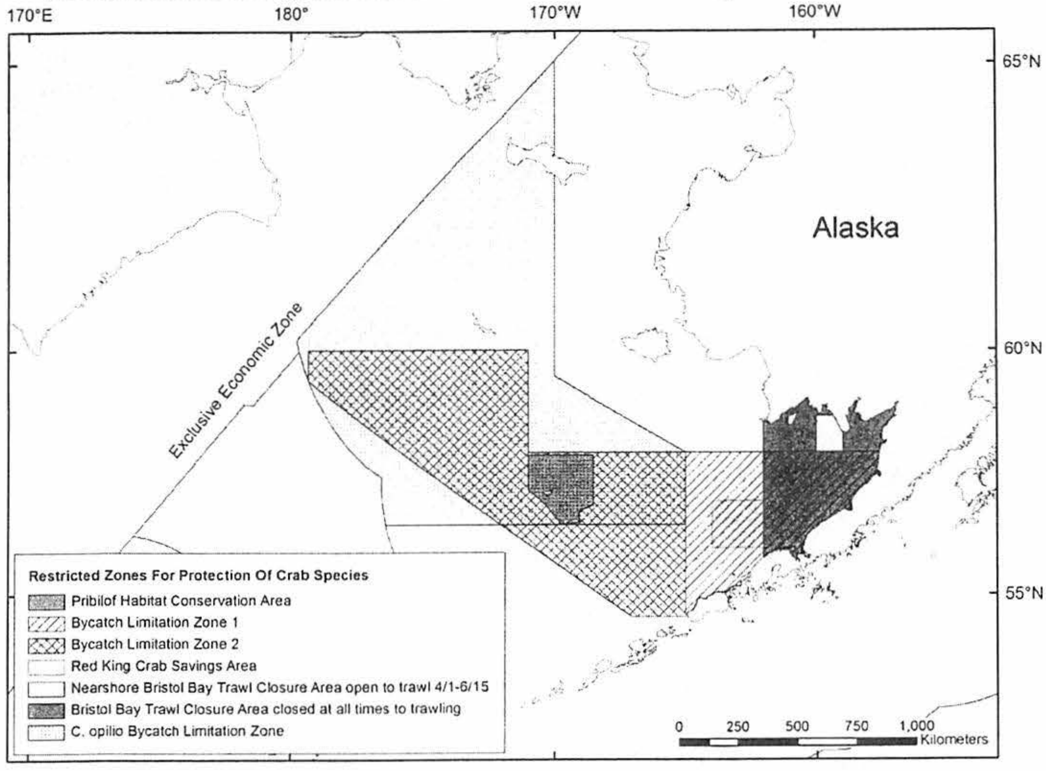
Habitat Impacts Relative to Feeding

Changes in growth for Bristol Bay red king crab are unknown. Most of the distribution of red king crab is to the north and east of the high fishing effects areas.

Habitat Impacts Relative to Growth to Maturity

There are essentially no fishing effects in areas important to juvenile red king crab. All known juvenile rearing areas are currently protected by trawl closure areas (Figure 2). Growth per molt for BS red king crab showed no change between the late 1950s and the 1990s based on tag data (Council 2004). Molting probability during different time periods has been estimated in a stock assessment model; however, parameters are confounded by change with natural mortality, and it is difficult to assess the age of crab. Molting probability was estimated as higher in the 1950s and lower in the 1960s from tag data (Balsiger 1974). Model estimates of molting probability were higher in the 1970s than those from the 1960s tag data and have been lower since then (Council 2004).

Figure 2 Restricted Zones for protection of crab in the eastern Bering Sea.



5 How might a better methodology for evaluating adverse impacts of fishing on crab EFH be devised?

To build upon previous analyses that assessed the available data on particular life history stages, future analyses should include modeling tools to extend the empirical data to probabilistic determinations of impacts on crab populations. The 2010, a CIE review of the Bristol Bay red king crab stock assessment model determined that a more descriptive understanding of the key temporal and spatial biological processes is necessary. Life history characteristics should include primiparous and multiparous mating locations and timing, hatching, larval period and movement, settlement period and location, growth at each stage, molt frequency and timing, time and size at maturity, and adult migration patterns. More specific understanding of these stages would promote a better understanding of habitat requirements and potential impacts of fishing on each stage. Such a conceptual model would help to interpret survey and model results as well as assess key bottlenecks in the life history to identify habitat fishery removal specific concerns.

