

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

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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 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

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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

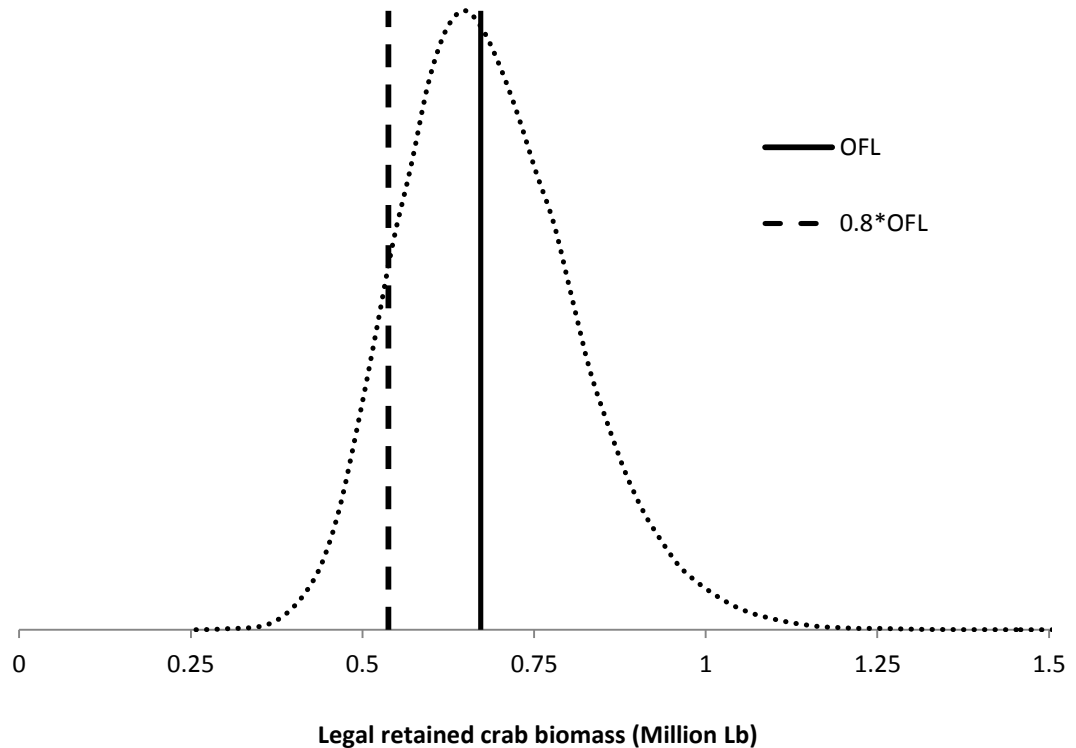
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Biomass in 1000t

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

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



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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).

- 1 c. Recalculation of the proportions of commercial crab harvests during the trawl
 2 surveys. Original data were based on equal daily harvest across the season.
 3 Now, the proportions are based on actual harvests.
 4 This data change resulted in a decline of the 2016 projected MMB from 5.87
 5 (SAFE 2016) to 5.60 million or about 5% (Figure 4a,b).
 6

7 3. Changes to the assessment methodology:

8 None

9 4. Changes to the assessment results.

10 None

11 B. *Response to SSC and CPT Comments*

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 13 Crab Plan Team – Sept. 22, 2016
 14

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

18 Authors' reply:

19 We tested this by estimating molt probability by for each length (Models 1 and 2). A second
 20 order smoothing penalty was incorporated into likelihood calculation as follows:
 21

22
$$W_s \sum_{l=1}^{l=n-2} \left[(\ln(m_{l+2}) - 2 \cdot \ln(m_{l+1}) + \ln(m_l))^2 + \sum_j (\ln(S_{j,l+2}) - 2 \cdot \ln(S_{j,l+1}) + \ln(S_{j,l}))^2 \right]$$

23 where m_l is a molting parameter of length class l . We also expanded this to selectivity parameters
 24 $S_{j,l}$ where j can be trawl survey, summer commercial fishery, and/or winter pot survey/harvest.
 25 Penalty weight W_s was set to 3.0 because it resulted in reasonably smooth molting probability and
 26 selectivity. We also experimented with 3rd order smoothing penalty; however, the penalty did not
 27 perform as well as 2nd order penalty.

