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

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

Executive Summary

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

2. Catches. This stock supports three 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 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 in recent years coincident with increases in estimated abundance.

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. However, uncertainty in historical biomass is high due in part to infrequent trawl surveys (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 slight downward trend from 1983 to 1993. Estimated recruitment has been highly variable but on an increasing trend in recent years.

5. Management performance.

Status and catch specifications (million lb.)

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

Status and catch specifications (1000t)

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

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

Biomass in millions of pounds

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

Biomass in 1000t

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

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

   TBD

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 into effect

2. Changes to the input data

   a. Data update: 2016 summer commercial fishery (total catch, catch length comp, discards length comp), 2015/2016 winter commercial and subsistence catch

   b. Data update: 1977-2016 standardized commercial catch CPUE and CV. No changes in standardization methodology (SAFE 2013).

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

3. Changes to the assessment methodology:

   None

4. Changes to the assessment results.

   None

B. *Response to SSC and CPT Comments*

All editorial requests -corrections by the SSC and CPT were implemented.

Crab Plan Team – Jan 12 2016

The CPT has the following recommendations for the next assessment: All the recommendations were evaluated (See results).

- Calculate OFL by including M from Feb. 1 to July 1. Provide OFL values calculated assuming:
- The winter fishery will take 8% of the OFL
- The winter fishery will take X% of the OFL, where X = the average fraction taken by the winter fishery over the last few (e.g., 5) years.

Author reply:

This issue came from the fact that the OFL includes both winter and summer fisheries that are 5 months apart. The issue is how to incorporate winter fishing and natural mortality and calculate total OFL.

OFL for 2015 was calculated as

$$OFL_r = (1 - \exp(-F_{OFL}))Legal\_B_w$$

where $Legal\_B_w$ is a projected winter legal crab biomass.

OFL for 2016 was calculated by incorporated M from Feb 1 to July 1 as:

$$Legal\_B_s = (Legal\_B_w)e^{-0.42M}$$

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

However, the above does not include winter fishing mortality and does not truly include winter harvest as part of OFL.

CPT and SSC's proposal is incorporating the new GHL regulation that 8% of GHL is allocated to winter and 92% is allocated to summer.

By incorporating projected winter fishery, the new retained OFL will be calculated as;

$$Legal\_B_s = (Legal\_B_w - X \cdot OFL_r)e^{-0.42M}$$

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

Where X can be (8%) or (16%: past year's proportion: recommended by ADF&G staff)

Solving the above, a revised retained OFL will be calculated as

$$OFL_r = \frac{Legal\_B_w(1 - \exp(-F_{OFL}))e^{-0.42M}}{1 - X + X \cdot (1 - \exp(-F_{OFL}))e^{-0.42M}}$$

Further discussing with the ADF&G staff, Norton Sound crab fishery also include CDQ fishery (7.5% of GHL) that can be allocated either in winter or summer fisheries. There is an ambiguity regarding how CDQ fishery, summer, and winter fishery is allocated. One interpretation is

CDQ fishery = Y*(GHL), and winter and summer fishery GHLs are = X(GHL) and (1-X)(GHL), where Y = 7.5% and X = 8%

The alternative interpretation is that

CDQ fishery = Y*(GHL), and winter and summer fishery GHLs are = X*(1-Y)(GHL) and (1-X)(1-Y)(GHL), where Y = 7.5% and X = 8%

CDQ fisheries can occur either in summer or winter fishery. During the 2016 season, more than 90% of the CDQ harvest occurred in the winter season, in addition to the open winter commercial fishery.

Assuming that all CDQ fishery occurs in winter,

CDQ fishery interpretation 1

$$Legal\_B_s = (Legal\_B_w - Y \cdot OFL_r - X \cdot OFL_r)e^{-0.42M}$$

$$(1 - X - Y)OFL_r = (1 - \exp(-F_{OFL}))Legal\_B_s$$

$$OFL_r = \frac{Legal\_B_w (1 - \exp(-F_{OFL}))e^{-0.42M}}{(1 - X - Y) + (X + Y) \cdot (1 - \exp(-F_{OFL}))e^{-0.42M}}$$

CDQ fishery interpretation 2

$$Legal\_B_s = (Legal\_B_w - Y \cdot OFL_r - X(1-Y) \cdot OFL_r)e^{-0.42M}$$

$$(1 - X)(1 - Y)OFL_r = (1 - \exp(-F_{OFL}))Legal\_B_s$$

$$OFL_r = \frac{Legal\_B_w (1 - \exp(-F_{OFL}))e^{-0.42M}}{(1 - X)(1 - Y) + (Y + X(1 - Y)) \cdot (1 - \exp(-F_{OFL}))e^{-0.42M}}$$

In 2016 SAFE, winter legal biomass was 4.654, M=F_{OFL} = 0.18

OFL calculated by the new method are

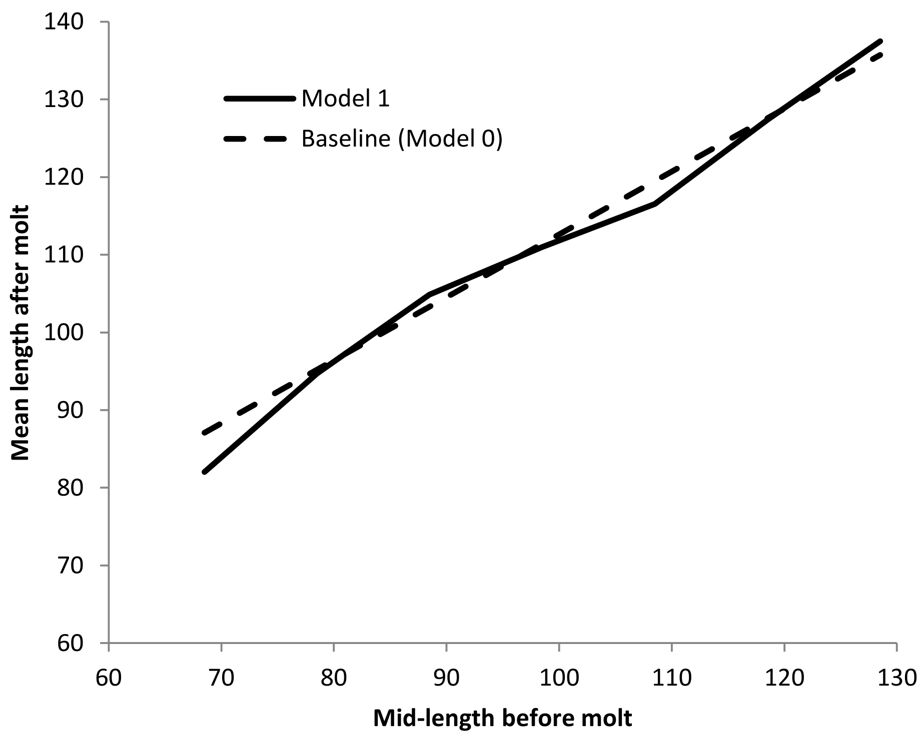
OFL_r = 0.711 : Default 2016 SAFE
OFL_r = 0.763: X = 0.08
OFL_r = 0.822: X = 0.16
OFL_r = 0.818: X = 0.08, Y = 0.075, CDQ interpretation 1
OFL_r = 0.814: X = 0.08, Y = 0.075, CDQ interpretation 2

In all cases, OFL will increase from the 2016 default calculation.

- Evaluate whether using a growth function that "slows" growth prior to the largest size bins can improve the model's estimation of abundance of large crab relative to size composition data without having to invoke a higher natural mortality for the large crab.
- Consider a piecewise linear growth model (like that used for snow crab)

Author reply:

Growth function is based on simple linear growth model. Since the NSRKC model has only 8 size classes, we implemented the above request by estimating the increment mean growth for each size class individually, with mortality constant for all length classes (Alternative model 1, Appendix C1)



However, this did not improve the model fit. Furthermore, the model indicated a slow growth occurring not at large size classes, but at the smallest and at first maturation size classes. Overall, linear growth approximation seems appropriate.

- Consider modeling molting probability using a nonparametric curve with a random walk penalty

Author reply:

We did not evaluate nonparametric curve, however, we implemented random walk option with penalty set to SD= 0.3. (Alternative model 2, Appendix C3). Implementation of the random walk improved the model fit to size composition and fit, but did not improve fit to trawl abundance survey data.

- Evaluate applying the natural mortality multiplier 'ms' to only the largest size bin, not all bins > 123 mm.

Author reply:

Estimate of 'ms' was 4.03 (SD 0.65). The model fit to size composition and trawl abundance survey data worsened from the base model (Alternative model 3: Appendix C4).

- Evaluate estimating selectivity in the summer pot fishery in two time periods: before and after the change in buyers' preferred size (2005).

Author reply:

Model estimated parameters for fishing selectivity was -2.085 (SD 0.07) for 1977-2004, and -2.023 (SD 0.08) for 2005-2015. The two estimates were not statistically different (Alternative model 4: Appendix C5), so that the assumption of single fishing selectivity seem still appropriate.

SSC – Feb 1-3 2016

The author indicated that this [fixing trawl survey selectivity to 1.0 for all length class] was not done because the parameter is not always 1.0. Please clarify the basis for this understanding that it is not always 1.0.

Author reply:
Trawl survey length selectivity is modeled as logistic curve, but estimated curve was 1.0 across all length classes. In some cases, the model does estimate trawl survey selectivity as logistic (See, Appendix C1-C5 for changes in trawl selectivity among alternative models). Fixing trawl selectivity to 1.0 is essentially adding another model assumption.

Does the timing indicate that crab may go "missing" in association with the molting period? The SSC appreciates this additional information.

Author reply:
Thus far, there is no additional information regarding the "lost" crab. In March 2016, 12 crabs were tagged with Satellite tag (Robert Foy NOAA personal com). Of those only 1 crab was 123mm CL (Tag number 972).

The SSC noted relatively high proportions of 134+ mm CL crab in the summer commercial catches taken during 1980-1982 (Table 4). The SSC requests the analyst investigate whether there are observer data that could be examined to verify those high proportions, including the geographic location of catches that included these animals.

Author reply:

There was no observer program during the 1980-1982. The table 4 data originated from Powell et al. (1983) report summary table. During the 1970-1980s, all fishery sampling and researches were conducted by the ADF&G Kodiak office staff, and trawl surveys were conducted by NOAA. I investigated the ADF&G Kodiak office warehouse; however, I was not able to find any commercial sampling data. During 1980-1982 periods, the majority of fishery occurred west of Nome (SAFE 2014 Norton Sound section Appendix E). Interestingly those 134+mm CL crabs were not observed during the 1979 and 1982 trawl surveys, though the survey covered the same area where commercial fishery occurred (SAFE 2014 Norton Sound section Appendix E).

The SSC was very interested in the conflicting observations about molt timing in April/May versus August/September.

Author reply:

The original April/May molt timing by Powell et al. (1983) is based not on direct observation, but on deduction that other red king crabs in Alaska molt in March and April and high proportion of newshell crabs (> 80%) in commercial catch (starting in July). However, the proportion of newshell crabs are also high (>80%) during the winter fishery season (Nov-May). Double shelled crabs were not observed during the winter survey but at later summer commercial season (Sept-Oct) (Joyce Soong ADF&G personal communication). Hemolymph studies also suggest that molt timing of Norton Sound Red King crab is late summer (Jenefer Bell ADF&G, see NSRKC SAFE progress report 2015). Our August/September molt timing observation is rather "correcting" long-held misassumptions about molt timing of the Norton Sound Red King crab.

C. Introduction

1. Species: red king crab (*Paralithodes camtschaticus*) in Norton Sound, Alaska.
2. General Distribution: Norton Sound red king crab is one of the northernmost red king crab populations that can support a commercial fishery (Powell et al. 1983). It is distributed throughout Norton Sound with a westward limit of 167-168^{o} W. longitude, depths less than 30 m, and summer bottom temperatures above 4^{o}C. The Norton Sound red king crab management area consists of two units: Norton Sound Section (Q3) and Kotzebue Section (Q4) (Menard et al. 2011). The Norton Sound Section (Q3) consists of all waters in Registration Area Q north of the latitude of Cape Romanzof, east of the International Dateline, and south of 66°N latitude (Figure 1). The Kotzebue Section (Q4) lies immediately north of the Norton Sound Section and includes Kotzebue Sound. Commercial fisheries have

not occurred regularly in the Kotzebue Section. This report deals with the Norton Sound Section of the Norton Sound red king crab management area.

3. Evidence of stock structure: Thus far, no studies have investigated possible stock separation within the putative Norton Sound red king crab stock.

4. Life history characteristics relevant to management: One of the unique life-history traits of Norton Sound red king crab is that they spend their entire lives in shallow water since Norton Sound is generally less than 40 m in depth. Distribution and migration patterns of Norton Sound red king crab have not been well studied. Based on the 1976-2006 trawl surveys, red king crab in Norton Sound are found in areas with a mean depth range of 19 ± 6 (SD) m and bottom temperatures of 7.4 ± 2.5 (SD) ^{o}C during summer. Norton Sound red king crab are consistently abundant offshore of Nome.

   Norton Sound red king crab migrate between deeper offshore and inshore shallow waters. Timing of the inshore mating migration is unknown, but is assumed to be during late fall to winter (Powell et al. 1983). Offshore migration occurs in late May - July (Jennifer Bell, ADF&G, personal communication). The results from a study funded by North Pacific Research Board (NPRB) during 2012-2014 suggest that older/large crab (> 104mm CL) stay offshore in winter, based on findings that large crab are not found nearshore during spring offshore migration periods (Jennifer Bell, ADF&G, personal communication). Timing of molting is unknown but is considered to occur in late August – September, based on increase catches of fresh-molted crab later in the fishing season (August- September) (Joyce Soong, ADF&G personal communication) and blood hormone (Jennifer Bell, ADF&G, personal communication). Recent observations indicate biennial mating (Robert Foy, NOAA, personal communication). Trawl surveys show that crab distribution is dynamic with recent surveys showing high abundance on the southeast side of the sound, offshore of Stebbins and Saint Michael.

