# Norton Sound Red King Crab Stock Assessment for the fishing year 2017

Toshihide Hamazaki[1] and Jie Zheng[2]
Alaska Department of Fish and Game Commercial Fisheries Division
[1]333 Raspberry Rd., Anchorage, AK 99518-1565
Phone: 907-267-2158
Email: Toshihide.Hamazaki@alaska.gov
[2]P.O. Box 115526, Juneau, AK 99811-5526
Phone : 907-465-6102
Email : Jie.Zheng@alaska.gov

## Executive Summary

1. Stock. Red king crab, *Paralithodes camtschaticus*, in Norton Sound, Alaska.

2. Catches. This stock supports three important fisheries: summer commercial, winter commercial, and winter subsistence fisheries. Of those, the summer commercial fishery accounts for more than 90% of total harvest. The summer commercial fishery started in 1977, and catch peaked in the late 1970s with retained catch of over 2.9 million pounds. Since 1982, retained catches have been below 0.5 million pounds, averaging 0.275 million pounds, including several low years in the 1990s. Retained catches have increased to about 0.4 million pounds coincident with increases in estimated abundance in recent years.

3. Stock Biomass. Following a peak in 1977, abundance of the stock collapsed to a historic low in 1982. Estimated mature male biomass (MMB) has shown an increasing trend since 1997, but is highly uncertain due, in part, to infrequent trawl (every 3 to 5 years) and limited winter pot surveys.

4. Recruitment. Model estimated recruitment was weak during the late 1970s and high during the early 1980s, with a slightly downward trend from 1983 to 1993. Estimated recruitment has been highly variable but on an increasing trend in recent years.

5. Management performance.

*Status and catch specifications (million lb.)*

| Year | MSST | Biomass (MMB) | GHL | Retained Catch | Total Catch | OFL | ABC |
|---|---|---|---|---|---|---|---|
| 2013/14 | 2.06[A] | 5.00 | 0.50 | 0.35 | 0.35 | 0.58[A] | 0.52 |
| 2014/15 | 2.11[B] | 3.71 | 0.38 | 0.39 | 0.39 | 0.46[B] | 0.42 |
| 2015 | 2.41[C] | 5.13 | 0.39 | 0.40 | 0.52 | 0.72[C] | 0.58 |
| 2016 | 2.26[D] | 5.87 | 0.52 | 0.51 | 0.52 | 0.71[D] | 0.57 |
| 2017 | TBD | TBD | TBD | TBD | TBD | TBD | TBD |

*Status and catch specifications (1000t)*

| Year | MSST | Biomass (MMB) | GHL | Retained Catch | Total Catch | OFL | ABC |
|---|---|---|---|---|---|---|---|
| 2013/14 | 0.93[A] | 2.27 | 0.23 | 0.16 | 0.16 | 0.26[A] | 0.24 |
| 2014/15 | 0.96[B] | 1.68 | 0.17 | 0.18 | 0.18 | 0.21[B] | 0.19 |
| 2015 | 1.09[C] | 2.33 | 0.18 | 0.18 | 0.24 | 0.33[C] | 0.26 |
| 2016 | 1.03[D] | 2.66 | 0.24 | 0.23 | 0;24 | 0.32[D] | 0.26 |
| 2017 | TBD | TBD | TBD | TBD | TBD | TBD | TBD |

Notes:
MSST was calculated as $B_{MSY}/2$
A-Calculated from the assessment reviewed by the Crab Plan Team in May 2013
B-Calculated from the assessment reviewed by the Crab Plan Team in May 2014
C-Calculated from the assessment reviewed by the Crab Plan Team in May 2015
D-Calculated from the assessment reviewed by the Crab Plan Team in Jan 2016
E-Calculated from the assessment reviewed by the Crab Plan Team in Jan 2017
Conversion to Metric ton: 1 Metric ton (t) = 2.2046× 1000 lb

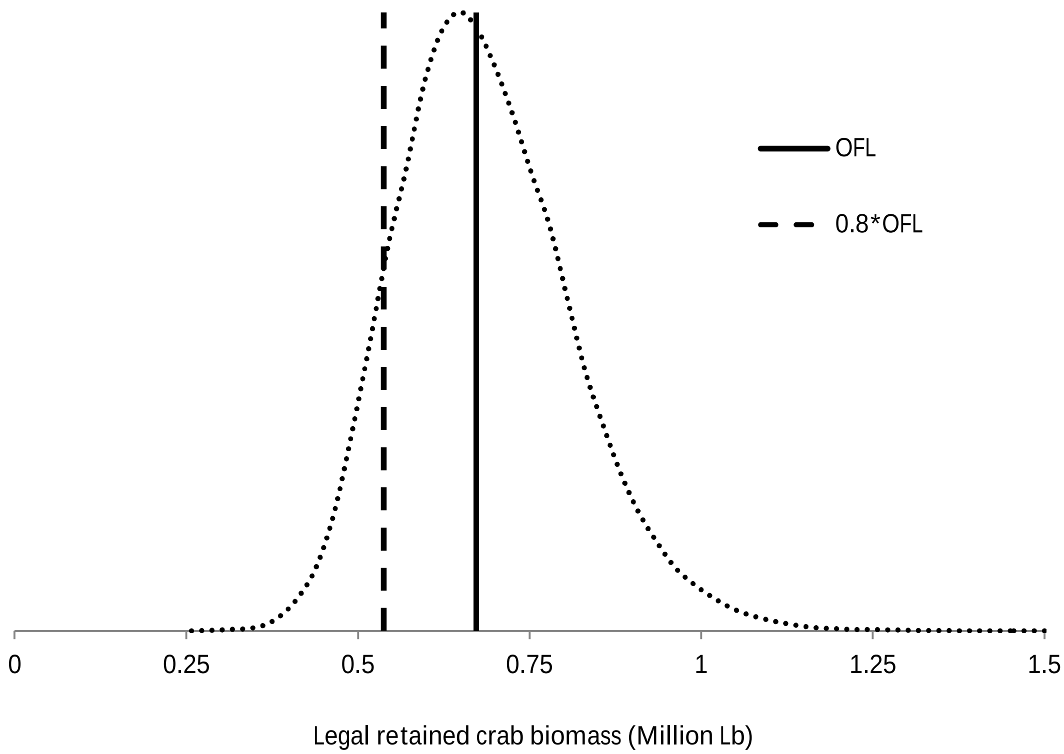
*Biomass in millions of pounds*

| Year | Tier | $B_{MSY}$ | Current MMB | $B/B_{MSY}$ (MMB) | $F_{OFL}$ | Years to define $B_{MSY}$ | M | 1-Buffer | ABC |
|---|---|---|---|---|---|---|---|---|---|
| 2013/14 | 4b | 4.12 | 5.00 | 1.2 | 0.18 | 1980-2013 | 0.18 | 0.9 | 0.52 |
| 2014/15 | 4b | 4.19 | 3.71 | 0.9 | 0.16 | 1980-2014 | 0.18 | 0.9 | 0.42 |
| 2015 | 4a | 4.81 | 5.13 | 1.1 | 0.18 | 1980-2015 | 0.18 | 0.8 | 0.58 |
| 2016 | 4a | 4.53 | 5.87 | 1.3 | 0.18 | 1980-2016 | 0.18 | 0.8 | 0.57 |
| 2017 | 4a | TBD | TBD | TBD | TBD | 1980-2017 | 0.18 | 0.8 | TBD |

