Norton Sound Red King Crab Stock Assessment for the fishing year 2011/12

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Executive Summary

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

2. Catches. This stock supports three main 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 catch reached a peak in the late 1970s at a little over 2.9 million pounds retained catch. Since 1982, retained catches have been below 0.5 million pounds, averaging 275,000 pounds, including several low years in the 1990s. Retained catches in the past two years have been about 400,000 pounds.

3. Stock Biomass. Mature male biomass is estimated to be on an upward trend following a recent low in 1997 and an historic low in 1982 following a crash from the peak in 1977. Uncertainty in biomass is driven in part by infrequent trawl surveys (every 3 to 5 years).

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

5. Management performance. Biomass quantities are in millions of pounds.

Status and catch specifications (million lbs.)

Year	MSST	Biomass (MMB)	GHL	Retained Catch	Total Catch[D]	OFL	ABC
2005/06		3.89	0.37	0.40	0.41		
2006/07		3.62	0.45	0.45	0.50		
2007/08		4.40	0.32	0.31	0.36		
2008/09	1.78[A]	5.24[A]	0.41	0.39	0.43	0.68[A]	
2009/10	1.54[B]	5.83[B]	0.38	0.40	0.43	0.71[B]	
2010/11	1.56[C]	5.44[C]	0.40	0.42	0.46	0.73[C]	
2011/12		4.70	TBD	TBD	TBD	0.655	0.388

Status and catch specifications (kt)

Year	MSST	Biomass (MMB)	GHL	Retained Catch	Total Catch	OFL	ABC
2005/06		1.76	0.17	0.18	0.19		
2006/07		1.64	0.20	0.20	0.23		
2007/08		2.00	0.15	0.14	0.18		
2008/09	0.81[A]	2.38[A]	0.19	0.18	0.21	0.31[A]	
2009/10	0.70[B]	2.64[B]	0.17	0.18	0.22	0.32[B]	
2010/11	0.71[C]	2.47[C]	0.18	0.19	0.22	0.33[C]	
2011/12		2.13	TBD	TBD	TBD	0.297	0.176

Notes:
A-Calculated from the assessment reviewed by the Crab Plan Team in May 2008
B-Calculated from the assessment reviewed by the Crab Plan Team in May 2009
C-Calculated from the assessment reviewed by the Crab Plan Team in May 2010
D- See Table 18

6. Basis for the OFL

Biomass in millions of pounds

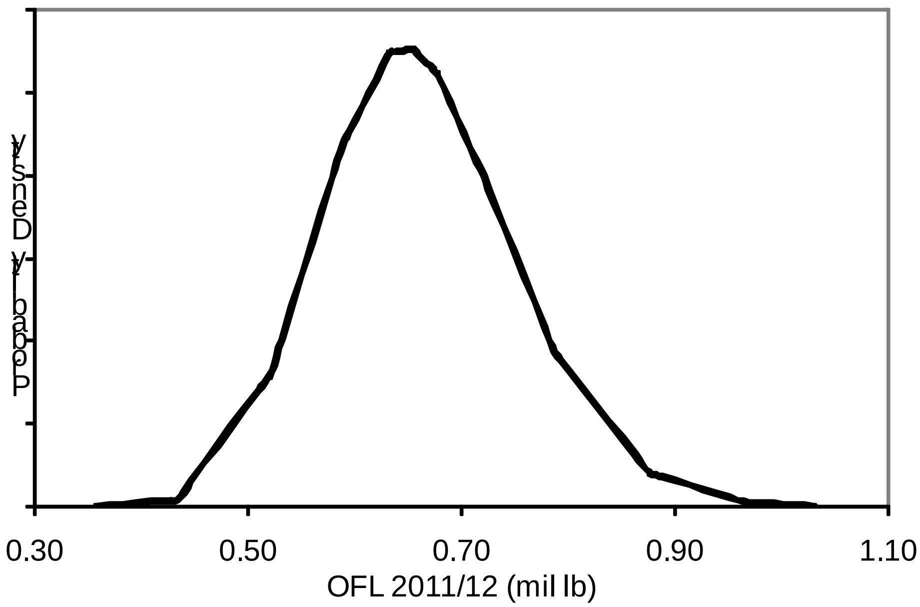
Year	Tier	B_{MSY}	Current MMB	B/B_{MSY} (MMB)	F_{OFL}	Years to define B_{MSY}	Natural Mortality (M)	P*	ABC
2008/09	4a	3.57[A]	5.24[A]	1.5	0.18	1983-2008	0.18		
2009/10	4a	3.07[B]	5.83[A]	1.9	0.18	1983-2009	0.18		
2010/11	4a	3.12[C]	5.44[C]	1.7	0.18	1983-2010	0.18		
2011/12	4a	2.97	4.70	1.6	0.18	1983-2011	0.18	0.49	0.388

Biomass in kt

Year	Tier	B_{MSY}	Current MMB	B/B_{MSY} (MMB)	F_{OFL}	Years to define B_{MSY}	Natural Mortality (M)	P*	ABC
2008/09	4a	1.62[A]	2.38[A]	1.5	0.18	1983-2008	0.18		
2009/10	4a	1.39[B]	2.64[A]	1.9	0.18	1983-2009	0.18		
2010/11	4a	1.42[C]	2.47[C]	1.7	0.18	1983-2010	0.18		
2011/12	4a	1.35	2.18	1.6	0.18	1983-2011	0.18	0.49	0.176

[A] Calculated from the assessment model agreed on by the Crab Plan Team in May 2008; $\gamma = 1$.
[B] Calculated from the assessment model agreed on by the Crab Plan Team in May 2009; $\gamma = 1$.
[C] Calculated from the assessment model agreed on by the Crab Plan Team in May 2010; $\gamma = 1$.
[D]

7. Probability Density Function of the OFL



8. The basis for the ABC recommendation

A retrospective analysis showed that the model predicted biomass is about 60% higher than the hindcast estimate for the same year. To correct this overestimation bias, a correction factor was calculated using a linear correlation, hindcast biomass = $\beta \times$ predicted biomass, where β was estimated to be 0.592. Applying this 59.2% bias correction factor, a recommended ABC was calculated as $0.655 \times 0.592 = 0.388$ million lbs.

9. A summary of the results of any rebuilding analyses.
N/A

A. Summary of Major Changes in 2011

1. Changes to the management of the fishery**:** None.
2. Changes to the input data
    a. Data update: the 2011 winter pot survey, 2010 summer commercial fishery, and 2010/2011 winter commercial and subsistence catch.
    b. New Data: Abundance estimate and proportion of size classes estimated from the 2010 NOAA trawl survey was included.
3. Changes to the assessment methodology: None. The 2010 model was used.
4. Changes to the assessment results.

B. Response to SSC and CPT Comments

CPT Review May 10-14, 2010

Jie Zheng presented the Norton Sound red king crab assessment. Jie identified the SSC and CPT recommendations regarding the 2009/10 assessment and the subsequent changes made in this year's assessment. Major changes include specification of $M=0.18yr^{-1}$ and $\gamma=1.0$. ***The CPT recommended that the next iteration explain the derivation of weights on fishing effort data.*** *Jie presented seven model alternatives, including the 2009/10 selected model and six model configurations with different assumptions. The conclusion that selectivity is uniform across all sizes should be re-evaluated for model 5, which specified a maximum effective sample size of 100 for the commercial catch and winter surveys.* ***Further biological justification should be provided for the value of M to $0.288yr^{-1}$ for last length group in model 6.*** *It was noted that the assumption that M is higher for the largest crab is not made in the assessments of other RKC stocks and alternative explanations include the potential that last length group moves to inaccessible area, resulting in lower selectivity. The lack of large individuals in the catch and survey is dealt with in two different ways in the assessment: dome-shaped selectivity (models 1-5) and higher M (models 6 and 7). The analysis should isolate effect of selectivity.* ***No additional comments outside of general changes.***

Authors' response: The rationales for increasing the last length group higher and changing weight of fishing efforts were included in the modeling section.

This assumption higher mortality rate for the last length class (>123 mm) is based on the observation that the observed length frequency in all summer trawl survey is less than 10% (Table 6), which cannot be explained by the constant mortality assumptions. It is possible, that the last length group may move to inaccessible area, or that their catch selectivity is lower. However, the trawl survey is conducted over most of the area, except for a few rocky bottom areas and shallow near coastal zone, so that it is unlikely that the trawl survey misses the largest crabs. It is possible that the catch selectivity of the largest crabs is lower than other length groups; however, attempts to lowering catch selectivity did not yield improved fit CPT (2010). High proportion of the > 123 mm crab (30-45%) occurred in 1980 and 1981 summer pot survey and in 1980-1982 summer commercial fishery (56-75%). Since then, high proportion of the large length has not been observed. It is unknown, why they disappeared.

SSC Review on June 7-9, 2010

The assessment updated the length-based model presented in the 2009 SAFE. In response to previous SSC comments, the model now includes discard mortality and pot fishery PSC. In response to SSC comments, the author applied a handling mortality rate of 0.2. ***The CPT recommended and the SSC agrees that the assessment model output should be used as the basis for estimating biological reference points for the 2010/11 season.***

Authors' response: As directed, the recommended model configuration was also used for 2011/12 season.

The author considered seven models. ***The CPT recommended, and the SSC agrees, that Model 6 should be used for estimation of the 2010/11 OFL.*** *While the SSC agrees with the use of Model 6 for the 2010/11 season,* ***we request that the author provides a rationale for why larger crab would have a higher natural mortality rate (M=0.288), and why this added mortality at large sizes is applied to only this population.***

Authors' response: the same as the response to the CPT.

The CPT also recommended, and the SSC concurs, that this stock qualifies for Tier 4 management and that the reference natural mortality rate for estimation of the OFL should be 0.18. ***The SSC continues to recommend that the reference time period for estimation of B_{MSY} proxy should be 1983-2009, and that gamma should be set at 1. The SSC continues to encourage the author to work on the Norton Sound red king crab assessment model with a long-term goal of moving this stock to Tier 3.***

Authors' response: As directed, M = 0.18 and 1983-2010 period was used for estimation of B_{MSY} for 2011/12 season.

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 with 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) (Soong et al. 2008). 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. Our 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 been made on possible stock separation within the putative stock known as Norton Sound red king crab.
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 the summer. Norton Sound red king crab are consistently abundant offshore of Nome, and hence the coastal area is closed for the summer commercial crab fishery (Figure 2).

   Red king crab migrates between deeper offshore waters during molting/feeding and inshore shallow waters during the mating period. Timing of the inshore mating migration is unknown. They are assumed to mate during March-June. Offshore migration is considered to begin in May-July. Trawl surveys during 1976-2010 show that crab distribution is dynamic. Recent surveys show high abundance on the southeast side of the Sound, offshore of Stebbins and Saint Michael. However, it is unknown whether this is due to a migratory shift because of oceanographic change or due to changes in stock composition.

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 in winter (December – May) (Soong et al. 2008). The majority of red king crabs (0.3 mil lb) are harvested by the summer commercial fisheries, whereas the majority of the winter fisheries are subsistence fishery with occurring near coast (0.023 mil lb).

Summer Commercial Fishery

A large-vessel summer commercial crab fishery existed in the Norton Sound Section from 1977 through 1990. No summer commercial fishery occurred in 1991 because there was no staff to manage the fishery. In 1992, the summer commercial fishery resumed. 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. Regulation changes and location of buyers resulted in harvest distribution moving eastward in Norton Sound in the mid 1990s. Commercial fisheries history and catch data are summarized in Table 1.

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 they make their first delivery. Fishers operate under authority of the CDQ group and each CDQ group decides how their crab quota is to be harvested. During the March 2002 BOF meeting, new regulations were adopted that affected the CDQ crab fishery and relaxed closed-water boundaries in eastern Norton Sound and waters west of Sledge Island. At its March 2008 meeting, the BOF changed the start date of the Norton Sound open-access portion of the fishery to be opened by emergency order and as early as June 15. The CDQ fishery may open at any time, by emergency order.

Winter Commercial Fishery

The Norton Sound winter commercial fishery is a small fishery using hand lines and pots through the nearshore ice. Approximately 10 permit holders participated in this fishery harvesting, on average 2,400 crabs on average annually during 1978-2007 (Soong 2007). The winter commercial fishery catch is influenced not only by crab abundance, but also by changes in near shore crab distribution, and ice conditions.

Subsistence Fishery

The Norton Sound subsistence crab fishery mainly occurs during winter using hand lines and pots through the nearshore ice. Average annual subsistence harvest was 5,300 crabs (1978-2007). Subsistence harvest need to obtain a permit before fishing and record daily effort and catch. There is no size limit in the subsistence fishery. 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).

Harvest Strategy

Norton Sound red king crab have been conservatively managed since 1997 from 5% to 10% of estimated legal male abundance with the guideline harvest level (GHL) for the summer fishery was adopted in 1999. GHL consists of three levels: (1) 0% harvest rate of legal crab when estimated legal biomass < 1.5 million lbs; (2) ≤ 5% of legal male abundance when the estimated legal biomass falls within the range 1.5-2.5 million lbs; and (3) ≤ 10% of legal male when estimated legal biomass >2.5 million lbs.

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 into effect. The end of large vessel commercial fishery operation. Participation limited to small boats. The majority of commercial fishery subsequently shifted to east of 164^{o}W line.
1998	Community Development Quota (CDQ) allocation into effect
1999	Guideline Harvest Limit (GHL) into effect
2000	North Pacific License Limitation Program (LLP) into effect.
2002	Change in closed water boundaries (Figure 2)
2006	The Statistical area Q3 section expanded (Figure 1)
2008	Start date to the open access fishery changed from July1 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.

D. Data

1. Summary of new information:
   a. The model was updated with new data from the 2010 summer trawl survey, 2011 winter pot survey, 2010 summer commercial fishery, and 2010/2011 winter commercial and subsistence fisheries.
   b. Included abundance and length composition estimates form the 2010 Trawl survey conducted by the NOAA fisheries.

2. Available survey, catch, and tagging data.

Data Set	Years	Data Types
Summer trawl survey	76,79,82,85,88,91,96, 99, 02,06,08,10	Abundance and proportion by length and shell condition
Summer pot survey	80-82,85	Abundance and proportion by length and shell condition
Winter pot survey	81-87, 89-91,93,95-00,02-11	Proportion by length and shell condition
Summer preseason survey	95	Proportion by length and shell condition
Summer commercial fishery	76-90,92-11	Catch abundance, effort, and proportion by length and shell condition
Observer bycatch data	87-90,92,94	Proportion by length and shell condition
Winter commercial fishery	76-11	Catch abundance
Subsistence fishery	76-11	Catch abundance
Tagging data	80-07	Mean and standard deviation of growth increment

   a. Summer commercial fishery and winter commercial and subsistence catch, and effort (potlifts) (ADF&G 1976-2010) (Tables 1 and 2).

   b. Bycatch and discards of sublegal males (observer data) from the summer fishery (ADF&G 1987-90, 1992, 1994). Since the observer coverage was not 100%, amounts of bycatch were not recorded. Only catch-at-length and shell condition were recorded. In Norton Sound, no other crab, groundfish, or shellfish fisheries exist.

	Fishery	Data availability
Directed pot fishery (males)	Summer commercial	Not available
Directed pot fishery (females)	Winter commercial/subsistence	Not available
Bycatch in other crab fisheries	Fishery does not exist	NA
Bycatch in ground pot	Fishery does not exist	NA
Bycatch in ground fish trawl	Fishery does not exist	NA
Bycatch in the scallop fishery	Fishery does not exist	NA

   c. Catch at length data for summer commercial fisheries (Table 3).

d. Survey biomass estimates:
   Triennial trawl surveys (NMFS: 1976-1991, ADF&G: 1996-2008, NMFS: 2010) (Table 4). Total population abundances and length and shell compositions for males >73 mm CL were estimated by "area-swept" methods from the trawl survey data (Alverson and Pereyra 1969). The compositions consisted of six 10-mm length groups (Table 5). If multiple hauls were conducted for a single station during a survey, then the average of abundances from all hauls within the station was used. Some trawl surveys occurred during September, the molting period for males. To make survey abundances comparable with premolt abundances, we adjusted trawl survey abundances by subtracting the average growth increment of each length class from the length of each soft-shell crab (assumed to have molted within the past 2 months).

