Norton Sound Red King Crab Stock Assessment for the fishing year 2018

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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. Since mid-2010s, winter commercial fisheries catches has been increased greatly.

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 Commercial Catch	Total Retained Catch	Retained OFL	Retained ABC
2014/15	2.11[A]	3.71	0.38	0.39	0.39	0.46[A]	0.42
2015	2.41[B]	5.13	0.39	0.40	0.52	0.72[B]	0.58
2016	2.26[C]	5.87	0.52	0.51	0.52	0.71[C]	0.57
2017	2.31[D]	5.14	0.50	0.49	0.50	0.67[D]	0.54
2018	4.41[E]	4.08	TBD	TBD	TBD	0.43[E]	0.35

Status and catch specifications (1000t)

Year	MSST	Biomass (MMB)	GHL	Retained Commercial Catch	Total Retained Catch	Retained OFL	Retained ABC
2014/15	0.96[A]	1.68	0.17	0.18	0.18	0.21[A]	0.19
2015	1.09[B]	2.33	0.18	0.18	0.24	0.33[B]	0.26
2016	1.03[C]	2.66	0.24	0.23	0.24	0.32[C]	0.26
2017	1.05[D]	2.33	0.23	0.22	0.24	0.30[D]	0.24
2018	2.00 [E]	1.85	TBD	TBD	TBD	0.20 [E]	0.16

Notes:
MSST was calculated as $B_{MSY}/2$
A-Calculated from the assessment reviewed by the Crab Plan Team in May 2014
B-Calculated from the assessment reviewed by the Crab Plan Team in May 2015
C-Calculated from the assessment reviewed by the Crab Plan Team in Jan 2016
D-Calculated from the assessment reviewed by the Crab Plan Team in Jan 2017
E-Calculated from the assessment reviewed by the Crab Plan Team in Jan 2018