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

<u>Summer Commercial Fishery</u>

A large-vessel summer commercial crab fishery started in 1977 in the Norton Sound Section (Table 1) and continued from 1977 through 1990. No summer commercial fishery occurred in 1991 because there was no staff to manage the fishery. In March 1993, the Alaska Board of Fisheries (BOF) limited participation in the fishery to small boats. Then on June 27, 1994, a super-exclusive designation went into effect for the fishery. This designation stated that a vessel registered for the Norton Sound crab fishery may not be used to take king crabs in any other registration areas during that registration year. A vessel moratorium was put into place before the 1996 season. This was intended to precede a license limitation program. In 1998, Community Development Quota (CDQ) groups were allocated a portion of the summer harvest; however, no CDQ harvest occurred until the 2000 season. On January 1, 2000 the

North Pacific License Limitation Program (LLP) went into effect for the Norton Sound crab fishery. The program dictates that a vessel which exceeds 32 feet in length overall must hold a valid crab license issued under the LLP by the National Marine Fisheries Service. Regulation changes and location of buyers resulted in harvest distribution moving eastward in Norton Sound in the mid-1990s. In Norton Sound, a legal crab is defined as ≥ 4-3/4 inch carapace width (CW, Menard et al. 2011), which is approximately equivalent to ≥ 104 mm carapace length mm CL. Since 2005, commercial buyers started accepting only legal crab of ≥ 5 inch CW.

Not all Norton Sound area is open for commercial fisheries. Since the beginning of the commercial fisheries in 1977, water approximately 5-10 miles offshore of southern Seward Peninsula from Port Clarence to St. Michael have been closed to protect crab nursery grounds during the summer commercial crab fishery (Figure 2). The spatial extent of closed waters has varied historically.

<u>CDQ Fishery</u>

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

<u>Winter Commercial Fishery</u>

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

<u>Subsistence Fishery</u>

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

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

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

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

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

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

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

Year	Notable historical management changes
1976	The abundance survey started
1977	Large vessel commercial fisheries began
1991	Fishery closed due to staff constraints
1994	Super exclusive designation went into effect. The end of large vessel commercial fishery operation. The majority of commercial fishery subsequently shifted to east of 164°W longitude.
1998	Community Development Quota (CDQ) allocation went into effect
1999	Guideline Harvest Level (GHL) went into effect
2000	North Pacific License Limitation Program (LLP) went into effect.
2002	Change in closed water boundaries (Figure 2)
2005	Commercially accepted legal crab size changed from ≥ 4-3/4 inch CW to ≥ 5 inch CW
2006	The Statistical area Q3 section expanded (Figure 1)
2008	Start date of the open access fishery changed from 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.
2012	The Board of Fisheries adopted a revised GHL for summer fishery.
2016	Winter GHL for commercial fisheries was established and modified winter fishing season dates were implemented.

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

NSRKC is a Tier4 crab stock. Direct estimation of the B_{MSY} is not possible. The B_{MSY} proxy is calculated as mean model estimated mature male biomass (MMB) from 1980 to present. Choice of this period was based on a hypothesized shift in stock productivity a due to a climatic regime shift indexed by the Pacific Decadal Oscillation (PDO) in 1976-77. Stock status of the NSRKC was Tier 4a until 2013. In 2014 the stock fell to Tier 4b, but came back to Tire 4a for 2015-2016 season.

D. Data

1. Summary of new information:

Winter commercial and subsistence fishery:

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

Summer commercial fishery:

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

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

2. Available survey, catch, and tagging data

	Years	Data Types	Tables
Summer trawl survey	76,79,82,85,88,91,96, 99, 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	2
		Retained catch	2
Winter commercial fishery	78-16	Retained catch	2
Tag recovery	80-16	Recovered tagged crab	8

Data available but not used for assessment

Data	Years	Data Types	Reason for not used
Summer pot survey	80-82,85	Abundance 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

Time series of available data

	Survey		Harvests			Tag	Data Not Used				
	S. Trawl	W. Pot	S.Com	S.Com Dis	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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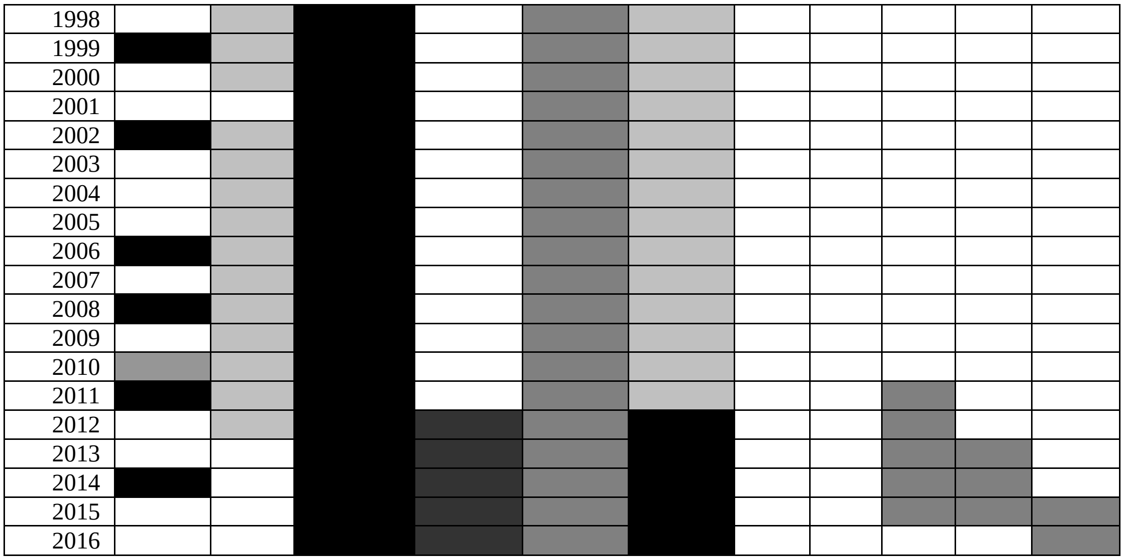


1: Index of abundance data: N: crab abundance, H: Crab harvest, CPUE: Catch cpue
2: Length data available

Catches in other fisheries

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

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

3. Other miscellaneous data:

    Satellite tag migration tracking (NOAA 2016)

    Spring offshore migration distance and direction (2013-2015)

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

Data aggregated:

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

Data estimated outside the model:

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

E. Analytic Approach

1. History of the modeling approach.

The Norton Sound red king crab stock was assessed using a length-based synthesis model (Zheng et al. 1998). Since adoption of the model, the major challenge is a conflict between model projection and data, specifically the model projects higher abundance-proportion of the largest size class of crab than in seen in data. This problem was further exasperated when natural mortality *M* was set as 0.18 from previous *M* = 0.3 in 2011 (SAFE 2011). This problem was examined and resolved by increasing *M* of the largest length crabs to 3.6×*M* or *M* = 0.648 (SAFE 2012). Profile likelihood analyses have been conducted several times, which resulted in the lowest likelihood at *M* = 0.34 (SAFE 2012, 2013). However, even at this higher *M*, the model was not able to resolve poor fits to the commercial catch. Profile likelihood of commercial catch was lowest around *M* = 0.5 or greater. From 2013 to 2014, the NSRKC model was thoroughly examined by the CPT during the modeling workshop. The workshop improved the model fit thorough excluding some data (summer pot survey), revising the trawl survey abundance estimates, standardizing commercial catch CPUE, including tag recovery data to estimate the growth transition matrix within the model, and changing weights in the likelihood. However, the issue of *M* was not addressed in this workshop. In 2016, this assumption was examined more fully. Model estimated *M* constant across all length groups was around 0.4, and *M* assuming the higher rate for the largest length group was 0.21 for all and 0.62 for the largest length group (SAFE 2016). The 2016 SAFE also examined the effect of changing length interval (10 mm vs. 5 mm) as well as the range of length categories (74mm – 124mm above, vs. 64mm – 134mm above). After examining data, the CPT chose extended length categories (64mm – 134mm above) with a 10 mm interval. Further, multipliers for the last length class are now estimated. Despite all those efforts, model estimates of higher natural mortality of > 123mm crab remain the greatest unknown for Norton Sound red king crab and the assessment model. For 2017 assessment, CPT and SSC requested additional model investigations to solve this issue: low 123+ mm crabs due to slow molting growth increment (Alt model 1).

Historical Model configuration progression:

2011 (SAFE 2011)

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

2012 (SAFE 2012)

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

2013 (SAFE 2013)

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

2014 (SAFE 2014)

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

2015 (SAFE 2015)

1. Winter pot survey selectivity is an inverse logistic, estimating selectivity of the smallest length group independently
2. Reduce Weight of tag-recovery: W = 0.5
3. Model parsimony: one trawl survey selectivity and one commercial pot selectivity

2016 (SAFE 2016)

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

2. Model Description

a. Description of overall modeling approach:

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

b-f. See Appendix A.

g. Critical assumptions of the model:

i. Male crab mature at CL length 94mm.

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

ii. Molting occurs in the fall after the fishery

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

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

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

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

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

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

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

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

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

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

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

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

xiii. Annual retained catch is measured without error.

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

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

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 code was reviewed at the CPT modeling workshop in 2013 and 2014. It is available from the authors.

3. Model Selection and Evaluation

a. Description of alternative model configurations.

As described in section E (1), all alternative model requests were to solve the question of low proportion of > 123mm crab. Alternative model (1) investigates if this is due to slow growth in larger crab, alternative model (2) investigates if this is due to changes in molting probability, and alternative model (3) investigates if the higher mortality occurs only for the largest > 134mm crab. Alternative model (4) is a re-investigation of model parsimony for commercial fishery selectivity endorsed by the CPT and SSC for 2016 SAFE.

List of model scenarios considered.

Scenario	
0 (Default)	
1	Non-linear growth
2	Random walk molting probability
3	Step increase in mortality at carapace length > 134 mm
4	Separate fishery selectivity

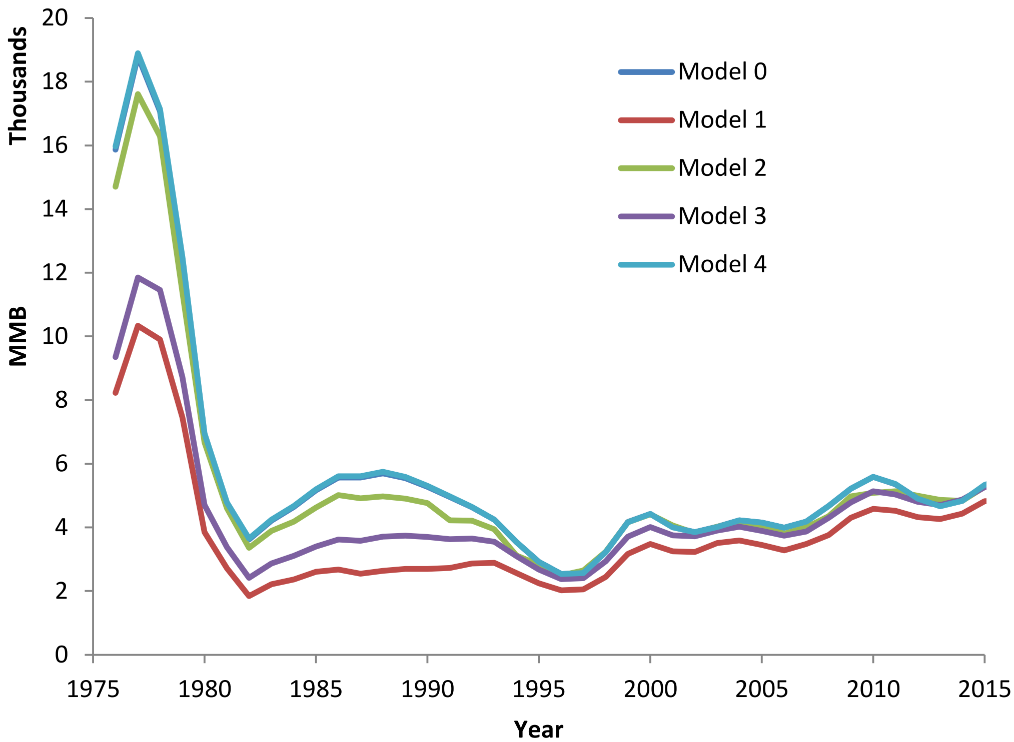
b. Evaluation of alternative models results:

Model	Number of Parameters	Total	TSA	St. CPUE	TLP	WLP	CLP	OBS	REC	TAG	Dev. molt
0	65	315.0	9.0	-22.1	104.5	42.5	59.5	36.0	11.6	74.7	
1	69	349.9	15.1	-21.8	112.4	45.3	91.4	34.3	14.5	61.8	
2	104	265.2	9.3	-21.8	71.4	40.9	48.6	27.6	12.3	71.7	5.2
3	65	352.3	9.5	-22.3	117.1	45.3	79.6	36.3	12.5	74.3	
4	66	328.4	9.0	-22.3	104.6	42.5	59.5	35.5	11.7	88.1	

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

c. Search for balance:

Diagnostics and output from alternative models are detailed in Appendices C1 (model 0) to C5 (model 4). While introduction of random walk (Model 2) did increase model fit to data, model estimated MMB did not differ from the baseline model. The assumption of constant M for all size classes (Model 1) and increased mortality for only the last (>134mm) length class (Model 3) did not improve model fit. MMB projections among the 5 models suggest that changes in likelihood are associated with model fits before 1995. Further, MMB of models 0 and 4 were almost identical. We recommend the baseline model (Model 0) for the 2017 assessment in January 2017.



MMB time series among 5 models. Note: MMB of Model 0 and Model 4 were identical.

4. Results (TBD in January 2017)

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

"Implied" effective sample sizes were calculated as

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

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

Maximum sample size for length proportion:

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

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

    b. Abundance and biomass time series (Table 14)

    c. Recruitment time series (Table 14).

    d. Time series of catch/biomass (Tables 14 and 15)

3. Graphs of estimates.
    a. Molting probability and trawl/pot selectivity (Figure 5)
    b. Trawl survey and model estimated trawl survey abundance (Figure 6)
    c. Estimated male abundances (recruits, legal, and total) (Figure 7)
    d. Estimated mature male biomass (Figure 8)
    e. Time series of standardized cpue for the summer commercial fishery (Figure 9).
    f. Time series of catch and estimated harvest rate (Figure 10).