   Summer pot surveys were conducted in 1980-82, 85. Survey biomass CV was not reported.

e. Survey catch-at-length data for triennial Trawl survey (Table 5) and winter pot survey (Table 6). Other survey catch-at-length data includes summer pot survey (1980-92, 85) and summer preseason survey (1995).

f. Other miscellaneous data: None.

3. Growth-per-molt (Table 7), estimated from tagging data (1991-2007).

E. Analytic Approach

1. History of the modeling approach.

The Norton Sound red king crab was assessed using a length-based synthesis model (Zheng et al. 1998). The model was updated in 2009-2010 to provide information for the federal OFL. At May 2010 CPT meeting, seven alternative models were presented: 1) based on 2009 model reviewed by Punt (University of Washington), 2) model 1 and including bycatch mortality, 3) model 2 with weight of fishing effort increased from 5 to 20; 4) model 3 with fishery selectivity for the last length group from 0.6 to being estimated from the model, 5) model 3 and reduce the maximum effective sample size for commercial catch and winter surveys from 200 to 100, 6) model 5 with M for the last length group increased from the default 0.18 to 0.288, and 7) model 6 with M increased to 0.34. The CPT and subsequent SSC recommended using the Model 6 for the 2010/11 iteration. In this iteration, model 6 was also used.

2. Model Description

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

b-f. See Appendix A.

g. Critical assumptions of the model:

i. Instantaneous natural mortality *M* is 18% and constant over time. This mortality is based on Bristol Bay red king crab, estimated with a maximum age 25 and the 1% rule (Zheng 2005).

ii. Natural mortality for the last length group (> 123mm) is 60% higher (28.8%) than the other length groups (Zheng et al. 1998). This assumption is based not on biological data, but rather a working hypothesis attempting to explain the low proportion (< 10%) of this group in summer trawl surveys (Table 6). It is possible, that the last length group may move into areas inaccessible to commercial fisheries, resulting in lower selectivity (CPT review 2010). However, this does not explain the lower proportion observed in the summer trawl survey, when all of the Norton Sound Area was surveyed. Furthermore, lowering the catch selectivity did not result in lower log likelihood than increasing the mortality (CPT 2010). Model estimated selectivity was also 1.0 for the last length class.

iii. Trawl survey catchability is 1.0 for legal males and a sigmoid function of length for the first 2 length groups. It is constant over time and shell condition. For winter survey, selectivity of the last length group is less than 1 (Table 7).

iv. Summer commercial fisheries selectivity is a sigmoid function of length peaking at the length class 5 (104-113 mm). It has two curves: before 1993 and after 1992, due to reflect changes in fishing vessel composition and pot limits.

v. Winter commercial and subsistence fishery selectivity and length-shell conditions are the same as those of winter pot survey.

vi. Growth is a function of length and is constant over time.

vii. Molting probabilities are an inverse logistic function of length for males.

viii. A summer fishing season for the directed fishery is short.

ix. Bycatch handling mortality is 20%.

x. Annual retained catch is measured without error.

xi. Trawl survey catchability is 1.0 for legal males.

xii. Male crabs mature knife-edged at sizes ≥94 mm CL.

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

h. Changes since last assessment: None

i. Code validation. The base model structure was error checked by A. Punt (University of Washington, Seattle, WA. pers. Comm..). Model code is available from the author.

3. Model Selection and Evaluation

a. Description of alternative model configurations.

   Following the CPT and SSC directives, no alternative model configurations were considered at this iteration.

b. NA

c. NA

d. NA

e. Sample sizes for length composition data (Tables 2,3,5,6, and 9).

f. Parameter estimates: Assuming M = 0.18 for all length classes resulted in an unrealistic build-up of abundance in the last length class. Setting M = 0.288 in the last length class helps reducing this bias.

g. Model selection criteria. The Likelihood values were used to evaluate model.

h. Residual analysis. Residual plots for length compositions are shown in Figures 5 and 6.

i. Model evaluation is provided under Results, below.

4. Results

1. Effective sample sizes and weighting factors.

Data	Weighting Factor
Summer Trawl Survey	200
Summer Pot Survey	200
Summer fishing effort	20
Recruitment	0.01
Maximum effective sample size for length proportion	200
Maximum effective sample size for length proportion: Summer commercial and winter pot	100

   a. Effective sample sizes for length compositions are given in Tables 2, 3, 5, 6, and 9.

2. Tables of estimates.

   a. Parameter estimates are provided in Table 10.

The parameters estimates were categorized as: Recruitment, catchability functions, and molting functions. Among those, CV of the Recruitment parameter ranged from 18% to 3576%, averaging 238%. For catchability function parameters, catchability of trawl survey was the worst, followed by summer commercial and winter pot.

b. Abundance and biomass time series are provided in Table 10 and Figure 3.

c. Recruitment time series are in Table 10 and Figure 3.

d. Time series of catch/biomass are in Table 11.

3. Graphs of estimates.

a. Selectivities, molting probabilities, and proportions of legal crabs by length are provided in Table 8.

b. Estimated male abundances (recruits, legal, and total) are plotted in Figures 3 and 4.

c. Estimated harvest rates are shown in Figure 5 upper.

d. Harvest rates are plotted against mature male biomass in Figure 5 lower.

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. Instead, summer commercial catch efforts were modeled (Figure 6).

Modeled efforts generally followed observed efforts, except in 1986 and 1988 when the observed effort was higher and in 1977 and 1992 when the observed effort was lower.

b. Model fits to survey numbers (Figure 7).

The majority of model estimated abundances of legal and sublegal crabs was within 95% confidence interval of the survey observed abundances, except in 1979 when the model estimated legal crab abundance was higher and in 1991 and 1999 when the model estimated legal crab abundance was lower. For sublegal crab, model estimated abundances were generally similar to observed estimates, although model estimates tended to be lower.

c. Model fits to catch and survey proportions by length (Figure 8).

The residuals of length compositions were generally large, especially for the largest size class (>123 mm). The model had two fishing selectivity curves, 1977-1992 and 1993-2010. During 1977-1992, the model tended to overestimate the proportion of 104-114 length class (negative residual) and underestimate the last length class (>123mm). During 1993-2010, the model tended to overestimate the last and the 94-103 length classes, and underestimated the proportion of 104-113 and 114-123 length classes.

d. Model fits to survey proportions by length

Winter pot survey, summer trawl survey, summer pot survey, and summer observer survey (Figure 9).

A residual plot for winter pot survey showed the model tended to overestimate (negative residuals) the proportion of large length classes (>103 mm), and underestimate the proportion of the small length classes. However, during 1991-1995, the pattern was reversed.

Plots of summer trawl, pot, and observer data did not seem show noticeable patterns. Similar to the winter pot survey, the model tended to overestimate proportion of large length classes. This tendency was most prominent during the last 3 trawl surveys.

e. Marginal distribution for the fits to the composition data: Not provided

f. Plots of implied versus input effective sample sizes and time-series of implied effective sample sizes: Not provided

g. Tables of RMSEs for the indices: Not provided

h. QQ plots and histograms of residuals: not provided.

5. Retrospective and historic analyses.

We examined performance of current model by creating retrospective predicted abundance estimate of legal crab from 2000 to 2010 using data available for the years of projection. In this, for instance, 1976-1999 data were used for prediction of red king crab abundance in 2000, 1976-2000 data were used for prediction of 2001, and so on. If the model is performing correctly, then model predicted biomass of a given year (e.g., 2002) should be similar to surveyed or hind cast estimated biomass of the same year (e.g., 2002).

a. Retrospective analysis (Figure 10).

The retrospective plots of 2000-2011 show that the model's tendency to overestimate the Norton Sound red king crab abundance. Hind cast abundance estimates of all the retrospective models converged for years of 1976-1988. For years of 1989-present, abundance estimates moved downward (i.e., lower biomass estimate) as more subsequent years of data were added. This shows that model tends to overestimate biomass.

b. Historic analysis (Figure 11).

Comparing retrospective predicted abundance estimates of the current model, with those of historical predicted, and hind cast abundance estimate using the 196-2010 data, the retrospective predicted estimates were higher than historical and hind casted estimates. On average (2000-2008), retrospective predicted estimates were 61% higher than hind casted estimates, whereas historical predicted estimates were 37% higher. This shows that current model overestimates crab abundance by 60%.

6. Uncertainty and sensitivity analyses.

As described in the above retrospective and historic analyses, the major deficiency of the current model is that predicted abundance is likely biased ~ 60% high (Figure 11). This issue has been persistent since model inception in 1999. Residual analyses indicate that this overestimation is likely due to the model overestimating the proportion of large length groups (i.e., negative residuals) in summer surveys and fisheries and in winter pot surveys (Figures 8 and 9). High model estimates of the large length group would result in high abundance; however, trawl survey did not show high abundance as predicted by the model.

Throughout the iteration, many attempts have been made to correct this bias, including model revisions, updates of growth matrix, inclusion of bycatch mortality, changing model weights, evaluation of *M*. Despite those efforts, the overestimation issue remained.

a. Evaluation of selectivity

The discrepancy can be due to misconfiguration of the selectivity, in which the assumption of constant selectivity for large class is incorrect. Since the selectivity function applied in this model is an asymptotic logistic form, selectivity of the large length group is 1.0. In the 2010 CPT review, a dorm shaped selectivity (model 4) was examined, but it generally did not improve the likelihood. The exception was an estimated selectivity of 0.39 in the winter pot survey. For the summer trawl survey selectivity was assumed to be 1.0 for legal sizes and was modeled estimate for small size classes (1 and 2). However, estimates of selectivity parameters (log_φ_{st}, log_ω_{st}) had high standard deviation and resulting selectivity equal to 1.0.

b. Weighting factors

Changing weighting factors and effective sample size affect reliability of data. Among the data, summer fishery data were more reliable, and thus given heavier weight. On the other hand, the maximum effective sample size for commercial catch and winter surveys was reduced because of uncertainties about representativeness of the data, especially for the large length size. It has been suspected that the length proportions for the winter pot survey are biased because the survey pots were located only Nome area where the majority of subsistence fisheries occur. While there is no size limit in the subsistence fishery, most harvests retain only large (e.g., legal size) crabs, which may resulted in under-representation of large crabs in the winter pot survey (e.g., localized depletion of large crabs). However, comparison of the size frequencies between winter pot survey and the subsequent trawl surveys suggests any bias may be weak (Figure 13). For summer commercial length proportion data, because of market changes, not all legal crabs were retained (Soong, ADF&G pers. comm.). The proportion of discarded legal crab is unknown, although this would affect the length class of 104-113 mm. Reducing the effective sample size improved model fitting (CPT 2010). Zheng et al. (1998) examined sensitivity of weighting factors and concluded that estimates of parameters and legal crab abundance were not very sensitive to weighting factors for survey abundances and fishing effort, and maximum effective sample size. Those conclusions may not apply to the current model. Zheng et al. (1998) assumed M = 0.3.

c. Uncertainties in the survey abundance

In the model, trawl survey abundance data are weighted highly, and measurement errors from a single trawl survey could also affect the model results greatly. However, the abundance survey is conducted every 3 or 4 years, and survey coverage varies (Table 3). It is difficult to determine whether the large projection errors were due to sampling errors in winter pot surveys or measurement errors in summer trawl surveys.

F. Calculation of the OFL

1. Specification of the Tier level and stock status.

The Norton Sound red king crab stock is currently placed in Tier 4 (NPFMC 2007) because 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 capture the essential population dynamics. Explicit to Tier 4 stock are reliable estimates of current survey biomass and instantaneous M. However, the Norton Sound red king crab stock has neither. Survey biomass is based on triennial trawl surveys with CVs ranging 15-42% (Table 4). The natural mortality of 18% adopted by the CPT (2010) is based on Bristol Bay red king crab with the maximum age 25 and the 1% rule (Zheng 2005); however, no data are available to support the assumption of a maximum age 25 for the Norton Sound red king crab.

The OFL is estimated by the F_{MSY} proxy, B_{MSY} proxy, and estimated legal male abundance and biomass:

$$F_{OFL} = \gamma M, \quad when\, B / B_{MSY^{prox}} > 1, \qquad (1)$$

$$F_{OFL} = \gamma M\, (B / B_{MSY^{prox}} - 0.1) / 0.9, \quad when \;\; 0.25 < B / B_{MSY^{prox}} \le 1, \qquad (2)$$

$$F_{OFL} = bycatch\, mortality \,\&\, directed\ fishery\, F = 0, \quad when\, B / B_{MSY^{prox}} \le 0.25, \qquad (3)$$

$$OFL = (1 - \exp(-F_{OFL}))B$$

where B is a mature male biomass, B_{MSY} proxy is average mature male biomass over a specified time period. $M = 0.18$ and $\gamma = 1$.

For Norton Sound red king crab, MMB is CL > 94 mm and legal size is CL > 103 mm.

$$OFL = \sum_l \left[(N_{s,l} + O_{s,l})\, legal_l\, w_l\, (1 - \exp(-F_{OFL})) \right]$$

where $N_{s,l}$ and $O_{s,l}$ are summer abundances of newshell and oldshell crabs in length class l in the terminal year, $legal_l$ is the proportion of legal males in length class l, and w_l is the weight in length class l.

For the selection of the B_{MSY} proxy, we chose a period from 1983 to present because year classes after the 1976/77 regime shift (Overland et al. 1999) were expected to reach the mature population after 1982. This resulted in B_{MSY} of (2.940 MMB). Although the CPT and SSC agreed our choice, it should be noted that the choice is arbitrary. Although we examined alternative periods, the increasing trend since 1997 resulted in the condition of B/B_{MSY} >1 being met at any choices of period.

Estimated legal male abundance and mature male biomass in 2011 are:

Legal males: 1.471 million crabs with a standard deviation of 0.199 million crabs.

Mature male biomass: 4.699 million lbs with a standard deviation of 0.644 million lbs.

The average of model estimated mature male biomasses during 1983-2011 was used as the B_{MSY} proxy.

Estimated B_{MSY} proxy, F_{OFL} and retained catch limit in 2011 are:

B_{MSY} proxy = 2.940 million lbs,

F_{OFL} = 0.18,

The model predicted legal male abundance in 2011 is 1.471 million crabs or 3.976 million lbs. Hence, the overfishing limits for retained catch in 2011 are F_{OFL} = 0.18 (γ=1.0), 0.242 million crabs (1.471×(1-exp(-0.18)) or 0.655 million lbs (3.976×(1-exp(-0.18)).

Thus, we determined 2011, OFL = 0.655 million lbs.

G. Calculation of the ABC

1. Specification of the probability distribution of the OFL.

The maximum P* = 49 percentile of the OFL. However, history of catch and estimated harvest rates (Figure 5) shows that the estimated harvest rate in the years 1998–2010 after the GHL was established ranged from 10.4 to 17.2%, exceeding maximum GHL harvest rates of 10%. This occurred not because harvests exceeded the GHL, but primarily because the model projected abundance at the time of setting the GHL was higher than the hindcast abundance (Figures 10 and 11). Since this model overestimation problem has persisted over time, the current OFL estimate may found be lower in future years. Considering this, we developed a correction factor by regressing retrospective predicted estimates (2000-2008) against hindcast estimates (Figure 12).

$$\hat{N}_{hd} = \beta N_{prd} \quad \beta = 0.952$$

Applying this ratio estimator instead of the P* estimate, ABC was calculated as

ABC = OFL × β = 0.655 × 0.952 = 0.388

The model indicates the stock has been increasing since 1996 after it declined by 75% from 1976 to 1980 and gradually declined from 1981 to 1985 (Figure 3). This decline may be due to heavy fishing during 1979-1981. However, poor recruitment was also estimated for Norton Sound red king crab before fishing started during 1976-1980. Because the transition from spawning to recruitment takes 6 or 7 years for red king crab, it would not have been possible to sustain the high abundance even without fishing during the late 1970s. These high abundances [B1]were the result of exceptionally strong recruitments, which were also observed for other king crab stocks in the eastern Bering Sea (Zheng and Kruse 2000, 2006).

H. Rebuilding Analyses

Not applicable

I. Data Gaps and Research Priorities

The major data gaps of the Norton Sound red king crab are: spatially and temporarily consistent estimate of abundance, estimates of bycatch from the summer commercial fisheries, and estimates of the instantaneous natural mortality. In addition, life-history of the Norton Sound red king crab stock is poorly understood. More basic life-history studies are needed.

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Table 1. Historical summer commercial red king crab fishery economic performance, Norton Sound Section, eastern Bering Sea, 1977-2010.