Conversion to Metric ton: 1 Metric ton (t) = 2.2046×1000 lb

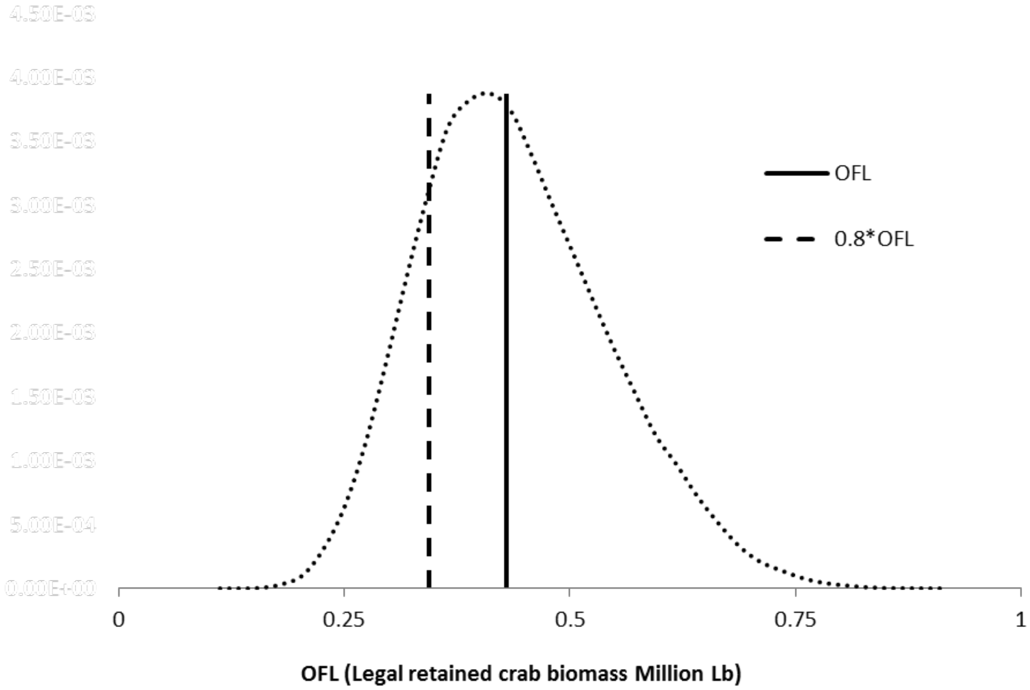
Biomass in millions of pounds

Year	Tier	B_{MSY}	Current MMB	B/B_{MSY} (MMB)	F_{OFL}	Years to define B_{MSY}	M	1-Buffer	Retained ABC
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	4.62	5.14	1.1	0.18	1980-2017	0.18	0.8	0.54
2018	4b	4.41	4.08	0.9	0.15	1980-2018	0.18	0.8	0.35

Biomass in 1000t

Year	Tier	B_{MSY}	Current MMB	B/B_{MSY} (MMB)	F_{OFL}	Years to define B_{MSY}	M	1-Buffer	Retained ABC
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	2.10	2.33	1.1	0.18	1980-2017	0.18	0.8	0.24
2018	4b	2.00	1.85	0.9	0.15	1980-2018	0.18	0.8	0.16

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 2017*

1. Changes to the management of the fishery**:**

   Winter commercial GHL went into effect

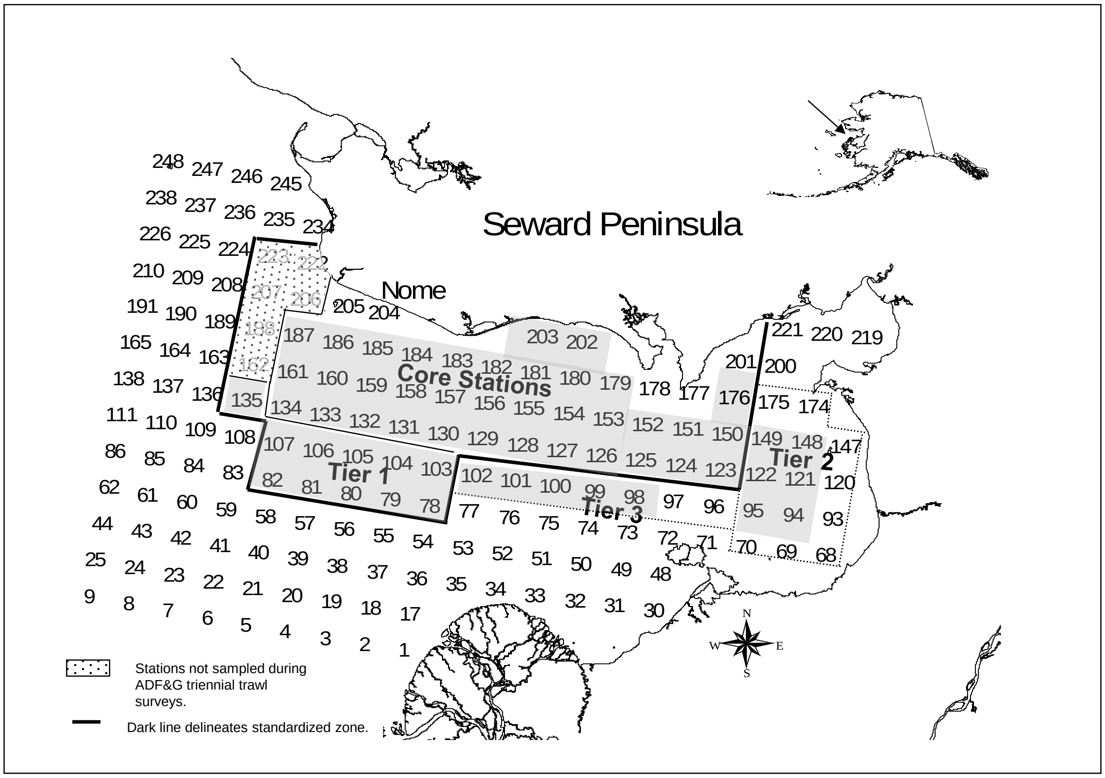
2. Changes to the input data

   a. Data update: 1977-2017 standardized commercial catch CPUE and CV. No changes in standardization methodology (NPFMC 2013).