*Biomass in 1000t*

| Year | Tier | $B_{MSY}$ | Current MMB | $B/B_{MSY}$ (MMB) | $F_{OFL}$ | Years to define $B_{MSY}$ | M | 1-Buffer | ABC |
|---|---|---|---|---|---|---|---|---|---|
| 2013/14 | 4a | 1.86 | 2.27 | 1.2 | 0.18 | 1980-2013 | 0.18 | 0.9 | 0.24 |
| 2014/15 | 4b | 1.90 | 1.68 | 0.9 | 0.16 | 1980-2014 | 0.18 | 0.9 | 0.19 |
| 2015 | 4a | 2.18 | 2.33 | 1.1 | 0.18 | 1980-2015 | 0.18 | 0.8 | 0.26 |
| 2016 | 4a | 2.06 | 2.66 | 1.3 | 0.18 | 1980-2016 | 0.18 | 0.8 | 0.26 |
| 2017 | 4a | TBD | TBD | TBD | 0.18 | 1980-2017 | 0.18 | 0.8 | TBD |

6. Probability Density Function of the OFL, OFL profile, and mcmc estimates.




7. The basis for the ABC recommendation

   For Tier 4 stocks, the default maximum ABC is based on P*=49% that is essentially identical to the OFL. Accounting for uncertainties in assessment and model results, the SSC chose to use 90% OFL (10% Buffer) for the Norton Sound red king crab stock from 2011 to 2014. In 2015, the buffer was increased to 20% (ABC = 80% OFL).

8. A summary of the results of any rebuilding analyses.

   N/A

## *A. Summary of Major Changes in 2016*

1. Changes to the management of the fishery:

   Winter commercial GHL goes into effect

2. Changes to the input data
   a. Data update: 2016 summer commercial fishery (total catch, catch length comp, discards length comp), 2015/2016 winter commercial and subsistence catch
   b. Data update: 1977-2016 standardized commercial catch CPUE and CV. No changes in standardization methodology (SAFE 2013).

c. Recalculation of the proportions of commercial crab harvests during the trawl surveys. Original data were based on equal daily harvest across the season. Now, the proportions are based on actual harvests.
This data change resulted in a decline of the 2016 projected MMB from 5.87 (SAFE 2016) to 5.60 million or about 5% (Figure 4a,b).

3. Changes to the assessment methodology:

   None

4. Changes to the assessment results.

   None

B. ***Response to SSC and CPT Comments***

Crab Plan Team – Sept. 22, 2016

- Consider calculating molt probability for each size class. Apply a smoothing penalty on the molt probabilities of individual size classes. Don't set the molt probability for the smallest size class at 1.0.

  Authors' reply:

  We tested this by estimating molt probability by for each length (Models 1 and 2). A second order smoothing penalty was incorporated into likelihood calculation as follows:

$$W_s \sum_{l=1}^{l=n-2}\left[\left(\ln(m_{l+2}) - 2\cdot\ln(m_{l+1}) + \ln(m_l)\right)^2 + \sum_j \left(\ln(S_{j,l+2}) - 2\cdot\ln(S_{j,l+1}) + \ln(S_{j,l})\right)^2\right]$$

  where $m_l$ is a molting parameter of length class $l$. We also expanded this to selectivity parameters $S_{j,l}$ where $j$ can be trawl survey, summer commercial fishery, and/or winter pot survey/harvest. Penalty weight $Ws$ was set to 3.0 because it resulted in reasonably smooth molting probability and selectivity. We also experimented with 3rd order smoothing penalty; however, the penalty did not perform as well as 2nd order penalty.

  Alternatively, we also put a reverse-logistic curve form to the original form of fixing the molting probability of the smallest sized crab to 0.9999: from

$$m_l = 1 - \frac{1}{1 + e^{(\alpha(L_1 - L) + \ln(1/0.001 - 1))}}$$

  to

$$m_l = 1 - \frac{1}{1 + e^{-\alpha(l-\beta)}}$$

In this form, the highest molting probability was estimated from the model.

We estimated parameters in both fixed (Alt Model 3) and random walk (Alt Model 4).

- Explore for correlation between Model 2 random walk and temperature

Authors' reply:
We obtained Nome airport air temperature data from 1976 to 2016. Of those, molting parameter deviations were the most correlated with July mean temperature ($R^2 = 0.09$).

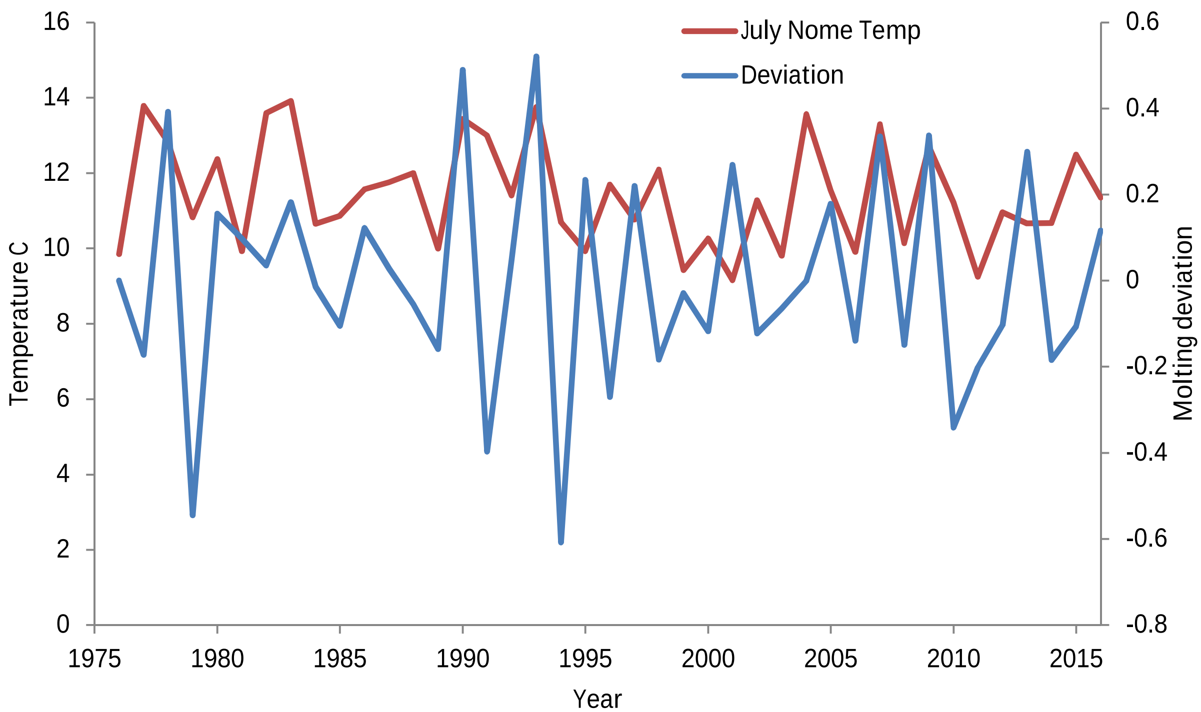



Figure A: Molting deviations and July Nome air temperatures (Model 2: CPT Sept 22).