Year	Guideline Harvest Level (lbs) [b]	Commercial Harvest (lbs) [a, b] Open Access	Commercial Harvest (lbs) [a, b] CDQ	Total Number (incl. CDQ) Vessels	Total Number (incl. CDQ) Permits	Total Number (incl. CDQ) Landings	Total Pots Registered	Total Pots Pulls	Total Exvessel Price/lb	Total Fishery Value (millions $)	Season Length Days	Season Length Dates
1977	[c]	0.52		7	7	13		5,457	0.75	0.229	60	[c]
1978	3.00	2.09		8	8	54		10,817	0.95	1.897	60	6/07-8/15
1979	3.00	2.93		34	34	76		34,773	0.75	1.878	16	7/15-7/31
1980	1.00	1.19		9	9	50		11,199	0.75	0.890	16	7/15-7/31
1981	2.50	1.38		36	36	108		33,745	0.85	1.172	38	7/15-8/22
1982	0.50	0.23		11	11	33		11,230	2.00	0.405	23	8/09-9/01
1983	0.30	0.37		23	23	26	3,583	11,195	1.50	0.537	3.8	8/01-8/05
1984	0.40	0.39		8	8	21	1,245	9,706	1.02	0.395	13.6	8/01-8/15
1985	0.45	0.43		6	6	72	1,116	13,209	1.00	0.427	21.7	8/01-8/23
1986	0.42	0.48		3	3		578	4,284	1.25	0.600	13	8/01-8/25
1987	0.40	0.33		9	9		1,430	10,258	1.50	0.491	11	8/01-8/12
1988	0.20	0.24		2	2		360	2,350	[c]	[c]	9.9	8/01-8/11
1989	0.20	0.25		10	10		2,555	5,149	3.00	0.739	3	8/01-8/04
1990	0.20	0.19		4	4		1,388	3,172	[c]	[c]	4	8/01-8/05
1991	0.34			No Summer Fishery								
1992	0.34	0.07		27	27		2,635	5,746	1.75	0.130	2	8/01-8/03
1993	0.34	0.33		14	20	208	560	7,063	1.28	0.430	52	7/01-8/28
1994	0.34	0.32		34	52	407	1,360	11,729	2.02	0.646	31	7/01-7/31
1995	0.34	0.32		48	81	665	1,900	18,782	2.87	0.926	67	7/01-9/05
1996	0.34	0.22		41	50	264	1,640	10,453	2.29	0.519	57	7/01-9/03
1997	0.08	0.09		13	15	100	520	2,982	1.98	0.184	44	7/01-8/13
1998	0.08	0.03	0.00	8	11	50	360	1,639	1.47	0.041	65	7/01-9/03
1999	0.08	0.02	0.00	10	9	53	360	1,630	3.08	0.073	66	7/01-9/04
2000	0.33	0.29	0.01	15	22	201	560	6,345	2.32	0.715	91	7/01- 9/29
2001	0.30	0.28	0.00	30	37	319	1,200	11,918	2.34	0.674	97	7/01- 9/09
2002	0.24	0.24	0.01	32	49	201	1,120	6,491	2.81	0.729	77	6/15-9/03
2003	0.25	0.25	0.01	25	43	236	960	8,494	3.09	0.823	68	6/15-8/24
2004	0.35	0.31	0.03	26	39	227	1,120	8,066	3.12	1.063	51	6/15-8/08
2005	0.37	0.37	0.03	31	42	255	1,320	8,867	3.14	1.264	73	6/15-8/27
2006	0.45	0.42	0.03	28	40	249	1,120	8,867	2.26	1.021	68	6/15-8/22
2007	0.32	0.29	0.02	38	30	251	1,200	9,118	2.49	0.750	52	6/15-8/17
2008	0.41	0.36	0.03	23	30	248	920	8,721	3.20	1.231	73	6/23-9/03
2009	0.38	0.37	0.03	22	27	359	920	11,934	3.17	1.225	98	6/15-9/20
2010	0.40	0.39	0.03	23	32	286	1,040	9,698	3.73	1.528	58	6/28-8/24

[a] Deadloss included in total. [b] Millions of pounds. [c] Information not available.

Table 2. Historical winter commercial and subsistence red king crab fishery economic performance, Norton Sound Section, eastern Bering Sea, 1977-2010.

	Commercial		Subsistence						
				Permits			Total Crab		Average
Year[a]	# of Fishers	# of Crab Harvested	Winter[b]	Issued	Returned	Fished	Caught[c]	Retained[d]	Permit Fished
1978	37	9,625	1977/78	290	206	149	[e]	12,506	84
1979	1[f]	221[f]	1978/79	48	43	38	[e]	224	6
1980	1[f]	22[f]	1979/80	22	14	9	[e]	213	24
1981	0	0	1980/81	51	39	23	[e]	360	16
1982	1[f]	17[f]	1981/82	101	76	54	[e]	1,288	24
1983	5	549	1982/83	172	106	85	[e]	10,432	123
1984	8	856	1983/84	222	183	143	15,923	11,220	78
1985	9	1,168	1984/85	203	166	132	10,757	8,377	63
1985/86	5	2,168	1985/86	136	133	107	10,751	7,052	66
1986/87	7	1,040	1986/87	138	134	98	7,406	5,772	59
1987/88	10	425	1987/88	71	58	40	3,573	2,724	68
1988/89	5	403	1988/89	139	115	94	7,945	6,126	65
1989/90	13	3,626	1989/90	136	118	107	16,635	12,152	114
1990/91	11	3,800	1990/91	119	104	79	9,295	7,366	93
1991/92	13	7,478	1991/92	158	105	105	15,051	11,736	112
1992/93	8	1,788	1992/93	88	79	37	1,193	1,097	30
1993/94	25	5,753	1993/94	118	95	71	4,894	4,113	58
1994/95	42	7,538	1994/95	166	131	97	7,777	5,426	56
1995/96	9	1,778	1995/96	84	44	35	2,936	1,679	48
1996/97	2[f]	83[f]	1996/97	38	22	13	1,617	745	57
1997/98	5	984	1997/98	94	73	64	20,327	8,622	135
1998/99	5	2,714	1998/99	95	80	71	10,651	7,533	106
1999/2000	10	3,045	1999/2000	98	64	52	9,816	5,723	107
2000/01	3	1,098	2000/01	50	27	12	366	256	21
2001/02	11	2,591	2001/02	114	61	45	5,119	2,177	48
2002/03	13	6,853	2002/03	107	70	61	9,052	4,140	68
2003/04[g]	2	522	2003/04[g]	96	77	41	1,775	1,181	29
2004/05	4	2,091	2004/05	170	98	58	6,484	3,973	112
2005/06	1[f]	75[f]	2005/06	98	97	67	2,083	1,239	18
2006/07	8	3,313	2006/07	129	127	116	21,444	10,690	92
2007/08	9	5,796	2007/08	139	137	108	18,621	9,485	88
2008/09	7	4,951	2008/09	105	105	70	6,971	4,752	68
2009/10		4,834	2009/10					7,044	
2010/11		4,834[i]	2010/11					8,288[i]	

a Prior to 1985 the winter commercial fishery occurred from January 1 - April 30. As of March 1985, fishing may occur from November 15 - May 15.

b The winter subsistence fishery occurs during months of two calendar years (as early as December, through May).

c The number of crab actually caught; some may have been returned.

d The number of crab Retained is the number of crab caught and kept.

e Information not available.

f Confidential under AS 16.05.815.

g Confidentiality was waived by the fishers.

h Prior to 2005, permits were only given out of the Nome ADF&G office. Starting with the 2004-5 season, permits were given out in Elim, Golovin, Shaktoolik, and White Mountain.

i Preliminary

Table 3. Summer commercial catch size/shell composition.

					New Shell					Old Shell					
Year	Sample	Model	Eff. N	Model	84-93	94-103	104-113	114-123	124+	74-83	84-93	94-103	104-113	114-123	124+
1977	1549	100	25	100	0	0.0032	0.4196	0.3422	0.122	0	0	0	0.0626	0.04	0.0103
1978	389	39	157	39	0	0.0103	0.1851	0.473	0.3059	0	0	0	0.0051	0.0103	0.0103
1979	1660	100	43	100	0	0.0253	0.2325	0.3831	0.3217	0	0	0	0.0253	0.0006	0.0114
1980	1068	100	34	100	0	0.0037	0.0983	0.3062	0.5543	0	0	0	0.0028	0.0112	0.0234
1981	1748	100	11	100	0	0.0039	0.0734	0.1541	0.509	0	0	0	0.0045	0.0504	0.2046
1982	1093	100	20	100	0	0.0421	0.1921	0.1647	0.505	0	0	0.0037	0.0128	0.022	0.0576
1983	802	80	28	80	0	0.0387	0.4127	0.3579	0.0973	0	0	0.0037	0.0362	0.01	0.0436
1984	963	96	28	96	0	0.0966	0.4195	0.2804	0.0717	0	0	0.0104	0.0654	0.0488	0.0073
1985	2691	100	57	100	0.0004	0.0643	0.3122	0.3716	0.1747	0	0	0.0026	0.0334	0.0312	0.0097
1986	1138	100	70	100	0	0.029	0.3559	0.3937	0.1353	0	0	0.0018	0.0202	0.0378	0.0264
1987	1542	100	11	100	0	0.0166	0.1788	0.2912	0.3798	0	0	0.0025	0.0267	0.065	0.0393
1988	1522	100	252	100	0	0.0237	0.2004	0.3003	0.2181	0	0	0.0059	0.0644	0.0972	0.0894
1989	2595	100	96	100	0	0.0127	0.1643	0.3185	0.2148	0	0	0.0042	0.0555	0.1215	0.1084
1990	1289	100	53	100	0	0.0147	0.1435	0.3468	0.3251	0	0	0.0008	0.0372	0.0737	0.0582
1991															
1992	2566	100	62	100	0	0.0172	0.201	0.2662	0.2244	0	0	0.0027	0.0792	0.1292	0.08
1993	1813	100	31	100	0	0.0142	0.2312	0.3939	0.263	0	0	0.0004	0.0173	0.0437	0.0362
1994	404	40	78	40	0	0.0248	0.0941	0.0817	0.0891	0	0	0.0248	0.1881	0.25	0.2475
1995	1174	100	34	100	0	0.0392	0.2615	0.2853	0.207	0	0	0.0077	0.0486	0.0741	0.0767
1996	787	79	26	79	0	0.0318	0.2236	0.2389	0.141	0	0	0.014	0.1194	0.136	0.0953
1997	1198	100	14	100	0	0.0292	0.3656	0.3414	0.1244	0	0	0.0033	0.0559	0.0417	0.0384
1998	1055	100	71	100	0	0.0284	0.2332	0.2427	0.1071	0	0	0.0218	0.1118	0.1431	0.1118
1999	561	38	11	38	0	0.0026	0.2434	0.2698	0.3836	0	0	0	0	0.0423	0.0582
2000	17213	100	49	100	0	0.0194	0.2991	0.3917	0.1249	0	0	0.0028	0.0531	0.0654	0.0436
2001	20030	100	645	100	0	0.0243	0.2232	0.3691	0.2781	0	0	0.0008	0.0241	0.0497	0.0304
2002	5198	100	180	100	0	0.0442	0.2341	0.2814	0.3253	0	0	0.0046	0.0282	0.0419	0.0402
2003	5220	100	110	100	0	0.0232	0.368	0.3197	0.1523	0	0	0.0011	0.0218	0.0465	0.0674
2004	9605	100	46	100	0	0.0087	0.3811	0.388	0.1395	0	0	0.0004	0.0255	0.0347	0.0221
2005	5360	100	30	100	0	0.0022	0.2539	0.4709	0.1823	0	0	0	0.0205	0.0451	0.025
2006	6707	100	54	100	0	0.0021	0.1822	0.3484	0.199	0	0	0.0003	0.0498	0.1375	0.0807
2007	6125	100	48	100	0	0.0111	0.3574	0.3407	0.1714	0	0	0.0008	0.0247	0.0573	0.0366
2008	5766	100	22	100	0	0.0047	0.3512	0.3476	0.0668	0	0	0.0014	0.0895	0.0928	0.0461
2009	6026	100	58	100	0	0.0105	0.3445	0.3294	0.1339	0	0	0.0012	0.0768	0.0795	0.0242
2010	5902	100	46	100	0	0.0053	0.3855	0.3617	0.1095	0	0	0.0019	0.0546	0.0546	0.0271

Table 4. Summary of triennial trawl survey Norton Sound male red king crab abundance estimates. Trawl survey abundance estimate is based on 10×10 $nmil^2$ grid, except for 2010 (20×20 $nmil^2$).

				Survey coverage		Abundance (1000s)	
Year	Dates	Survey Agency	Survey method	Number of Survey stations	n $mile^2$ covered	>73 mm Males	CV
1976	9/02 - 9/05	NMFS	Trawl	70	6957	4580.637	0.201
1979	7/26 - 8/05	NMFS	Trawl	47	4621	757.550	0.316
1980	7/04 - 7/14	ADF&G	Pots			2082.986	N/A
1981	6/28 - 7/14	ADF&G	Pots			2427.557	N/A
1982	7/06 - 7/20	ADF&G	Pots			1020.387	N/A
1982	9/05 - 9/11	NMFS	Trawl	58	5721	2096.418	0.256
1985	7/01 - 7/14	ADF&G	Pots			2291.085	N/A
1985	9/16 -10/01	NMFS	Trawl	78	7388	2553.083	0.263
1988	8/16 - 8/30	NMFS	Trawl	78	7421	2335.195	0.298
1991	8/22 - 8/30	NMFS	Trawl	71	7083	2207.410	0.350
1996	8/07 - 8/18	ADF&G	Trawl	28	2800	1271.023	0.230
1999	7/28 - 8/07	ADF&G	Trawl	30	3000	2276.095	0.142
2002	7/27 - 8/06	ADF&G	Trawl	31	3100	1747.581	0.265
2006	7/25 - 8/08	ADF&G	Trawl	51	5083	2611.617	0.208
2008	7/24 - 8/11	ADF&G	Trawl	61	6630	2712.776	0.202
2010*	7/27 - 8/09	NMFS	Trawl	35	13749	2041.020	0.424

*: 20×20 n $mile^2$ grid survey

Table 5. Summer Trawl Survey size composition.

				New Shell						Old Shell					
Year	Sample	Model	Eff N	74-83	84-93	94-103	104-113	114-123	124+	74-83	84-93	94-103	104-113	114-123	124+
1976	1311	200		0.0214	0.1053	0.1915	0.3455	0.1831	0.029	0.0046	0.0114	0.0252	0.032	0.0366	0.0145
1979	133	66.5	35	0.015	0.0075	0.0301	0.0752	0.0827	0.0602	0	0.0075	0.0301	0.1203	0.3835	0.188
1982	256	128	25	0.0898	0.2031	0.2891	0.2109	0.0352	0.0078	0	0.0156	0.0195	0.043	0.0234	0.0625
1985	311	155.5	117	0.119	0.2122	0.1865	0.1768	0.0643	0.0193	0	0	0.0193	0.0514	0.0868	0.0643
1988	306	153	33	0.2255	0.1405	0.1536	0.1275	0.0686	0.0392	0	0.0065	0.0131	0.0392	0.0882	0.098
1991	250	125	38	0.0967	0.0223	0.0372	0.0743	0.0409	0.0223	0.0706	0.0297	0.0967	0.197	0.1747	0.1375
1996	196	98	57	0.2959	0.1786	0.1224	0.0816	0.0051	0.0153	0.0051	0.0357	0.0459	0.0612	0.0612	0.0918
1999	274	137	135	0.0109	0.1058	0.2993	0.2701	0.1314	0.0401	0	0.0036	0.0292	0.0511	0.0401	0.0182
2002	230	115	83	0.1261	0.1435	0.1565	0.0304	0.0348	0.0348	0.0304	0.0739	0.1087	0.0957	0.0913	0.0739
2006	208	104	95	0.3235	0.2614	0.1405	0.0752	0.0458	0.0294	0	0	0.0196	0.0458	0.0458	0.0131
2008	242	121	76	0.1743	0.2407	0.1286	0.112	0.0332	0.029	0.0083	0.0498	0.0705	0.0954	0.0125	0.0456
2010	68	68	51	0.1202	0.1366	0.2077	0.1257	0.1093	0.0437	0.0109	0.0328	0.082	0.071	0.0383	0.0219

Table 6. Winter pot survey length composition.