4. Evaluation of the fit to the data.

    a. Fits to observed and model predicted catches.
    Not applicable. Catch is assumed to be measured without error; however fits of cpue are available (Figures 9, 11).

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

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

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

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

    e. Marginal distribution for the fits to the composition data

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

g. Tables of RMSEs for the indices:

Trawl survey: 0.36
Summer commercial standardized CPUE: 0.5.

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

5. Retrospective and prospective analyses (Figure 17,18).

6. Uncertainty and sensitivity analyses.

See Sections 2 and 5.

F. Calculation of the OFL (TBD in January 2017)

1. Specification of the Tier level and stock status.

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

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

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

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

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

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

Predicted mature male biomass in 2017 in February 01 is:

Mature male biomass : million lb.

Estimated B_{MSY} proxy is:

million lb.

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

2. Calculation of OFL.

The OFL was calculated for retained, un-retained, and total male catch, in which OFL is calculated by applying F_{OFL} control rule to crab abundance estimates.

Legal_B, biomass of legal crab subject to fisheries is calculated as : Projected abundance by length crab × fishing selectivity by length crab × Proportion of legal crab per length class × Average lb per length class (Appendix A)

The Norton Sound red king crab fishery consists of a small (1-17% of total catch biomass) winter subsistence and commercial fishery from January to May and summer commercial fishery (83-99% of total catch biomass) from mid-June to September. The two fisheries use different fishing gears and thus have different catch selectivities (Figure 5, Table 11).

In determination of OFL, *Legal_B* should be biomass right before the majority of fisheries occur that is July 01, which is calculated as: (Feb 1st abundance – winter fishery harvests – winter fishery discards × handling mortality) × natural mortality from Feb 1st to June 30th. However, because model assessment is based on February 01 population, and winter fishery is yet to occur, predicted July 01 population cannot be calculated directly.

Hence, under the direction of the CPT (Jan 12, 2016), the crab abundance (*Legal_B*) used for calculation of the OFL the July 01 *Legal_B* was calculated as: Projected legal abundance (Feb 1st) × Commercial pot selectivity × Proportion of legal crab per length class × average lb per length class × natural mortality from February 1st to July 1st.

For next year (2017) calculation of (*Legal_B*) will be updated to incorporate projected winter fishery removal.

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

where $N_{s,l}$ and $O_{s,l}$ are summer abundances of newshell and oldshell crab in length class l in the terminal year, L_l is the proportion of legal males in length class l, $S_{s,l}$ is summer commercial catch selectivity, wm_l is average weight in length class l and hm is handling mortality rate. .

The total male OFL is

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

For calculation of the OFL 2017

Legal male biomass (July 01): 4.31 (SD 0.89) million lb
OFL_r = million lb.
OFL_{nr} = million lb.
OFL_T = million lb.

G. Calculation of the ABC

1. Specification of the probability distribution of the OFL.

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

Retained ABC for legal male crab is 80% of OFL

ABC = 0.710× 0.8 = 0.568 million lb.

H. Rebuilding Analyses

Not applicable

I. Data Gaps and Research Priorities

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

Acknowledgments

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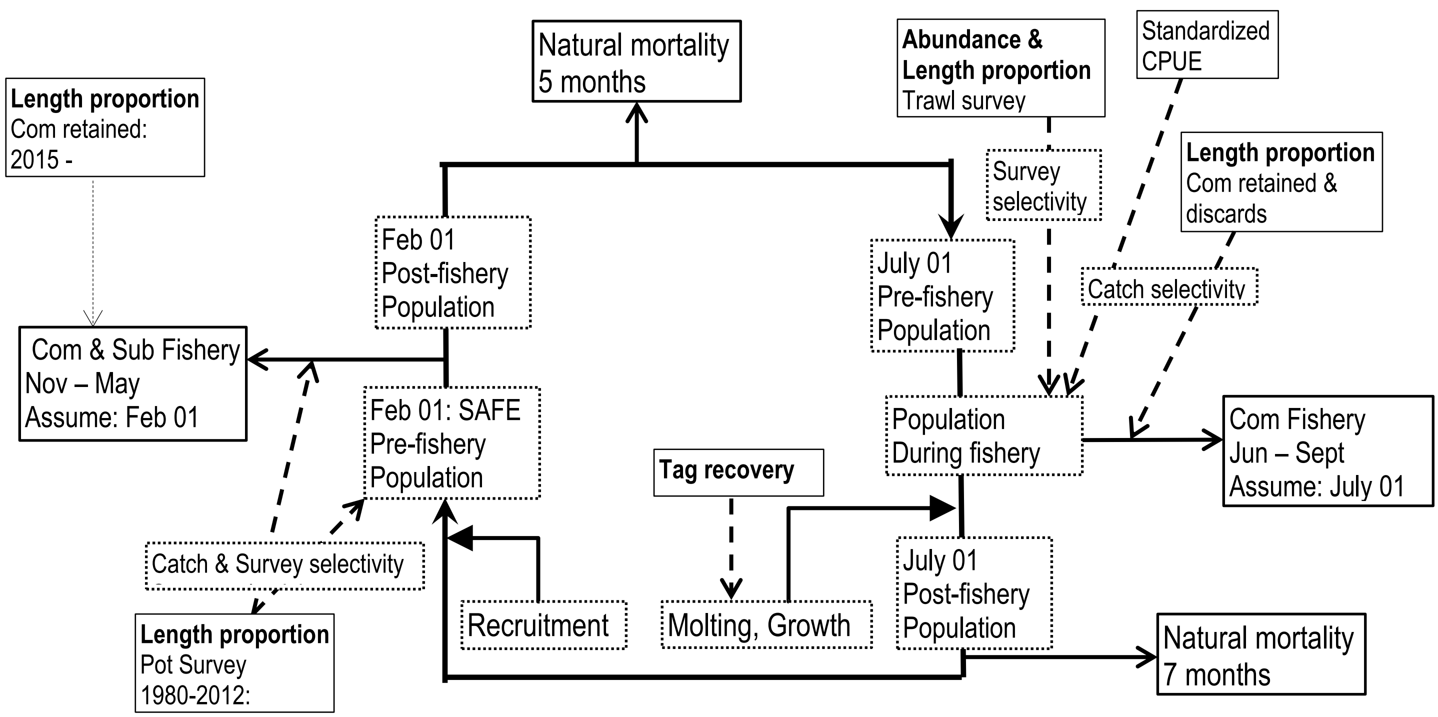
Appendix A. Description of the Norton Sound Red King Crab Model

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 male length classes with model parameters estimated by the maximum likelihood method. The model estimates abundances of crab with CL ≥74 mm and with 10-mm length intervals (6 length classes) because few crab measuring less than 74 mm CL were caught during surveys or fisheries and there were relatively small sample sizes for trawl and winter pot surveys. The model treats newshell and oldshell male crab separately but assumes they have the same molting probability and natural mortality.

Norton Sound Red King Crab Modeling Scheme



Timeline of calendar events and crab modeling events:

- **Model year starts February 1st to January 31st of the following year.**
- **All winter fishery harvest occurs on February 1st**
- **Molting and recruitment occur on July 1st**
- **Initial Population Date: February 1st 1976**

Initial pre-fishery summer crab abundance on February 1st 1976

Abundance of the initial pre-fishery population was assumed consist of newshell crab to reduce the number of parameters, and estimated as

$$N_{l,1} = p_l e^{\log\_N_{76}} \quad (1)$$

where, length proportion of the first year (p_l)was calculated as

$$p_l = \frac{\exp(a_l)}{1+\sum_{l=1}^{n-1}\exp(a_l)} \text{ for } l = 1,..,n\text{-}1$$
$$p_n = 1 - \frac{\sum_{l=1}^{n-1}\exp(a_l)}{1+\sum_{l=1}^{n-1}\exp(a_l)} \quad (2)$$

for model estimated parameters a_l.

Crab abundance on July 1st

Summer (01 July) crab abundance of new and oldshells consists of survivors of winter commercial and subsistence crab fisheries and natural mortality from 01Feb to 01July:

$$N_{s,l,t} = (N_{w,l,t-1} - C_{w,t-1}P_{w,n,l,t-1} - C_{p,t}P_{p,n,l,t-1} - D_{w,n,l,t-1} - D_{p,n,l,t-1})e^{-0.42M_l}$$
$$O_{s,l,t} = (O_{w,l,t-1} - C_{w,t-1}P_{w,o,l,t-1} - C_{p,t}P_{p,o,l,t-1} - D_{w,o,l,t-1} - D_{p,o,l,t-1})e^{-0.42M_l} \quad (3)$$

where

$N_{s,l,t}$, $O_{s,l,t}$: summer abundances of newshell and oldshell crab in length class l in year t ,
$N_{w,l,t-1}$, $O_{w,l,t-1}$: winter abundances of newshell and oldshell crab in length class l in year $t-1$,
$C_{w,t-1}$, $C_{p,t-1}$: total winter commercial and subsistence catches in year $t-1$,
$P_{w,n,l,t-1}$, $P_{w,o,l,t-1}$: Proportion of newshell and oldshell length class l crab in year $t-1$, harvested by winter commercial fishery,
$P_{p,n,l,t-1}$, $P_{p,o,l,t-1}$: Proportion of newshell and oldshell length class l crab in year $t-1$, harvested by winter subsistence fishery,
$D_{w,n,l,t-1}$, $D_{w,o,l,t-1}$: Discard mortality of newshell and oldshell length class l crab in winter commercial fishery in year $t-1$,

$D_{p,n,l,t-1}$, $D_{p,o,l,t-1}$: Discard mortality of newshell and oldshell length class *l* crab in winter subsistence fishery in year *t-1*,
M_l : instantaneous natural mortality in length class *l*,
0.42 : proportion of the year from Feb 1 to July 1 is 5 months.

Length proportion compositions of winter commercial catch ($P_{w,n,l,t}$, $P_{w,o,l,t}$) in year *t* were estimated as:

$$\begin{aligned} P_{w,n,l,t} &= N_{w,l,t} S_{w,l} L_l / \sum_{l=1} [(N_{w,l,t} + O_{w,l,t}) S_{w,l} L_l] \\ P_{w,o,l,t} &= O_{w,l,t} S_{w,l} L_l / \sum_{l=1} [(N_{w,l,t} + O_{w,l,t}) S_{w,l} L_l] \end{aligned} \tag{4}$$

where
L_l : the proportion of legal males in length class *l* ,
$S_{w,l}$: Selectivity of winter fishery pot.

The subsistence fishery does not have a size limit; however, crab of size smaller than length class 3 are generally not retained. Hence, we assumed proportion of length composition *l* = 1 and 2 as 0, and estimated length compositions ($l \geq 3$) as follows

$$\begin{aligned} P_{p,n,l,t} &= N_{w,l,t} S_{w,l} / \sum_{l=3} [(N_{w,l,t} + O_{w,l,t}) S_{w,l}] \\ P_{p,o,l,t} &= O_{w,l,t} S_{w,l} / \sum_{l=3} [(N_{w,l,t} + O_{w,l,t}) S_{w,l}] \end{aligned} \tag{5}$$

Crab abundance on Feb 1st

Newshell Crab: Abundance of newshell crab of year *t* and length-class *l* ($N_{w,l,t}$) year-t consist of: (1) new and oldshell crab that survived the summer commercial fishery and molted, and (2) recruitment ($R_{l,t}$) .

$$N_{w,l,t} = \sum_{l'=1}^{l'=l} G_{l',l} [(N_{s,l',t-1} + O_{s,l',t-1}) e^{-y_c M_l} - C_{s,t} (P_{s,n,l',t-1} + P_{s,o,l',t-1}) - D_{l',t-1}] m_{l'} e^{-(0.58-y_c) M_l} + R_{l,t} \tag{6}$$

Oldshell Crab: Abundance of oldshell crabs of year *t* and length-class *l* ($O_{w,l,t}$) consists of the non-molting portion of survivors from the summer fishery:

$$O_{w,l,t} = [(N_{s,l,t-1} + O_{s,l,t-1}) e^{-y_c M_l} - C_{s,t} (P_{s,n,l,t-1} + P_{s,o,l,t-1}) - D_{l,t-1}] (1 - m_l) e^{-(0.58-y_c) M_l} \tag{7}$$

where

$G_{l',l}$: a growth matrix representing the expected proportion of crabs growing from length class l' to length class l
$C_{s,t}$: total summer catch in year t
$P_{s,n,l,t}$, $P_{s,o,l,t}$: proportion of summer catch for newshell and oldshell crabs of length class l in year t,
$D_{l,t}$: summer discard mortality of length class l in year t,
m_l : molting probability of length class l,
y_c : the time in year from July 1 to the mid-point of the summer fishery,
0.58: Proportion of the year from July 1st to Feb 1st is 7 months is 0.58 year,
$R_{l,t}$: recruitment into length class l in year t.

Discards

Discards are crabs that were caught by fisheries but were not retained, which consists of summer commercial, winter commercial, and winter subsistence.