An additional analysis to evaluate the adverse impacts of fishing would be to build upon the conceptual model approach to quantify potential losses as a result of management actions. This could occur in concert with a Management Strategy Evaluation with the existing stock assessment model or more directly applied to a specific life history parameter. To assess the impacts of fishing on adult female red king crab in southwestern Bristol Bay, a retrospective assessment of potential losses to reproductive fitness may lend insight into the relative importance of protecting habitat important for larval drift and subsequent recruitment into the important Bristol Bay habitat.

Lastly, and in concert with the above two approaches, a more detailed analysis of the importance of the physical environment on various stages of development is necessary to properly understand how temporally or spatially specific removals would impact a stocks. It is not, however, satisfactory to say that these influences are unknown and therefore the impacts are likely unimportant. Coupled bio-physical models to better understand the effects of temperature and currents on larval drift and the effects of changing the release site as a result of commercial removals would be an important step forward.

6 Distribution of the red king crab population and southwestern Bristol Bay

The Crab Plan Team identified a particular area in southwest Bristol Bay where there has recently been an increase in the red king crab population, and where there has also been an increase in trawling activity over the last 5 years. This section evaluates the potential for adverse interactions of trawling on crab in this area, and whether any adverse interaction is likely to be from increased bycatch and mortality and/or adverse modification of habitat that is essential to increasing the red king crab population.

6.1 Importance of southwestern Bristol Bay

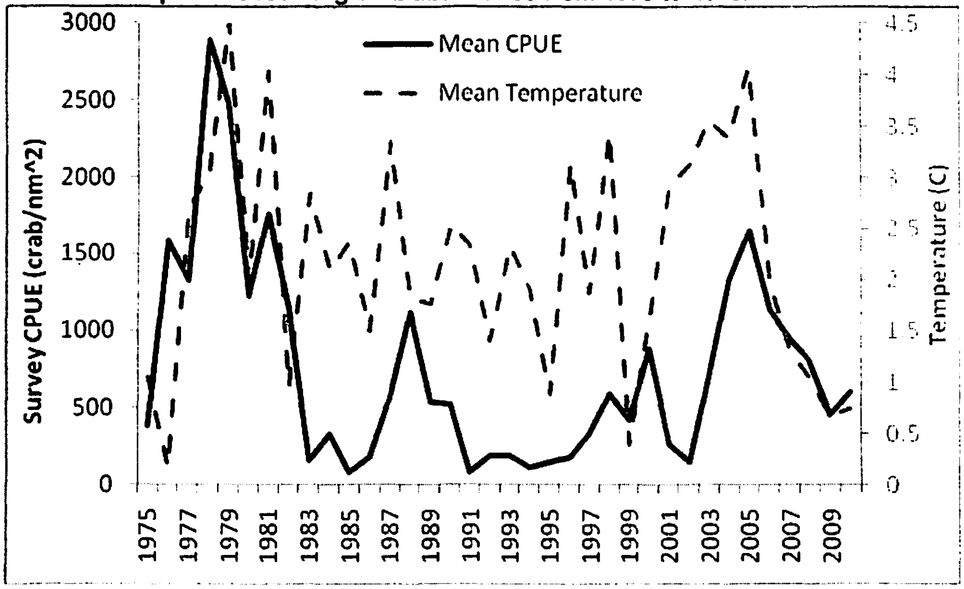
The Bristol Bay red king stock assessment and the technical memo reporting on the results of the NMFS eastern Bering Sea bottom trawl survey described the increase of adult red king crab in the southwestern region of Bristol Bay. While the spatial distribution of red king crab fluctuates, a significant presence in this region has not been seen since the 1970s. Previous publications have commented on the likely importance of the region for larval release (Dew and McConnaughey, 2005), however, mechanisms have not been developed further. In a recent publication regarding the effects of temperature in Bristol Bay on red king movement and molt-mate timing, the effects of the "cold pool" moving adult red king crab into the nearshore region and possibly laterally along the shore were discussed (Chilton et al. in press). This region may be critical to providing the Bristol Bay red king crab stock with high recruitment events not observed since the 1970s. The specific identification of this region will require a multivariate analysis of environmental variables and timing related to adult female movement associated with larval hatching, molting, and mating. The importance of this region to positive recruitment in the Bristol Bay stock will require additional analyses on regional temperatures (affecting larval growth) and currents (affecting larval transport distance).