28
 29 Alternatively, we also put a reverse-logistic curve form to the original form of fixing the
 30 molting probability of the smallest sized crab to 0.9999: from
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$$m_l = 1 - \frac{1}{1 + e^{(\alpha(L_1 - L) + \ln(1/0.001 - 1))}}$$

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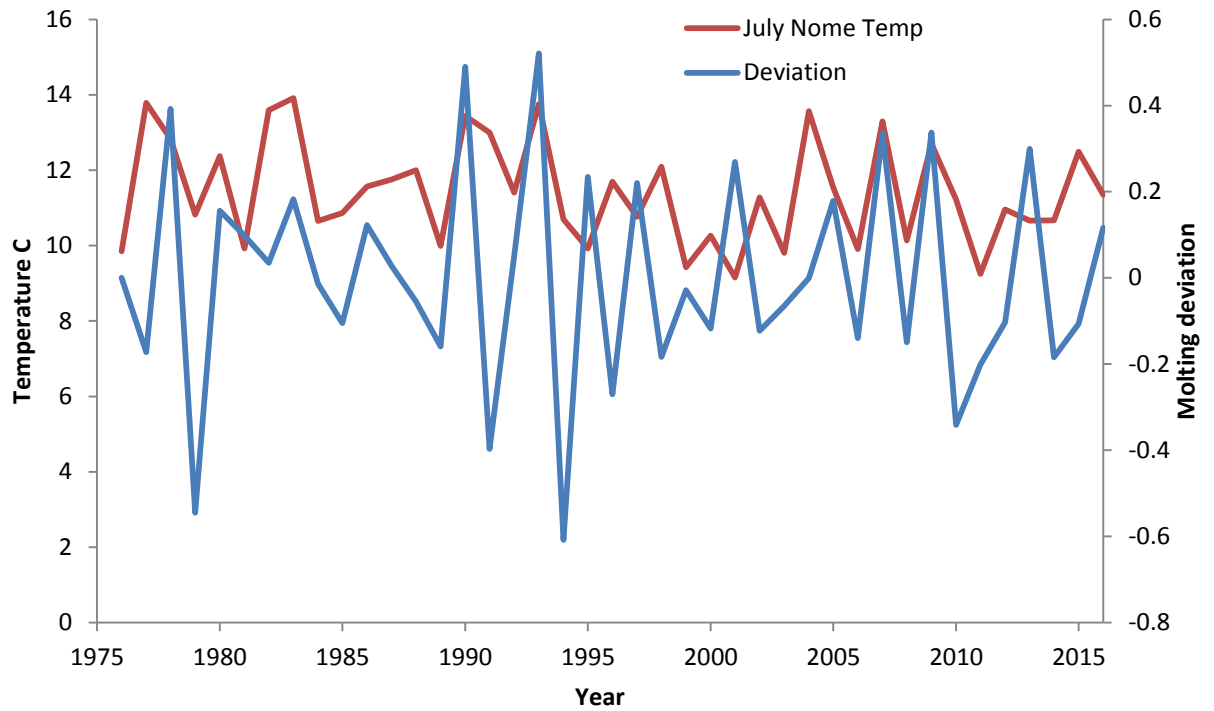
$$m_l = 1 - \frac{1}{1 + e^{-\alpha(l - \beta)}}$$

1 In this form, the highest molting probability was estimated from the model.
2
3 We estimated parameters in both fixed (Alt Model 3) and random walk (Alt Model 4).