				New Shell						Old Shell					
Year	Sample	Model	Eff N	74-83	84-93	94-103	104-113	114-123	124+	74-83	84-93	94-103	104-113	114-123	124+
1981/82	243	24	130	0.1481	0.3374	0.3169	0.1029	0.0288	0.0247	0	0	0.0041	0.0082	0.0082	0.0206
1982/83	2520	100	115	0.0855	0.2824	0.2854	0.2155	0.0706	0.0085	0	0	0.004	0.0194	0.0097	0.0189
1983/84	1655	100	418	0.1638	0.2626	0.2291	0.1502	0.0601	0.0057	0	0	0.0178	0.065	0.0329	0.0127
1984/85	773	77	38	0.0932	0.2589	0.3618	0.1586	0.057	0.0097	0	0	0.0065	0.0291	0.0239	0.0013
1985/86	568	57	59	0.1276	0.1831	0.2553	0.2025	0.0863	0.0132	0	0	0.015	0.0607	0.044	0.0123
1986/87	144	14	68	0.0556	0.1597	0.1944	0.0694	0.0417	0	0	0	0.0417	0.2986	0.1111	0.0278
1987/88								No winter pot survey							
1988/89	492	49	282	0.1341	0.1514	0.1352	0.1941	0.1758	0.0346	0	0	0.002	0.0528	0.0854	0.0346
1989/90	2072	100	84	0.0495	0.2075	0.2616	0.1795	0.1221	0.0726	0	0	0.001	0.0263	0.056	0.0239
1990/91	1281	100	105	0.0125	0.0921	0.2857	0.2678	0.096	0.0109	0	0	0.0039	0.0265	0.1163	0.0882
1992/93	181	18	13	0.0055	0.0331	0.0552	0.1271	0.116	0.0276	0	0	0.0166	0.1934	0.2707	0.1547
1993/94								No winter pot survey							
1994/95	850	85	24	0.0588	0.08	0.0988	0.2576	0.2341	0.0847	0	0	0.0035	0.0329	0.0718	0.0776
1995/96	776	78	325	0.1214	0.1835	0.1733	0.1022	0.0599	0.0265	0	0	0.0181	0.1214	0.1242	0.0695
1996/97	1582	100	69	0.2297	0.2351	0.1189	0.1568	0.1216	0.0676	0	0	0	0.0189	0.027	0.0243
1997/98	399	40	22	0.1395	0.4136	0.2653	0.0544	0.0236	0.0034	0	0	0.0238	0.0317	0.017	0.0272
1998/99	882	88	59	0.0192	0.1168	0.3566	0.3605	0.0838	0.0154	0	0	0.01	0.0223	0.0069	0.0085
1999/00	1308	100	215	0.0885	0.1062	0.1646	0.3345	0.1788	0.0372	0	0	0.0018	0.0513	0.023	0.0142
2000/01								No winter pot survey							
2001/02	832	83	22	0.3136	0.2763	0.1761	0.0681	0.0668	0.0501	0	0	0.0077	0.0051	0.0154	0.0064
2002/03	826	83	146	0.0994	0.2236	0.2994	0.1801	0.0559	0.0261	0	0	0.0224	0.0273	0.0261	0.0273
2003/04	286	29	73	0.0175	0.1643	0.2622	0.3462	0.1119	0.0105	0	0	0.0175	0.021	0.014	0.0245
2004/05	406	41	110	0.0741	0.1407	0.1827	0.2173	0.1852	0.0765	0	0	0.0025	0.0395	0.0593	0.0173
2005/06	512	51	63	0.1406	0.2266	0.209	0.1563	0.0547	0.0215	0	0	0.0176	0.043	0.0742	0.0352
2006/07	160	16	51	0.1486	0.2095	0.3784	0.1419	0.0473	0	0	0	0.0068	0.0203	0.0405	0
2007/08	3482	100	91	0.1898	0.3219	0.1703	0.1479	0.0672	0.0083	0	0	0.0359	0.0339	0.0155	0.0092
2008/09	526	53	96	0.0706	0.1336	0.3511	0.2023	0.084	0.0134	0	0	0.0019	0.0382	0.0992	0.0057
2009/10	581	58	202	0.047	0.1357	0.2157	0.2452	0.113	0.0191	0	0	0.0591	0.1009	0.0539	0.0104
2010/11	597	56	115	0.0786	0.1368	0.2103	0.1744	0.1333	0.0513	0	0.012	0.0325	0.1128	0.0462	0.012

Table 7. Estimated selectivities, molting probabilities, and proportions of legal crabs by length (mm CL) class for Norton Sound male red king crab.

		Selectivity					
Length Class	Proportion of Legal	Summer Trawl	Summer Pot Survy	Winter Pot Survy	Summer Fishery		Molting Probability
					77-92	93-09	
74 - 83	0.00	1.00	0.80	0.65	0.30	0.13	1.00
84 - 93	0.00	1.00	0.88	1.00	0.41	0.22	0.82
94 - 103	0.15	1.00*	1.00*	1.00*	0.55	0.41	0.66
104 - 113	0.92	1.00*	1.00*	1.00*	0.74	0.67	0.53
114 - 123	1.00	1.00*	1.00*	1.00*	1.00*	1.00*	0.41
124+	1.00	1.00*	1.00*	0.39	1.00	1.00	0.32

*: Assumed to be 1.0

Table 8. Growth matrix (proportion of crabs molting from a given premolt carapace length range into postmolt length ranges) for Norton Sound male red king crab. Length is measured as mm CL. Results are derived from mark-recapture data from 1991 to 2007.

Pre-molt		Post-molt Length Class					
Length Class	Mean weight (lb)	74-83	84-93	94-103	104-113	114-123	124+
74-83	0.854	0	0.33	0.67	0	0	0
84-93	1.210	0	0	0.56	0.44	0	0
94-103	1.652	0	0	0	0.76	0.24	0
104-113	2.187	0	0	0	0.18	0.61	0.21
114-123	2.825	0	0	0	0	0.33	0.67
124+	3.697	0	0	0	0	0	1.00

Table 9. Sample sizes for length compositions in the summer pot survey.

Year	Observed	Model	Effective N
1980	3619	200	32
1981	4588	200	52
1982	6354	200	343
1985	9900	200	80

Table 10. Summary of parameter estimates for a length-based stock synthesis population model of Norton Sound red king crab. Total number of free parameters: 51.

Parameter	Value	Std	Parameter	Value	Std
Log_N_{76}	8.7206	0.0204	Log_R_{01}	0.9583	0.2893
Log_mean	5.6240	0.2474	Log_R_{02}	1.0371	0.2751
Log_R_{77}	-3.4071	3.2374	Log_R_{03}	0.4663	0.3488
Log_R_{78}	-3.4422	3.0373	Log_R_{04}	-1.1208	0.9987
Log_R_{79}	-1.7157	0.6418	Log_R_{05}	0.5566	0.3263
Log_R_{80}	-0.6860	0.3383	Log_R_{06}	1.3648	0.2751
Log_R_{81}	1.2753	0.2644	Log_R_{07}	0.8164	0.3534
Log_R_{82}	0.6183	0.2832	Log_R_{08}	1.5052	0.2760
Log_R_{83}	0.8752	0.2944	Log_R_{09}	0.6533	0.4270
Log_R_{84}	1.0452	0.2721	Log_R_{10}	0.5697	0.3898
Log_R_{85}	0.6439	0.2758	log_q_1	-10.8560	0.0677
Log_R_{86}	-0.0442	0.3498	log_q_2	-10.9410	0.1036
Log_R_{87}	0.2205	0.2853	r1	0.5901	0.0219
Log_R_{88}	-0.0183	0.2829	log_α	-3.5647	0.3781
Log_R_{89}	0.3653	0.2802	log_β	3.9625	1.4105
Log_R_{90}	-0.0082	0.2932	log_ϕ_{st}	-1.3954	135.2700
Log_R_{91}	-0.8723	0.3479	log_ω_{st}	1.8486	999.5400
Log_R_{92}	0.2298	0.3596	log_ϕ_{sp}	-2.7799	1.6095
Log_R_{93}	-0.7765	0.7009	log_ω_{sp}	4.0327	0.7207
Log_R_{94}	-0.0801	0.3484	log_ϕ_{sw}	0.1098	0.2805
Log_R_{95}	-0.4781	0.3543	log_ω_{sw}	4.3560	0.0038
Log_R_{96}	0.2334	0.2819	Sw_6	0.3866	0.0450
Log_R_{97}	0.7508	0.2968	log_$\phi_{\square}$	-3.5035	0.1466
Log_R_{98}	0.9294	0.2708	log_$\omega_{\square}$	6.6126	270.0200
Log_R_{99}	-2.0872	0.6052	log_ϕ_2	-2.7150	0.3012
Log_R_{00}	-0.3781	0.4078	log_ω_2	4.7885	0.1373

Data Component	Neg.Likelihood
Trawl immat. Indices	18.260
Trawl mat. indices	0.093
Pot immat. Indices	1.661
Pot mat. Indices	3.491
Total effort	5.448
Trawl length compos.	2313.58
Pot length compos.	1283.06
Winter length compos.	2716.38
Summer length compos	3546.70
Observed length comp.	531.865
Recruitment deviation	0.482945
Total	10511.5

Table 11. Annual abundance estimates (million crabs) and mature male biomass (MMB, million lbs) for Norton Sound red king crab estimated by length-based analysis from 1976-2011.

				Legal (> 103 mm)				MMB	
Year	Recruitment	Total (> 73 mm)	Matures (> 93 mm)	Abundance	St. Dev.	Biomass	St. Dev.	Biomass	St. Dev.
1976		6.030	5.254	3.940	0.080	9.772	0.199	12.041	0.246
1977	0.009	5.000	4.857	4.117	0.075	11.032	0.196	12.335	0.227
1978	0.009	3.916	3.886	3.579	0.068	10.242	0.188	10.798	0.201
1979	0.050	2.672	2.620	2.505	0.058	7.535	0.167	7.752	0.173
1980	0.139	1.478	1.338	1.280	0.048	3.972	0.145	4.077	0.148
1981	0.992	1.831	0.881	0.804	0.039	2.537	0.122	2.670	0.127
1982	0.514	1.635	0.954	0.544	0.038	1.508	0.113	2.194	0.148
1983	0.664	1.892	1.138	0.740	0.047	1.923	0.126	2.599	0.172
1984	0.788	2.159	1.271	0.842	0.052	2.168	0.138	2.895	0.177
1985	0.527	2.136	1.461	0.965	0.057	2.478	0.149	3.318	0.190
1986	0.265	1.867	1.484	1.058	0.063	2.753	0.166	3.481	0.208
1987	0.345	1.706	1.311	1.024	0.065	2.744	0.176	3.238	0.202
1988	0.272	1.560	1.225	0.969	0.063	2.675	0.175	3.114	0.198
1989	0.399	1.575	1.136	0.917	0.061	2.583	0.172	2.959	0.195
1990	0.275	1.460	1.112	0.863	0.060	2.444	0.170	2.869	0.196
1991	0.116	1.239	1.060	0.839	0.060	2.384	0.169	2.762	0.193
1992	0.349	1.314	0.956	0.813	0.058	2.357	0.165	2.605	0.182
1993	0.127	1.164	0.968	0.770	0.053	2.247	0.154	2.584	0.178
1994	0.256	1.076	0.801	0.660	0.050	1.916	0.146	2.157	0.159
1995	0.172	0.932	0.714	0.557	0.046	1.603	0.135	1.871	0.154
1996	0.350	0.992	0.623	0.485	0.046	1.374	0.132	1.610	0.150
1997	0.587	1.292	0.669	0.472	0.047	1.302	0.134	1.635	0.162
1998	0.702	1.679	0.894	0.574	0.053	1.524	0.146	2.064	0.193
1999	0.034	1.401	1.203	0.777	0.064	2.019	0.172	2.739	0.216
2000	0.190	1.314	1.106	0.893	0.069	2.401	0.188	2.770	0.214
2001	0.722	1.650	0.936	0.779	0.066	2.178	0.186	2.450	0.208
2002	0.781	1.993	1.111	0.761	0.066	2.095	0.187	2.685	0.230
2003	0.442	1.966	1.371	0.898	0.078	2.378	0.211	3.176	0.269
2004	0.090	1.621	1.417	1.026	0.087	2.715	0.236	3.383	0.283
2005	0.483	1.671	1.186	0.981	0.086	2.682	0.241	3.040	0.269
2006	1.084	2.258	1.146	0.876	0.083	2.435	0.236	2.896	0.273
2007	0.627	2.298	1.476	0.931	0.093	2.476	0.255	3.393	0.333
2008	1.248	2.942	1.618	1.116	0.113	2.918	0.303	3.772	0.387
2009	0.532	2.791	2.013	1.305	0.142	3.375	0.373	4.573	0.496
2010	0.490	2.621	2.013	1.477	0.176	3.875	0.462	4.793	0.583
2011		2.755	1.892	1.471	0.200	3.976	0.536	4.699	0.644

Table 12. Summary of catch and bycatch (million lbs) for Norton Sound red king crab. The bycatch is estimated from the model. Summer commercial catches are from ADF&G fish ticket database during 1985-2009 and from Soong et al. (2008) during 1977 to 1984. Winter commercial and subsistence catches are from ADF&G permit reporting and average weight of 2.5 lbs for the winter commercial catch and 2.0 lbs for the subsistence catch were assumed to estimate total weight.

Year	*Summer*	*Winter*	*Subsistence*	*Bycatch*	*Total*	*Catch/MMB*
1977	0.5200	0.0241	0.0250	0.0080	0.5775	0.05
1978	2.0900	NA	0.0004	0.0132	2.1041	0.19
1979	2.9300	NA	0.0004	0.0122	2.9425	0.38
1980	1.1900	0.0000	0.0007	0.0060	1.1966	0.29
1981	1.3800	NA	0.0026	0.0389	1.4219	0.52
1982	0.2300	0.0014	0.0209	0.0153	0.2674	0.12
1983	0.3700	0.0021	0.0224	0.0239	0.4182	0.16
1984	0.3900	0.0029	0.0168	0.0248	0.4342	0.15
1985	0.4270	0.0054	0.0141	0.0225	0.4686	0.14
1986	0.4795	0.0026	0.0115	0.0175	0.5108	0.14
1987	0.3271	0.0011	0.0054	0.0088	0.3424	0.10
1988	0.2367	0.0010	0.0123	0.0060	0.2561	0.08
1989	0.2465	0.0091	0.0243	0.0066	0.2865	0.09
1990	0.1928	0.0095	0.0147	0.0052	0.2222	0.08
1991	Closed	0.0187	0.0235	0.0000	0.0422	0.01
1992	0.0740	0.0045	0.0022	0.0011	0.0820	0.03
1993	0.3358	0.0144	0.0082	0.0057	0.3645	0.13
1994	0.3289	0.0188	0.0109	0.0053	0.3645	0.16
1995	0.3227	0.0044	0.0034	0.0062	0.3374	0.16
1996	0.2235	NA	0.0015	0.0054	0.2302	0.12
1997	0.0930	0.0025	0.0172	0.0037	0.1161	0.07
1998	0.0297	0.0068	0.0151	0.0014	0.0531	0.02
1999	0.0235	0.0076	0.0114	0.0008	0.0433	0.01
2000	0.3125	0.0027	0.0005	0.0053	0.3210	0.11
2001	0.2877	0.0065	0.0073	0.0065	0.3080	0.12
2002	0.2596	0.0171	0.0083	0.0097	0.2951	0.10
2003	0.2672	0.0013	0.0024	0.0098	0.2811	0.08
2004	0.3407	0.0053	0.0079	0.0081	0.3620	0.10
2005	0.4011	NA	0.0025	0.0072	0.4111	0.13
2006	0.4517	0.0083	0.0214	0.0142	0.4966	0.16
2007	0.3129	0.0145	0.0190	0.0134	0.3607	0.10
2008	0.3951	0.0124	0.0095	0.0161	0.4346	0.10
2009	0.3976	0.0121	0.0141	0.0151	0.4329	0.08
2010	0.4173	0.0121	0.0166	0.0108	0.4568	0.10