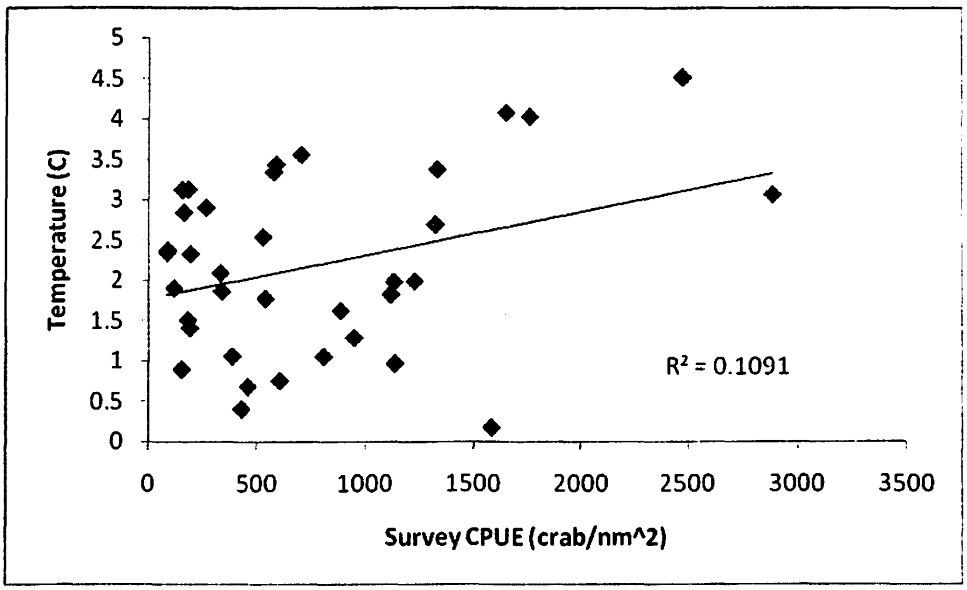
6.2 Changing distribution of red king crab throughout their range

NMFS survey data

The NMFS eastern Bering Sea bottom trawl survey collects data on the red king crab distribution in June each year (Chilton et al. 2011). This time period is in the middle of when red king crab molt and mate. In cold years the survey misses this event and in warm years collects crab just subsequent to this event (Chilton et al. in press). Since the beginning of the survey, the abundance of adult female red king crab increased to a maximum 3,000 crab/nmi^2 in the late 1970s before declining rapidly in the early 1980s (Figure 3). Abundance remained at a lower mean except for recruitment events in 1988, 2000, and 2005. Female red king crab were located inside Bristol Bay during 1980-1987 and 1992-2006 (Zheng and Kruse 2006). From 1988-1991, the adult female distribution slightly shifted south but not near the maximum southern extent previously found in the 1970s. Loher and Armstrong (2005) hypothesized that a similar shift in inner Bristol Bay during the late 1970s and early 1980s was the result of increased bottom temperatures. In more recent years when the cold pool extended onto the Bristol Bay shelf area in 2006-2010, the summer distribution of ovigerous RKC had moved from the central area of Bristol Bay to the nearshore areas along the Alaska Peninsula (Zheng and Siddeek 2010, Chilton et al. *in review*).

Figure 3 **Relationship of survey mean CPUE of adult female red king crab with mean temperature of all stations with positive red king crab abundance from 1975 to 2010.**





Changes in the seasonal variability and magnitude of bottom water temperatures impact the amount of benthic habitat available to crab species during critical life history stages. As an example, mature female snow crab distribution in the eastern Bering Sea shifted to the northwest EBS shelf concurrent with temperature decreases (Orensanz et al. 2004). To relate adult female abundance and potential influence of temperature on red king crab production temperature was overlaid on the time series of CPUE (Figure 4). Peak mean CPUEs correspond with increases in warmer temperature suggesting a number of possible mechanisms. First, the survey may be missing adult crab during the colder year due to movement. Second, there may be a positive feedback in larval recruitment during cold years that produce large abundances of adult crab and an apparently negative feedback on larval survival in warm years. To look for corresponding differences in variability between temperature and adult abundance, the standard deviation of both were plotted with little evidence of a consistent relationship (Figure 5).