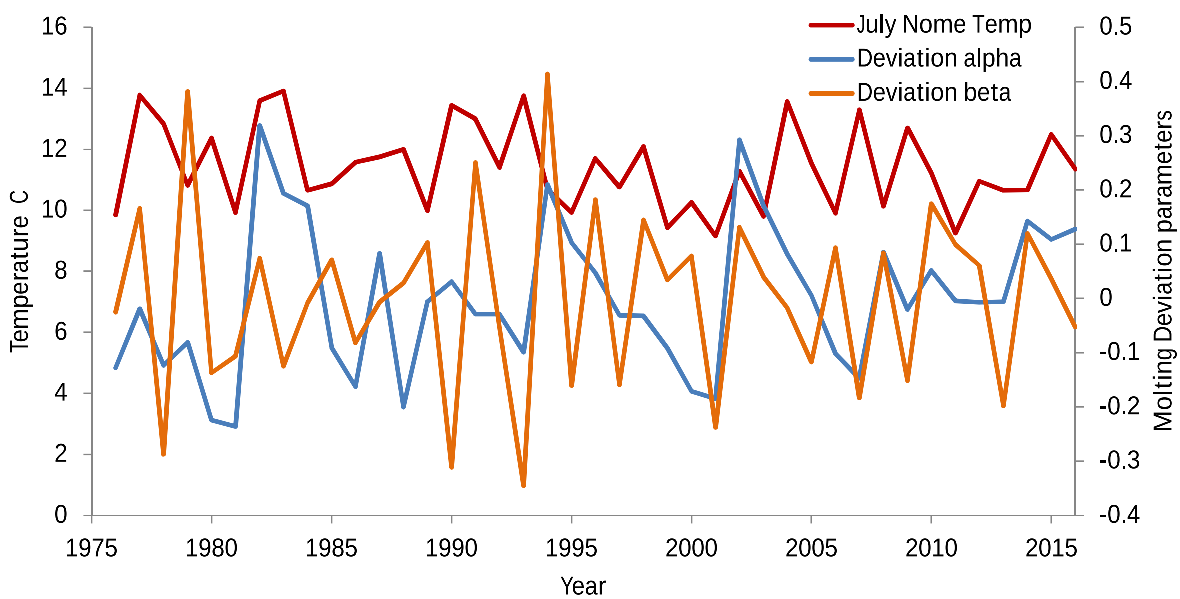



Figure B: Molting deviations and July Nome air temperatures (Model 4)

- Estimate molt probabilities with the time series broken into two periods

Authors' reply: We were unable to perform this request because molting deviation time series did not show any discernible patterns that reasonably justify time series separation (Figures A & B). We welcome CPT's suggestion of possible two periods.

- **In summary, the CPT recommends bringing forward Model 0 (base model), but also Model 2 with some of the variations suggested above.**

Authors' reply: Models presented.

SSC – Oct 4 2016

- Lack of fit to Model 3 was surprising, given the disappearance of the largest size class from the survey. The SSC expected that the model with the additional parameter could only fit better than the base model. **The SSC recommends that the authors confirm this result.** If an error is discovered associated with the lack of fit, then the SSC encourages the authors to bring forward a corrected version of this model for further evaluation, as well.

Author's reply:

Contrary to the SSC's expectation, Model 3 does not increase the number of parameters. The difference between Model 0 and Model 3 is the minimum length in application of a higher M.

Assumption of M for Model 0 and Model 3

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Length class | 64-73 | 74-83 | 84-93 | 94-103 | 104-113 | 114-123 | 124-133 | 134+ |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Model 0 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | *ms* *0.18 | *ms* *0.18 |
| Model 3 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | *ms* *0.18 |

Negative log-likelihood

| Model | Number of Parameters | Total | TSA | St. CPUE | TLP | WLP | CLP | OBS | REC | TAG |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | **65** | 315.0 | 9.0 | -22.1 | 104.5 | 42.5 | 59.5 | 36.0 | 11.6 | 74.7 |
| 3 | **65** | 352.3 | 9.5 | -22.3 | 117.1 | 45.3 | 79.6 | 36.3 | 12.5 | 74.3 |

TSA: Trawl Survey Abundance
St. CPUE: Summer commercial catch standardized CPUE
TLP: Trawl survey length composition:
WLP: Winter pot survey length composition
CLP: Summer commercial catch length composition
REC: Recruitment deviation
OBS: Summer commercial catch observer discards length composition
TAG: Tagging recovery data composition

Lack of fit to Model 3 simply indicates that Model does not support the assumption of M = 0.18 for size class 124-133mm.

## C. Introduction

1. Species: red king crab (*Paralithodes camtschaticus*) in Norton Sound, Alaska.
2. General Distribution: Norton Sound red king crab is one of the northernmost red king crab populations that can support a commercial fishery (Powell et al. 1983). It is distributed throughout Norton Sound with a westward limit of 167-168° W. longitude, depths less than 30 m, and summer bottom temperatures above 4°C. The Norton Sound red king crab management area consists of two units: Norton Sound Section (Q3) and Kotzebue Section (Q4) (Menard et al. 2011). The Norton Sound Section (Q3) consists of all waters in Registration Area Q north of the latitude of Cape Romanzof, east of the International Dateline, and south of 66°N latitude (Figure 1). The Kotzebue Section (Q4) lies immediately north of the Norton Sound Section and includes Kotzebue Sound. Commercial fisheries have not occurred regularly in the Kotzebue Section. This report deals with the Norton Sound Section of the Norton Sound red king crab management area.
3. Evidence of stock structure: Thus far, no studies have investigated possible stock separation within the putative Norton Sound red king crab stock.
4. Life history characteristics relevant to management: One of the unique life-history traits of Norton Sound red king crab is that they spend their entire lives in shallow water since Norton Sound is generally less than 40 m in depth. Distribution and migration patterns of Norton Sound red king crab have not been well studied. Based on the 1976-2006 trawl surveys, red king crab in Norton Sound are found in areas with a mean depth range of 19 ± 6 (SD) m and bottom temperatures of 7.4 ± 2.5 (SD) °C during summer. Norton Sound red king crab are consistently abundant offshore of Nome.

   Norton Sound red king crab migrate between deeper offshore and inshore shallow waters. Timing of the inshore mating migration is unknown, but is assumed to be during late fall to winter (Powell et al. 1983). Offshore migration occurs in late May - July (Jennifer Bell, ADF&G, personal communication). The results from a study funded by North Pacific

Research Board (NPRB) during 2012-2014 suggest that older/large crab (> 104mm CL) stay offshore in winter, based on findings that large crab are not found nearshore during spring offshore migration periods (Jennifer Bell, ADF&G, personal communication). Timing of molting is unknown but likely occurs in late August – September, based on increase catches of newly-molted crab late in the fishing season (August- September) (Joyce Soong, ADF&G personal communication) and evaluation of molting hormone profiles in the hemolymph (Jennifer Bell, ADF&G, personal communication). Recent observations also indicate that mating may be biennial (Robert Foy, NOAA, personal communication). Trawl surveys show that crab distribution is dynamic with recent surveys showing high abundance on the southeast side of Norton Sound, offshore of Stebbins and Saint Michael.

5. Brief management history: Norton Sound red king crab fisheries consist of commercial and subsistence fisheries. The commercial red king crab fishery started in 1977 and occurs in summer (June – August) and winter (December – May). The majority of red king crab harvest occurs offshore during the summer commercial fishery, whereas the winter commercial and subsistence fisheries occur nearshore.

Summer Commercial Fishery

A large-vessel summer commercial crab fishery started in 1977 in the Norton Sound Section (Table 1) and continued from 1977 through 1990. No summer commercial fishery occurred in 1991 because there were no staff to manage the fishery. In March 1993, the Alaska Board of Fisheries (BOF) limited participation in the fishery to small boats. Then on June 27, 1994, a super-exclusive designation went into effect for the fishery. This designation stated that a vessel registered for the Norton Sound crab fishery may not be used to take king crabs in any other registration areas during that registration year. A vessel moratorium was put into place before the 1996 season. This was intended to precede a license limitation program. In 1998, Community Development Quota (CDQ) groups were allocated a portion of the summer harvest; however, no CDQ harvest occurred until the 2000 season. On January 1, 2000 the North Pacific License Limitation Program (LLP) went into effect for the Norton Sound crab fishery. The program dictates that a vessel which exceeds 32 feet in length overall must hold a valid crab license issued under the LLP by the National Marine Fisheries Service. Changes in regulations and the location of buyers resulted in eastward movement of the harvest distribution in Norton Sound in the mid-1990s. In Norton Sound, a legal crab is defined as ≥ 4-3/4 inch carapace width (CW, Menard et al. 2011), which is approximately equivalent to ≥ 104 mm carapace length mm CL. Since 2005, commercial buyers started accepting only legal crab of ≥ 5 inch CW.