Summer and Winter commercial Discards

In summer ($D_{l,t}$) and winter ($D_{w,n,l,t}$, $D_{w,o,l,t}$) commercial fisheries, sublegal males (<4.75 inch CW and <5.0 inch CW since 2005) are discarded. Those discarded crabs are subject to handling mortality. The number of discards was not directly observed, and thus was estimated from the model as: Observed Catch x (estimated abundance of crab that are not caught by commercial pot)/(estimated abundance of crab that are caught by commercial pot)

Model discard mortality in length-class l in year t from the summer and winter commercial pot fisheries is given by

$$D_{l,t} = C_{s,t} \frac{(N_{s,l,t} + O_{s,l,t}) S_{s,l} (1 - L_l)}{\sum_l (N_{s,l,t} + O_{s,l,t}) S_{s,l} L_l} hm_s \quad (8)$$

$$D_{w,n,l,t} = C_{w,t} \frac{N_{w,l,t} S_{w,l} (1 - L_l)}{\sum_l (N_{w,l,t} + O_{w,l,t}) S_{w,l} L_l} hm_w \quad (9)$$

$$D_{w,o,l,t} = C_{w,t} \frac{O_{w,l,t} S_{w,l} (1 - L_l)}{\sum_l (N_{w,l,t} + O_{w,l,t}) S_{w,l} L_l} hm_w \quad (10)$$

where

hm_s: summer commercial handling mortality rate assumed to be 0.2,
hm_w: winter commercial handling mortality rate assumed to be 0.2,
$S_{s,l}$: Selectivity of the summer commercial fishery,
$S_{w,l}$: Selectivity of the winter commercial fishery,

Winter subsistence Discards

Discards of winter subsistence fishery is reported in a permit survey ($C_{d,t}$), though its catch composition is unknown. We assumed that subsistence fishers discarded all crabs of length classes 1 -2.

$$D_{p,n,l,t} = C_{d,t} \frac{N_{w,l,t} S_{w,l}}{\sum_{l=1}^{2} (N_{w,l,t} + O_{w,l,t}) S_{w,l}} hm_w \quad (11)$$

$$D_{p,o,l,t} = C_{d,t} \frac{O_{w,l,t} S_{w,l}}{\sum_{l=1}^{2} (N_{w,l,t} + O_{w,l,t}) S_{w,l}} hm_w \quad (12)$$

$C_{d,t}$: Winter subsistence discards catch,

Recruitment

Recruitment of year *t*, R_t, is a stochastic process around the geometric mean, R_0:

$$R_t = R_0 e^{\tau_t}, \tau_t \sim N(0, \sigma_R^2) \quad (13)$$

R_t of the last year was assumed to be an average of previous 5 years: $R_t = (R_{t-1} + R_{t-2} + R_{t-3} + R_{t-4} + R_{t-5})/5$.

R_t was assumed to be newshell crab of immature (< 94mm) length classes 1 to *r*

$$R_{r,t} = p_r \, R_t \quad (14)$$

where *r* takes multinomial distribution, same as the equation (2)

Molting Probability

Molting probability for length class *l*, m_l, was fitted as a decreasing logistic function of length-class mid carapace length and constrained to equal 0.999 for the smallest length-class (L_1):

$$m_l = \frac{1}{1 + e^{(\alpha(L_1 - L) + \ln(1/0.001 - 1))}} \quad (15)$$

Trawl net and summer commercial pot selectivity

Trawl and summer commercial pot selectivity was assumed to be a logistic function of mid-length-class, constrained to be 0.999 at the largest length-class (L_{max}):

$$S_l = \frac{1}{1 + e^{(\phi(L_{\max} - L) + \ln(1/0.999 - 1))}} \quad (16)$$

Winter pot selectivity

Winter pot selectivity was assumed to be a dome shaped decreasing logistic function of mid-length-class, constrained to 0.999 at a small length-class (L_s):

$$S_{w,l} = \frac{1}{1 + e^{(\phi_w(L_1 - L) + \ln(1/0.001 - 1))}} \quad (17)$$

Selectivity of the smaller length classes $S_{w,s}$ were individually estimated.

Growth transition matrix

The growth matrix $G_{l',l}$ (the expected proportion of crab molting from length class l' to length class l) was assumed to be normally distributed

$$G_{l',l} = \begin{cases} \dfrac{\int_{lm_l - h}^{lm_l + h} N(L \mid \mu_{l'}, \sigma^2)\,dL}{\sum_{l=1}^{n} \int_{lm_l - h}^{lm_l + h} N(L \mid \mu_{l'}, \sigma^2)\,dL} & \text{when } l \geq l' \\ 0 & \text{when } l < l' \end{cases} \quad (18)$$

Where

$$N(x \mid \mu_{l'}, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(L - \mu_{l'})^2}{\sigma^2} \right)$$

$$lm_l = L_1 + st \cdot l$$

$$\mu_l = L_1 + \beta_0 + \beta_1 \cdot l$$

Observation model

Summer trawl survey abundance

Modeled trawl survey abundance of *t-th* year ($B_{st,t}$) is July 1st abundance subtracted by summer commercial fishery harvest occurring from the July 1st to the mid-point of summer trawl survey, multiplied by natural mortality occurring between mid-point of commercial fishery date and trawl survey date, and multiplied by trawl survey selectivity. For the first year (1976) trawl survey, the commercial fishery did not occur.

$$\hat{B}_{st,t} = \sum_{l}[(N_{s,l,t} + O_{s,l,t})e^{-y_c M_l} - C_{s,t} P_{c,t}(P_{s,n,l,t} + P_{s,o,l,t})]e^{-(y_{st} - y_c)M_l} S_{st,l} \quad (19)$$

where
y_{st} : the time in year from July 1 to the mid-point of the summer trawl survey,
y_c: the time in year from July 1 to the mid-point for the catch before the survey, ($y_{st} > y_c$: Trawl survey starts after opening of commercial fisheries),
$P_{c,t}$: proportion of summer commercial crab harvested before the mid-point of trawl survey date.

Winter pot survey CPUE

Winter pot survey cpue (f_{wt}) was calculated with catchability coefficient q and exploitable abundance

$$\hat{f}_{wt} = q_w \sum_{l}[(N_{w,l,t} + O_{w,l,t})S_{w,l}] \quad (20)$$

Summer commercial CPUE

Summer commercial fishing CPUE (f_t) was calculated as a product of catchability coefficient q and mean exploitable abundance minus one half of summer catch, A_t.

$$\hat{f}_t = q_i(A_t - 0.5C_t) \quad (21)$$

Because fishing fleet and pot limit configuration changed in 1993, q_1 is for fishing efforts before 1993, q_2 is from 1994 to present.

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

$$A_t = \sum_{l}[(N_{s,l,t} + O_{s,l,t})S_{s,l} L_l] \quad (22)$$

Summer pot survey abundance (Removed from likelihood components)
Abundance of *t*-th year pot survey was estimated as

$$\hat{B}_{p,t} = \sum_{l}[(N_{s,l,t} + O_{s,l,t})e^{-y_p M_l}]S_{p,l} \quad (23)$$

Where

y_p : the time in year from July 1 to the mid-point of the summer pot survey.
Length composition

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 modeled based on the summer population, selectivity, and legal abundance:

$$\hat{P}_{s,n,l,t} = N_{s,l,t}S_{s,l}L_l / A_t \qquad (24)$$
$$\hat{P}_{s,o,l,t} = O_{s,l,t}S_{s,l}L_l / A_t$$

Summer commercial fishery discards

Length/shell compositions of observer discards were modeled as

$$\hat{P}_{b,n,l,t} = N_{s,l,t}S_{s,l}(1-L_l) / \sum_l [(N_{s,l,t}+O_{s,l,t})S_{s,l}(1-L_l)] \qquad (25)$$
$$\hat{P}_{b,o,l,t} = O_{s,l,t}S_{s,l}(1-L_l) / \sum_l [(N_{s,l,t}+O_{s,l,t})S_{s,l}(1-L_l)]$$

Summer trawl survey

Proportions of newshell and oldshell crab, $P_{st,n,l,t}$ and $P_{st,o,l,t}$ were given by

$$\hat{P}_{st,n,l,t} = \frac{[N_{s,l,t}e^{-y_cM_l} - C_{s,t}P_{c,t}\hat{P}_{s,n,l',t}]e^{-(y_{st}-y_c)M_l}S_{st,l}}{\sum_l [(N_{s,l,t}+O_{s,l,t})e^{-y_cM_l} - C_{s,t}P_{c,t}(\hat{P}_{s,n,l',t}+\hat{P}_{s,o,l',t})]e^{-(y_{st}-y_c)M_l}S_{st,l}} \qquad (26)$$
$$\hat{P}_{st,o,l,t} = \frac{[O_{s,l,t}e^{-y_cM_l} - C_{s,t}\hat{P}_{s,o,l',t}P_{c,t}]e^{-(y_{st}-y_c)M_l}S_{st,l}}{\sum_l [(N_{s,l,t}+O_{s,l,t})e^{-y_cM_l} - C_{s,t}P_{c,t}(\hat{P}_{s,n,l,t}+\hat{P}_{s,o,l,t})]e^{-(y_{st}-y_c)M_l}S_{st,l}}$$

Winter pot survey

Winter pot survey length compositions for newshell and oldshell crab, $P_{sw,n,l,t}$ and $P_{sw,o,l,t}$ ($l \geq 1$) were calculated as

$$\hat{P}_{sw,n,l,t} = N_{w,l,t}S_{w,l} / \sum_l [(N_{w,l,t}+O_{w,l,t})S_{w,l}] \qquad (27)$$
$$\hat{P}_{sw,o,l,t} = O_{w,l,t}S_{w,l} / \sum_l [(N_{w,l,t}+O_{w,l,t})S_{w,l}]$$

Estimates of tag recovery

The proportion of released tagged length class *l'* crab recovered after *t-th* year with length class of *l* by a fishery of *s-th* selectivity (S_l) was assumed proportional to the growth matrix, catch selectivity, and molting probability (m_l) as

$$\hat{P}_{l',l,t,s} = \frac{S_l \cdot [X^t]_{l',l}}{\sum_{l=1}^{n} S_l \cdot [X^t]_{l',l}} \tag{28}$$

where *X* is a molting probability adjusted growth matrix with each component consisting of

$$X_{l',l} = \begin{cases} m_{l'} \cdot G_{l',l} & \text{when } l' \neq l \\ m_l \cdot G_{l',l} + (1\text{-}m_i) & \text{when } l' = l \end{cases} \tag{29}$$

b. Software used: AD Model Builder (Fournier et al. 2012).

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:

$$\begin{aligned} &\sum_{i=1}^{i=4}\sum_{t=1}^{t=n_i} K_{i,t}\left[\sum_{l=1}^{l=n} P_{i,l,t}\ln(\hat{P}_{i,l,t}+\kappa) - \sum_{l=1}^{l=n} P_{i,l,t}\ln(P_{i,l,t}+\kappa)\right] \\ &-\sum_{t=1}^{t=n_i}\frac{[\ln(q\cdot\hat{B}_{i,t}+\kappa) - \ln(B_{i,t}+\kappa)]^2}{2\cdot ln(CV_{i,t}^2+1)} \\ &-\sum_{t=1}^{t=n_i}\left[\frac{\ln\left[\ln(CV_t^2+1)+w_t\right]}{2} + \frac{[\ln(\hat{f}_t+\kappa) - \ln(f_t+\kappa)]^2}{2\cdot\left[\ln(CV_t^2+1)+w_t\right]}\right] \\ &-\sum_{t=1}\frac{\tau_t^2}{2\cdot SDR^2} \\ &+W\sum_{s=1}^{s=2}\sum_{t=1}^{t=3}\sum_{l'=1}^{l'=n} K_{l',t,s}\left[\sum_{l=1}^{l=n} P_{l',l,t}\ln(\hat{P}_{l',l,t,s}+\kappa) - \sum_{l=1}^{l=n} P_{l',l,t}\ln(P_{l',l,t,s}+\kappa)\right] \end{aligned} \tag{30}$$

where

i: length/shell compositions of :

1 triennial summer trawl survey,
2 annual winter pot survey,
3 summer commercial fishery,
4 observer discards during the summer fishery.

n_i: the number of years in which data set *i* is available,

$K_{i,t}$: 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 0.0001,
CV : coefficient of variation for the survey abundance,
$B_{i,k,t}$: observed and estimated annual total abundances for data set *i* and year *t*,
f_t : observed and estimated summer fishing CPUE,
w^2_t: extra variance factor,
SDR_w : Standard deviation of winter survey CPUE = 0.3,
SDR : Standard deviation of recruitment = 0.5,
$K_{l',t}$: the effective sample size of length class *l'* released and recovered after *t-th* in year,
$K_{l',t}$: the effective sample size of length class *l'* released and recovered after *t-th* in year,
$P_{l',l,t,s}$: observed and estimated proportion of tagged crab released at length *l'* and recaptured at length *l*, after *t-th* year by commercial fishy pot selectivity *s*,
s: fishery selectivity (1) 1976-1992, (2) 1993- present,
W: weighting for the tagging survey likelihood

It is generally believed that total annual commercial crab catches in Alaska are fairly accurately reported. Thus, total annual catch was assumed known.

d. 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.

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

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

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 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.

Proportions of legal males (CW > 4.75 inches) by length group were estimated from the ADF&G trawl data 1996-2011 (Table 11).

ii. Parameters Estimated Conditionally

Estimated parameters are listed in Table 10. Selectivity and molting probabilities based on these estimated parameters are summarized in Tables 11.