Figure 4 **Mean adult female red king crab CPUE across all stations in the Bristol Bay red king crab management area with dark bars representing warm years and light bars representing cold years from 1975 to 2010.**

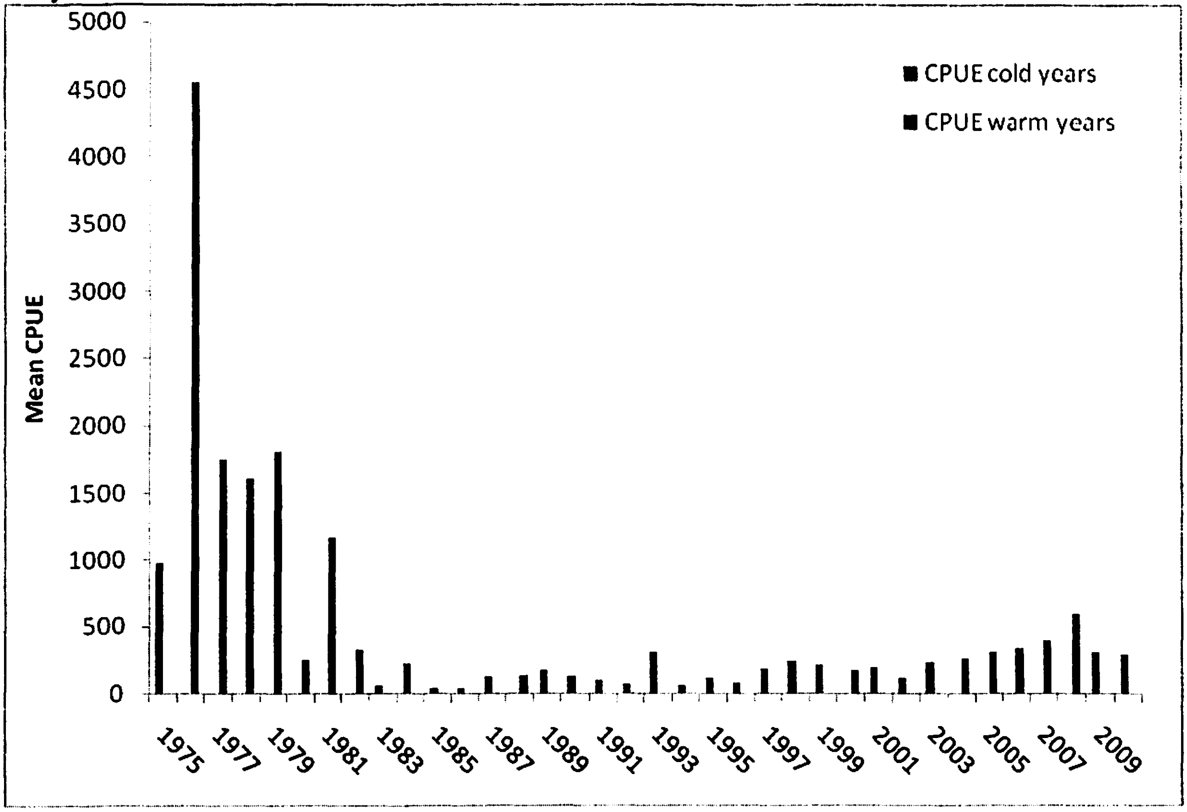
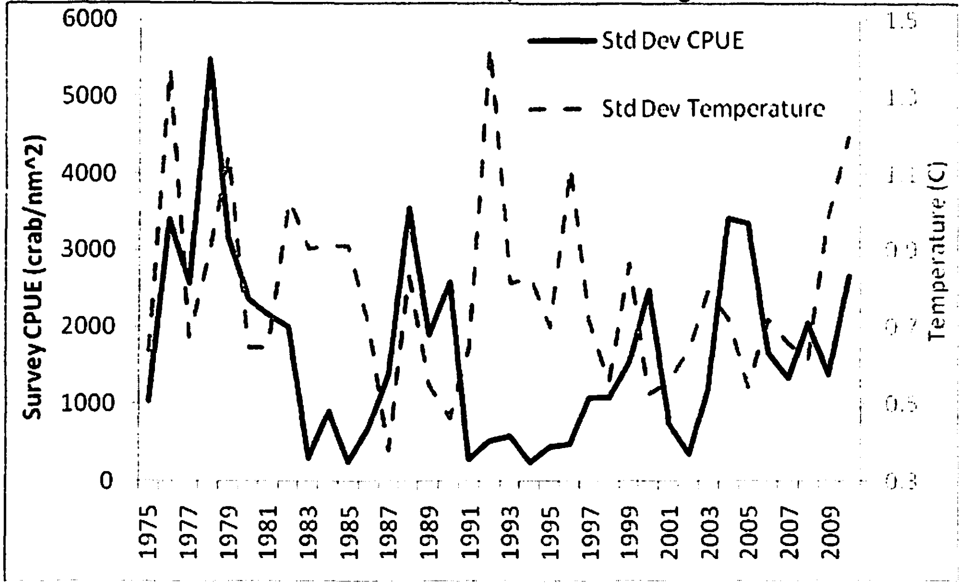
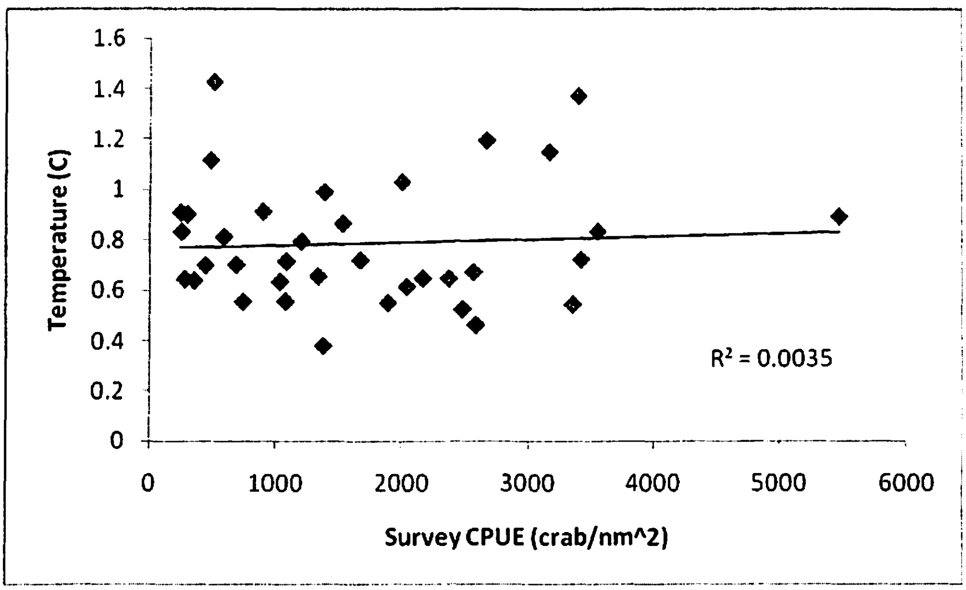