Portions of Norton Sound area are closed to commercial fishing for red king crab. Since the beginning of the commercial fisheries in 1977, waters approximately 5-10 miles offshore of southern Seward Peninsula from Port Clarence to St. Michael have been closed to protect crab nursery grounds during the summer commercial crab fishery (Figure 2). The spatial extent of closed waters has varied historically.

CDQ Fishery

The Norton Sound and Lower Yukon CDQ groups divide the CDQ allocation. Only fishers designated by the Norton Sound and Lower Yukon CDQ groups are allowed to participate in this portion of the king crab fishery. Fishers are required to have a CDQ fishing permit from the Commercial Fisheries Entry Commission (CFEC) and register their vessel with the Alaska Department of Fish and Game (ADF&G) before begin fishing. Fishers operate under the authority of each CDQ group who decides how their crab quota is to be harvested. During the March 2002 BOF meeting, new regulations for the CDQ crab fishery were adopted that affected; closed-water boundaries were relaxed in eastern Norton Sound and waters west of Sledge Island. In March 2008, the BOF changed the start date of the Norton Sound open-access portion of the fishery to be opened by emergency order as early as June 15. The CDQ fishery may open at any time (as soon as ice is out), by emergency order. CDQ harvest share is 7.5% of total projected harvest.

Winter Commercial Fishery

The winter commercial crab fishery is a small fishery using hand lines and pots through the nearshore ice. On average 10 permit holders harvested 2,500 crabs during 1978-2009. From 2007 to 2015 the winter commercial catch increased from 3,000 crabs to over 40,000 (Table 2). In 2015 winter commercial catch reached 20% of total crab catch. The BOF responded in May 2015 by amending regulations to allocate 8% of the total commercial guideline harvest level (GHL) to the winter commercial fishery. The winter red king crab commercial fishing season was also set from January 15 to April 30, unless changed by emergency order. The new regulation became in effect since the 2016 season.

Subsistence Fishery

While the winter subsistence fishery has a long history, harvest information is available only since the 1977/78 season. The majority of the subsistence crab fishery harvest occurs using hand lines and pots through nearshore ice. Average annual winter subsistence harvest was 5,400 crab (1977-2010). Subsistence harvesters need to obtain a permit before fishing and record daily effort and catch. There are no size or sex specific harvest limits; however, the majority of retained catches are males of near legal size. The subsistence fishery catch is influenced not only by crab abundance, but also by changes in distribution, changes in gear (e.g., more use of pots instead of hand lines since 1980s), and ice conditions (e.g., reduced catch due to unstable ice conditions: 1987-88, 1988-89, 1992-93, 2000-01, 2003-04, 2004-05, and 2006-07).

The summer subsistence crab fishery harvest has been monitored since 2004 with an average harvest of 712 crab per year. Since this harvest is very small, the summer subsistence fishery was not included in the assessment model.

6. Brief description of the annual ADF&G harvest strategy

Since 1997 Norton Sound red king crab has been managed based on a guideline harvest level (GHL). From 1999 to 2011 the GHL for the summer commercial fishery was determined by a prediction model and the model estimated predicted biomass: (1) 0% harvest rate of legal crab when estimated legal biomass < 1.5 million lb; (2) ≤ 5% of legal male abundance when the estimated legal biomass falls within the range 1.5-2.5 million lb; and (3) ≤ 10% of legal male when estimated legal biomass >2.5 million lb.

In 2012 a revised GHL for the summer commercial fishery was implemented: (1) 0% harvest rate of legal crab when estimated legal biomass < 1.25 million lb; (2) ≤ 7% of legal male abundance when the estimated legal biomass falls within the range 1.25-2.0 million lb; (3) ≤ 13% of legal male abundance when the estimated legal biomass falls within the range 2.0-3.0 million lb; and (3) ≤ 15% of legal male biomass when estimated legal biomass >3.0 million lb.

In 2015 the Alaska Board of Fisheries passed the following regulations regarding winter commercial fisheries:

1. Revised GHL to include summer and winter commercial fisheries.
2. Set guideline harvest level for winter commercial fishery ($GHL_w$) at 8% of the total GHL
3. Dates of the winter red king crab commercial fishing season are from January 15 to April 30.

| Year | Notable historical management changes |
|---|---|
| 1976 | The abundance survey started |
| 1977 | Large vessel commercial fisheries began |
| 1991 | Fishery closed due to staff constraints |
| 1994 | Super exclusive designation went into effect. The end of large vessel commercial fishery operation. The majority of commercial fishery subsequently shifted to east of 164ºW longitude. |
| 1998 | Community Development Quota (CDQ) allocation went into effect |
| 1999 | Guideline Harvest Level (GHL) went into effect |
| 2000 | North Pacific License Limitation Program (LLP) went into effect. |
| 2002 | Change in closed water boundaries (Figure 2) |
| 2005 | Commercially accepted legal crab size changed from ≥ 4-3/4 inch CW to ≥ 5 inch CW |
| 2006 | The Statistical area Q3 section expanded (Figure 1) |
| 2008 | Start date of the open access fishery changed from July 1 to after June 15 by emergency order. Pot configuration requirement: at least 4 escape rings (>4½ inch diameter) per pot located within one mesh of the bottom of the pot, or at least ½ of the vertical surface of a square pot or sloping side-wall surface of a conical or pyramid pot with mesh size > 6½ inches. |
| 2012 | The Board of Fisheries adopted a revised GHL for summer fishery. |
| 2016 | Winter GHL for commercial fisheries was established and modified winter fishing season dates were implemented. |

7. Summary of the history of the $B_{MSY}$.

NSRKC is a Tier 4 crab stock. Direct estimation of the $B_{MSY}$ is not possible. The $B_{MSY}$ proxy is calculated as mean model estimated mature male biomass (MMB) from 1980 to present. Choice of this period was based on a hypothesized shift in stock productivity a due to a climatic regime shift indexed by the Pacific Decadal Oscillation (PDO) in 1976-77. Stock status of the NSRKC was Tier 4a until 2013. In 2014 the stock fell to Tier 4b, but came back to Tier 4a for the 2015-2016 seasons.

## *D. Data*

1. Summary of new information:

Winter commercial and subsistence fishery:

Winter commercial fishery catch in 2016 was 29,792 crab (79,980 lb.), which was the highest harvest record since development of the fishery. Subsistence retained crab catch was 5,340 (13,350 lb., Table 2).

Summer commercial fishery:

The summer commercial fishery opened on June 27 and closed on July 21. This was the shortest fishery in the history. A total of 138,997 crab (420,159 lb.) were harvested (Table 1).

Total harvest for 2016 season was 168,789 crab (500,138 lb.) and did not exceed the 2016 ABC of 0.57 million lb.