A likelihood approach was used to estimate parameters

e. Definition of model outputs.

i. Estimate of mature male biomass (MMB) is on **February 1st** and is consisting of the biomass of male crab in length classes 3 to 6

$$MMB = \sum_{l=3} (N_{s,l,} + O_{s,l,}) wm_l$$

wm$_l$: mean weight of each length class (Table 11).

ii. Projected legal male biomass for winter and summer fishery OFL was calculated as

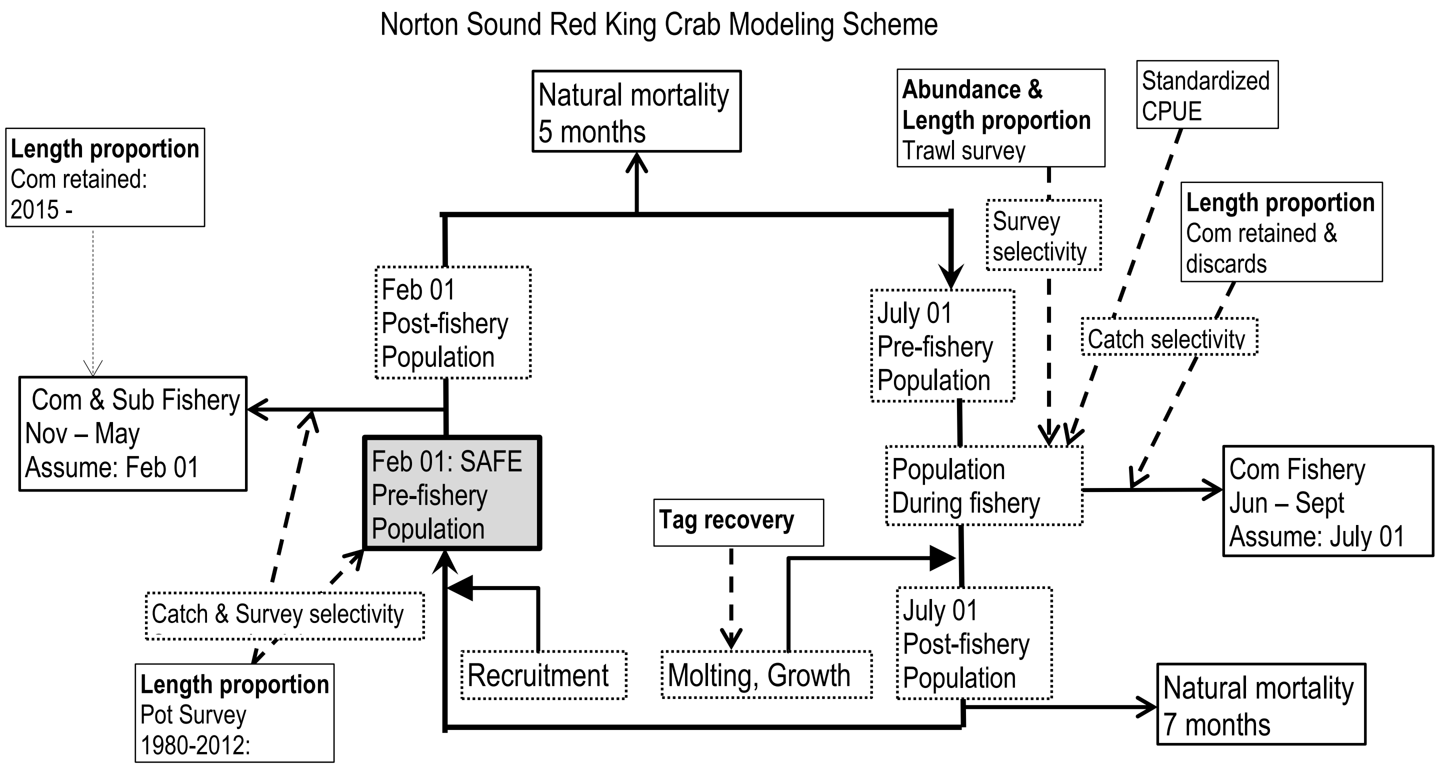
$$Legal\_B = \sum_{l} (N_{s,l,} + O_{s,l,}) S_{s,l} L_l wm_l$$

iii. Recruitment: the number of males in length classes 1 and 2.

Appendix A1. 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 male length classes with model parameters estimated by the maximum likelihood method. The model estimates abundances of crab with CL ≥74 mm and with 10-mm length intervals (6 length classes) because few crab measuring less than 74 mm CL were caught during surveys or fisheries and there were relatively small sample sizes for trawl and winter pot surveys. The model treats newshell and oldshell male crab separately but assumes they have the same molting probability and natural mortality.



Timeline of calendar events and crab modeling events:

- **Model year starts February 1st to January 31st of the following year.**
- **All winter fishery harvest occurs on February 1st**
- **Molting and recruitment occur on July 1st**
- **Initial Population Date: February 1st 1976**

Initial pre-fishery summer crab abundance on February 1st 1976

Abundance of the initial pre-fishery population was assumed consist of newshell crab to reduce the number of parameters, and estimated as

$$N_{l,1} = p_l e^{\log\_N_{76}} \qquad (1)$$

where, length proportion of the first year (p_l)was calculated as

$$p_l = \frac{\exp(a_l)}{1+\sum_{l=1}^{n-1}\exp(a_l)} \text{ for } l = 1,..,n\text{-}1$$
$$p_n = 1 - \frac{\sum_{l=1}^{n-1}\exp(a_l)}{1+\sum_{l=1}^{n-1}\exp(a_l)} \qquad (2)$$

for model estimated parameters a_l.

Crab abundance on July 1st

Summer (01 July) crab abundance of new and oldshells consists of survivors of winter commercial and subsistence crab fisheries and natural mortality from 01Feb to 01July:

$$N_{s,l,t} = (N_{w,l,t-1} - C_{w,t-1}P_{w,n,l,t-1} - C_{p,t}P_{p,n,l,t-1} - D_{w,n,l,t-1} - D_{p,n,l,t-1})e^{-0.42M_l}$$
$$O_{s,l,t} = (O_{w,l,t-1} - C_{w,t-1}P_{w,o,l,t-1} - C_{p,t}P_{p,o,l,t-1} - D_{w,o,l,t-1} - D_{p,o,l,t-1})e^{-0.42M_l} \qquad (3)$$

where

$N_{s,l,t}$, $O_{s,l,t}$: summer abundances of newshell and oldshell crab in length class *l* in year *t* ,
$N_{w,l,t-1}$, $O_{w,l,t-1}$: winter abundances of newshell and oldshell crab in length class *l* in year *t-1* ,
$C_{w,t-1}$, $C_{p,t-1}$: total winter commercial and subsistence catches in year *t-1*,
$P_{w,n,l,t-1}$, $P_{w,o,l,t-1}$: Proportion of newshell and oldshell length class *l* crab in year *t-1*, harvested by winter commercial fishery,
$P_{p,n,l,t-1}$, $P_{p,o,l,t-1}$: Proportion of newshell and oldshell length class *l* crab in year *t-1*, harvested by winter subsistence fishery,
$D_{w,n,l,t-1}$, $D_{w,o,l,t-1}$: Discard mortality of newshell and oldshell length class *l* crab in winter commercial fishery in year *t-1* ,

$D_{p,n,l,t-1}$, $D_{p,o,l,t-1}$: Discard mortality of newshell and oldshell length class l crab in winter subsistence fishery in year $t-1$,
M_l : instantaneous natural mortality in length class l,
0.42 : proportion of the year from Feb 1 to July 1 is 5 months.

Length proportion compositions of winter commercial catch ($P_{w,n,l,t}$, $P_{w,o,l,t}$) in year t were estimated as:

$$P_{w,n,l,t} = N_{w,l,t} S_{w,l} L_l / \sum_{l=1} [(N_{w,l,t} + O_{w,l,t}) S_{w,l} L_l]$$
$$P_{w,o,l,t} = O_{w,l,t} S_{w,l} L_l / \sum_{l=1} [(N_{w,l,t} + O_{w,l,t}) S_{w,l} L_l] \qquad (4)$$

where
L_l : the proportion of legal males in length class l ,
$S_{w,l}$: Selectivity of winter fishery pot.

The subsistence fishery does not have a size limit; however, crab of size smaller than length class 3 are generally not retained. Hence, we assumed proportion of length composition l = 1 and 2 as 0, and estimated length compositions ($l \geq 3$) as follows

$$P_{p,n,l,t} = N_{w,l,t} S_{w,l} / \sum_{l=3} [(N_{w,l,t} + O_{w,l,t}) S_{w,l}]$$
$$P_{p,o,l,t} = O_{w,l,t} S_{w,l} / \sum_{l=3} [(N_{w,l,t} + O_{w,l,t}) S_{w,l}] \qquad (5)$$

Crab abundance on Feb 1st

Newshell Crab: Abundance of newshell crab of year t and length-class l ($N_{w,l,t}$) year-t consist of: (1) new and oldshell crab that survived the summer commercial fishery and molted, and (2) recruitment ($R_{l,t}$) .

$$N_{w,l,t} = \sum_{l'=1}^{l'=l} G_{l',l} [(N_{s,l',t-1} + O_{s,l',t-1}) e^{-y_c M_l} - C_{s,t} (P_{s,n,l',t-1} + P_{s,o,l',t-1}) - D_{l',t-1}] m_{l'} e^{-(0.58-y_c) M_l} + R_{l,t} \qquad (6)$$

Oldshell Crab: Abundance of oldshell crabs of year t and length-class l ($O_{w,l,t}$) consists of the non-molting portion of survivors from the summer fishery:

$$O_{w,l,t} = [(N_{s,l,t-1} + O_{s,l,t-1}) e^{-y_c M_l} - C_{s,t} (P_{s,n,l,t-1} + P_{s,o,l,t-1}) - D_{l,t-1}] (1 - m_l) e^{-(0.58-y_c) M_l} \qquad (7)$$

where

$G_{l',l}$: a growth matrix representing the expected proportion of crabs growing from length class l' to length class l
$C_{s,t}$: total summer catch in year t
$P_{s,n,l,t}$, $P_{s,o,l,t}$: proportion of summer catch for newshell and oldshell crabs of length class l in year t,
$D_{l,t}$: summer discard mortality of length class l in year t,
m_l : molting probability of length class l,
y_c : the time in year from July 1 to the mid-point of the summer fishery,
0.58: Proportion of the year from July 1st to Feb 1st is 7 months is 0.58 year,
$R_{l,t}$: recruitment into length class l in year t.

Discards

Discards are crabs that were caught by fisheries but were not retained, which consists of summer commercial, winter commercial, and winter subsistence.

Summer and Winter commercial Discards

In summer ($D_{l,t}$) and winter ($D_{w,n,l,t}$, $D_{w,o,l,t}$) commercial fisheries, sublegal males (<4.75 inch CW and <5.0 inch CW since 2005) are discarded. Those discarded crabs are subject to handling mortality. The number of discards was not directly observed, and thus was estimated from the model as: Observed Catch x (estimated abundance of crab that are not caught by commercial pot)/(estimated abundance of crab that are caught by commercial pot)

Model discard mortality in length-class l in year t from the summer and winter commercial pot fisheries is given by

$$D_{l,t} = C_{s,t} \frac{(N_{s,l,t} + O_{s,l,t}) S_{s,l} (1 - L_l)}{\sum_l (N_{s,l,t} + O_{s,l,t}) S_{s,l} L_l} hm_s \tag{8}$$

$$D_{w,n,l,t} = C_{w,t} \frac{N_{w,l,t} S_{w,l} (1 - L_l)}{\sum_l (N_{w,l,t} + O_{w,l,t}) S_{w,l} L_l} hm_w \tag{9}$$

$$D_{w,o,l,t} = C_{w,t} \frac{O_{w,l,t} S_{w,l} (1 - L_l)}{\sum_l (N_{w,l,t} + O_{w,l,t}) S_{w,l} L_l} hm_w \tag{10}$$

where

hm_s: summer commercial handling mortality rate assumed to be 0.2,
hm_w: winter commercial handling mortality rate assumed to be 0.2,
$S_{s,l}$: Selectivity of the summer commercial fishery,
$S_{w,l}$: Selectivity of the winter commercial fishery,

Winter subsistence Discards

Discards of winter subsistence fishery is reported in a permit survey ($C_{d,t}$), though its catch composition is unknown. We assumed that subsistence fishers discarded all crabs of length classes 1 -2.

$$D_{p,n,l,t} = C_{d,t} \frac{N_{w,l,t} S_{w,l}}{\sum_{l=1}^{2} (N_{w,l,t} + O_{w,l,t}) S_{w,l}} hm_w \tag{11}$$

$$D_{p,o,l,t} = C_{d,t} \frac{O_{w,l,t} S_{w,l}}{\sum_{l=1}^{2} (N_{w,l,t} + O_{w,l,t}) S_{w,l}} hm_w \tag{12}$$

$C_{d,t}$: Winter subsistence discards catch,

Recruitment

Recruitment of year *t*, R_t, is a stochastic process around the geometric mean, R_0:

$$R_t = R_0 e^{\tau_t}, \tau_t \sim N(0, \sigma_R^2) \tag{13}$$

R_t of the last year was assumed to be an average of previous 5 years: $R_t = (R_{t-1} + R_{t-2} + R_{t-3} + R_{t-4} + R_{t-5})/5$.

R_t was assumed to be newshell crab of immature (< 94mm) length classes 1 to *r*

$$R_{r,t} = p_r \, R_t \tag{14}$$

where *r* takes multinomial distribution, same as the equation (2)

Molting Probability

Molting probability for length class *l*, m_l, was fitted as a decreasing logistic function of length-class mid carapace length and constrained to equal 0.999 for the smallest length-class (L_1):

$$m_l = \frac{1}{1 + e^{(\alpha(L_1 - L) + \ln(1/0.001 - 1))}} \tag{15}$$

Trawl net and summer commercial pot selectivity

Trawl and summer commercial pot selectivity was assumed to be a logistic function of mid-length-class, constrained to be 0.999 at the largest length-class (L_{max}):

$$S_l = \frac{1}{1 + e^{(\phi(L_{\max} - L) + \ln(1/0.999 - 1))}} \tag{16}$$

Winter pot selectivity

Winter pot selectivity was assumed to be a dome shaped decreasing logistic function of mid-length-class, constrained to 0.999 at a small length-class (L_s):

$$S_{w,l} = \frac{1}{1 + e^{(\phi_w (L_1 - L) + \ln(1/0.001 - 1))}} \tag{17}$$

Selectivity of the smaller length classes $S_{w,s}$ were individually estimated.

Growth transition matrix

The growth matrix $G_{l',l}$ (the expected proportion of crab molting from length class l' to length class l) was assumed to be normally distributed

$$G_{l',l} = \begin{cases} \dfrac{\int_{lm_l - h}^{lm_l + h} N(L \mid \mu_{l'}, \sigma^2) dL}{\sum_{l=1}^{n} \int_{lm_l - h}^{lm_l + h} N(L \mid \mu_{l'}, \sigma^2) dL} & \text{when } l \geq l' \\ 0 & \text{when } l < l' \end{cases} \tag{18}$$

Where

$$N(x \mid \mu_{l'}, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(L - \mu_{l'})^2}{\sigma^2} \right)$$

$$lm_l = L_1 + st \cdot l$$

$$\mu_l = L_1 + \beta_0 + \beta_1 \cdot l$$

Observation model

Summer trawl survey abundance

Modeled trawl survey abundance of *t-th* year ($B_{st,t}$) is July 1st abundance subtracted by summer commercial fishery harvest occurring from the July 1st to the mid-point of summer trawl survey, multiplied by natural mortality occurring between mid-point of commercial fishery date and trawl survey date, and multiplied by trawl survey selectivity. For the first year (1976) trawl survey, the commercial fishery did not occur.

$$\hat{B}_{st,t} = \sum_{l}[(N_{s,l,t} + O_{s,l,t})e^{-y_c M_l} - C_{s,t} P_{c,t}(P_{s,n,l,t} + P_{s,o,l,t})]e^{-(y_{st} - y_c)M_l} S_{st,l} \qquad (19)$$

where
y_{st} : the time in year from July 1 to the mid-point of the summer trawl survey,
y_c: the time in year from July 1 to the mid-point for the catch before the survey, ($y_{st} > y_c$: Trawl survey starts after opening of commercial fisheries),
$P_{c,t}$: proportion of summer commercial crab harvested before the mid-point of trawl survey date.