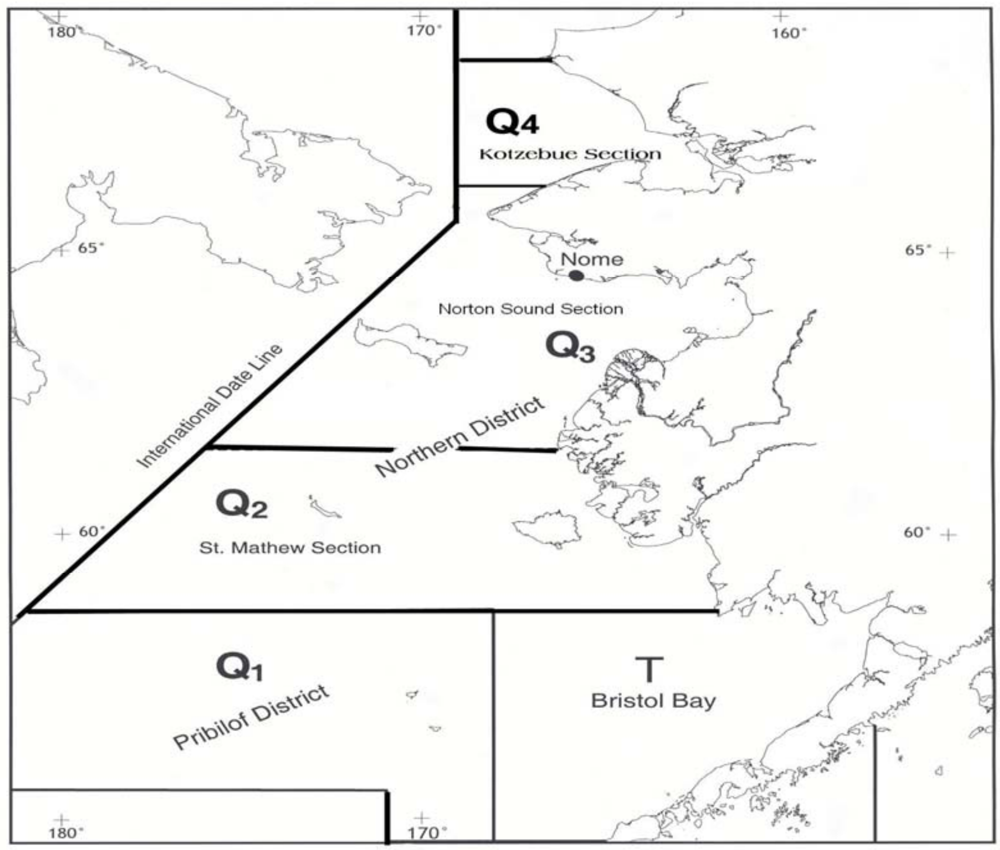


Figure 1. King crab fishing districts and sections of Statistical Area Q.

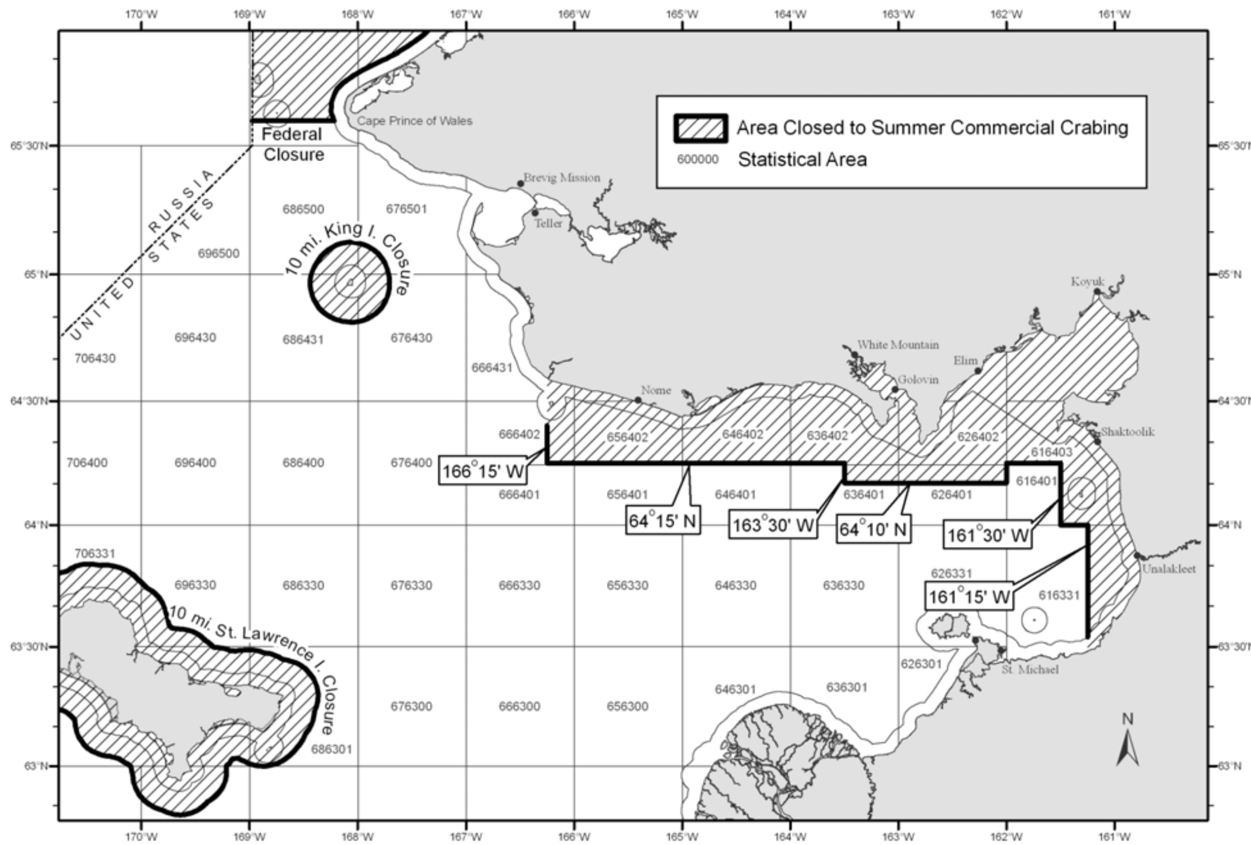


Figure 2. Closed water regulations in effect for the Norton Sound commercial crab fishery.

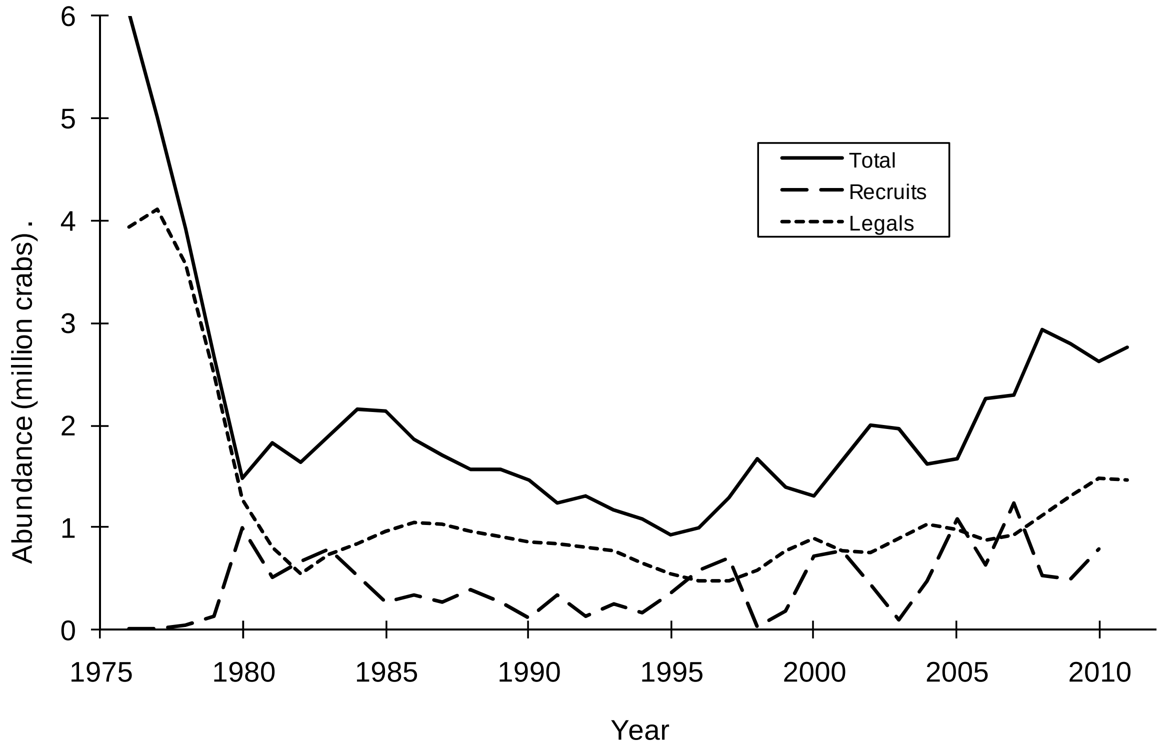


Figure 3. Estimated abundance of total (crabs > 74 mm CL), legal male, and recruits from 1976-2010.

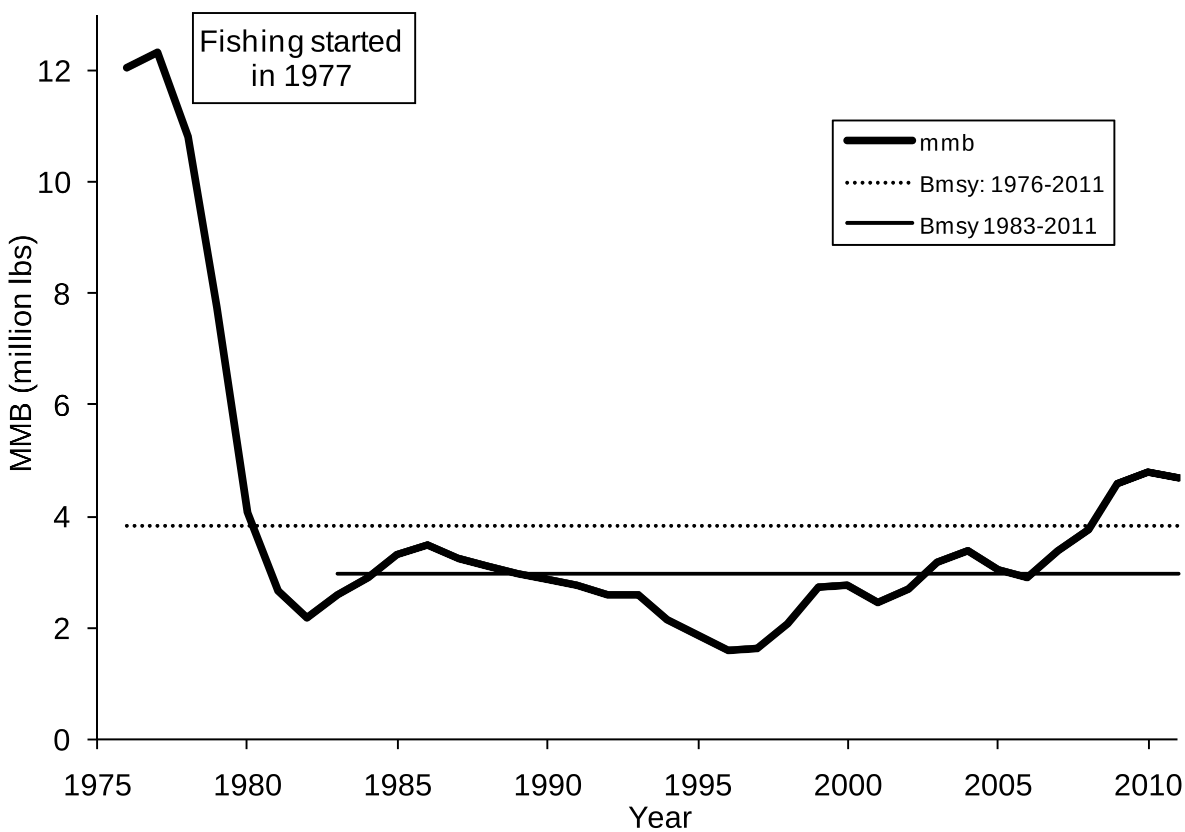
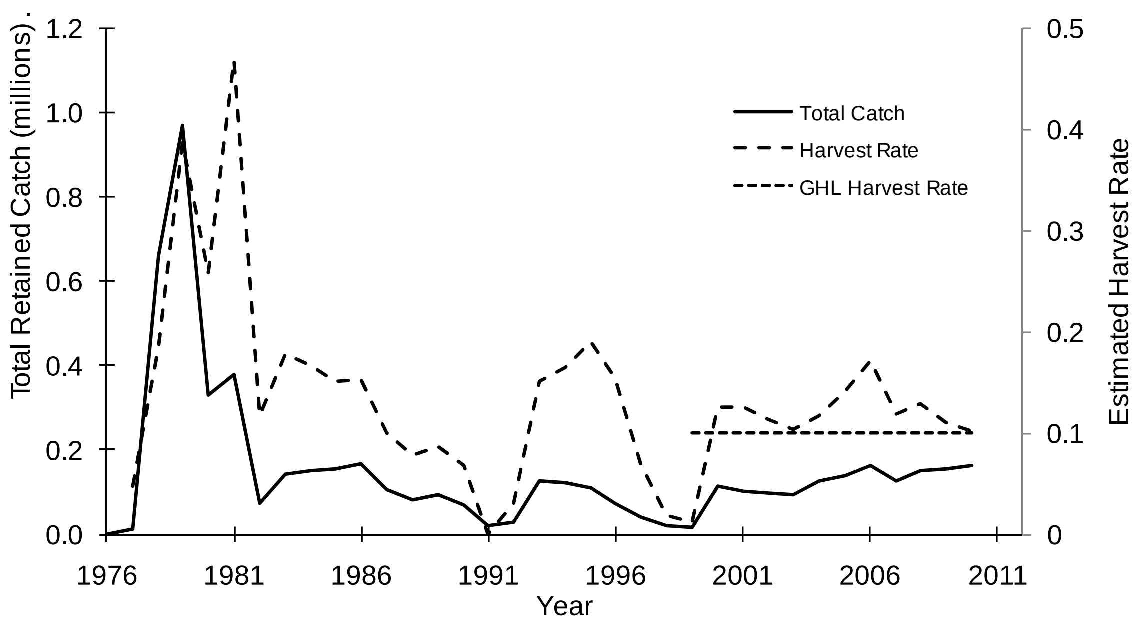


Figure 4. Estimated mature male biomass from 1976-2011.



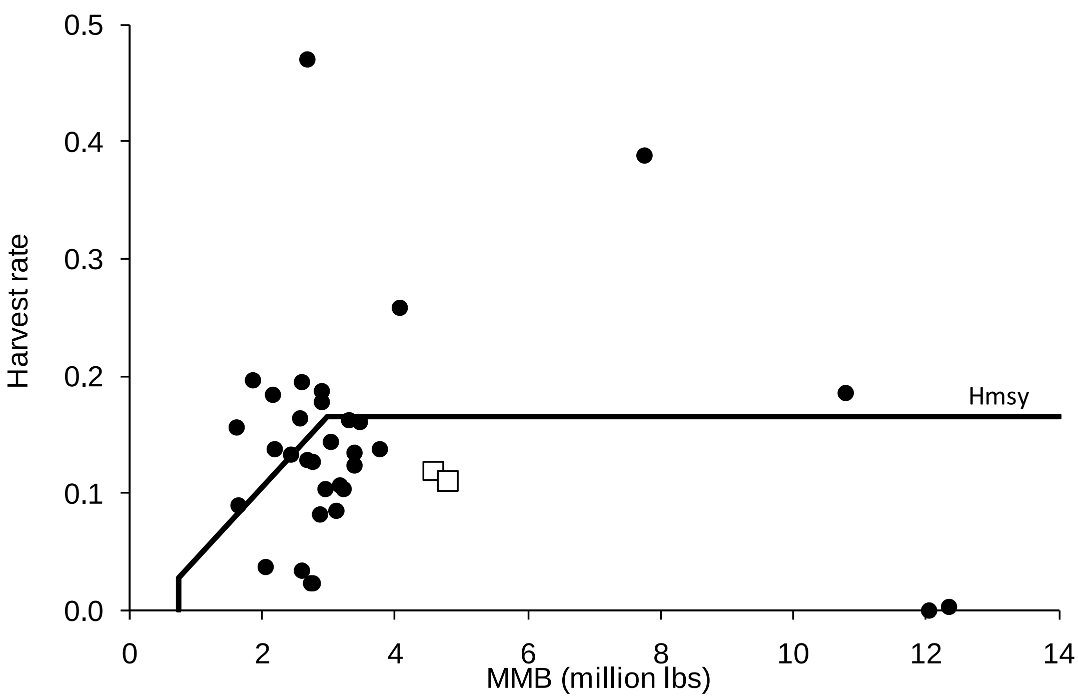


Figure 5. Total retained catches and harvest rates (upper plot) and relationship between harvest rates and mature male biomass (lower plot) of Norton Sound red king crab from June 1, 1976 to May 31, 2011. *Hmsy* is a proxy MSY harvest rate corresponding to *Fmsy* with γ=1.0 and M=0.18. White box are data for 2009 and 2010.