   b. Recalculation and standardization of 1996-2017ADFG trawl survey abundance.
      i. Size class was changed from ≥ 74mm to ≥ 64mm to be consistent with the modeled size range
      ii. Re-tow data were removed from abundance calculation, unless the first trawl failed.

iii. Estimates of abundance are based on core, tier 1, and tier 3 area only.

iv. Abundance of untrawled stations within the standard station was considered zero crabs. All untrawled stations were outer edge of standard stations (Appendix E).



Gray shaded area is standard stations.

3. Changes to the assessment methodology:

   None

4. Changes to the assessment results.

   None

B. Response to SSC and CPT Comments

Crab Plan Team – January 17, 2017

- The CPT recommends breaking out natural mortality by size class for future model evaluation.

  Authors' reply:

  OFL calculation will change from

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

to

$$OFL = \sum_l\left[Legal\_B_{w,l}\left(1-e^{-(F_{OFL,l}+0.42M_l)}-(1-e^{-0.42M_l})\left(\frac{1-p(1-e^{-(F_{OFL,l}+0.42M_l)})}{1-p(1-e^{-0.42M_l})}\right)\right)\right]$$

- Assess which (2017 NOAA vs. ADFG survey) data inputs are most influential for the assessment.

Author reply: Model fit to ADFG trawl survey was better than NOAA trawl survey.

Model	Model 4 ADFG trawl	Model 4 NOAA trawl
No. Parameters	69	69
Total	261.0	266.2
TSA	8.0	9.1
St.CPUE	-30.7	-30.7
TLP	85.1	88.6
WLP	39.2	39.2
CLP	50.5	50.6
OBS	23.0	23.3
REC	13.8	13.7
TAG	72.2	72.5
MMB(mil.lb)	4.25	4.16

- Assess which (discard length data, survey data, etc.) data inputs are most influential for the assessment.

Author reply:
Likelihood was calculated as follows

Model	Model 3*	-TSA	-CPUE	-TLP	-WLP	-CLP	-OBS	-TAG
Total	260.0	244.8	283.6	159.2	215.8	193.9	222.3	182.7
TSA	8.5	ND	8.1	9.4	9.7	8.7	8.7	9.1
St.CPUE	-30.4	-31.8	ND	-33.7	-30.8	-29.3	-30.3	-29.8
TLP	84.0	83.0	81.6	ND	84.0	67.0	80.4	79.0
WLP	38.7	38.7	37.9	41.5	ND	38.2	39.4	22.0
CLP	50.2	49.0	49.0	39.2	46.5	ND	49.7	48.0
OBS	22.9	23.0	22.6	26.2	22.8	24.0	ND	22.0
REC	14.1	12.8	13.8	12.4	12.3	14.7	15.2	13.8
TAG	71.9	69.6	70.5	67.1	71.5	71.5	59.1	ND
MMB(mil.lb)	3.52	10.9	3.33	3.41	3.58	3.89	3.43	3.42
Legal (mil.lb)	3.05	9.1	2.80	2.87	3.03	3.39	2.87	2.88
Diff		-6.8	-6.8	-12.2	-5.7	-16.1	-12.7	+0.7

*: Model 3 is 2017 final model with commercial fishery selectivity changed to 2 parameters logistic function. (See alternative model section)
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
Legal: Exploitable legal male crab

See Appendix C6-C13 for standard output figures. Estimates of parameters for each model are available by request.

The most influential data for the assessment is trawl survey abundance data that determined biomass. For length proportion data, model seems to resolve conflicts among various data, so that removing one data would increase fit to other data.

- Explore bycatch data to see if it is possible to determine the OFL as total catch.