Winter pot survey CPUE

Winter pot survey cpue (f_{wt}) was calculated with catchability coefficient q and exploitable abundance

$$\hat{f}_{wt} = q_w \sum_{l}[(N_{w,l,t} + O_{w,l,t})S_{w,l}] \qquad (20)$$

Summer commercial CPUE

Summer commercial fishing CPUE (f_t) was calculated as a product of catchability coefficient q and mean exploitable abundance minus one half of summer catch, A_t.

$$\hat{f}_t = q_i(A_t - 0.5C_t) \qquad (21)$$

Because fishing fleet and pot limit configuration changed in 1993, q_1 is for fishing efforts before 1993, q_2 is from 1994 to present.

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

$$A_t = \sum_{l}[(N_{s,l,t} + O_{s,l,t})S_{s,l} L_l] \qquad (22)$$

Summer pot survey abundance (Removed from likelihood components)
Abundance of *t*-th year pot survey was estimated as

$$\hat{B}_{p,t} = \sum_{l}[(N_{s,l,t} + O_{s,l,t})e^{-y_p M_l}]S_{p,l} \qquad (23)$$

Where

y_p : the time in year from July 1 to the mid-point of the summer pot survey.
Length composition

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 modeled based on the summer population, selectivity, and legal abundance:

$$\hat{P}_{s,n,l,t} = N_{s,l,t} S_{s,l} L_l / A_t$$
$$\hat{P}_{s,o,l,t} = O_{s,l,t} S_{s,l} L_l / A_t \qquad (24)$$

Summer commercial fishery discards

Length/shell compositions of observer discards were modeled as

$$\hat{P}_{b,n,l,t} = N_{s,l,t} S_{s,l} (1 - L_l) / \sum_l [(N_{s,l,t} + O_{s,l,t}) S_{s,l} (1 - L_l)]$$
$$\hat{P}_{b,o,l,t} = O_{s,l,t} S_{s,l} (1 - L_l) / \sum_l [(N_{s,l,t} + O_{s,l,t}) S_{s,l} (1 - L_l)] \qquad (25)$$

Summer trawl survey

Proportions of newshell and oldshell crab, $P_{st,n,l,t}$ and $P_{st,o,l,t}$ were given by

$$\hat{P}_{st,n,l,t} = \frac{[N_{s,l,t} e^{-y_c M_l} - C_{s,t} P_{c,t} \hat{P}_{s,n,l',t}] e^{-(y_{st} - y_c) M_l} S_{st,l}}{\sum_l [(N_{s,l,t} + O_{s,l,t}) e^{-y_c M_l} - C_{s,t} P_{c,t} (\hat{P}_{s,n,l',t} + \hat{P}_{s,o,l',t})] e^{-(y_{st} - y_c) M_l} S_{st,l}}$$
$$\hat{P}_{st,o,l,t} = \frac{[O_{s,l,t} e^{-y_c M_l} - C_{s,t} \hat{P}_{s,o,l',t} P_{c,t}] e^{-(y_{st} - y_c) M_l} S_{st,l}}{\sum_l [(N_{s,l,t} + O_{s,l,t}) e^{-y_c M_l} - C_{s,t} P_{c,t} (\hat{P}_{s,n,l,t} + \hat{P}_{s,o,l,t})] e^{-(y_{st} - y_c) M_l} S_{st,l}} \qquad (26)$$

Winter pot survey

Winter pot survey length compositions for newshell and oldshell crab, $P_{sw,n,l,t}$ and $P_{sw,o,l,t}$ ($l \geq 1$) were calculated as

$$\hat{P}_{sw,n,l,t} = N_{w,l,t} S_{w,l} / \sum_l [(N_{w,l,t} + O_{w,l,t}) S_{w,l}]$$
$$\hat{P}_{sw,o,l,t} = O_{w,l,t} S_{w,l} / \sum_l [(N_{w,l,t} + O_{w,l,t}) S_{w,l}] \qquad (27)$$

Estimates of tag recovery

The proportion of released tagged length class *l'* crab recovered after *t-th* year with length class of *l* by a fishery of *s-th* selectivity (S_l) was assumed proportional to the growth matrix, catch selectivity, and molting probability (m_l) as

$$\hat{P}_{l',l,t,s} = \frac{S_l \cdot [X^t]_{l',l}}{\sum_{l=1}^{n} S_l \cdot [X^t]_{l',l}} \tag{28}$$

where X is a molting probability adjusted growth matrix with each component consisting of

$$X_{l',l} = \begin{cases} m_{l'} \cdot G_{l',l} & \text{when } l' \neq l \\ m_l \cdot G_{l',l} + (1\text{-}m_i) & \text{when } l' = l \end{cases} \tag{29}$$

b. Software used: AD Model Builder (Fournier et al. 2012).

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:

$$\begin{aligned}
&\sum_{i=1}^{i=4}\sum_{t=1}^{t=n_i} K_{i,t}\left[\sum_{l=1}^{l=n} P_{i,l,t}\ln(\hat{P}_{i,l,t}+\kappa) - \sum_{l=1}^{l=n} P_{i,l,t}\ln(P_{i,l,t}+\kappa)\right] \\
&-\sum_{t=1}^{t=n_i}\frac{[\ln(q\cdot\hat{B}_{i,t}+\kappa) - \ln(B_{i,t}+\kappa)]^2}{2\cdot \ln(CV_{i,t}^2+1)} \\
&-\sum_{t=1}^{t=n_i}\left[\frac{\ln\left[\ln(CV_t^2+1)+w_t\right]}{2} + \frac{[\ln(\hat{f}_t+\kappa) - \ln(f_t+\kappa)]^2}{2\cdot\left[\ln(CV_t^2+1)+w_t\right]}\right] \\
&-\sum_{t=1}\frac{\tau_t^2}{2\cdot SDR^2} \\
&+W\sum_{s=1}^{s=2}\sum_{t=1}^{t=3}\sum_{l'=1}^{l'=n} K_{l',t,s}\left[\sum_{l=1}^{l=n} P_{l',l,t}\ln(\hat{P}_{l',l,t,s}+\kappa) - \sum_{l=1}^{l=n} P_{l',l,t}\ln(P_{l',l,t,s}+\kappa)\right]
\end{aligned} \tag{30}$$

where

i: length/shell compositions of :

1 triennial summer trawl survey,

2 annual winter pot survey,

3 summer commercial fishery,

4 observer discards during the summer fishery.

n_i: the number of years in which data set *i* is available,

$K_{i,t}$: 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 0.0001,
CV : coefficient of variation for the survey abundance,
$B_{i,k,t}$: observed and estimated annual total abundances for data set *i* and year *t*,
f_t : observed and estimated summer fishing CPUE,
w^2_t: extra variance factor,
SDR_w : Standard deviation of winter survey CPUE = 0.3,
SDR : Standard deviation of recruitment = 0.5,
$K_{l',t}$: the effective sample size of length class *l'* released and recovered after *t-th* in year,
$K_{l',t}$: the effective sample size of length class *l'* released and recovered after *t-th* in year,
$P_{l',l,t,s}$: observed and estimated proportion of tagged crab released at length *l'* and recaptured at length *l*, after *t-th* year by commercial fishy pot selectivity *s*,
s: fishery selectivity (1) 1976-1992, (2) 1993- present,
W: weighting for the tagging survey likelihood

It is generally believed that total annual commercial crab catches in Alaska are fairly accurately reported. Thus, total annual catch was assumed known.

d. 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.

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

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

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 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.

Proportions of legal males (CW > 4.75 inches) by length group were estimated from the ADF&G trawl data 1996-2011 (Table 11).

ii. Parameters Estimated Conditionally

Estimated parameters are listed in Table 10. Selectivity and molting probabilities based on these estimated parameters are summarized in Tables 11.

A likelihood approach was used to estimate parameters

e. Definition of model outputs.

i. Estimate of mature male biomass (MMB) is on **February 1st** and is consisting of the biomass of male crab in length classes 3 to 6

$$MMB = \sum_{l=3} (N_{s,l,} + O_{s,l,}) wm_l$$

wm_l: mean weight of each length class (Table 11).

ii. Projected legal male biomass for winter and summer fishery OFL was calculated as

$$Legal\_B = \sum_{l} (N_{s,l,} + O_{s,l,}) S_{s,l} L_l wm_l$$

iii. Recruitment: the number of males in length classes 1 and 2.

Appendix A2

Norton Sound Red King Crab CPUE Standardization

Note: This is an update of model by G. Bishop (SAFE 2013).

Methods

Data Source & Cleaning

Commercial fishery harvest data were obtained from a fish ticket database, which included: Landing Date, Fish Ticket Number, Vessel Number, Permit Fishery ID, Statistical Area(s) fished, Effort, and Number and Pounds of Crab harvested (Table A2-1,2,3, Figure A2-1). Fish ticket database may have multiple entries of identical Fish Ticket Number, Vessel Number, Permit Fishery ID, and Statistical Area. In those cases, at least one Effort data are missing or zero with the Number and Pounds of Crab harvested. These entries indicate that crabs were either retained from commercial fishery (i.e., not sold), or dead loss.

Following data cleaning and combining methods were conducted.

1. Sum crab number and efforts by Fish Ticket Number, Vessel Number, Permit Fishery ID, Statistical Area
2. Remove data of missing or zero Efforts, Number of Crab, Pounds of Crab (Those are considered as true missing data)
3. Calculate CPUE as Number of Crab/Effort

The data were separated into two periods: 1977-1992 and 1993-2016. The two periods represents before and after super exclusive status enacted since 1993.

Data Censoring

We first investigated distribution of fishing vessels by frequency of deliveries and years of operation (Table A2-4, 5). The number of vessels operated ranged from 2 (1988) to 48 (1995). None of vessels operated consecutively from 1977 to 2015, and many vessels operated only 1 year.

During 1977-92 period, vessels of 1 year of operation and/or 1 delivery per year harvested 20-90% of crabs (Table A2-5, Figure A2-2). For instance, all vessels did only 1 delivery in 1989, and in 1988 64% of crabs were harvested by 1 vessel that did only 1 delivery. On the other hand, during the 1993-2016 period of post super-exclusive fishery status, the majority of commercial crab fishery and harvest was done by vessels with more than 5 years of operations and more than 5 deliveries per year. For 1977 – 1992, censoring was made for vessels of more than 2 years of operations. Increasing deliveries to more than one would result in no estimates for some years. Further increasing years of operation would also limit the number of vessel to only 1 or 2. For 1993 – 2016, censoring was made for vessels of more than 5 years of operations and 5 deliveries per year.

Analyses

A GLM was constructed as

$$\ln(CPUE) = YR + VSL + MSA + WOY + PF$$

Where YR: Year, VSL: Vessel, MSA: Modified Statistical Area, WOY: Week of Year, PF: Week of Year (Table 1). All variables were treated as categorical. Inclusion of interaction terms were not considered because they were absent (SAFE 2013).

For selection of the best model, forward and backward stepwise selection was conducted. (R step function)

```
fit <- glm(L.CPUE.NO ~ factor(YR) + factor(VSL) + factor(WOY) + factor(MSA) +
factor(PF),data=NSdata.C)
step <- step(fit, direction='both', trace = 10)
best.glm<-glm(formula(step), data=NSdata.C)
```

The analyses were conducted for both censored and full data.

Results

Of the five variables included, the final model included four variables for 1977-1992, and all variables remained for 1993-2015 (Tables A2-6).

Norton Sound red king crab CPUE standardization

Model estimated standardized and observed CPUYE differed for 1977-1980 period, but similar for 1981 to 2015 (Figure A2-3, Tables A2-7,8). During 1977-1980 period, censored data model showed decline in 1978 and increase in 1979-1980, full data model showed steady decline from 1977 to 1980, and observed CPUE showed a peak in 1978 (Figure A2-3, Tables A2-7,8). Other notable difference was in 1989 when model estimated CPUE showed an increase while the observed CPUE showed a decline.

Table A2-1. List of variables in the fish ticket database. Variables in bold face were used for generalized linear modeling.

Variable	Description
YR	Year of commercial fishery
VSL	Unique vessel identification number
Fish Ticket Number	Unique delivery to a processor by a vessel.
PF	Unique Permit Fishery categories
Statistical Area	Unique fishery area.
MOA	Modified statistical area, combining each statistical area into 4 larger areas: Inner, Mid, Outer, Outer North
Fishing beginning date	Date of pots set
Landing date	Date of crab landed to processor
WOY	Week of Landing Date **(calculated)**
Effort	The number of pot lift
Crab Numbers	Total number of crabs harvested from pots
Crab Pounds	Total pounds of crab harvested from pots
ln(CPUE)	ln(Crab Numbers/Effort) **(calculated)**

Table A2-2. Permit fisheries, descriptions, and years with deliveries for Norton Sound summer commercial red king crab harvest data.

Permit fishery	Type	Description	Years
K09Q	Open access	KING CRAB , POT GEAR VESSEL UNDER 60', BERING SEA	1994–2002
K09Z	Open access	KING CRAB , POT GEAR VESSEL UNDER 60', NORTON SOUND	1992–2015
K09ZE	CDQ	KING CRAB , POT GEAR VESSEL UNDER 60', NORTON SOUND CDQ, NSEDC	2000–2015
K09ZF	CDQ	KING CRAB , POT GEAR VESSEL UNDER 60', NORTON SOUND CDQ, YDFDA	2002–2004
K91Q	Open access	KING CRAB , POT GEAR VESSEL 60' OR OVER, BERING SEA	1978–1989
K91Z	Open access	KING CRAB , POT GEAR VESSEL 60' OR OVER, NORTON SOUND	1982–1994

Appendix A2-3. Modified statistical area definitions used for analysis of Norton Sound summer commercial red king crab harvest data.