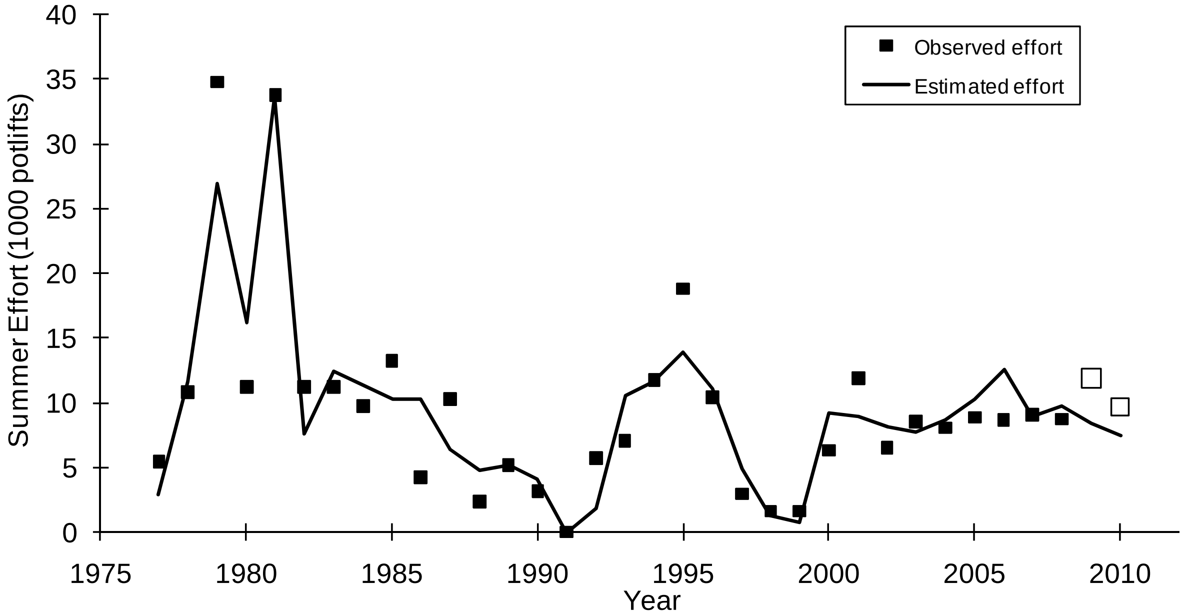
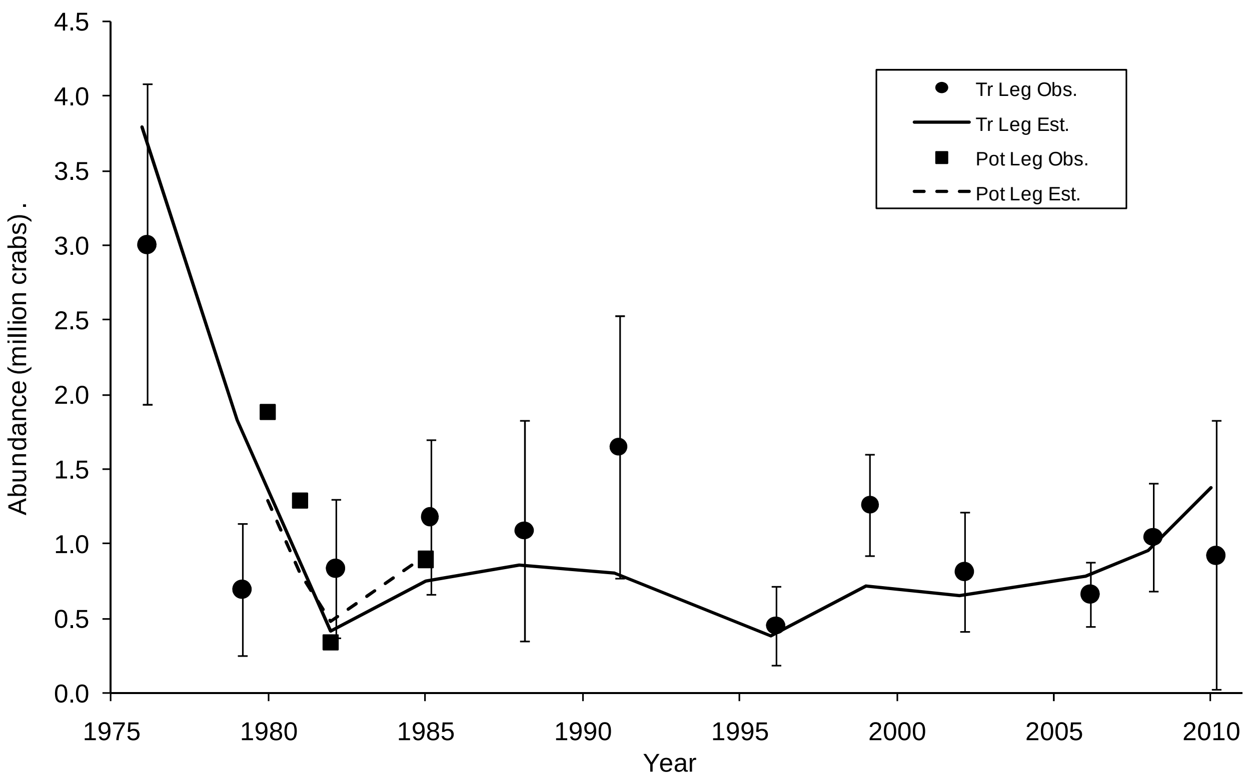


Figure 6. Comparison of observed and estimated summer fishing efforts (upper plot) during 1977-2010. White boxes are 2009 and 2010 data points.



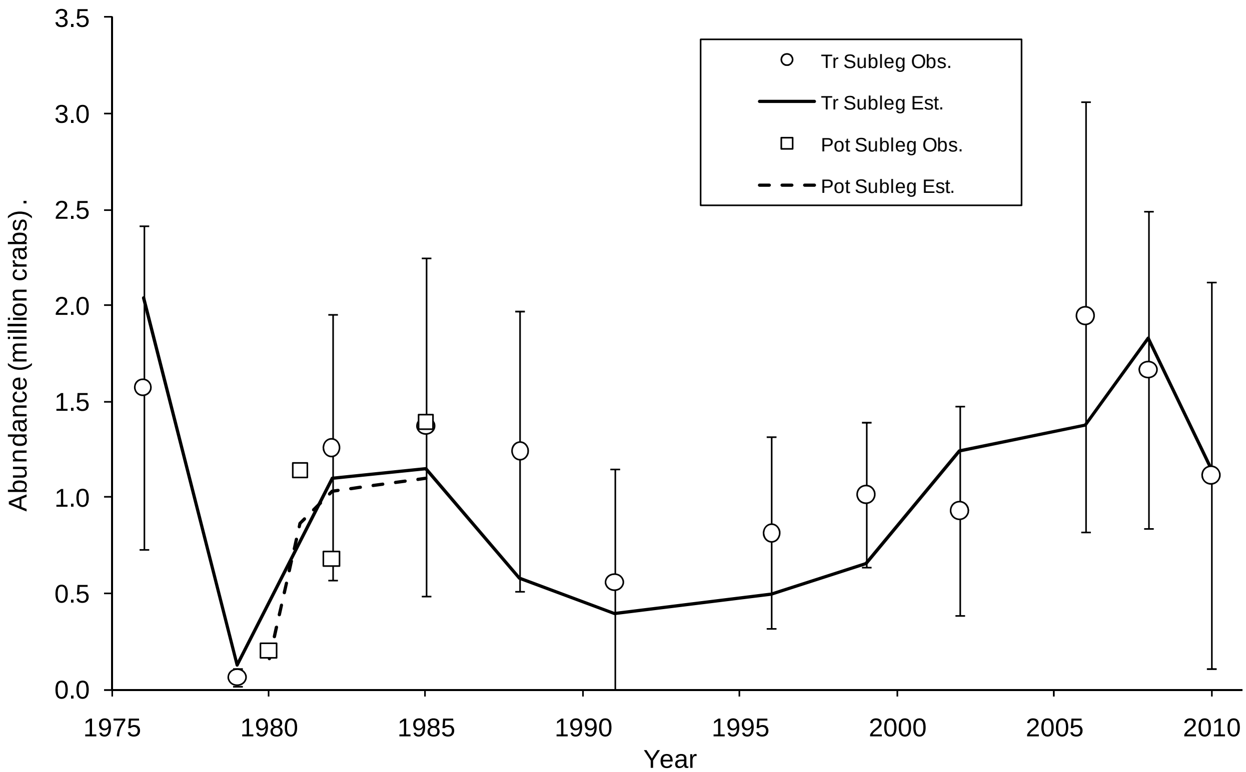


Figure 7. Comparison of observed and estimated Norton Sound red king crab abundances (legal: upper, and sublegal: bottom) males by summer trawl and pot surveys. “Tr” is trawl, “Leg” is legal, “Obs.” is observed or survey abundance, and “Est.” is estimated catchable abundance. The 95% C.I. were plotted separately for sublegal and legal crabs from the summer trawl surveys.

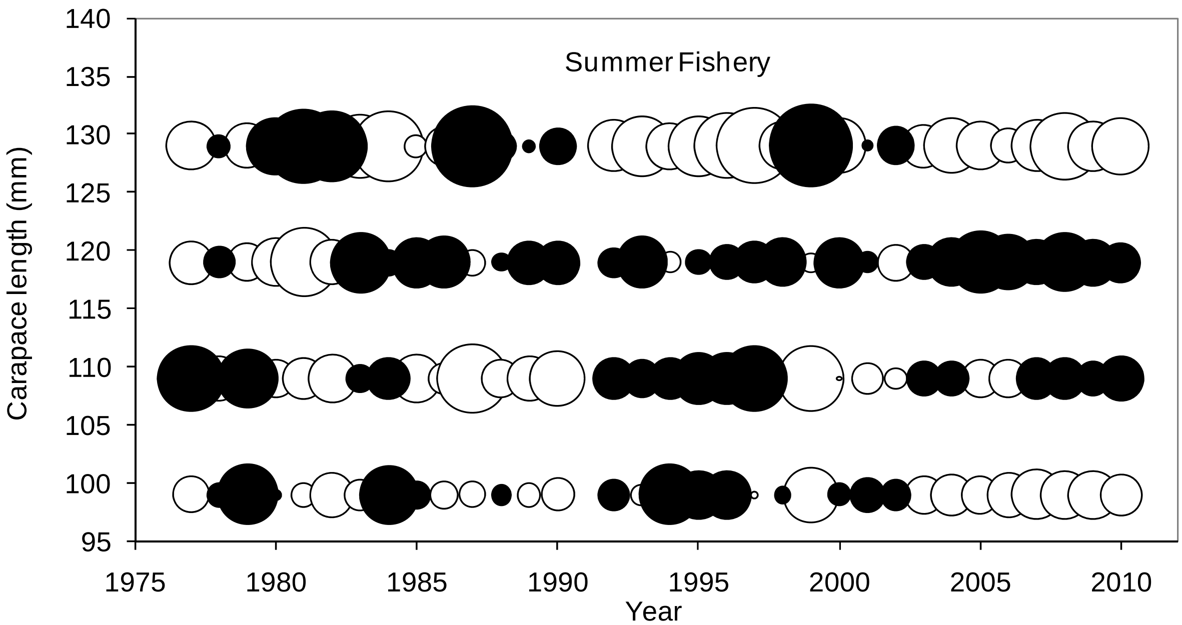
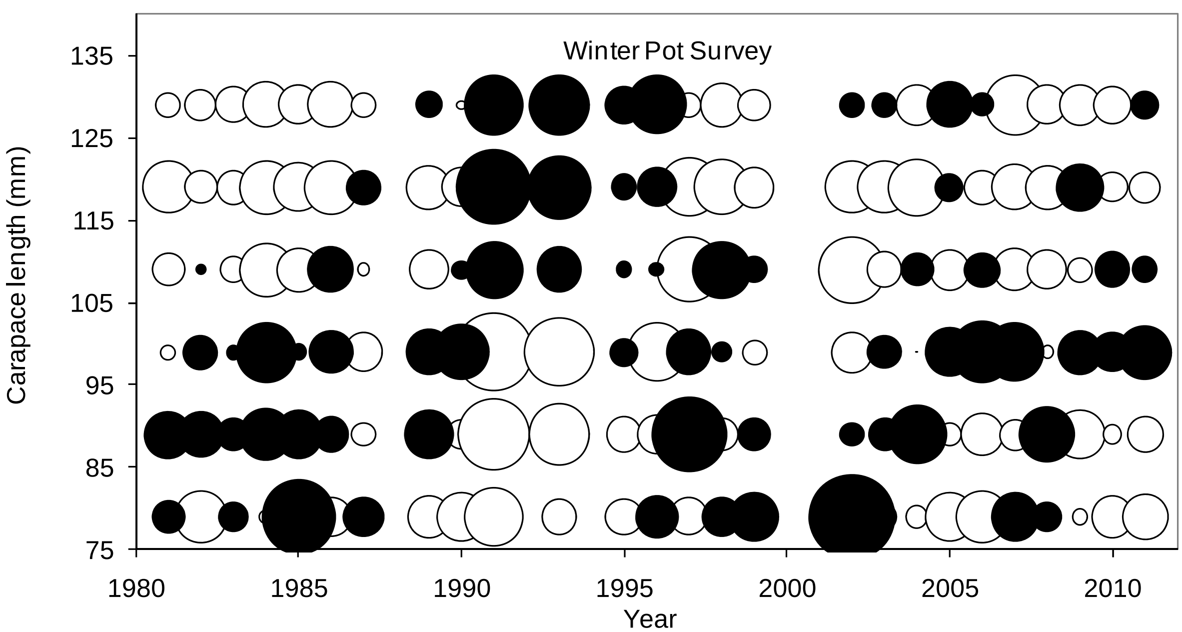


Figure 8. Residuals of catch length compositions by year for summer fishery for Norton Sound red king crab. Solid circles are positive residuals, and open circles are negative residuals.