2. Available survey, catch, and tagging data

| | Years | Data Types | Tables |
|---|---|---|---|
| Summer trawl survey | 76,79,82,85,88,91,96, 99,<br>02,06,08,10,11, 14 | Abundance<br>Length proportion | 3<br>5, Figure 3 |
| Winter pot survey | 81-87, 89-91,93,95-00,02-12 | Length proportion | 6, Figure 3 |
| Summer commercial<br>fishery | 76-90,92-16 | Retained catch<br>Standardized CPUE,<br>Length proportion | 1<br>1<br>4, Figure 3 |
| Summer commercial<br>Discards | 87-90,92,94, 2012-2016 | Length proportion<br>(sublegal only) | 7, Figure 3 |
| Winter subsistence fishery | 76-16 | Total catch | 2 |
| | | Retained catch | 2 |
| Winter commercial fishery | 78-16 | Retained catch | 2 |
| Tag recovery | 80-16 | Recovered tagged crab | 8 |

Data available but not used for assessment

| Data | Years | Data Types | Reason for not used |
|---|---|---|---|
| Summer pot survey | 80-82,85 | Abundance<br>Length proportion | Uncertainties on how estimates were made. |
| Summer preseason survey | 95 | Length proportion | Just one year of data |
| Summer subsistence fishery | 2005-2013 | retained catch | Too few catches compared to commercial |
| Winter Pot survey | 87, 89-91,93,95-00,02-12 | CPUE,<br>Length | Not reliable due to ice conditions |

| | | | |
|---|---|---|---|
| Winter Commercial | 2015-16 | Length proportion | Years of data too short |
| Preseason Spring pot survey | 2011-15 | CPUE, Length proportion | Years of data too short |
| Postseason Fall pot survey | 2013-15 | CPUE, Length proportion | Years of data too short |

Time series of available data

| | Survey | | Harvests | | | Tag | Data Not Used[3] | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | S. Trawl | W. Pot | S.Com | S.Com Discards | W. Com, Sub | | S. Pot | Pre fish | Sp. Tag | F. Tag, | W. Com |
| N[1] | N | | H, CPUE | | H | | | | | | |
| Length[2] | X | X | X | X | | X | X | X | X | X | X |
| 1976 | | | | | | | | | | | |
| 1977 | | | | | | | | | | | |
| 1978 | | | | | | | | | | | |
| 1979 | | | | | | | | | | | |
| 1980 | | | | | | | | | | | |
| 1981 | | | | | | | | | | | |
| 1982 | | | | | | | | | | | |
| 1983 | | | | | | | | | | | |
| 1984 | | | | | | | | | | | |
| 1985 | | | | | | | | | | | |
| 1986 | | | | | | | | | | | |
| 1987 | | | | | | | | | | | |
| 1988 | | | | | | | | | | | |
| 1989 | | | | | | | | | | | |
| 1990 | | | | | | | | | | | |
| 1991 | | | | | | | | | | | |
| 1992 | | | | | | | | | | | |
| 1993 | | | | | | | | | | | |
| 1994 | | | | | | | | | | | |
| 1995 | | | | | | | | | | | |
| 1996 | | | | | | | | | | | |
| 1997 | | | | | | | | | | | |
| 1998 | | | | | | | | | | | |
| 1999 | | | | | | | | | | | |
| 2000 | | | | | | | | | | | |
| 2001 | | | | | | | | | | | |
| 2002 | | | | | | | | | | | |
| 2003 | | | | | | | | | | | |
| 2004 | | | | | | | | | | | |
| 2005 | | | | | | | | | | | |
| 2006 | | | | | | | | | | | |
| 2007 | | | | | | | | | | | |
| 2008 | | | | | | | | | | | |
| 2009 | | | | | | | | | | | |
| 2010 | | | | | | | | | | | |
| 2011 | | | | | | | | | | | |
| 2012 | | | | | | | | | | | |
| 2013 | | | | | | | | | | | |
| 2014 | | | | | | | | | | | |
| 2015 | | | | | | | | | | | |
| 2016 | | | | | | | | | | | |

1: Index of abundance data: N: Abundance, H: Harvest, CPUE: Catch cpue
2: Length data available

3: Data were not used for the assessment model because of short term data.
4: Different colors indicate changes in fishery characteristics or survey methodologies.

Catches in other fisheries

In Norton Sound, no other crab, groundfish, or shellfish fisheries exist.

| | Fishery | Data availability |
|---|---|---|
| Bycatch in other crab fisheries | Does not exist | NA |
| Bycatch in groundfish pot | Does not exist | NA |
| Bycatch in groundfish trawl | Does not exist | NA |
| Bycatch in the scallop fishery | Does not exist | NA |

3. Other miscellaneous data:
   - Satellite tag migration tracking (NOAA 2016)
   - Spring offshore migration distance and direction (2013-2015)
   - Monthly blood hormone level (indication of molting timing) (2014-2015)

Data aggregated:
   - Proportion of legal size crab, estimated from trawl survey and observer data. (Table 11)

Data estimated outside the model:
   - Summer commercial catch standardized CPUE (Table 1, Appendix A2)

## *E. Analytic Approach*

### 1. History of the modeling approach.

The Norton Sound red king crab stock was assessed using a length-based synthesis model (Zheng et al. 1998). Since adoption of the model, the major challenge is a conflict between model projection and data, specifically the model projects higher abundance-proportion of the largest size class of crab than observed. This problem was further exasperated when natural mortality $M$ was set as 0.18 from previous $M$ = 0.3 in 2011 (SAFE 2011). This problem was examined and resolved by increasing $M$ of the largest length crabs to 3.6×$M$ or $M$ = 0.648 (SAFE 2012). Profile likelihood analyses have been conducted several times, which resulted in the lowest likelihood at $M$ = 0.34 (SAFE 2012, 2013). However, even at this higher $M$, the model was not able to resolve poor fits to the commercial catch. Profile likelihood of commercial catch was lowest around $M$ = 0.5 or greater. From 2013 to 2014, the NSRKC model was thoroughly examined by the CPT modeling workshop. The workshop improved the model fit thorough excluding some data (summer pot survey), revising trawl survey abundance estimates, standardizing commercial catch CPUE, including tag recovery data to estimate the growth transition matrix within the model, and changing weights in the likelihood. However, the issue of *M* was not addressed in this workshop. In 2016, this assumption was examined more fully. Model estimated *M* constant across all length groups was around 0.4, and *M* assuming the higher rate for the largest length group was 0.21 for all and 0.62 for the largest length group (SAFE 2016). The 2016 SAFE also examined the effect of changing length interval (10 mm vs. 5 mm) as well as the range of length categories (74mm – 124mm above, vs. 64mm – 134mm above). After examining data, the CPT chose extended length categories (64mm – 134mm above) with a 10 mm interval. Further, multipliers for the last length class are now estimated. Despite all those efforts, model estimates of higher natural mortality of > 123mm crab remain the greatest unknown for Norton Sound red king crab and the assessment model. For 2017 assessment, CPT and SSC requested additional model explorations to solve this issue.

Historical Model configuration progression:

2011 (SAFE 2011)

1. *M* =0.18
2. *M* of the last length class = 0.288
3. Include summer commercial discards mortality = 0.2
4. Weight of fishing effort = 20,
5. The maximum effective sample size for commercial catch and winter surveys = 100,

2012 (SAFE 2012)

1. *M* of the last length class = 3.6×*M*
2. The maximum effective sample size for commercial catch and winter surveys = 50,
3. Weight of fishing effort = 50.

2013 (SAFE 2013)

1. Standardize commercial catch cpue and replace likelihood of commercial catch efforts to standardized commercial catch cpue with weight = 1.0
2. Eliminate summer pot survey data from likelihood
3. Estimate survey *q* of 1976-1991 NMFS survey with maximum of 1.0
4. The maximum effective sample size for commercial catch and winter surveys = 20.

2014 (SAFE 2014)

1. Modify functional form of selectivity and molting probability to improve parameter estimates (2 parameter logistic to 1 parameter logistic)
2. Include additional variance for the standardized cpue.
3. Include winter pot survey cpue (But was removed from the final model due to lack of fit)
4. Estimate growth transition matrix from tagged recovery data.