- 4
- 5 • Explore for correlation between Model 2 random walk and temperature

6 Authors' reply:

7 We obtained Nome airport air temperature data from 1976 to 2016. Of those, molting parameter
8 deviations were the most correlated with July mean temperature ($R^2 = 0.09$).
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11 Figure A: Molting deviations and July Nome air temperatures (Model 2: CPT Sept 22).
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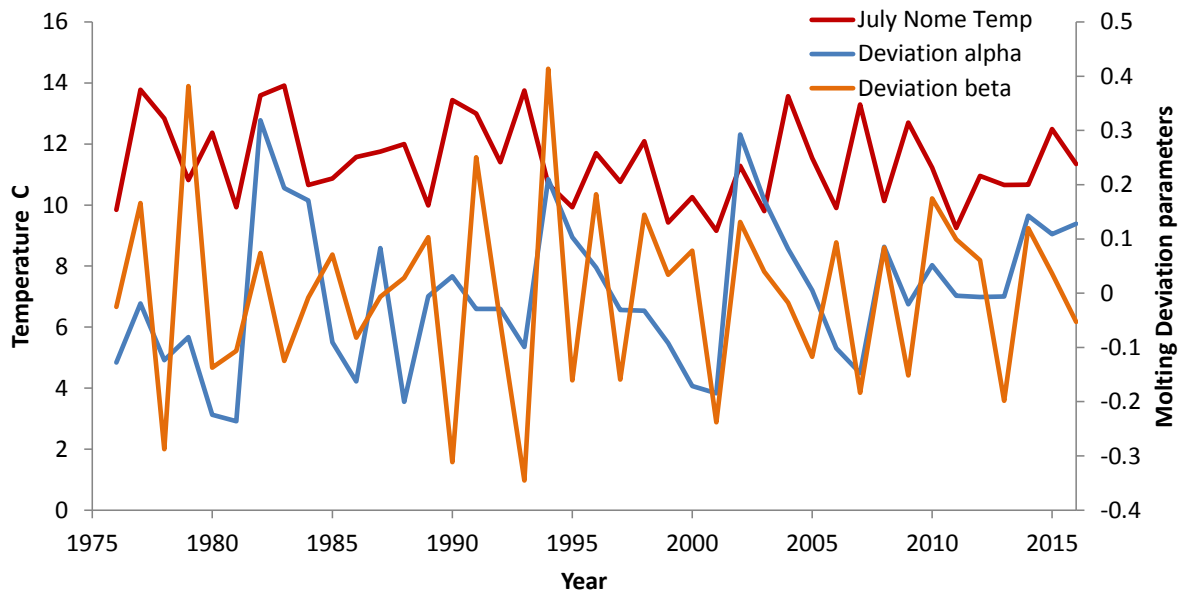


Figure B: Molting deviations and July Nome air temperatures (Model 4)

- 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+
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Model 0	0.18	0.18	0.18	0.18	0.18	0.18	<i>ms</i> *0.18	<i>ms</i> *0.18
Model 3	0.18	0.18	0.18	0.18	0.18	0.18	0.18	<i>ms</i> *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

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

- 11
- 12 5. Brief management history: Norton Sound red king crab fisheries consist of commercial and
13 subsistence fisheries. The commercial red king crab fishery started in 1977 and occurs in
14 summer (June – August) and winter (December – May). The majority of red king crab
15 harvest occurs offshore during the summer commercial fishery, whereas the winter
16 commercial and subsistence fisheries occur nearshore.

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18 Summer Commercial Fishery

19 A large-vessel summer commercial crab fishery started in 1977 in the Norton Sound Section
20 (Table 1) and continued from 1977 through 1990. No summer commercial fishery occurred
21 in 1991 because there were no staff to manage the fishery. In March 1993, the Alaska Board
22 of Fisheries (BOF) limited participation in the fishery to small boats. Then on June 27, 1994,
23 a super-exclusive designation went into effect for the fishery. This designation stated that a
24 vessel registered for the Norton Sound crab fishery may not be used to take king crabs in any
25 other registration areas during that registration year. A vessel moratorium was put into place
26 before the 1996 season. This was intended to precede a license limitation program. In 1998,
27 Community Development Quota (CDQ) groups were allocated a portion of the summer
28 harvest; however, no CDQ harvest occurred until the 2000 season. On January 1, 2000 the
29 North Pacific License Limitation Program (LLP) went into effect for the Norton Sound crab
30 fishery. The program dictates that a vessel which exceeds 32 feet in length overall must hold
31 a valid crab license issued under the LLP by the National Marine Fisheries Service. Changes
32 in regulations and the location of buyers resulted in eastward movement of the harvest
33 distribution in Norton Sound in the mid-1990s. In Norton Sound, a legal crab is defined as \geq
34 4-3/4 inch carapace width (CW, Menard et al. 2011), which is approximately equivalent to \geq
35 104 mm carapace length mm CL. Since 2005, commercial buyers started accepting only legal
36 crab of \geq 5 inch CW.