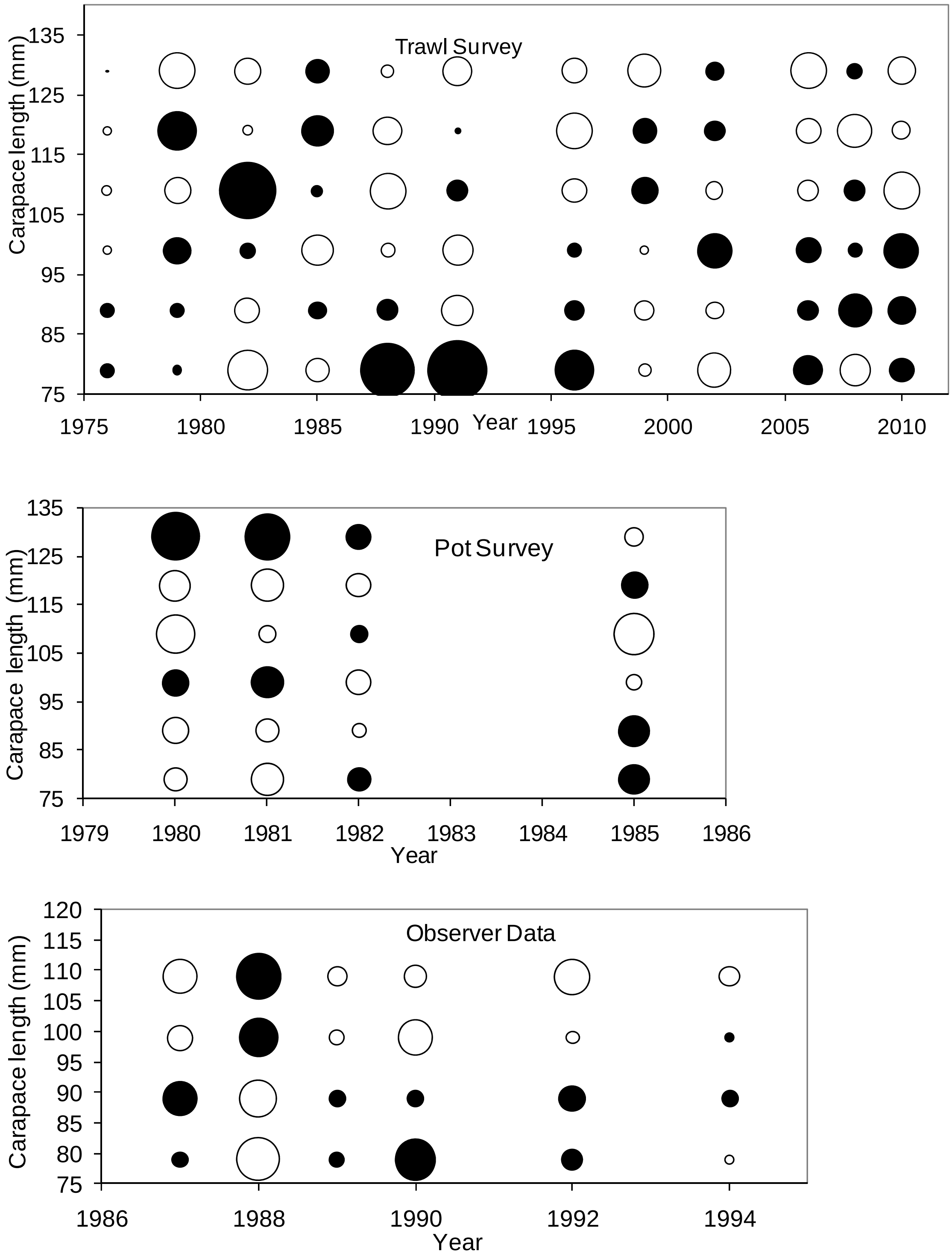


Figure 9. Residuals of length compositions by year for winter pot survey, summer trawl and pot surveys and observer data for Norton Sound red king crab. Solid circles are positive residuals, and open circles are negative residuals.

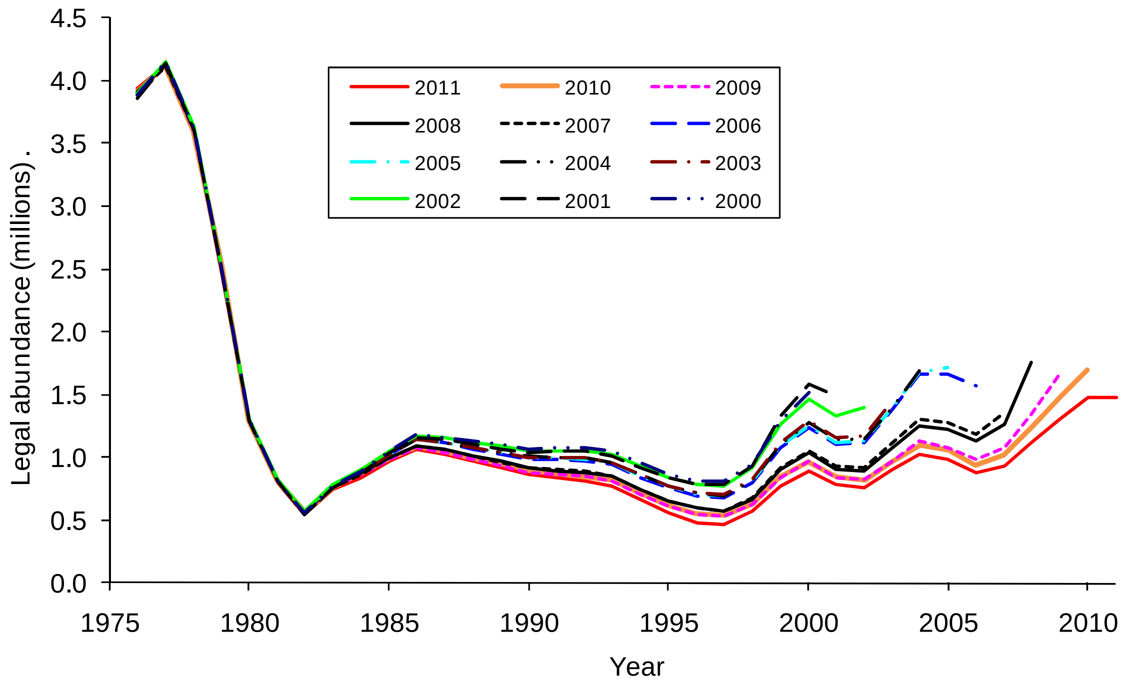


Figure 10. Comparison of estimates of legal male abundance of Norton Sound red king crab from 1976 to 2011 made with terminal years 2000-2011. Legend shows the year in which the assessment was conducted.

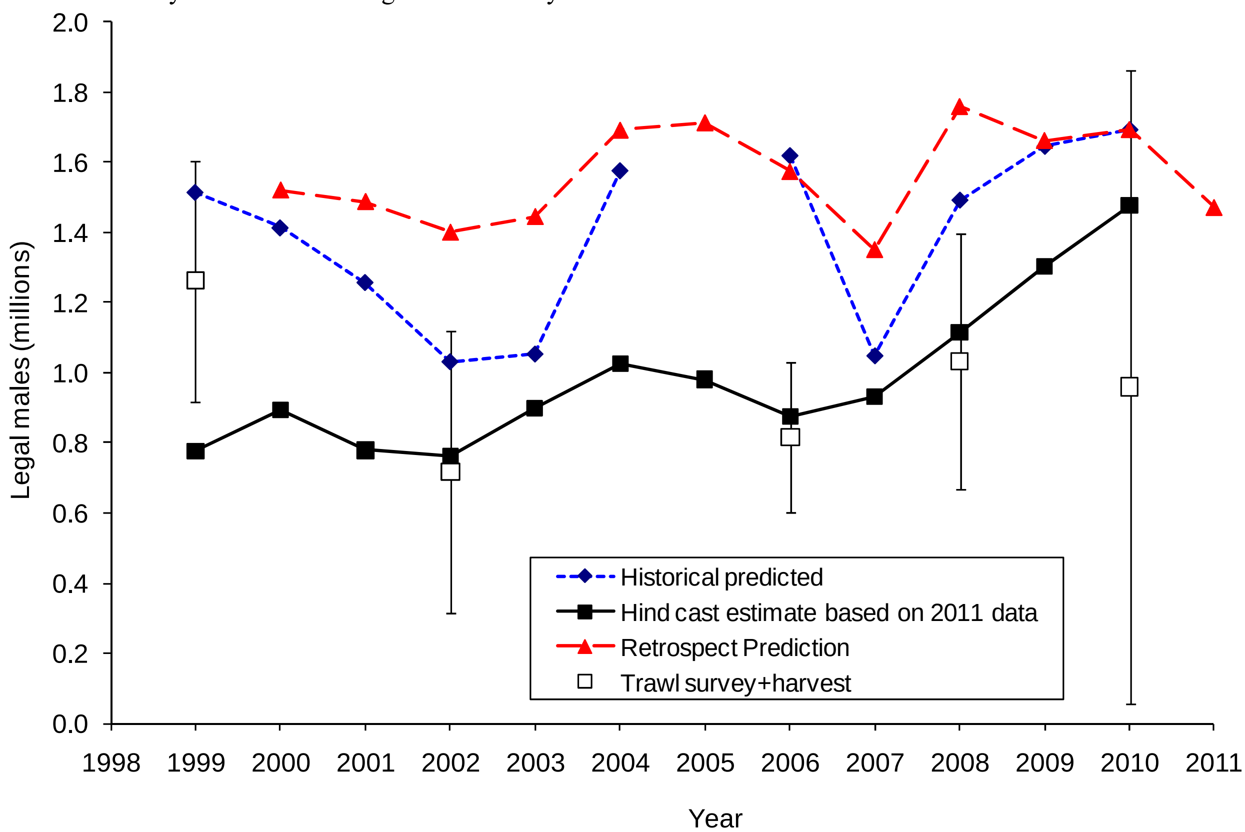


Figure 11. Comparison of estimates of legal male abundance of Norton Sound red king crab with terminal years 1999-2011.
Historical predicted: Predicted abundance reported.
Hind cast estimate: Hind cast model estimate of legal abundance from 2011 data.
Retrospect Prediction: Predicted legal crab abundance using current model and data used up to the predicted year (e.g., use 1976-199 data for estimation of prediction of 2000 legal male abundance).

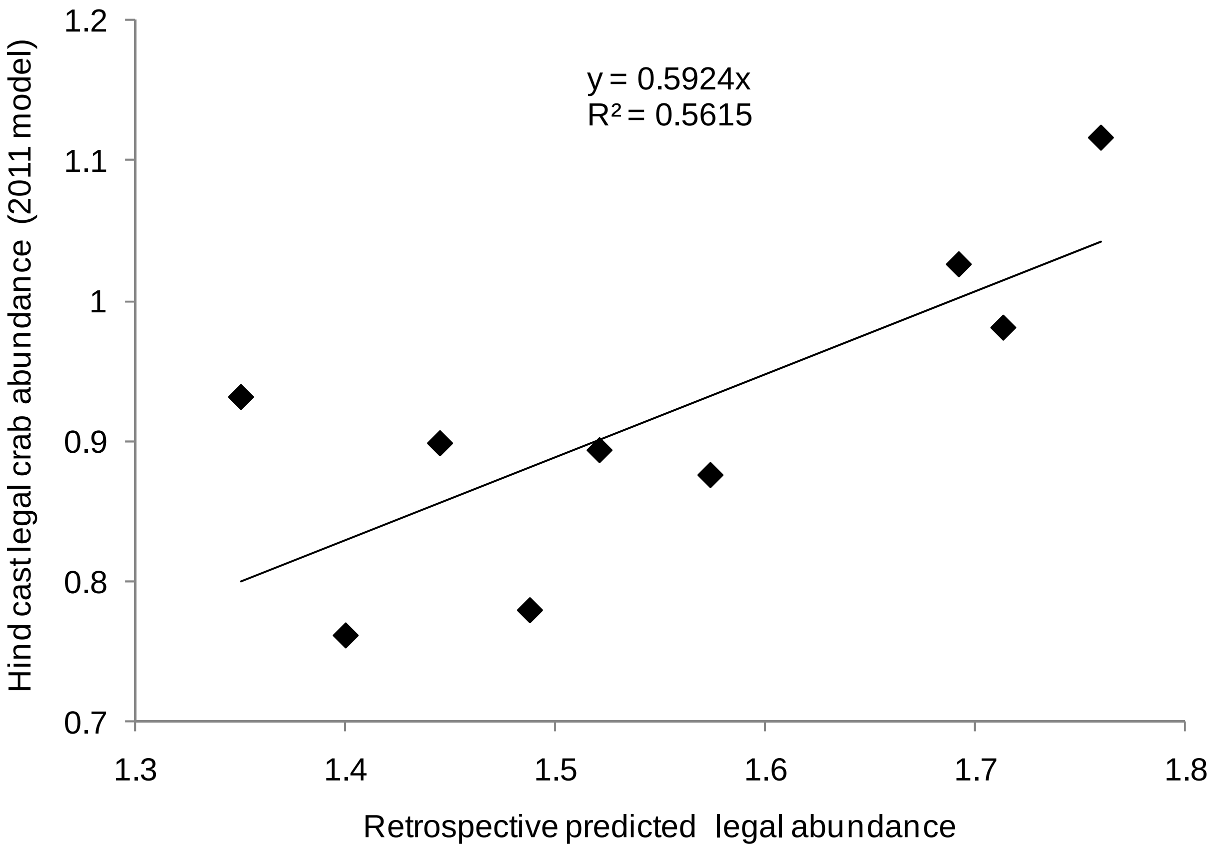


Figure 12. Correlation between retrospective predicted and hind cast legal male red king crab abundance: 2000-2008.

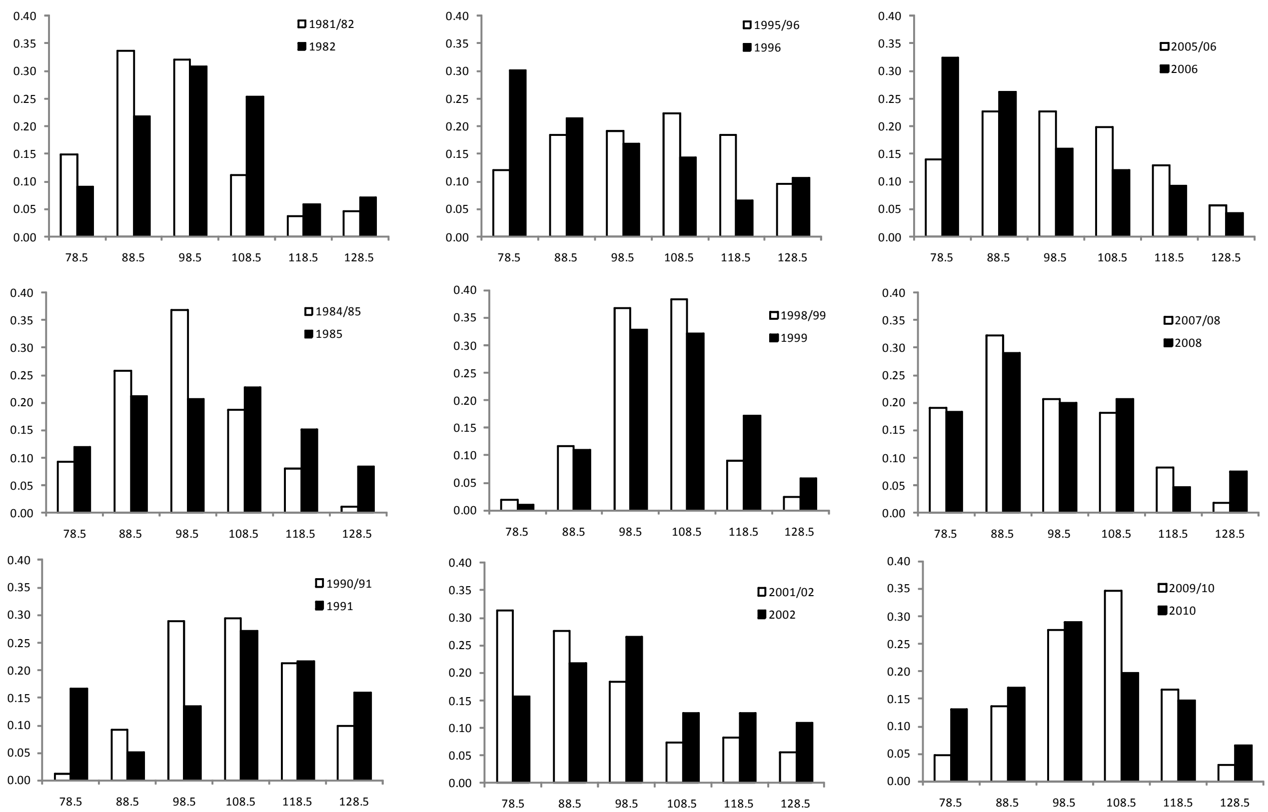


Figure 13. Comparison of length composition between Winter pot survey (white) and summer trawl survey (black) 1981-2010.

Appendix A. Description of the Norton Sound Red King Crab Model

a. Model description.

The model is an extension of the length-based model developed by Zheng et al. (1998) for Norton Sound red king crab. The model has 6 length classes with model parameters estimated by the maximum likelihood method. The model estimates abundances of crabs with CL ≥74 mm and with 10-mm length intervals because few crabs with CL <74 mm were caught during surveys or fisheries and there were relatively small sample sizes for trawl and winter pot surveys. The model was made for newshell and oldshell male crabs separately, but assumed they have the same molting probability and natural mortality.