2015 (SAFE 2015)

1. Winter pot survey selectivity is an inverse logistic, estimating selectivity of the smallest length group independently

2. Reduce Weight of tag-recovery: W = 0.5
3. Model parsimony: one trawl survey selectivity and one commercial pot selectivity

2016 (SAFE 2016)

1. Length range extended from 74mm – 124mm above to 64mm – 134mm above.
2. Estimate multiplier for the largest (> 123mm) length classes.

## 2. Model Description

a. Description of overall modeling approach:

The model is a male-only size structured model that combines multiple sources of survey, catch, and mark-recovery data using a maximum likelihood approach to estimate abundance, recruitment, catchability of the commercial pot gear, and parameters for selectivity and molting probabilities (See Appendix A for full model description).

b-f. See Appendix A.

g. Critical assumptions of the model:

i. Male crab mature at CL length 94mm.

Size at maturity of NSRKC (CL 94 mm) was determined by adjusting that of BBRKC (CL 120mm) reflect the slower growth and smaller size of NSRKC.

ii. Molting occurs in the fall after the fishery

iii. Instantaneous natural mortality *M* is 0.18 for all length classes, except for the last length group (> 123mm).

iv. Trawl survey selectivity is a logistic function with 1.0 for length classes 5-6. . Selectivity is constant over time.

v. Winter pot survey selectivity is a dome shaped function: Reverse logistic function of 1.0 for length class CL 84mm, and model estimate for CL < 84mm length classes. Selectivity is constant over time.

This assumption is based on the fact that a low proportion of large crab are caught in the nearshore area where winter surveys occur. Causes of this pattern may be that (1) large crab do not migrate into nearshore waters in winter or (2) large crab are fished out by winter fisheries where the survey occurs (i.e., local depletion). Recent studies suggest that the first explanation is more likely than second (Jennifer Bell, ADFG, personal communication).

vi. Summer commercial fisheries selectivity is an asymptotic logistic function of 1.0 at the length class CL 124mm. While the fishery changed greatly between the periods (1977-1992 and 1993-present) in terms of fishing vessel composition and pot configuration, the selectivity of each period was assumed to be identical. Model fits of separating and combining the two periods were examined in 2015, and showed no difference between the two models (SAFE 2015). For model parsimony, the two were combined.

vii. Summer trawl survey selectivity is an asymptotic logistic function of 1.0 at the length of CL 124mm. While the survey changed greatly between NOAA (1976-1991) and ADF&G (1996-present) in terms of survey vessel and trawl net structure, selectivity of both periods was assumed to be identical. Model fits separating and combining the two surveys were examined in 2015. No differences between the two models were observed (SAFE 2015) and for model parsimony the two were combined.

viii. Winter commercial and subsistence fishery selectivity and length-shell conditions are the same as those of the winter pot survey. All winter commercial and subsistence harvests occur February 1st.

Winter commercial king crab pots can be any dimension (5AAC 34.925(d)). No length composition data exists for crab harvested in the winter commercial or subsistence fisheries. However, because commercial fishers are also subsistence fishers, it is reasonable to assume that the commercial fishers used crab pots that they use for subsistence harvest, and hence both fisheries have the same selectivity.

ix. Growth increments are a function of length, are constant over time, estimated from tag recovery data.

x. Molting probability is an inverse logistic function of length for males.

xi. A summer fishing season for the directed fishery is short. All summer commercial harvests occur July 1st.

xii. Discards handling mortality rate for all fisheries is 20%.
No empirical estimate is available.

xiii. Annual retained catch is measured without error.

xiv. All legal size crab (≥ 4-3/4 inch CW) are retained.

Since 2005, buyers announced that only legal crab with ≥ 5 inch CW are acceptable for purchase. Since samples are taken at a commercial dock, it was anticipated that this change would lower the proportion of legal crab for length class 4. However, the model was not sensitive to this change (SAFE 2013).

xv. All sublegal size crab or commercially unacceptable size crab (< 5 inch CW, since 2005) are discarded.

xvi. Length compositions have a multinomial error structure and abundance has a log-normal error structure.

h. Changes of assumptions since last assessment:

None.

i. Code validation

The model codes were reviewed at the CPT modeling workshops in 2013 and 2014. In 2016, during revision a code mistake was found on calculation of summer commercial discards.

$$D_{l,t} = C_{s,t} \frac{(N_{s,l,t} + O_{s,l,t}) S_{s,l} (1 - L_l)}{\sum_l (N_{s,l,t} + O_{s,l,t}) S_{s,l} L_l} hm_s$$ Correct equation (Appendix A)

$$D_{l,t} = C_{s,t} \frac{(N_{s,l,t} + O_{s,l,t}) S_{s,l} (1 - L_l)}{\sum_l (N_{s,l,t} + O_{s,l,t}) L_l} hm_s$$ Equation in the code(mistake)

The code was corrected to match the equation in Appendix A.

## 3. Model Selection and Evaluation

a. Description of alternative model configurations.

As described in historical modeling approaches (E.1), all alternative model requests were developed to address the question of low proportion of > 123mm crab. Alternative Model 1 estimates molting probability of each length class independently while allowing the model to increase *M* for > 123mm crab. Model 2 is the same as Model 1 except assuming *M* = 0.18 for all lengths. Model 3 is similar to Model 0, except for using a 2 parameter inverse logistic model. Model 4 allows Model 3 to random walk annual molting probability.

Model 5 estimates selectivity and molting probability for individual length class while assuming *M* = 0.18 for all lengths. This allows the model to consider dome-shaped selectivities (i.e., large crab move out of fishing-survey area). Model 6 is similar to Model 5 except for letting the model to estimate *M*.

List of model scenarios considered.

| Scenario | M | ms | Molt Prob | Com Sel | Trawl Sel |
|---|---|---|---|---|---|
| 0 | 0.18 | Est | Inv. Log | Logistic | Logistic |
| 1 | 0.18 | Est | Ind. Est | Logistic | Logistic |
| 2 | 0.18 | 1.0 | Ind. Est | Logistic | Logistic |
| 3 | 0.18 | Est | Inv. Log (2p) | Logistic | Logistic |
| 4 | 0.18 | Est | Inv. Log (2pR) | Logistic | Logistic |
| 5 | 0.18 | 1.0 | Ind. Est | Ind. Est | Ind. Est |
| 6 | Est | 1.0 | Ind. Est | Ind. Est | Ind. Est |

b. Evaluation of negative loglikelihood alternative models results:

| Model | Model 0 | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 | Model 6 |
|---|---|---|---|---|---|---|---|
| No. Parameters | 65 | 72 | 71 | 66 | 148 | 85 | 86 |
| Total | 311.9 | 266.8 | 317.3 | 271.5 | 208.3 | 272.1 | 252.0 |
| TSA | 9.1 | 9.2 | 14.3 | 9.1 | 8.8 | 6.7 | 9.5 |
| St.CPUE | -22.7 | -22.5 | -22.0 | -22.5 | -22.3 | -21.0 | -22.1 |
| TLP | 104.3 | 83.7 | 98.4 | 82.8 | 47.2 | 80.8 | 76.0 |
| WLP | 42.5 | 38.5 | 38.5 | 39.3 | 37.4 | 46.4 | 43.6 |
| CLP | 79.0 | 47.9 | 69.3 | 48.5 | 36.8 | 51.0 | 47.0 |
| OBS | 32.2 | 22.9 | 22.0 | 22.8 | 12.2 | 29.9 | 20.2 |
| REC | 12.6 | 12.4 | 14.2 | 12.4 | 13.6 | 12.8 | 13.1 |
| TAG | 74.8 | 74.4 | 86.4 | 79.2 | 70.9 | 65.4 | 60.8 |
| Smth | | 0.50 | 0.23 | | | 8.3 | 2.9 |
| Mol.R | | | | | 3.8 | | |
| MMB(mil.lb) | 5.16 | 5.16 | 5.60 | 5.08 | 5.02 | 10.31 | 5.64 |
| Legal (mil.lb) | 4.50 | 4.44 | 5.05 | 4.35 | 4.45 | 4.85 | 2.93 |
| OFL(mil.lb) | 0.70 | 0.69 | 0.78 | 0.67 | 0.69 | 0.75 | 0.89 |