  Author reply:
  Only discard length data were collected during the summer observer surveys. The author appreciates CPT's guidance for estimating the number and biomass of discarded crab from the length data.

SSC – January 30

- SSC suggests that the author examine available evidence for higher mortality rates at larger sizes and perhaps an alternative way to parameterizing higher mortality at age rather than a step change at the largest size class.

  Author's reply:

  Because NSRKC has only 8 size classes, we examined step change for each length classes in the following scenario:

  1. One mortality for the last 2 length classes (default: ms = 1)
  2. Two separate mortalities for the last 2 length classes (ms = 2)
  3. Three separate mortalities for the last 3 length classes (ms = 3)

The results showed that estimating mortality of the last 3 length classes seem to improve model fit, especially when fishery selectivity was converted from 1 parameter logistic to 2 parameters logistic model

Scenario	M	ms	Fishery Selectivity	Estimated Mortality
0	0.18	1	1p	0.558
1	0.18	2	1p	0.52, 0.63
2	0.18	3	1p	0.23, 0.52, 0.62
3	0.18	1	2p	0.571
4	0.18	2	2p	0.55,0.61
5	0.18	3	2p	0.34,0.55,0.58

1 parameter logistic selectivity model

$$S_l = \frac{1}{1 + e^{(\phi(L_{\max} - L) + \ln(1/0.999 - 1))}}$$

2 parameters logistic selectivity model

$$S_l = \frac{1}{1 + e^{-\alpha(L - \beta)}}$$

a. Evaluation of negative log likelihood alternative models results:

Model	Model 0	Model 1	Model 2	Model 3	Model 4	Model 5
No. Parameters	67	68	69	68	69	70
Total	272.5	272.1	271.7	260.0	259.9	256.5
TSA	8.4	8.4	8.6	8.5	8.4	9.0
St.CPUE	-30.4	-30.4	-30.3	-30.4	-30.4	-30.0
TLP	88.6	88.5	87.2	84.0	84.0	82.7
WLP	38.5	38.5	38.3	38.7	38.8	38.3
CLP	50.0	49.6	49.8	50.2	50.0	48.3
OBS	25.1	25.1	25.1	22.9	23.0	22.9
REC	13.6	13.7	13.7	14.1	14.1	14.5
TAG	78.6	78.7	78.6	71.9	72.0	70.8
MMB(mil.lb)	3.66	3.67	3.68	3.52	3.52	3.56
Legal (mil.lb)	3.21	3.21	3.21	3.05	3.06	3.03
OFL(mil.lb)						

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
Legal: Exploitable legal male crab

Crab Plan Team – Sept 20, 2017

- Include a graphic on where pot-pulls have been observed.

  Author's reply
  See Appendix D. The majority of observer surveys were conducted where the majority of crabs were harvested. This is expected. Observers can board on boats that are large enough that can harvest more crabs.

Bring forward default model, model 3, 4, 5 for the January 2018 assessment

  Author's reply:
  Base model along with alternative model 3,4,5 were presented in the result section.

- Conduct likelihood profile on the M parameter

  Author's reply:
  See Appendix F.
  Likelihood profile shows that M = 0.26 appeared to be the lowest. Among the likelihood components, influential factors were trawl and summer commercial length compositions.

- Include results for 2014-2016 pot survey data (but not for assessment)
  This was conducted only for the model 3.

SSC – Oct 02, 2017

- Same as CPT

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^{o} W. longitude, depths less than 30 m, and summer bottom temperatures above 4^{o}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) ºC 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 through ice.

<u>Summer Commercial Fishery</u>

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 (Norton Sound Economic Development Corporation) started accepting only legal crab of ≥ 5 inch CW. This may have increased discards; however, because discards have not been monitored until 2012, impact of this change on discards is unknown. This issue was also examined in assessment model selection, which showed no difference in estimates of selectivity functions before and after 2005 (NPFMC 2016).