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

42

43 CDQ Fishery

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

13 14 Winter Commercial Fishery

15 The winter commercial crab fishery is a small fishery using hand lines and pots through the
16 nearshore ice. On average 10 permit holders harvested 2,500 crabs during 1978-2009. From
17 2007 to 2015 the winter commercial catch increased from 3,000 crabs to over 40,000 (Table
18 2). In 2015 winter commercial catch reached 20% of total crab catch. The BOF responded in
19 May 2015 by amending regulations to allocate 8% of the total commercial guideline harvest
20 level (GHL) to the winter commercial fishery. The winter red king crab commercial fishing
21 season was also set from January 15 to April 30, unless changed by emergency order. The
22 new regulation became in effect since the 2016 season.

23 24 Subsistence Fishery

25 While the winter subsistence fishery has a long history, harvest information is available only
26 since the 1977/78 season. The majority of the subsistence crab fishery harvest occurs using
27 hand lines and pots through nearshore ice. Average annual winter subsistence harvest was
28 5,400 crab (1977-2010). Subsistence harvesters need to obtain a permit before fishing and
29 record daily effort and catch. There are no size or sex specific harvest limits; however, the
30 majority of retained catches are males of near legal size. The subsistence fishery catch is
31 influenced not only by crab abundance, but also by changes in distribution, changes in gear
32 (e.g., more use of pots instead of hand lines since 1980s), and ice conditions (e.g., reduced
33 catch due to unstable ice conditions: 1987-88, 1988-89, 1992-93, 2000-01, 2003-04, 2004-05,
34 and 2006-07).

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

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

39 Since 1997 Norton Sound red king crab has been managed based on a guideline harvest level
40 (GHL). From 1999 to 2011 the GHL for the summer commercial fishery was determined by
41 a prediction model and the model estimated predicted biomass: (1) 0% harvest rate of legal
42 crab when estimated legal biomass < 1.5 million lb; (2) $\leq 5\%$ of legal male abundance when

1 the estimated legal biomass falls within the range 1.5-2.5 million lb; and (3) $\leq 10\%$ of legal
 2 male when estimated legal biomass >2.5 million lb.

3 In 2012 a revised GHL for the summer commercial fishery was implemented: (1) 0% harvest
 4 rate of legal crab when estimated legal biomass < 1.25 million lb; (2) $\leq 7\%$ of legal male
 5 abundance when the estimated legal biomass falls within the range 1.25-2.0 million lb; (3) \leq
 6 13% of legal male abundance when the estimated legal biomass falls within the range 2.0-3.0
 7 million lb; and (3) $\leq 15\%$ of legal male biomass when estimated legal biomass >3.0 million
 8 lb.

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

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

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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 $\geq 4\text{-}3/4$ 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 ($>4\frac{1}{2}$ inch diameter) per pot located within one mesh of the bottom of the pot, or at least $\frac{1}{2}$ of the vertical surface of a square pot or sloping side-wall surface of a conical or pyramid pot with mesh size $> 6\frac{1}{2}$ 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.

17

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

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

25

1 **D. Data**

2 1. Summary of new information:

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4 Winter commercial and subsistence fishery:

5
6 Winter commercial fishery catch in 2016 was 29,792 crab (79,980 lb.), which was the highest
7 harvest record since development of the fishery. Subsistence retained crab catch was 5,340
8 (13,350 lb., Table 2).

9
10 Summer commercial fishery:

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

14
15 Total harvest for 2016 season was 168,789 crab (500,138 lb.) and did not exceed the 2016
16 ABC of 0.57 million lb.

17
18 2. Available survey, catch, and tagging data

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

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22 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	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

1

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

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2: Length data available

- 1 3: Data were not used for the assessment model because of short term data.
 2 4: Different colors indicate changes in fishery characteristics or survey methodologies.

3
 4 Catches in other fisheries

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

6

	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

7

8 3. Other miscellaneous data:

9 Satellite tag migration tracking (NOAA 2016)

10 Spring offshore migration distance and direction (2013-2015)

11 Monthly blood hormone level (indication of molting timing) (2014-2015)

12 Data aggregated:

13 Proportion of legal size crab, estimated from trawl survey and observer data. (Table 11)

14 Data estimated outside the model:

15 Summer commercial catch standardized CPUE (Table 1, Appendix A2)

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17 ***E. Analytic Approach***