Modified statistical area	**Statistical areas included**
Inner	616331, 616401, 626331, 626401, 626402
Mid	636330, 636401, 636402, 646301, 646330, 646401, 646402
Outer	656300, 656330, 656401, 656402, 666230, 666300, 666330, 666401
Outer North	666402, 666431, 676300, 676330 ,676400, 676430, 676501, 686330

Table A2-4. The number of vessels by the number of years operated and deliveries made per year.

Years	1					2					3					4					>5					Total
Deliveries	1	2	3	4	>5	1	2	3	4	>5	1	2	3	4	>5	1	2	3	4	>5	1	2	3	4	>5	
1977	4							1					1					1								7
1978	1					1	1			1		1		1	1					2				1		10
1979	6	6	1		1	4	3	1		1	2	2		1		1	1		1	1	1	1				34
1980		1	1		1			1		1										1		1				7
1981	2	1	8	3	3	2	4	2		1	1	1	2		1	1	1				1			1	1	36
1982	1	1	1	1				2						1					1		1			2		11
1983	8					6	1				3	1				1					2	1				23
1984	1		2			1							1						1				2			8
1985	1				1	1				1					1										1	6
1986						1															2					3
1987			5	1												1					2					9
1988	1						1																			2
1989	5					2										1					2					10
1990	2																				1	1				4
1992	10	1				6										2					1					20
1993	3				4			1							3					1					5	17
1994	1	2	3		2		1			1					7					4		3			11	35
1995		2			9	1				9					5			1		4			1	1	15	48
1996		1		1	4	2		2	1	4	2	2			3					3	3	2	1		10	41
1997					2				1						1					2	1		1		5	13
1998										1	1				1						1				4	8
1999					1						1		1			1					1		2		3	10
2000					1					1			1		1							1		1	9	15
2001			1		2					1					1				1	2			1	1	20	30
2002		2			1	1				1					2	1				1	1	3	2	1	16	32
2003							1																1		23	25
2004	1		1																	1			2	3	18	26
2005												1			1				1		1	1	1		24	30
2006	2												1		1					1			1		22	28
2007	2														2					1	2		3		20	30
2008						1														1	1			1	18	22
2009																		1					1		21	23
2010															1									1	21	23
2011														1							1				22	24
2012											1				1							1	1		25	29
2013											1									3					29	33
2014															2					3		1	2		25	33
2015			1				1							1	2					4				3	24	36
2016		1	1							1					2			2	1	2	1	2	1	2	20	36

Table A2-5. Proportion of red king crab harvest by the number of years operated and deliveries made per year.

Years	1					2					3					4					>5				
Deliveries	1	2	3	4	>5	1	2	3	4	>5	1	2	3	4	>5	1	2	3	4	>5	1	2	3	4	>5
1977	0.25	0	0	0	0	0	0	0.29	0	0	0	0	0.29	0	0	0	0	0.17	0	0	0	0	0	0	0
1978	0	0	0	0	0	0.04	0.04	0	0	0.2	0	0.08	0	0.15	0.09	0	0	0	0	0.26	0	0	0	0.13	0
1979	0.11	0.17	0.01	0	0.05	0.08	0.11	0.02	0	0.09	0.03	0.1	0	0.04	0	0.02	0.02	0	0.02	0.02	0.01	0.08	0	0	0
1980	0	0.04	0	0	0.19	0	0	0.24	0	0.19	0	0	0	0	0	0	0	0	0	0.13	0	0.2	0	0	0
1981	0.01	0.01	0.18	0.05	0.17	0.02	0.06	0.07	0	0.02	0	0.03	0.03	0	0.09	0.04	0.02	0	0	0	0.07	0	0	0.08	0.05
1982	0.01	0.04	0.03	0.03	0	0	0	0.07	0	0	0	0	0	0.06	0	0	0	0	0.04	0	0.32	0	0	0.4	0
1983	0.24	0	0	0	0	0.22	0.02	0	0	0	0.13	0.03	0	0	0	0.09	0	0	0	0	0.21	0.06	0	0	0
1984	0.01	0	0.11	0	0	0.19	0	0	0	0	0	0	0.08	0	0	0	0	0	0.17	0	0	0	0.44	0	0
1985	0.14	0	0	0	0.24	0.06	0	0	0	0.19	0	0	0	0	0.15	0	0	0	0	0	0	0	0	0	0.21
1986	0	0	0	0	0	0.07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.93	0	0	0	0
1987	0	0	0.25	0.09	0	0	0	0	0	0	0	0	0	0	0	0.24	0	0	0	0	0.41	0	0	0	0
1988	0.64	0	0	0	0	0	0.36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1989	0.54	0	0	0	0	0.08	0	0	0	0	0	0	0	0	0	0.11	0	0	0	0	0.27	0	0	0	0
1990	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.28	0.32	0	0	0
1992	0.51	0.17	0	0	0	0.21	0	0	0	0	0	0	0	0	0	0.02	0	0	0	0	0.09	0	0	0	0
1993	0.01	0	0	0	0.4	0	0	0.01	0	0	0	0	0	0	0.28	0	0	0	0	0	0	0	0	0	0.29
1994	0	0	0.01	0	0.1	0	0	0	0	0.01	0	0	0	0	0.31	0	0	0	0	0.12	0	0	0	0	0.45
1995	0	0	0	0	0.17	0	0	0	0	0.25	0	0	0	0	0.07	0	0	0	0	0.09	0	0	0	0	0.41
1996	0	0	0	0	0.1	0	0	0	0.02	0.26	0	0.01	0	0	0.2	0	0	0	0	0.06	0.01	0	0.01	0	0.33
1997	0	0	0	0	0.11	0	0	0	0.06	0	0	0	0	0	0.09	0	0	0	0	0.12	0.02	0	0.04	0	0.56
1998	0	0	0	0	0	0	0	0	0	0.09	0	0	0	0	0.08	0	0	0	0	0	0.01	0	0	0	0.82
1999	0	0	0	0	0.39	0	0	0	0	0	0	0	0.15	0	0	0.03	0	0	0	0	0	0	0.12	0	0.31
2000	0	0	0	0	0.1	0	0	0	0	0.02	0	0	0.01	0	0.1	0	0	0	0	0	0	0	0	0.01	0.77
2001	0	0	0.01	0	0.07	0	0	0	0	0.02	0	0	0	0	0.06	0	0	0	0.03	0.05	0	0	0.03	0	0.72
2002	0	0.01	0	0	0.05	0	0	0	0	0.07	0	0	0	0	0.04	0	0	0	0	0.04	0	0.04	0.02	0.01	0.72
2003	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
2004	0	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05	0	0	0.03	0.05	0.87
2005	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.02	0	0	0.02	0.02	0	0.93
2006	0.01	0	0	0	0	0	0	0	0	0	0	0	0.01	0	0	0	0	0	0	0.04	0	0	0.01	0	0.92
2007	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0.02	0	0	0	0	0.06	0.01	0	0.05	0	0.85
2008	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.06	0	0	0	0.01	0.93
2009	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0	0.99
2010	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0	0	0	0	0	0	0	0	0.01	0.98
2011	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.99
2012	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0	0	0	0.01	0	0	0.98
2013	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.07	0	0	0	0	0.02	0	0	0	0	0.91
2014	0	0	0	0	0	0	0	0	0	0.07	0	0	0	0	0.07	0	0	0	0	0.03	0	0	0.01	0	0.81
2015	0	0	0	0	0	0	0	0	0	0.08	0	0	0	0.01	0.07	0	0	0	0	0.04	0	0	0	0.05	0.75

Table A2-6. Final generalized linear model formulae and associated R^2 selected for Norton Sound summer commercial red king crab fishery. The dependent variable is ln(CPUE) in numbers.

Time series	Years	Deliveries	Explanatory variables	Null dev.	Null df	Resid. dev.	Resid. df	AIC	R^2
1977–1992	All	All	YR+VSL+WOY+MSA	1163.1	797	445.4	653	2091	0.68
	≥2	≥1	YR+VSL+WOY+MSA	703.7	483	379.9	420	1188	0.60
1993–2015	All	All	YR+VSL+WOY+MSA+PF	5608.4	6459	3230.3	6364	14332	0.51
	≥5	≥5	YR+VSL+WOY+MSA+PF	3531.2	4971	2291.7	4880	10445	0.47

Table A2-7. Standardized (Censored/full data), and scaled arithmetic observed CPUE indices from 1977–1992.

	Censored		**Full data**		**Observed**
Year	**CPUE**	**SE**	**CPUE**	**SE**	**CPUE**
1977	4.18	0.34	3.43	0.34	2.08
1978	2.21	0.23	2.83	0.23	3.73
1979	3.09	0.18	2.59	0.17	1.62
1980	3.03	0.26	2.43	0.25	1.80
1981	0.89	0.19	0.74	0.17	0.64
1982	0.11	0.25	0.13	0.25	0.33
1983	1.00	0.22	0.90	0.22	0.68
1984	0.94	0.23	1.09	0.23	0.83
1985	0.34	0.20	0.37	0.21	0.62
1986	0.76	0.41	1.00	0.43	2.20
1987	0.57	0.32	0.63	0.32	0.58
1988	1.44	0.67	1.51	0.71	1.88
1989	1.80	0.32	1.61	0.33	0.89
1990	1.13	0.40	1.18	0.42	1.10
1991	NA	NA	NA	NA	NA
1992	0.30	0.31	0.26	0.31	0.25

Table A2-8. Standardized (Censored/full data), and scaled arithmetic observed CPUE indices from 1993–2016.

	Censored		Full data		Observed
Year	**CPUE**	**SE**	**CPUE**	**SE**	**CPUE**
1993	0.90	0.10	0.90	0.08	1.38
1994	0.80	0.06	0.80	0.05	0.79
1995	0.43	0.05	0.48	0.05	0.48
1996	0.53	0.08	0.46	0.06	0.60
1997	0.83	0.10	0.83	0.08	0.92
1998	0.78	0.13	0.73	0.12	0.56
1999	0.92	0.13	0.77	0.12	0.45
2000	1.25	0.06	1.23	0.06	1.49
2001	0.65	0.05	0.69	0.05	0.70
2002	1.22	0.06	1.18	0.06	1.13
2003	0.86	0.05	0.87	0.05	0.93
2004	1.33	0.05	1.34	0.05	1.27
2005	1.23	0.05	1.26	0.05	1.33
2006	1.36	0.05	1.42	0.05	1.46
2007	1.06	0.05	1.13	0.05	1.02
2008	1.38	0.05	1.43	0.05	1.39
2009	0.88	0.04	0.90	0.04	1.02
2010	1.23	0.04	1.28	0.04	1.30
2011	1.59	0.05	1.61	0.05	1.75
2012	1.34	0.04	1.37	0.04	1.35
2013	0.66	0.04	0.68	0.04	0.73
2014	1.12	0.05	1.16	0.04	1.08
2015	1.53	0.05	1.55	0.05	1.48
2016	1.40	0.06	1.27	0.05	1.76