Figure 5 Relationship of survey standard deviation of adult female red king crab CPUE with the standard deviation of temperature of all stations with positive red king crab abundance from 1975 to 2010.

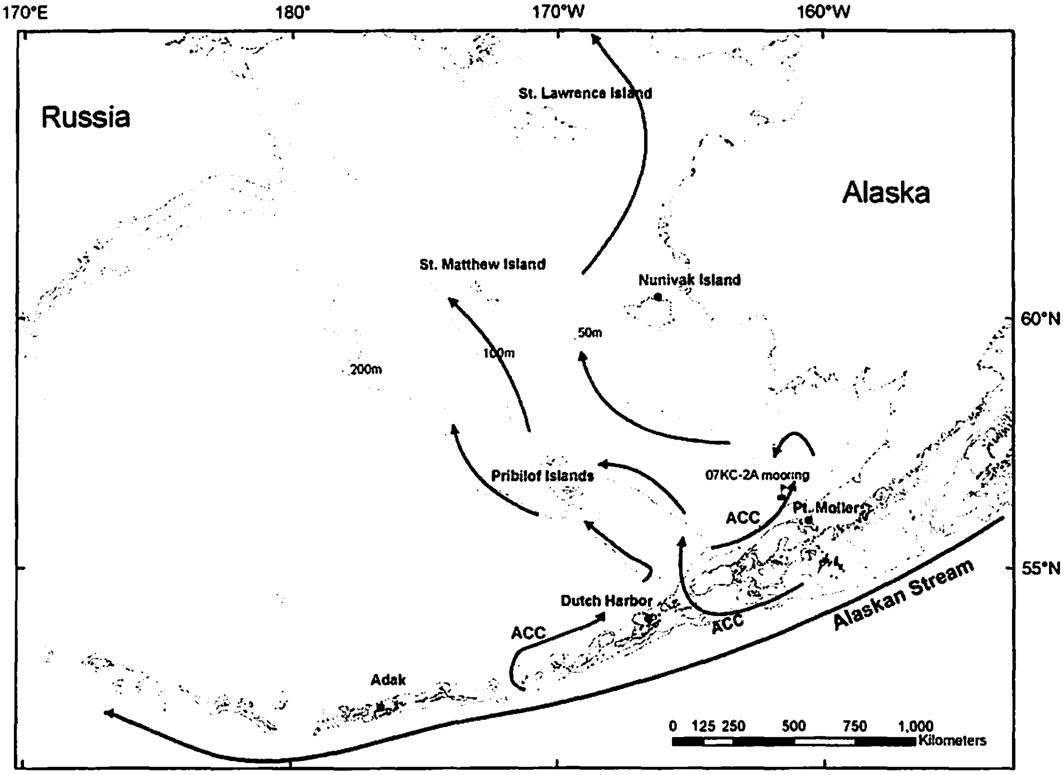




Role of environmental variables

Red king crab recruitment has been related to larger scale climate variability. As stated above year class strength has been negatively correlated with temperature but weak relationships suggest that temperature alone does not account for all the variability in year class strength (Zheng and Kruse 2000). Additional environmental variables such as the intensity of the Aleutian Low atmospheric pressure system is positively correlated with year class strength (Tyler and Kruse 1996; Zheng and Kruse 2000). Variables affecting larval survival and dispersal are likely important for red king crab. As an example in eastern Bering Sea Tanner crabs, warm seawater temperatures during gonadal development and embryo incubation coupled with northeast winds during the larval stages promote larval survival (Rosenkranz et al. 2001). Therefore, having an understanding of expected climatic variability is critical for forecasting crab behavior and identifying management efforts that may mitigate some of the effects. Predictions of climate forcing changes in the Bering Sea region include increases in air temperature, storm intensity, storm frequency, southerly wind, humidity, and precipitation (Barange and Perry 2009, Brander 2010, Hoegh-Guldberg and Bruno 2010). As a result, the Alaska Stream, Near Strait Inflow, Bering Slope Current, and Kamchatka Current are likely to affect changes in Unimak Pass inflow, the shelf coastal current, and the Bering Strait outflow. Figure 6 shows the currents important to red king crab larval dispersal in the western Bristol bay region. These changes lead to uncertain impacts on red king crab larval habitat requirements however they highlight the importance of collecting baseline information to forecast impacts.

Figure 6 **Current structure in the eastern Bering Sea shelf.** Oceanographic mooring 2A (KC-2A) location depicted with a flag and the flow of the Alaska Coastal Current (ACC) from the Gulf of Alaska into the eastern Bering Sea is shown. (Adapted from Stabeno et al. 2001).



7 Research questions

- **Adult distribution (tagging and observation):** As both red king crab and Tanner crab aggregate during larval release, molting, and mating, it is imperative to identify the habitats and areas in which these occur. By dual tagging ovigerous females during the EBS Trawl Survey with pop-up tags programmed to pop-up during the larval release season and acoustic tags, we should be able to locate the general area of hatching from the pop-up tag, and then locate the females or their exoskeletons (as they molt soon after hatching) at a much smaller scale using the acoustic tag. An alternative means of locating the aggregations would be to use a high-resolution side-scan sonar to locate the females. Then a remotely operated vehicle or video sled would be used to estimate habitat type and abundance of females in the area. This work would help to identify the specific areas of larval release.
- **Juvenile assessment:** Assess juvenile crab distribution in the nearshore region of Bristol Bay to predict likely larval release locations (based on temperature and current patterns) in cold and warm year. This study would include both Tanner and red king crab because both species demonstrate aggregative hatching behavior which makes them prime candidates for examining

how larval release area affects recruitment and because they are likely to recruit into similar areas along the nearshore of Bristol Bay. To date, dive surveys have been the most reliable methods for juvenile crab habitat assessment due to the small and cryptic nature juveniles (Loher and Armstrong, 2000; Sundberg and Clausen, 1977). In 2010 an effort is underway in collaboration with the Bering Sea Research Foundation and the National Marine Fisheries Service to conduct nearshore surveys using a small mesh net to assess potential future recruits to the Bristol Bay red king crab stock.