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, which became in effect since 2017 season. 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 164°W 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:

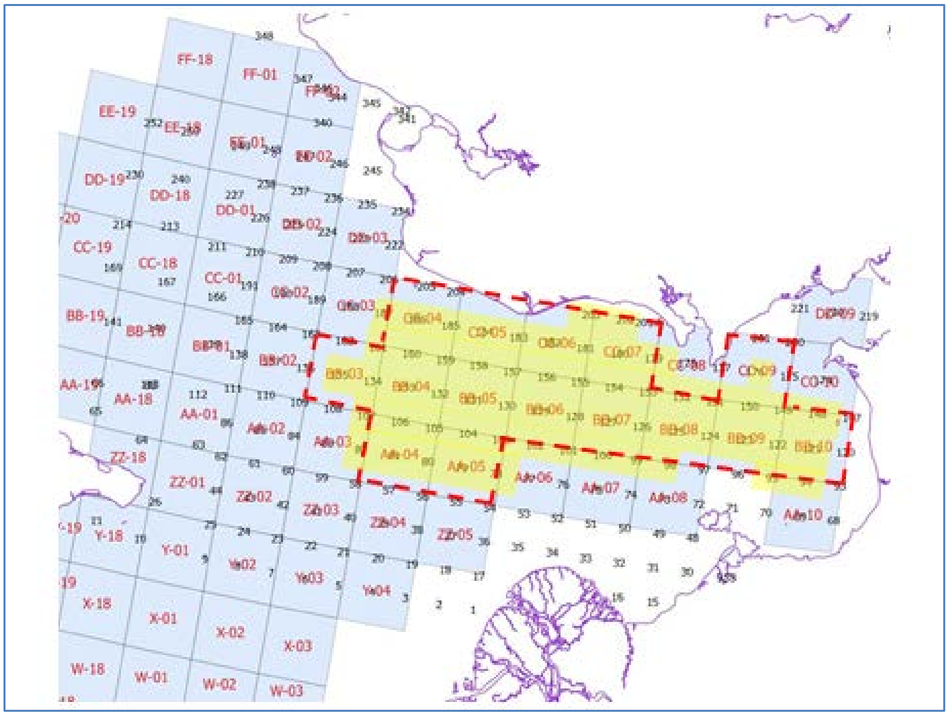
   Winter commercial fishery catch in 2017 was 26,008 crab (77,843 lb.), declined slightly from 2016. Subsistence retained crab catch was 6,039 and unretained was 1,146 or 16% of total catch (Table 2).

   Summer commercial fishery:

   The summer commercial fishery opened on June 26 and closed on July 25. Total of 135,322 crab (411,736 lb.) were harvested (Table 1).

   Total retained harvest for 2017 season was 167,369 crab (501,637 lb.) and did not exceed the 2017 ABC of 0.54 million lb.

   Summer Trawl abundance survey ADFG (7/28-8/08), and NOAA (8/18-829).
   Abundance estimated by ADFG survey was 1762.1 (x 1000) crab with CV 0.22, and that by NOAA survey was 1035.8 (x 1000) crab with CV 0.40 (Table 3). It should be noted that total estimation arear and survey station density differ between the two trawl surveys. ADFG survey is based on 10nm grids whereas NOAA survey is based on 20nm grids.



2017 ADFG trawl survey coverage (Yellow shade) and NOAA Trawl survey coverage where abundance estimates were made (Red hashed line)