TSA: Trawl Survey Abundance
St. CPUE: Summer commercial catch standardized CPUE
TLP: Trawl survey length composition:
WLP: Winter pot survey length composition
CLP: Summer commercial catch length composition
REC: Recruitment deviation
OBS: Summer commercial catch observer discards length composition
TAG: Tagging recovery data composition
Smth: Second order smoothing penalty
Mol.R: Molting deviation
Legal: Exploitable legal male crab

c. Search for balance:

Individually estimating molting parameters [Model 0 vs. Model 1] or not assuming molting probability 1.0 at the smallest crab length [Model 0 vs. Model 3] improved the model fit. However, the Model 2 indicates that misidentification of molting parameters was not a major factor for explaining the absence of large sized crab because the negative log likelihood of commercial catch length composition increased from Model 1 to Model 2. Varying annual molting probability improved the model fit [Model 4]; however, this also increased the numbers of parameters more than twice (148) from that of time invariant one (Model 3: 66 parameters). By changing trawl and commercial selectivity to free parameters, we were able to create a model with an alternative assumption that large (> 123mm CL) crab move out of Norton Sound (Model 5). Model 5 also fit data as well as base model variants [Models 0, l, 3], especially fit to trawl survey biomass and its length proportions. Simultaneously, comparison of MMB and exploitable legal crab biomass in Model 5 suggests that about 50% of mature crab that mostly consist of large crab migrate out of Norton Sound, or move to part of Norton Sound where they are hardly caught or surveyed. However, the 2010 NOAA bottom trawl survey did not find high concentration of large crab outside of the Norton Sound survey and fishery area (Lauth 2011; Figure D).

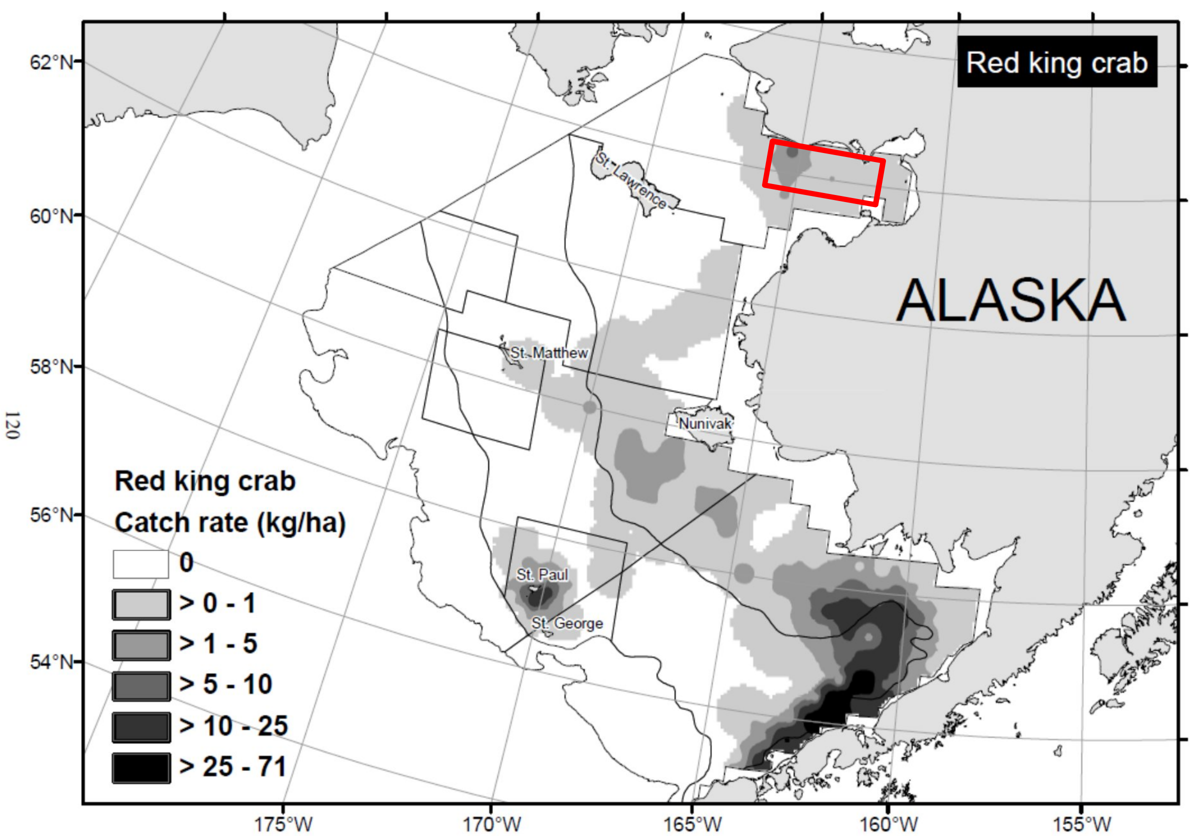



Figure D: Red king crab distribution from Lauth (2011). Red rectangular shows approximate triennial survey and fishing area.

It is possible that large crab dispersed so widely along the coast of Norton Sound that they were less likely caught by fisheries or trawl surveys, or that they were migrating down to St. Mathews Island or to Nunivak Island.

Alternatively, the absence of large crab can be explained by a higher natural mortality (Model 6). Model 6 showed better fits than Model 5 and eliminated the dome-shaped selectivity (i.e., outmigration of large crab). However, estimated $M$ was 0.44 that was about 2.5 times higher than current assumption of $M$ = 0.18. Considering differences in habitat conditions of Norton Sound, it is possible that their natural mortality is higher than other regions.

In conclusion, we were faced with the 3 alternative realities of Norton Sound Red King Crab life-history that are equally likely in terms of model fit, but biologically unusual.

1. 3.3-4.0 times higher natural mortality for large sized crab (Models 0, 1, 3).
2. Large crab consisting of 50% of MMB move out of Norton Sound fishery and survey area (Model 5).
3. 2.5 times higher natural mortality for all crab lengths (Model 6).

In the absence of any external data to verify any of the three life-history alternatives, we recommend Model 3 based on fewer parameters and improvement of model fit. Retrospective analyses suggest that the model prediction is biased negatively (i.e., predicted MMB tends to be lower than retrospective MMB) with Mohn's rho (Mohn 1999) of -0.645 (Figure 17). Fits of alternative models are summarized in Appendix C1 (Model 0), Appendix C2 (Model 1), Appendix C3 (Model 2), Appendix C4 (Model 3), Appendix C5 (Model 4), Appendix C6 (Model 5), Appendix C7 (Model 6).

## 4. **Results**

1. List of effective sample sizes and weighting factors (Figure 4)

"Implied" effective sample sizes were calculated as

$$n = \sum_l \hat{P}_{y,l}(1-\hat{P}_{y,l}) \Big/ \sum_l (P_{y,l} - \hat{P}_{y,l})^2$$

Where $P_{y,l}$ and $\hat{P}_{y,l}$ are observed and estimated length compositions in year $y$ and length group $l$, respectively. Estimated effective sample sizes vary greatly over time.