18

19 **1. History of the modeling approach.**

20 The Norton Sound red king crab stock was assessed using a length-based synthesis model
 21 (Zheng et al. 1998). Since adoption of the model, the major challenge is a conflict
 22 between model projection and data, specifically the model projects higher abundance-
 23 proportion of the largest size class of crab than observed. This problem was further
 24 exasperated when natural mortality M was set as 0.18 from previous $M = 0.3$ in 2011
 25 (SAFE 2011). This problem was examined and resolved by increasing M of the largest
 26 length crabs to $3.6 \times M$ or $M = 0.648$ (SAFE 2012). Profile likelihood analyses have been
 27 conducted several times, which resulted in the lowest likelihood at $M = 0.34$ (SAFE 2012,
 28 2013). However, even at this higher M , the model was not able to resolve poor fits to the
 29 commercial catch. Profile likelihood of commercial catch was lowest around $M = 0.5$ or
 30 greater. From 2013 to 2014, the NSRKC model was thoroughly examined by the CPT
 31 modeling workshop. The workshop improved the model fit thorough excluding some data
 32 (summer pot survey), revising trawl survey abundance estimates, standardizing
 33 commercial catch CPUE, including tag recovery data to estimate the growth transition

1 matrix within the model, and changing weights in the likelihood. However, the issue of M
2 was not addressed in this workshop. In 2016, this assumption was examined more fully.
3 Model estimated M constant across all length groups was around 0.4, and M assuming the
4 higher rate for the largest length group was 0.21 for all and 0.62 for the largest length
5 group (SAFE 2016). The 2016 SAFE also examined the effect of changing length
6 interval (10 mm vs. 5 mm) as well as the range of length categories (74mm – 124mm
7 above, vs. 64mm – 134mm above). After examining data, the CPT chose extended length
8 categories (64mm – 134mm above) with a 10 mm interval. Further, multipliers for the
9 last length class are now estimated. Despite all those efforts, model estimates of higher
10 natural mortality of > 123mm crab remain the greatest unknown for Norton Sound red
11 king crab and the assessment model. For 2017 assessment, CPT and SSC requested
12 additional model explorations to solve this issue.
13
14

15 Historical Model configuration progression:

16
17 2011 (SAFE 2011)

- 18 1. $M=0.18$
- 19 2. M of the last length class = 0.288
- 20 3. Include summer commercial discards mortality = 0.2
- 21 4. Weight of fishing effort = 20,
- 22 5. The maximum effective sample size for commercial catch and winter surveys = 100,
23

24 2012 (SAFE 2012)

- 25 1. M of the last length class = $3.6 \times M$
- 26 2. The maximum effective sample size for commercial catch and winter surveys = 50,
- 27 3. Weight of fishing effort = 50.
28

29 2013 (SAFE 2013)

- 30 1. Standardize commercial catch cpue and replace likelihood of commercial catch
31 efforts to standardized commercial catch cpue with weight = 1.0
- 32 2. Eliminate summer pot survey data from likelihood
- 33 3. Estimate survey q of 1976-1991 NMFS survey with maximum of 1.0
- 34 4. The maximum effective sample size for commercial catch and winter surveys = 20.
35

36 2014 (SAFE 2014)

- 37 1. Modify functional form of selectivity and molting probability to improve parameter
38 estimates (2 parameter logistic to 1 parameter logistic)
- 39 2. Include additional variance for the standardized cpue.
- 40 3. Include winter pot survey cpue (But was removed from the final model due to lack of
41 fit)
- 42 4. Estimate growth transition matrix from tagged recovery data.
43

44 2015 (SAFE 2015)

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

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

3
4 2016 (SAFE 2016)

- 5 1. Length range extended from 74mm – 124mm above to 64mm – 134mm above.
- 6 2. Estimate multiplier for the largest ($> 123\text{mm}$) length classes.

9 **2. Model Description**

- 10 a. Description of overall modeling approach:

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

- 16
17 b-f. See Appendix A.

- 18
19 g. Critical assumptions of the model:

- 20
21 i. Male crab mature at CL length 94mm.

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

- 24
25 ii. Molting occurs in the fall after the fishery

- 26 iii. Instantaneous natural mortality M is 0.18 for all length classes, except for the last
27 length group ($> 123\text{mm}$).

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

- 30
31 v. Winter pot survey selectivity is a dome shaped function: Reverse logistic function
32 of 1.0 for length class CL 84mm, and model estimate for $\text{CL} < 84\text{mm}$ length
33 classes. Selectivity is constant over time.