2. Available survey, catch, and tagging data

	Years	Data Types	Tables
Summer trawl survey	NMFS: 76,79,82,85,88,91,10, 17	Abundance	3
	ADFG: 96, 99, 02,06,08,11, 14, 17	Length proportion	5
Winter pot survey	81-87, 89-91,93,95-00,02-12	Length proportion	6
Summer commercial fishery	76-90,92-17	Retained catch	1
		Standardized CPUE,	1
		Length proportion	4
Summer commercial Discards	87-90,92,94, 2012-2017	Length proportion (sublegal only)	7
Winter subsistence fishery	76-17	Total catch	2
		Retained catch	2
Winter commercial fishery	78-17	Retained catch	2
Tag recovery	80-17	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 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, Length	CPUE data Not reliable due to ice conditions
Winter Commercial	2015-17	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 NMFS	S. Trawl ADFG	W. Pot	S.Com	S.Com Discards	W. Com, Sub	Tag recovery	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
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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 large size class (> 123mm CL) of crab than observed. This problem was further exasperated when natural mortality *M* was set to 0.18 from previous *M* = 0.3 in 2011 (NPFMC 2011). This issue has been resolved by assuming (3-4 times) higher *M* for the length crabs (i.e., *M* = 1.8 for length classes ≤ 123mm, and higher M for > 123mm) (NPFMC 2012, 2013, 2014, 2015, 2016, 2017). Alternative assumptions have been explored, such as changing molting probability (i.e., crab matured quicker or delayed maturation), higher natural mortality, and dorm shaped selectivity (i.e., large crab are not caught, or moved out of fishery/survey grounds). However, those alternative assumptions did not produce better model fits. Model estimated length specific molting probability was similar to inverse logistic curve, and did not improve model fit (NPFMC 2016). Assuming constant across all length classes resulted in higher *M* (0.3-0.45) (NPFMC 2013, 2017). Assuming dome shaped selectivity resulted in large (>123mm CL) of crabs consisting of 50% of MMB move out of Norton Sound fishery and survey area and never been seen. For the 2018 gradual increase of *M* across length classes was assessed.

Historical Model configuration progression:

2011 (NPFMC 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 (NPFMC 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 (NPFMC 2013)
1. Eliminate likelihood for fishing effort and use standardized commercial catch cpue likelihood. 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 input sample size for commercial catch and winter surveys = 10.
5. The maximum input sample size for trawl survey = 20.

2014 (NPFMC 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 (NPFMC 2015)
1. Change winter pot survey selectivity is to 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
4. Change assessment model periods from July 01 – June 30 to Feb 01 – Jam 31.
5. OFL winter and summer fishery combined.

2016 (NPFMC 2016)
1. Length range extended from 74mm – 124mm above (6 length classes) to 64mm – 134mm above (8 length classes).
2. Estimate multiplier for the largest (> 123mm) length classes.

2017 (NPFMC 2017)
1. Change molting probability function form 1 to 2 parameter logistic. Assume molting probability not reaching 1 for the smallest length class.

2. OFL account for winter and summer fishery separately. Account for natural mortality between the two fishery periods (5 months)

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).

Unlike other crab assessment models, NSRK modeling year is starts from February 1st to January 31st of the following year. This schedule was selected because Norton Sound winter crab fisheries can start when Norton Sound ice become thick enough to operate fishery safely, which can be as earliest as mid-late January.

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 summer 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 134mm. 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 (NPFMC 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 (NPFMC 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, and sublegal size crab or commercially unacceptable size crab (< 5 inch CW, since 2005) are discarded.

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. However, the model was not sensitive to this change (NPFMC 2013, 2017).

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

h. Changes of assumptions since last assessment:

None.

3. Model Selection and Evaluation

a. Description of alternative model configurations.

Following CPT and SSC's recommendation in fall 2017, we brought base model (2017 assessment model), model 3, 4, and 5. Also, we examined potential impacts of spring survey data (model 6).