Maximum sample sizes for length proportions:

| Survey data | Sample size |
|---|---|
| Summer commercial, winter pot, and summer observer | minimum of 0.1× actual sample size or 10 |
| Summer trawl and pot survey | minimum of 0.5× actual sample size or 20 |

2. Tables of estimates.

a. Model parameter estimates (Tables 10, 11, 12, 13).

b. Abundance and biomass time series (Table 13)

c. Recruitment time series (Table 13).

d. Time series of catch/biomass (Tables 13 and 14)

3. Graphs of estimates.

a. Molting probability and trawl/pot selectivity (Figure 5)

b. Trawl survey and model estimated trawl survey abundance (Figure 6)

c. Estimated male abundances (recruits, legal, and total) (Figure 7)

d. Estimated mature male biomass (Figure 8)

e. Time series of standardized cpue for the summer commercial fishery (Figure 9).

f. Time series of catch and estimated harvest rate (Figure 10).

4. Evaluation of the fit to the data.

a. Fits to observed and model predicted catches.

Not applicable. Catch is assumed to be measured without error; however fits of cpue are available (Figures 9, 11).

b. Model fits to survey numbers (Figures 6, 11).

All model estimated abundances of total crab were within the 95% confidence interval of the survey observed abundance, except for 1976 and 1979, where model estimates were higher than the observed abundances.

c. Fits of catch proportions by lengths (Figures 12, 13).

d. Model fits to catch and survey proportions by length (Figures 12, 14, 15, 16).

e. Marginal distribution for the fits to the composition data

f. Plots of implied versus input effective sample sizes and time-series of implied effective sample size (Figure 4).

g. Tables of RMSEs for the indices:

Trawl survey:
Summer commercial standardized CPUE: (Table 1)

h. QQ plots and histograms of residuals (Figure 11).

5. Retrospective analyses (Figure 17).

6. Uncertainty and sensitivity analyses.
   See Sections 2 and 5.

## *F. Calculation of the OFL*

1. Specification of the Tier level and stock status.

The Norton Sound red king crab stock is placed in Tier 4. It is not possible to estimate the spawner-recruit relationship, but some abundance and harvest estimates are available to build a computer simulation model that captures the essential population dynamics. Tier 4 stocks are assumed to have reliable estimates of current survey biomass and instantaneous *M*; however, the estimates for the Norton Sound red king crab stock are uncertain.

Tire 4 level and the OFL are determined by the $F_{MSY}$ proxy, $B_{MSY}$ proxy, and estimated legal male abundance and biomass:

| level | Criteria | $F_{OFL}$ |
|---|---|---|
| a | $B/B_{MSY^{prox}} > 1$ | $F_{OFL} = \gamma M$ |
| b | $\beta < B/B_{MSY^{prox}} \le 1$ | $F_{OFL} = \gamma M (B/B_{MSY^{prox}} - \alpha)/(1-\alpha)$ |
| c | $B/B_{MSY^{prox}} \le \beta$ | $F_{OFL} = bycatch\ mortality\ \&\ directed\ fishery\ F = 0$ |

where $B$ is a mature male biomass (MMB), $B_{MSY}$ proxy is average mature male biomass over a specified time period, $M = 0.18$, $\gamma = 1$, $\alpha = 0.1$, and $\beta = 0.25$

For Norton Sound red king crab, MMB is defined as the biomass of males > 94 mm CL on February 01 (Appendix A). $B_{MSY}$ proxy is

$B_{MSY}$ proxy = average model estimated MMB from 1980-2017

Predicted mature male biomass in 2017 on February 01 is:

Mature male biomass : 5.14 million lb.

Estimated $B_{MSY}$ proxy is:

4.62 million lb.

Since projected MMB is greater than $B_{MSY}$ proxy, **Norton Sound red king crab stock status is Tire 4 a.**

2. Calculation of OFL.

OFL was calculated for retained ($OFL_r$), un-retained ($OFL_{ur}$), and total ($OFL_T$) for legal sized crab, *Legal_B*, by applying $F_{OFL}$.

*Legal_B* is a biomass of legal crab subject to fisheries and is calculated as: Projected abundance by length crab × fishing selectivity by length class × Proportion of legal crab per length class × Average lb per length class.

The Norton Sound red king crab fishery consists of two distinct fisheries: winter and summer. The two fisheries are discontinuous with 5 months between the two fisheries during which natural mortalities occur. To incorporate this fishery, the CPT in 2016 recommended the following formula:

$$Legal\_B_s = Legal\_B_w(1-\exp(-x \cdot F_{OFL}))e^{-0.42M}$$

$$OFL_r = (1-\exp(-(1-x) \cdot F_{OFL}))Legal\_B_s$$

And $$p = \frac{Legal\_B_w(1-\exp(-x \cdot F_{OFL}))}{OFL_r}$$

Where $p$ is a specific proportion of winter crab harvest to total (winter + summer) harvest.

Solving $x$ of the above, a revised retained OFL is

$$OFL = Legal\_B_w\left(1-e^{-(F_{OFL}+0{,}42M)} - (1-e^{-0.42M})\left(\frac{1-p(1-e^{-(F_{OFL}+0.42M)})}{1-p(1-e^{-0.42M})}\right)\right)$$

Unretained OFL ($OFL_{ur}$) is a sub-legal crab biomass catchable to summer commercial pot fisheries calculated as: Projected legal abundance (Feb 1st) × Commercial pot selectivity × Proportion of sub-legal crab per length class × Average lb per length class × handling mortality.

The total male OFL is

$$OFL_T = OFL_r + OFL_{ur}$$

For calculation of the OFL 2017

Legal male biomass (July 01): 4.32 (SD 0.89) million lb
$OFL_r$ = 0.67 million lb.
$OFL_{nr}$ = 0.14 million lb.
$OFL_T$ = 0.81 million lb.

## G. Calculation of the ABC

1. Specification of the probability distribution of the OFL.

Probability distribution of the OFL was determined based on the CPT recommendation in January 2015 of 20% buffer:

Retained ABC for legal male crab is 80% of OFL

ABC = 0.54 million lb

## H. Rebuilding Analyses

Not applicable

## I. Data Gaps and Research Priorities

The major data gap is the fate of crab greater than 123 mm.

## Acknowledgments

We thank all CPT members for all review of the assessment model and suggestions for improvements and diagnoses and Joel Webb for ADF&G internal review.

## References

Fournier, D., and C.P. Archibald. 1982. A general theory for analyzing catch at age data. Can. J. Fish. Aquat. Sci. 39:1195-1207.

Fournier, D.A., H.J. Skaug, J. Ancheta, J. Ianelli, A. Magnusson, M.N. Maunder, A. Nielsen, and J. Sibert. 2012. AD Model Builder: using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. Optim. Methods Softw. 27:233-249.

Menard, J., J. Soong, and S. Kent 2011. 2009 Annual Management Report Norton Sound, Port Clarence, and Kotzebue. Fishery Management Report No. 11-46.

Methot, R.D. 1989. Synthetic estimates of historical abundance and mortality for northern anchovy. Amer. Fish. Soc. Sym. 6:66-82.

Mohn, R. 1999. The retrospective problem in sequential population analysis: An investigation using cod fishery and simulated data. ICES Journal of Marine Science, 56:473-488.

Powell, G.C., R. Peterson, and L. Schwarz. 1983. The red king crab, *Paralithodes camtschatica* (Tilesius), in Norton Sound, Alaska: History of biological research and resource utilization through 1982. Alaska Dept. Fish and Game, Inf. Leafl. 222. 103 pp.

Zheng, J., G.H. Kruse, and L. Fair. 1998. Use of multiple data sets to assess red king crab, *Paralithodes camtschaticus*, in Norton Sound, Alaska: A length-based stock synthesis approach. Pages 591-612 *In* Fishery Stock Assessment Models, edited by F. Funk, T.J. Quinn II, J. Heifetz, J.N. Ianelli, J.E. Powers, J.F. Schweigert, P.J. Sullivan, and C.-I. Zhang, Alaska Sea Grant College Program Report No. AK-SG-98-01, University of Alaska Fairbanks