34 This assumption is based on the fact that a low proportion of large crab are caught
35 in the nearshore area where winter surveys occur. Causes of this pattern may be
36 that (1) large crab do not migrate into nearshore waters in winter or (2) large crab
37 are fished out by winter fisheries where the survey occurs (i.e., local depletion).
38 Recent studies suggest that the first explanation is more likely than second
39 (Jennifer Bell, ADFG, personal communication).
40
41

- 1 vi. Summer commercial fisheries selectivity is an asymptotic logistic function of 1.0
2 at the length class CL 124mm. While the fishery changed greatly between the
3 periods (1977-1992 and 1993-present) in terms of fishing vessel composition and
4 pot configuration, the selectivity of each period was assumed to be identical.
5 Model fits of separating and combining the two periods were examined in 2015,
6 and showed no difference between the two models (SAFE 2015). For model
7 parsimony, the two were combined.
8
- 9 vii. Summer trawl survey selectivity is an asymptotic logistic function of 1.0 at the
10 length of CL 124mm. While the survey changed greatly between NOAA (1976-
11 1991) and ADF&G (1996-present) in terms of survey vessel and trawl net
12 structure, selectivity of both periods was assumed to be identical. Model fits
13 separating and combining the two surveys were examined in 2015. No differences
14 between the two models were observed (SAFE 2015) and for model parsimony
15 the two were combined.
16
- 17 viii. Winter commercial and subsistence fishery selectivity and length-shell conditions
18 are the same as those of the winter pot survey. All winter commercial and
19 subsistence harvests occur February 1st.
20 Winter commercial king crab pots can be any dimension (5AAC 34.925(d)). No
21 length composition data exists for crab harvested in the winter commercial or
22 subsistence fisheries. However, because commercial fishers are also subsistence
23 fishers, it is reasonable to assume that the commercial fishers used crab pots that
24 they use for subsistence harvest, and hence both fisheries have the same
25 selectivity.
26
- 27 ix. Growth increments are a function of length, are constant over time, estimated
28 from tag recovery data.
29
- 30 x. Molting probability is an inverse logistic function of length for males.
31
- 32 xi. A summer fishing season for the directed fishery is short. All summer commercial
33 harvests occur July 1st.
34
- 35 xii. Discards handling mortality rate for all fisheries is 20%.
36 No empirical estimate is available.
37
- 38 xiii. Annual retained catch is measured without error.
39
- 40 xiv. All legal size crab ($\geq 4\text{-}3/4$ inch CW) are retained.
41
42 Since 2005, buyers announced that only legal crab with ≥ 5 inch CW are acceptable for
43 purchase. Since samples are taken at a commercial dock, it was anticipated that this
44 change would lower the proportion of legal crab for length class 4. However, the model
45 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.

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

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

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 .

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2
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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

4
5
6

b. Evaluation of negative loglikelihood alternative models results:

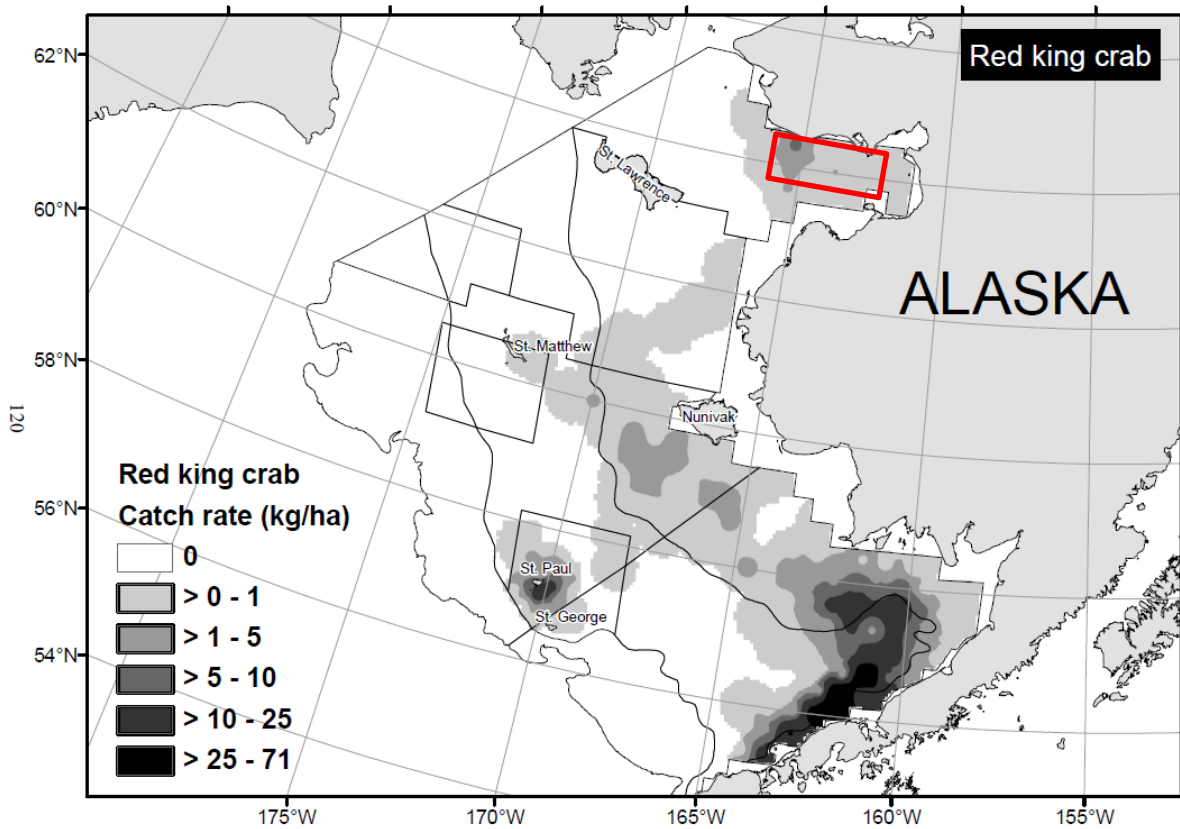
Model	Model 0	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
No. Parameters	65	72	71	66	148	85	86
Total	311.9	266.8	317.3	271.5	208.3	272.1	252.0
TSA	9.1	9.2	14.3	9.1	8.8	6.7	9.5
St.CPUE	-22.7	-22.5	-22.0	-22.5	-22.3	-21.0	-22.1
TLP	104.3	83.7	98.4	82.8	47.2	80.8	76.0
WLP	42.5	38.5	38.5	39.3	37.4	46.4	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

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- 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:

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



17
18 Figure D: Red king crab distribution from Lauth (2011). Red rectangular shows approximate triennial
19 survey and fishing area.

20 It is possible that large crab dispersed so widely along the coast of Norton Sound that they
21 were less likely caught by fisheries or trawl surveys, or that they were migrating down to St.
22 Mathews Island or to Nunivak Island.
23

1 Alternatively, the absence of large crab can be explained by a higher natural mortality
 2 (Model 6). Model 6 showed better fits than Model 5 and eliminated the dome-shaped
 3 selectivity (i.e., outmigration of large crab). However, estimated M was 0.44 that was about
 4 2.5 times higher than current assumption of $M = 0.18$. Considering differences in habitat
 5 conditions of Norton Sound, it is possible that their natural mortality is higher than other
 6 regions.

7
 8 In conclusion, we were faced with the 3 alternative realities of Norton Sound Red King Crab
 9 life-history that are equally likely in terms of model fit, but biologically unusual.

- 10
 11 1. 3.3-4.0 times higher natural mortality for large sized crab (Models 0, 1, 3).
 12 2. Large crab consisting of 50% of MMB move out of Norton Sound fishery and
 13 survey area (Model 5).
 14 3. 2.5 times higher natural mortality for all crab lengths (Model 6).

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

22
 23 **4. Results**

- 24
 25 1. List of effective sample sizes and weighting factors (Figure 4)

26 "Implied" effective sample sizes were calculated as

27
$$n = \frac{\sum_l \hat{P}_{y,l}(1-\hat{P}_{y,l})}{\sum_l (P_{y,l} - \hat{P}_{y,l})^2}$$

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

30
 31 Maximum sample sizes for length proportions:

32

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

- 33
 34 2. Tables of estimates.