List of model scenarios explored:

Scenario	I	ms	Fishery Selectivity	Estimated M
0	0.18	1	1p	0.579
3	0.18	1	2p	0.595
4	0.18	2	2p	0.576, 0.634
5	0.18	3	2p	0.340, 0.547, 0.584
6	0.18	1	2p	0.592

ms=1: Estimate one mortality for the last 2 length classes (124mm, 134mm)
ms=2: Estimate two separate mortalities for the last 2 length classes (124mm, 134mm)
ms=3: Estimate three separate mortalities for the last 3 length classes (114mm,124mm, 134mm)

Fishery selectivity model function

1 parameter logistic selectivity model

$$S_l = \frac{1}{1 + e^{(\phi(L_{\max} - L) + \ln(1/0.999 - 1))}}$$

2 parameters logistic selectivity model

$$S_l = \frac{1}{1 + e^{-\alpha(L-\beta)}}$$

b. Evaluation of negative log-likelihood alternative models results:

Model	Model 0	Model 3	Model 4	Model 5	Model 6
No. Parameters	67	68	69	70	68
Total	281.1	269.2	269.1	265.44	286.01
TSA	9.1	9.1	9.1	9.36	9.24
St.CPUE	-30.6	-30.7	-30.7	-30.4	-30.6
TLP	95.1	90.6	90.6	89.8	90.8
WLP	38.7	39.1	39.1	38.5	39.3
CLP	50.8	51.4	51.2	49.2	51.3
OBS	25.2	23.2	23.2	23.1	23.0
REC	13.6	14.0	13.9	14.5	16.5
TAG	79.2	72.5	72.6	71.3	72.5
SP					14.0
MMB(mil.lb)	4.08	3.94	3.95	3.91	4.00
Legal crab Catchable (mil.lb)	3.55	2.58	2.60	2.13	2.63

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
Legal: Exploitable legal male crab

See Appendix C1-C5 for standard output figures and estimated parameters.

a. Search for balance:

Changing to 2 parameters logistic model and stepwise length specific mortality decreased negative log-likelihood and improved model fit. Relative gain of model improvement was the largest from model 0 to model 3 (i.e., changing the shape of commercial pot selectivity). The majority of model fit was attributed to likelihood of Trawl survey and tag recovery length proportion (cf. Appendix C1, C2 Figures 11, 12, 13). Simultaneously, it should be noted that extent of reduction depends upon assumed input sample size. Subdividing natural mortality and increasing one more parameter size (from model 3 to 4) did not change model fit. Though some improvement was seen from model 4 to 5, it was argued that assuming natural mortality increase of crab size 114-123mm would be biologically unreasonable (CPT Sept 2017). Changing of fishery selectivity or subdividing mortality did not change MMB projections, but reduced legal crab biomass catchable to commercial fishery. This is because the shape of the selectivity became steeper (cf. Appendix C1, C2 Figure 3).

While there was an improvement in fit from model 0 to model 3, the improvement in fit was not to the fishery length composition data as would be expected, but instead to other data sets unrelated to the fishery, such as the tagging data and the survey size composition. In addition, the estimated selectivity pattern was gradually inclining curve that continued to increase at sizes above the legal limit, a pattern which the CPT found difficult to rationalize. This suggests that the model uses more flexible two-parameter selectivity curve to account for some other unmodeled process, and therefore should not be considered a model improvement.

Based on the above arguments the Model 0 was selected for assessment of 2018

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 input sample sizes for length proportions: The maximum input sample size was arbitrary selected for better fit (NPFMC 2013)

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

Weighting factor

Recruitment SD 0.5

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).

Mohn's rho was 0.213 from 2007-2017. Mohn's rho suggests that retrospective projections are more likely to overestimate abundance. However, Mohns' rho has NO statistical range criteria of whether an assessment model is deemed acceptable/ unacceptable.

6. Uncertainty and sensitivity analyses.

See Sections 2 and 5.

a) 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.

Tier 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	$\beta < B/B_{MSY^{prox}} \le 1$	$F_{OFL} = \gamma M_l (B/B_{MSY^{prox}} - \alpha)/(1-\alpha)$
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 1980-2018

Predicted mature male biomass in 2018 on February 01 is:

Mature male biomass: 4.08 (SD 0.54) million lb.

Estimated B_{MSY} proxy is:

4.82 million lb.

Since projected MMB is less than B_{MSY} proxy, **Norton Sound red king crab stock status is Tier 4b**

2. Calculation of OFL.

OFL for the Norton Sound Red King Crab is retained (OFL_r) of legal sized crab biomass, *Legal_B*.