- **Larval assessment:** Although larval assessment is time and cost intensive, the previous two projects could be combined with intensive sampling for larval crab. The movement of larvae could be documented and used to parameterize a larval drift model by sampling multiple times over the summer. By combining this data with data on juvenile habitat from the previous project, the most important hatching areas could be identified.
- Conduct a time series analysis on female egg condition and distribution (eg. Chilton et al. in press) with a focus on spatial distribution along the outer edges of the Bristol Bay stock.
- Conduct a time series analysis of environmental conditions and red king crab abundance related to recruit abundance to assess potential stock production processes related to temperature fluctuations in the eastern Bering Sea.

8 Options for Council action

This discussion paper provides an initial look at some of the concerns raised by the Crab Plan Team during the EFH 5-year review in 2010. The 2005 EFH EIS ties the evaluation of fishing impacts on habitat specifically to living and non-living structures on and in the ocean bottom. For crab species, however, oceanic parameters and pelagic habitat are critical for spawning success. Given the additional background provided in this discussion paper, the Council should decide whether further evaluation of this effects analysis is called for. Of note, the Crab Plan Team has not had an opportunity to review this discussion paper, as their next meeting does not take place until May 2011.

With respect to the protection of red king crab in southwestern Bristol Bay, there are also several avenues available to the Council. Some suggestions for possible Council action are the following:

- No management action, but encourage further research in this area to better understand adult, juvenile and larval distribution and habitat usage
- Extend or establish trawl closure areas in the affected area as EFH conservation measures
  - Extend the range of the red king crab savings area to protect more of the stock.
  - Apply a seasonal closure to protect the adult female red king crab from March to May during molting and mating
  - Close area southwest of Amak Island
- Designate a HAPC priority for areas important for red king crab egg hatching, and consider designating this area as a HAPC

9 Literature Cited

Armstrong, D.A., Armstrong, J.L., Jenson, G., Palacios, R., Williams, G., 1987. Distribution, abundance, and biology of blue king and Korean hair crabs around the Pribilof Islands, Outer Continental Shelf Environmental Assessment Program: Final Reports of Principal Investigators. U.S. Department of Commerce, NOAA, pp. 1-278.

Barange, M. and R. I. Perry. 2009. Physical and ecological impacts of climate change relevant to marine and inland capture fisheries and aquaculture. In K. Cochrane, C. De. Young, D. Soto, and T. Bahri (eds). Climate change implications for fisheries and aquaculture: overview of current scientific knowledge. FOA Fisheries and Aquaculture technical paper. No. 530. Rome, FAO. pp 7-106.

Chilton, E.A., C.E. Armistead, and R.J. Foy. 2011. The 2011 eastern Bering Sea continental shelf bottom trawl survey: results for commercial crab species. NOAA Tech. Memo. NMFS AFSC 1989. 144 pp.

Dew, C.B., 1990. Behavioral ecology of podding red king crab, *Paralithodes camtschatica*. Canadian Journal of Fisheries and Aquatic Sciences 47, 1944-1958.

Dew, C.B., McConnaughey, R.A., 2005. Did trawling on the brood stock contribute to the collapse of Alaska's king crab? Ecological Applications 15, 919-941.

Loher, T., and D.A. Armstrong. 2005. Historical changes in the abundance and distribution of ovigerous red king crabs (*Paralithodes camtschaticus*) in Bristol Bay (Alaska), and potential relationship with bottom temperature. Fish. Oceanogr. 14:292-306.

Loher, T., Armstrong, D.A., 2000. Effects of habitat complexity and relative larval supply on the establishment of early benthic phase red king crab (*Paralithodes camtschaticus* Tilesius, 1815) populations in Auke Bay, Alaska. Journal of Experimental Marine Biology and Ecology 245, 83-109.