- 1 a. Model parameter estimates (Tables 10, 11, 12, 13).
- 2
- 3 b. Abundance and biomass time series (Table 13)
- 4
- 5 c. Recruitment time series (Table 13).
- 6
- 7 d. Time series of catch/biomass (Tables 13 and 14)
- 8
- 9 3. Graphs of estimates.
- 10 a. Molting probability and trawl/pot selectivity (Figure 5)
- 11 b. Trawl survey and model estimated trawl survey abundance (Figure 6)
- 12 c. Estimated male abundances (recruits, legal, and total) (Figure 7)
- 13 d. Estimated mature male biomass (Figure 8)
- 14 e. Time series of standardized cpue for the summer commercial fishery (Figure 9).
- 15 f. Time series of catch and estimated harvest rate (Figure 10).
- 16
- 17 4. Evaluation of the fit to the data.
- 18
- 19 a. Fits to observed and model predicted catches.
- 20 Not applicable. Catch is assumed to be measured without error; however fits of cpue
- 21 are available (Figures 9, 11).
- 22
- 23 b. Model fits to survey numbers (Figures 6, 11).
- 24
- 25 All model estimated abundances of total crab were within the 95% confidence interval of
- 26 the survey observed abundance, except for 1976 and 1979, where model estimates were
- 27 higher than the observed abundances.
- 28
- 29 c. Fits of catch proportions by lengths (Figures 12, 13).
- 30
- 31 d. Model fits to catch and survey proportions by length (Figures 12, 14, 15, 16).
- 32
- 33 e. Marginal distribution for the fits to the composition data
- 34
- 35 f. Plots of implied versus input effective sample sizes and time-series of implied effective
- 36 sample size (Figure 4).
- 37
- 38 g. Tables of RMSEs for the indices:
- 39

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

3
 4

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

6
 7

8 5. Retrospective analyses (Figure 17).

9

10 6. Uncertainty and sensitivity analyses.

11 See Sections 2 and 5.

12

13 ***F. Calculation of the OFL***

14

15 1. Specification of the Tier level and stock status.

16

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

22

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

25

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

26

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

29

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

32

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

2

3 Predicted mature male biomass in 2017 on February 01 is:

4

5 Mature male biomass : 5.14 million lb.

6

7 Estimated B_{MSY} proxy is:

8

9 4.62 million lb.

10

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

13

14 2. Calculation of OFL.

15

16 OFL was calculated for retained (OFL_r), un-retained (OFL_{ur}), and total (OFL_T) for legal sized crab,
 17 $Legal_B$, by applying F_{OFL} .

18

19 $Legal_B$ is a biomass of legal crab subject to fisheries and is calculated as: Projected abundance by
 20 length crab \times fishing selectivity by length class \times Proportion of legal crab per length class \times
 21 Average lb per length class.

22

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

27
$$Legal_B_s = Legal_B_w(1 - \exp(-x \cdot F_{OFL}))e^{-0.42M}$$

28
$$OFL_r = (1 - \exp(-(1-x) \cdot F_{OFL}))Legal_B_s$$

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

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

31

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

33
$$OFL = Legal_B_w \left(1 - e^{-(F_{OFL} + 0.42M)} - (1 - e^{-0.42M}) \left(\frac{1 - p(1 - e^{-(F_{OFL} + 0.42M)})}{1 - p(1 - e^{-0.42M})} \right) \right)$$

1 Unretained OFL (OFL_{ur}) is a sub-legal crab biomass catchable to summer commercial pot fisheries
2 calculated as: Projected legal abundance (Feb 1st) \times Commercial pot selectivity \times Proportion of
3 sub-legal crab per length class \times Average lb per length class \times handling mortality.
4

5 The total male OFL is

$$6 \quad \quad \quad OFL_T = OFL_r + OFL_{ur}$$

7
8 For calculation of the OFL 2017
9

10 Legal male biomass (July 01): 4.32 (SD 0.89) million lb
11 $OFL_r = 0.67$ million lb.
12 $OFL_{nr} = 0.14$ million lb.
13 $OFL_T = 0.81$ million lb.
14

15 ***G. Calculation of the ABC***

16

17 1. Specification of the probability distribution of the OFL.

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

20 Retained ABC for legal male crab is 80% of OFL

21

22 $ABC = 0.54$ million lb
23

24 ***H. Rebuilding Analyses***

25 Not applicable
26

27 ***I. Data Gaps and Research Priorities***

28

29 The major data gap is the fate of crab greater than 123 mm.
30
31

32 **Acknowledgments**

33 We thank all CPT members for all review of the assessment model and suggestions for
34 improvements and diagnoses and Joel Webb for ADF&G internal review.
35

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