Legal_B is a biomass of legal sized crab subject to fisheries and is calculated as: Projected abundance by length class on Feb 01 ($N_{w,l} + O_{w,l}$)× summer fishing selectivity by length class ($S_{s,l}$)× Proportion of legal crab per length class ($P_{lg,l}$)× average lb per length class (wm_l).

For the Norton Sound red king crab assessment, *Legal_B* was defined as winter biomass catchable to summer commercial pot fishery gear $Legal\_B_w$, as

$$Legal\_B_w = \sum_l (N_{w,l,} + O_{w,l,}) S_{s,l} P_{lg,l} wm_l$$

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

$$OFL_r = Legal\_B_w \left(1 - e^{-(F_{OFl} + 0.42M)} - (1 - e^{-0.42M}) \left(\frac{1 - p \cdot (1 - e^{-(F_{OFL} + 0.42M)})}{1 - p \cdot (1 - e^{-0.42M})} \right) \right)$$

Accounting for difference in length specific natural mortality

$$OFL_r = \sum_l \left[Legal\_B_{w,l} \left(1 - e^{-(F_{OF,l} + 0.42M_l)} - (1 - e^{-0.42M_l}) \left(\frac{1 - p \cdot (1 - e^{-(F_{OFL,l} + 0.42M_l)})}{1 - p \cdot (1 - e^{-0.42M_l})} \right) \right) \right]$$

For calculation of the OFL_r 2018, we specified p = 0.16, M_l = 0.18 for all length classes for calculation of F_{OFL}, and M_l = 0.58 for length classes greater than 123mm.

Legal male biomass catchable to fishery (Feb 01): 3.549 million lb
OFL_r = 0.43 million lb. or 0.20 kMT

b) Calculation of the ABC

1. Specification of the probability distribution of the OFL.

Retained ABC for legal male crab is 80% of OFL

ABC = 0.35 million lb or 0.16 kMT

c) Rebuilding Analyses

Not applicable

d) Data Gaps and Research Priorities

The major data gap is the fate of crab greater than 123 mm.
Estimates of discard is needed for calculation of total OFL.

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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.

NPFMC 2011. Stock assessment and fishery evaluation report for the King and Tanner crab fisheries of the Bering Sea and Aleutian Islands regions. 2011 Crab SAFE. North Pacific Fishery Management Council, Anchorage, AK, USA

NPFMC 2012. Stock assessment and fishery evaluation report for the King and Tanner crab fisheries of the Bering Sea and Aleutian Islands regions. 2012 Crab SAFE. North Pacific Fishery Management Council, Anchorage, AK, USA

NPFMC 2013. Stock assessment and fishery evaluation report for the King and Tanner crab fisheries of the Bering Sea and Aleutian Islands regions. 2013 Crab SAFE. North Pacific Fishery Management Council, Anchorage, AK, USA

NPFMC 2014. Stock assessment and fishery evaluation report for the King and Tanner crab fisheries of the Bering Sea and Aleutian Islands regions. 2014 Crab SAFE. North Pacific Fishery Management Council, Anchorage, AK, USA

NPFMC 2015. Stock assessment and fishery evaluation report for the King and Tanner crab fisheries of the Bering Sea and Aleutian Islands regions. 2015 Crab SAFE. North Pacific Fishery Management Council, Anchorage, AK, USA

NPFMC 2016. Stock assessment and fishery evaluation report for the King and Tanner crab fisheries of the Bering Sea and Aleutian Islands regions. 2016 Crab SAFE. North Pacific Fishery Management Council, Anchorage, AK, USA

NPFMC 2017. Stock assessment and fishery evaluation report for the King and Tanner crab fisheries of the Bering Sea and Aleutian Islands regions. 2017 Crab SAFE. North Pacific Fishery Management Council, Anchorage, AK, USA

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