Summer crab abundance

Summer crab abundances are the survivors of crabs from the previous winter:

$$
\begin{aligned}
N_{s,l,t+1} &= (N_{w,l,t} - C_{w,t}\,P_{w,n,l,t} - C_{p,t}\,P_{p,n,l,t})\,e^{-0.417M_l} \\
O_{s,l,t+1} &= (O_{w,l,t} - C_{w,t}\,P_{w,o,l,t} - C_{p,t}\,P_{p,o,l,t})\,e^{-0.417M_l}
\end{aligned}
\qquad (1)
$$

where

$N_{s,l,t}$, $O_{s,l,t}$: summer abundances of newshell and oldshell crabs in length class l in year t
$N_{w,l,t}$, $O_{w,l,t}$:winter abundances of newshell and oldshell crabs in length class l in year t
$C_{w,t}$, $C_{p,t}$: total winter and subsistence catches in year t,
$P_{w,n,l,t}$, $P_{p,n,l,t}$: Length proportion of winter and subsistence catches for newshell crabs for length class l in year t
$P_{w,o,l,t}$, $P_{p,o,l,t}$: length compositions of winter and subsistence catches for oldshell crabs in length class l in year t
M_l : instantaneous natural mortality in length class l, constant for all sizes and shell conditions except for the last length class, in which M is 60% higher than the other classes.
0.417 : proportion of the year from Feb. 1 to July 1 is 5 months, or 0.417

Winter crab abundance

Winter crab abundance for newshell, $N_{w,l,t}$, is the combined result of growth, molting probability, mortality, and recruitment from the summer population:

$$
N_{w,l,t} = \sum_{l'=1}^{l'=l} [\, G_{l',l}((N_{s,l',t} + O_{s,l',t})e^{-y_t M_l} - C_{s,t}(P_{s,n,l',t} + P_{s,o,l',t}) - D_{l',t})\, m_{l'}\, e^{-(0.583-y_t)M_l} \,] + R_{l,t} \qquad (2)
$$

Winter abundance of oldshell crabs $O_{s,l,t}$ is the non-molting portion of survivors of crabs from summer:

$$O_{w,l,t} = [\,(N_{s,l,t} + O_{s,l,t})e^{-y_t M_l} - C_{s,t}\,(P_{s,n,l,t} + P_{s,o,l,t}) - D_{l,t}\,]\,(1 - m_l)\,e^{-(0.583 - y_t)M_l} \qquad (3)$$

where

$G_{l',l}$: a growth matrix representing the expected proportion of crabs molting from length class l' to length class l,
$C_{s,t}$: total summer catch in year t,
$P_{s,n,l,t}$, $P_{s,o,l,t}$: Compositions of summer catch for newshell and oldshell crabs in length class l in year t,
$D_{l,t}$: bycatches in length class l in year t,
m_l : molting probability in length class l,
y_t : the time in year from July 1 to the mid-point of the summer fishery
0.583: Proportion of the year from July 1 to Feb. 1 is 7 months, or 0.583 year
$R_{l,t}$: recruitment into length class l in year t.

Molting Probability

Molting probability for length class l, m_l, was calculated using a reverse logistic function fitted as a function of length and time (Balsiger's 1974)

$$m_l = 1 - \frac{1}{1 + e^{-\alpha(i-\beta)}} \qquad (4)$$

where
α and β are parameters, and i is the mid-length of length class l.
m_l was re-scaled such that $m_l = 1$.

Discards

In summer commercial fisheries, sublegal males (<104 mm CL) are not legally retained but are sorted and discarded, which are subject to handling mortality. Due to complexity and lack of data, we did not model handling mortality, but assumed to be 0.2.

Discards of length class l in year t from the commercial pot fishery were estimated as:

$$D_{l,t} = (N_{s,l,t} + O_{s,l,t})\,S_{s,l}\,(1 - legal_l)\,hm\,[C_{s,t} / \sum_l (N_{s,l,t} + O_{s,l,t})\,legal_l] \qquad (5)$$

where
hm: handling mortality rate assumed to be 0.2
$legal_l$: the proportion of legal males in length class l.
$S_{s,l}$: Selectivity of the summer commercial fishery.

Selectivity of summer commercial fishery

Selectivity of the summer commercial fishery for length class l, $S_{s,l}$, was calculated a logistic function with parameters ϕ and ω, where i is the mid-length of the length class l.

$$S_{s,l} = \frac{1}{1+e^{-\phi(i-\omega)}} \tag{6}$$

$S_{s,l}$ was re-scaled such that $S_{s,5} = 1$ and $S_{s,6} \le 1$. Two sets of parameters (ϕ_1, ω_1) and (ϕ_2, ω_2) were estimated for selectivities before 1993 and after 1992 to reflect the vessel changes and pot limits.

The above selectivity model was also used to estimate selectivity of the first two length size groups of the summer pot survey (ϕ_{sp}, ω_{sp}), summer trawl survey (ϕ_{st}, ω_{st}), and winter pot survey (ϕ_{sw}, ω_{sw}).

Recruitment Estimation

Because sample size of the mark-recapture data was too small to estimate annual molting probabilities, we modeled recruitment of year t, R_t, as a stochastic process around the mean, R_0:

$$R_t = R_0 e^{\tau_t}, \tau_t \sim N(0, \sigma_R^2) \tag{7}$$

R_t was assumed to come from only length classes 1 ($R_{1,t}$) and 2 ($R_{2,t}$) , and was calculated as

$$\begin{aligned} R_{1,t} &= r\, R_t \\ R_{2,t} &= (1-r)\, R_t \end{aligned} \tag{8}$$

where r is a parameter with a value less than or equal to 1. $R_{l,t} = 0$ when $l \ge 3$.

Length compositions of winter commercial catch

Length compositions of winter commercial catch ($P_{w,n,l,t}$, $P_{w,o,l,t}$) for length l in year t were estimated from the winter population, winter selectivity for pots, and proportion of legal crabs for each length class:

$$\begin{aligned} P_{w,n,l,t} &= N_{w,l,t} S_{w,l} L_l / \sum_l [(N_{w,l,t} + O_{w,l,t}) S_{w,l} L_l] \\ P_{w,o,l,t} &= O_{w,l,t} S_{w,l} L_l / \sum_l [(N_{w,l,t} + O_{w,l,t}) S_{w,l} L_l] \end{aligned} \tag{9}$$

where

L_l : proportion of legal crabs for length class l, estimated from the observer data

$S_{w,l}$: winter selectivity for pots for length class l.

$S_{w,1}$ and $S_{w,2}$ were estimated using the equation (6) parameters estimated from the model (ϕ_{ws}, ω_{ws}).

$S_{w,3}$ - $S_{w,5}$ were assumed to be 1,

$S_{w,6}$ was directly estimated from the model.

Length compositions of winter subsistence catch

Subsistence fishery does not have a size limit; however, crabs of size smaller than length class 3 are generally not retained. Hence, we estimated length compositions of subsistence catch (l >2) as follows

$$P_{p,n,l,t} = N_{w,l,t} S_{w,l} / \sum_l [(N_{w,l,t} + O_{w,l,t}) S_{w,l}]$$
$$P_{p,o,l,t} = O_{w,l,t} S_{w,l} / \sum_l [(N_{w,l,t} + O_{w,l,t}) S_{w,l}] \tag{10}$$

The above equations were also used to calculate length compositions of winter pot survey for newshell and oldshell crabs, $P_{sw,n,l,t}$ and $P_{sw,o,l,t}$ ($l \geq 1$).

$$P_{sw,n,l,t} = N_{w,l,t} S_{w,l} / \sum_l [(N_{w,l,t} + O_{w,l,t}) S_{w,l}]$$
$$P_{sw,o,l,t} = O_{w,l,t} S_{w,l} / \sum_l [(N_{w,l,t} + O_{w,l,t}) S_{w,l}] \tag{11}$$

Length composition of summer commercial catch

Length compositions of the summer commercial catch for new and old shell crabs $P_{s,n,l,t}$ and $P_{s,o,l,t}$, were calculated based on summer population, selectivity, and legal abundance;

$$P_{s,n,l,t} = N_{s,l,t} S_{s,l} L_l / A_t$$
$$P_{s,o,l,t} = O_{s,l,t} S_{s,l} L_l / A_t \tag{12}$$

Where A_t is exploitable legal abundance in year t, estimated as

$$A_t = \sum_l [(N_{s,l,t} + O_{s,l,t}) S_{s,l} L_l] \tag{13}$$

Summer commercial fishing effort

Summer fishing effort (f_t) measured as the number of pot-lifts was calculated as total summer catch, C_t, divided by the product of catchability coefficient q and mean exploitable abundance:

$$f_t = C_t / [q_i (A_t - 0.5 C_t)] \tag{14}$$

Because fishing fleet and pot limit changed in 1993, q_1 is for fishing efforts before 1993 and q_2 is after 1992.

Length/shell compositions of Observer bycatch in 87-90, 92, 94 were estimated as

$$P_{b,n,l,t} = N_{s,l,t} S_{s,l}(1-L_l) / \sum_l [(N_{s,l,t} + O_{s,l,t}) S_{s,l}(1-L_l)]$$
$$P_{b,o,l,t} = O_{s,l,t} S_{s,l}(1-L_l) / \sum_l [(N_{s,l,t} + O_{s,l,t}) S_{s,l}(1-L_l)] \tag{15}$$

Summer pre-season survey (1976)

The same selectivity for the summer commercial fishery was applied to the summer pre-season survey, resulting in estimated length compositions for both newshell and oldshell crabs as:

$$P_{sf,n,l,t} = N_{s,l,t} S_{s,l} / \sum_l [(N_{s,l,t} + O_{s,l,t}) S_{s,l}]$$
$$P_{sf,o,l,t} = O_{s,l,t} S_{s,l} / \sum_l [(N_{s,l,t} + O_{s,l,t}) S_{s,l}] \tag{16}$$

Length/shell composition of summer pot survey (1980-82, 85)

The length/shell condition compositions of summer pot survey were estimated as

$$P_{sp,n,l,t} = N_{s,l,t} S_{sp,l} / \sum_l [(N_{s,l,t} + O_{s,l,t}) S_{sp,l}]$$
$$P_{sp,o,l,t} = O_{s,l,t} S_{sp,l} / \sum_l [(N_{s,l,t} + O_{s,l,t}) S_{sp,l}] \tag{17}$$

Where fishing selectivity, $S_{sp,l}$ was assumed to be 1 for $l \geq 3$, and $S_{sp,1}$ and $S_{sp,2}$ were estimated using the equation (6) parameters estimated from the model (ϕ_{sp}, ω_{sp}).

Length/shell compositions of summer trawl survey

Some trawl surveys occurred during the molting period, and thus we combined the length compositions of newshell and oldshell crabs as one single shell condition, $P_{st,l,t}$, and were estimated as

$$P_{st,,l,t} = N_{s,l,t} S_{st,l} / \sum_l [(N_{s,l,t} + O_{s,l,t}) S_{st,l}] \tag{18}$$

Where catch selectivity, $S_{st,l}$ was assumed to be 1 for $l \geq 3$, and $S_{st,1}$ and $S_{st,2}$ were estimated using the equation (6) parameters estimated from the model (ϕ_{st}, ω_{st}).

b. Software used: AD Model Builder (Otter Research Ltd. 1994).

c. Likelihood components.

Under assumptions that measurement errors of annual total survey abundances and summer commercial fishing efforts follow lognormal distributions and each type of length composition has a multinomial error structure (Fournier and Archibald 1982; Methot 1989), the log-likelihood function is:

$$\sum_{i=1}^{i=5}\sum_{t=1}^{t=n_i}\{K_{i,t}\sum_{l=1}^{l=6}[\hat{P}_{i,l,t}\,ln(P_{i,l,t}+\kappa)]\}-\sum_{i=1}^{i=2}\sum_{k=1}^{k=2}\sum_{t=1}^{t=n_i}[ln(\hat{B}_{i,k,t}+\kappa)-ln(B_{i,k,t}+\kappa)]^2/(2*ln(CV_{i,k,t}^2+1))$$
$$-W_f\sum_{t=1}^{t=32}[ln(\hat{f}_t+\kappa)-ln(f_t+\kappa)]^2-W_R\sum_{t=1}^{t=32}\tau_t^2 \qquad (18)$$

where

i: length/shell compositions of :

1 triennial summer trawl survey
2 summer pot survey (1980-82, 85)
3 annual winter pot survey
4 summer commercial fishery
5 observer bycatch during the summer fishery

n_i: the number of years in which data set i is available
k : 1 legal crabs, 2 sub-legal crabs
$K_{i,t}$: the effective sample size of length/shell compositions for data set i in year t
$P_{i,l,t}$: observed and estimated length compositions for data set i, length class l, and year t
In this, while observation and estimation were made for oldshell and newshell separately, both were combined for likelihood calculations.
κ : a constant equal to 0.001
CV : coefficient of variation for the survey abundance for legal, sub-legal, and total.
$B_{i,k,t}$: observed and estimated annual total abundances for data set i and year t
W_f : the weighting factor of the summer fishing effort
f_t : observed and estimated summer fishing efforts
W_R : the weighting factor of recruitment.

It is generally believed that total annual commercial crab catches in Alaska are fairly accurately reported. Thus, no measurement error was imposed on total annual catch. Variances for total survey abundances and summer fishing effort were not estimated; rather, we used weighting factors to reflect these variances.

d. Population state in year 1.

Length and shell compositions from the first year (1976) summer trawl survey data approximated the true relative compositions.

e. Parameter estimation framework:

i. Parameters Estimated Independently

The following parameters were estimated independently: natural mortality (M =0.18), proportions of legal males by length group, and the growth matrix. Natural mortality is based on an assumed maximum age of about 25 and the 1% rule (Zheng 2005). Tagging data were used to estimate mean growth increment per molt, standard deviation for each pre-molt length class, and the growth matrix (Table 3). Proportions of legal males by length group were estimated from the observer data (Table 4).

Natural mortality was based on an assumed maximum age, t_{max}, and the 1% rule (Zheng 2005):

$$M = -\ln(p)/t_{\max}, \quad (19)$$

where p is the proportion of animals that reach the maximum age and is assumed to be 0.01 for the 1% rule (Shepherd and Breen 1992, Clarke et al. 2003). The maximum age of 25, which was used to estimate M for U.S. federal overfishing limits for red king crab stocks (NPFMC 2007) results in an estimated M of 0.18. Among the 199 recovered crabs from the tagging returns during 1991-2007 in Norton Sound, the longest time at liberty was 6 years and 4 months from a crab tagged at 85 mm CL. The crab was below the mature size and was likely less than 6 years old when tagged. Therefore, the maximum age from tagging data is about 12, which does not support the maximum age of 25 chosen by the CPT.

ii. Parameters Estimated Conditionally

Estimated parameters are listed in Table 5 in the primary document. Selectivities and molting probabilities based on these estimated parameters are summarized in Table 4 (also in the primary document).

A likelihood approach was used to estimate parameters, which include fishing catchability, parameters for selectivities of survey and fishing gears and for molting probabilities, recruits each year (except the first and the last years), and total abundance in the first year (Table 5).

Crabs usually aggregate, and this increases the uncertainty in survey estimates of abundance. To reduce the effect of aggregation, annual total sample sizes for summer trawl and pot survey data sets were reduced to 50% and all other sample sizes were reduced to 10%. Also, annual effective sample sizes were capped at 200 for summer trawl and pot surveys and 100 for the other data to avoid overweighting the data with a large sample size (Fournier and Archibald 1982). Weighting factors represent prior assumptions about the accuracy or the variances of the observed data or random variables. W_f was set to be 20, and W_R was set to be 0.01. According to the fishery manager, the estimate of fishing effort in 1992 was not as reliable as in the other years (C. Lean, ADF&G, personal communication). Thus, we weighted the effort in 1992 half as much as in the other years. W_f and maximum effective sample size was investigated.

To reduce the number of parameters, we assumed that length and shell compositions from the first year (1976) summer trawl survey data approximated the true relative compositions. Abundances by length and shell condition in all other years were computed recursively from abundances by length and shell condition in the first year and by annual recruitment, catch, and model parameters. Initial parameter estimates were an educated guess based on observation and current knowledge.

f. Definition of model outputs.

i. Biomass: mature males are defined as those 94 mm carapace length and above (size classes 3 to 6).

The mean weights for size classes 1-6 are 0.854, 1.210, 1.652, 2.187, 2.825 and 3.697 lbs.

ii. Recruitment: number of males in the 1st two length classes.

iii. Fishing mortality: applied as an annual exploitation rate to the legal segment of the stock per equations 2 and 3 (above), including bycatch mortality according to equation 4 (above).