Loher, T., Armstrong, D.A., 2000. Effects of habitat complexity and relative larval supply on the establishment of early benthic phase red king crab (*Paralithodes camtschaticus* Tilesius, 1815) populations in Auke Bay, Alaska. Journal of Experimental Marine Biology and Ecology 245, 83-109.

McMurray, G., Vogel, A.H., Fishman, P.A., 1984. Distruibution of larval and juvenile red king crab (*Paralithoides camtschatica*) in Bristol Bay, Outer Continental Shelf Environmental Assessment Program: Final Reports of Principal Investigators. U.S. Department of Commerce, NOAA, pp. 267-477.

NMFS. 2004. Final Environmental Impact Statement for Bering Sea and Aleutian Islands Crab Fisheries. National Marine Fisheries Service, Alaska Region

Orensanz, J., Ernst, B., Armstrong, D., Stabeno, P., Livingston, P., 2005. Contraction of the Geographic Range of Distribution of Snow Crab (Chionoecetes opilio) in the Eastern Bering Sea: An Environmental Ratchet? Reports of California Cooperative Oceanic Fisheries Investigations 45, 65-79.

Orensanz, J.M., Ernst, B., Armstrong, D., Stabeno, P., Livingston, P., 2004. Contraction of the geographic range of distribution of snow crab (*Chionoecetes opilio*) in the eastern Bering Sea: An environmental ratchet? CalCOFI Rep. 45, 65-79.

Rosenkranz, G., Tyler, A., Kruse, G., Niebauer, H., 1998. Relationship between wind and year class strength of Tanner crabs in the southeastern Bering Sea. Alaska Fishery Research Bulletin 5, 18-24.

Rosenkranz, G.E., Tyler, A.V., Kruse, G.H., 2001. Effects of water temperature and wind on year-class success of Tanner crabs in Bristol Bay, Alaska. Fisheries Oceanography 10, 1-12.

Shirley, T., Shirley, S., 1989. Temperature and salinity tolerances and preferences of red king crab larvae. Marine and Freshwater Behaviour and Physiology 16, 19-30.

Shirley, T., Zhou, S., 1997. Lecithotrophic development of the golden king crab Lithodes aequispinus (Anomura: Lithodidae). Journal of Crustacean Biology 17, 207-216.

Stabeno, P.J., N.A. Bond, N.B. Kachel, S.A. Salo, and J.D. Schumacher. 2001. On the temporal variability of the physical environment over the south-eastern Bering Sea. Fish. Oceanogr. 10:81-98.

Stone, R., O'Clair, C., Shirley, T., 1992. Seasonal migration and distribution of female red king crabs in a southeast Alaskan estuary. Journal of Crustacean Biology 12, 546-560.

Stone, R.P., Oclair, C.E., Shirley, T.C., 1993. Aggregating behavior of ovigerous female red king crab, *Paralithodes camtschaticus*, in Auke Bay, Alaska. Canadian Journal of Fisheries and Aquatic Sciences 50, 750-758.

Sundberg, K., Clausen, D., 1977. Post-larval king crab (*Paralithodes camtschatica*) distribution and abundance in Kachemak Bay Lower Cook Inlet, Alaska, 1976. In: Trasky, L., Flagg, L., Burbank, D. (Eds.), Environmental studies of Kachemk Bay and Lower Cook Inlet. Alaska Department of Fish and Game, Anchorage.

Tyler, A.V. and G.H. Kruse. 1996. Conceptual modeling of brood strength of red king crabs in the Bristol Bay region of the Bering Sea, p. 511-543. In High Latitude Crabs: Biology, Management, and

Economics. Alaska Sea Grant College Program Report No. 96-02, University of Alaska, Fairbanks, AK.
Zheng, J., and G.H. Kruse. 2006. Recruitment variation of eastern Being Sea crabs: Climate-forcing or top-down effects? Prog. Oceanogr. 68:184-204.
Zheng, J., Kruse, G., 2000. Recruitment patterns of Alaskan crabs in relation to decadal shifts in climate and physical oceanography. ICES J. Mar. Sci. 57, 438.
Zheng, J., Kruse, G., 2000. Recruitment patterns of Alaskan crabs in relation to decadal shifts in climate and physical oceanography. ICES J. Mar. Sci. 57, 438.