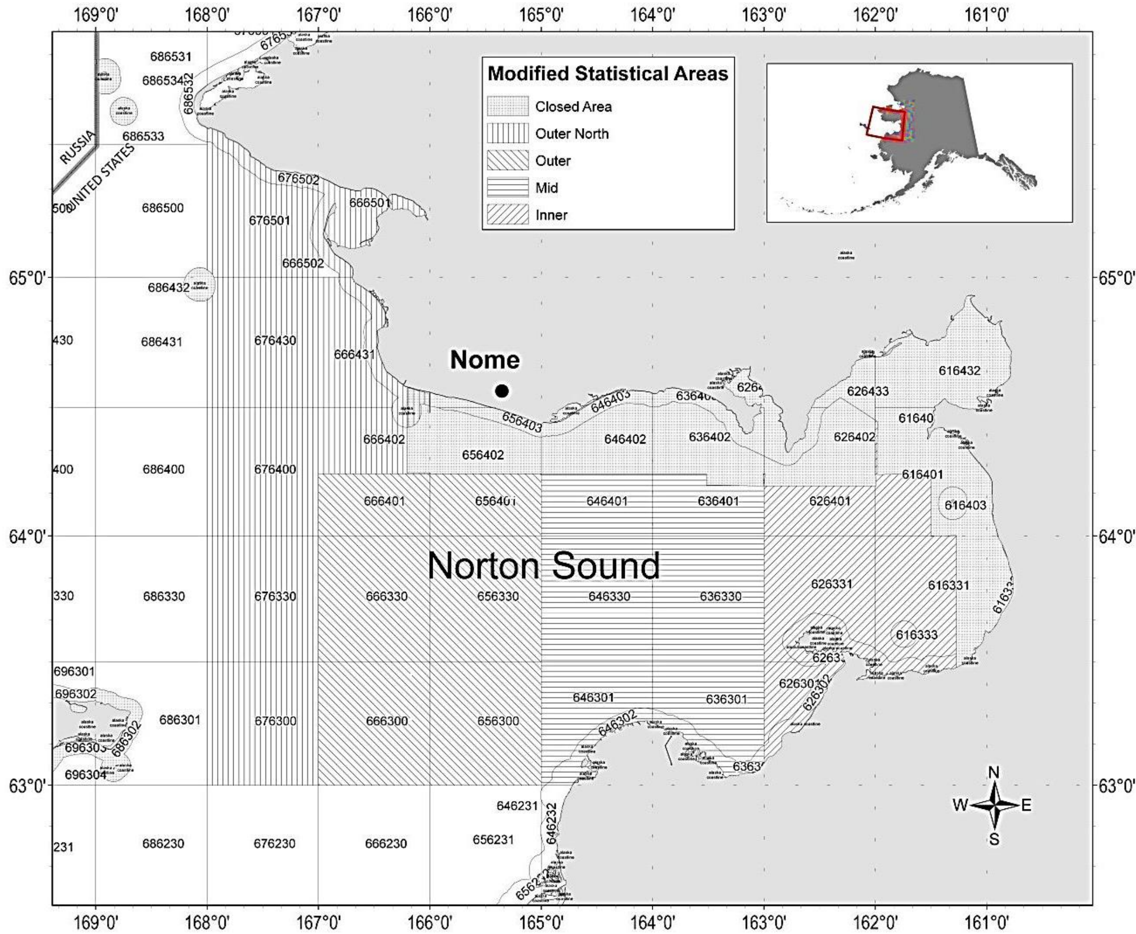
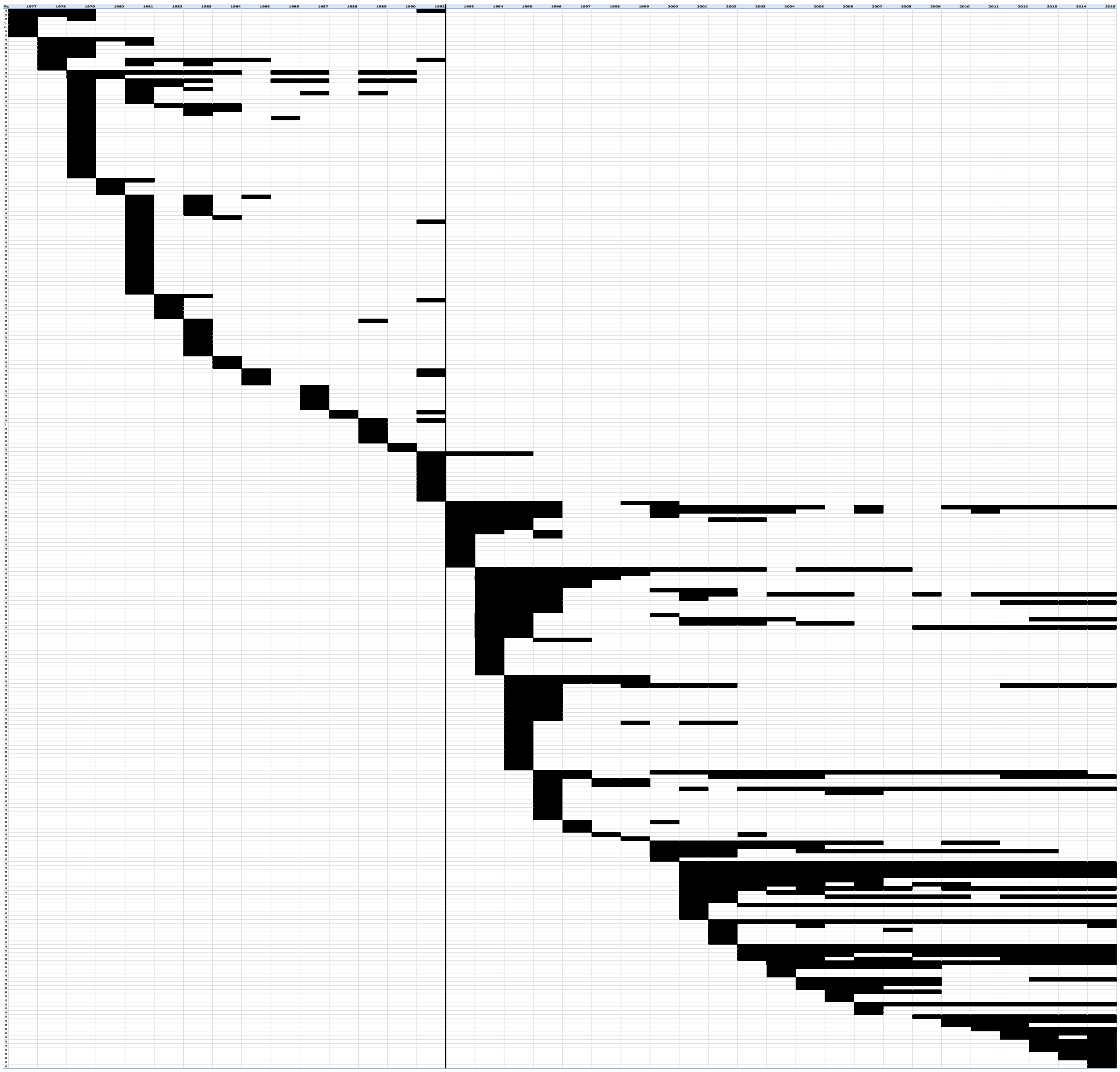


Figure A2-1. Closed area and statistical area boundaries used for reporting commercial harvest information for red king crab in Registration Area Q, Northern District, Norton Sound Section and boundaries of the new *Modified Statistical Areas* used in this analysis.

Figure A2-2. Distribution of unique vessel from 1976 (left) to 2015 (right). Each row indicates unique vessel, and each black represents the year vessel was operated. Vertical black line shows division between 1992 and 1993.



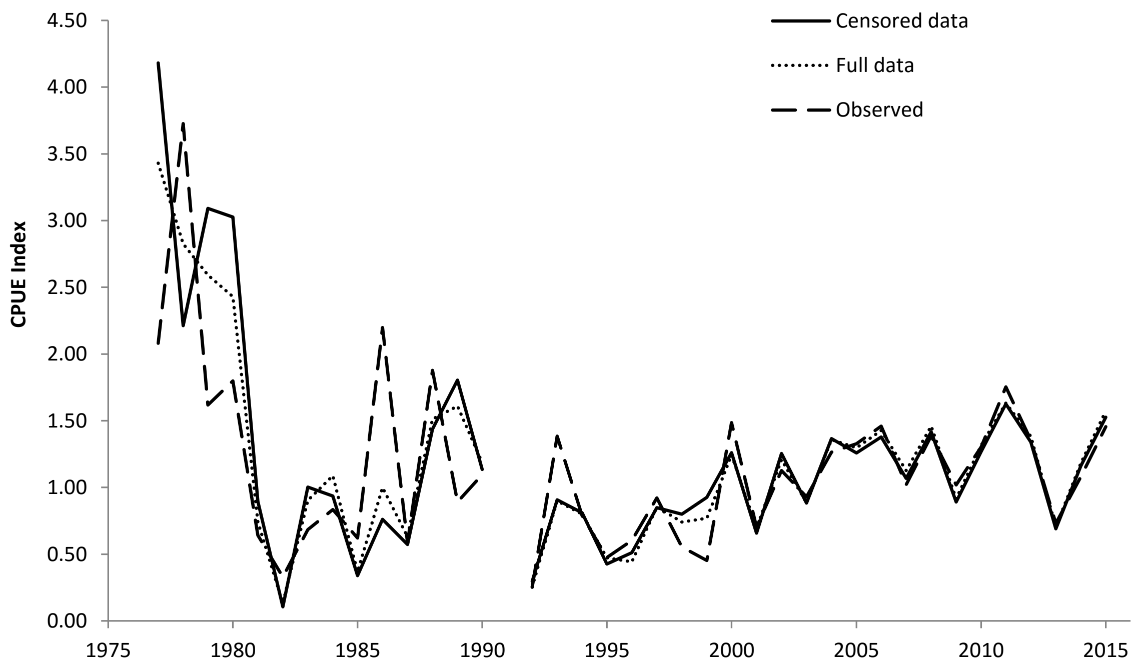


Figure A2-3. Comparison of CPUE among Observed, Standardized (censored data), and Standardized (full data) in 1977-2016.

Appendix C1: Results Model 0

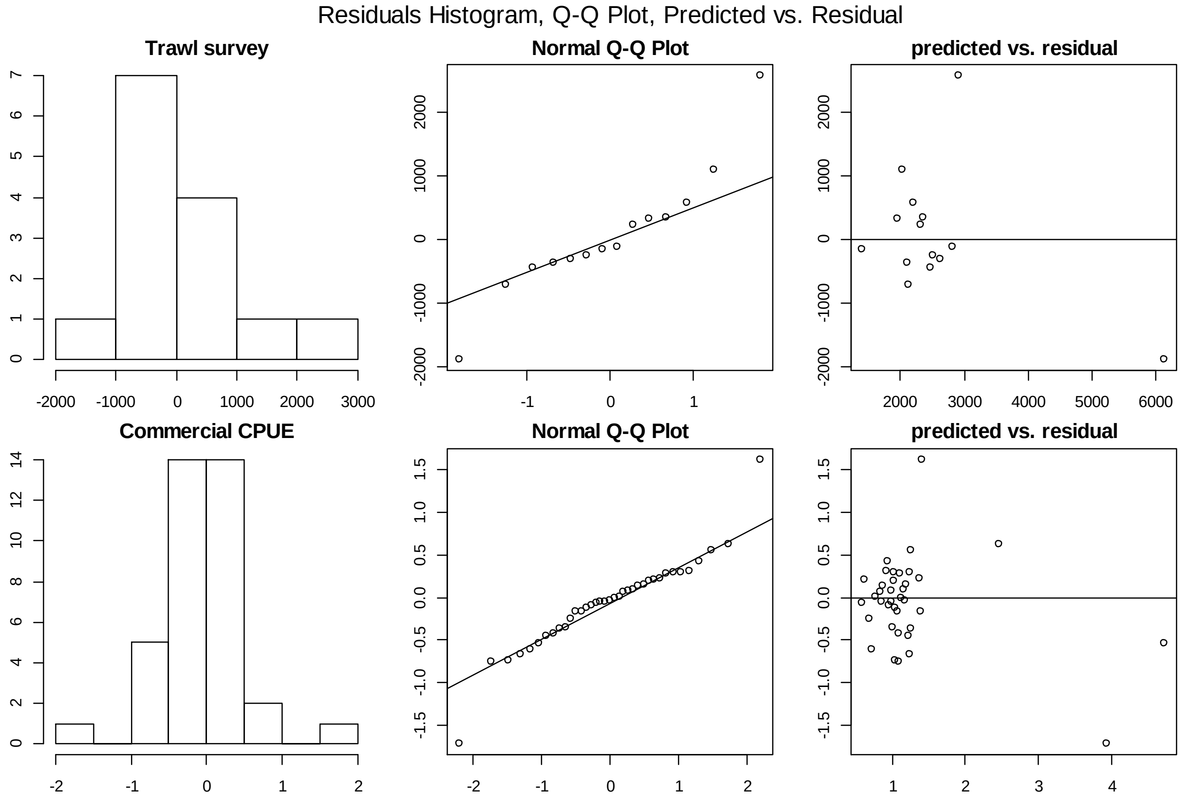


Figure C1-1. QQ Plot of Trawl survey and Commercial CPUE.

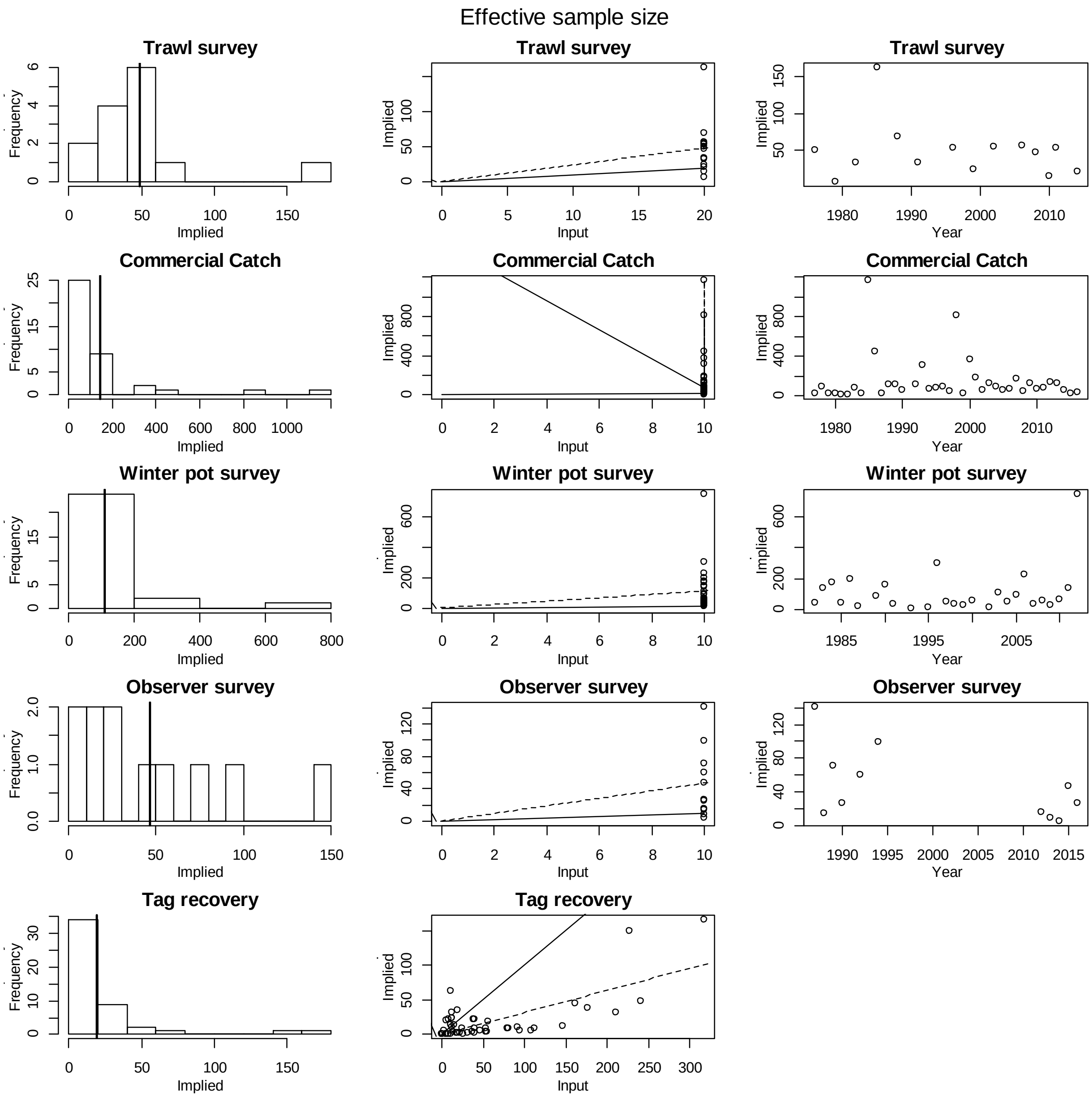


Figure C1-2: Implied effective samples. Figures in the first column show implied effective sample size (x-axis) vs. frequency (y-axis). Vertical solid line is the mean implied effective sample size. The second column show input sample size (x-axis) vs. implied effective sample size (y-axis). Dashed line indicates linear regression slope, and solid line is 1:1 line. The third column show year (x-axis) vs. implied effective sample size (y-axis).

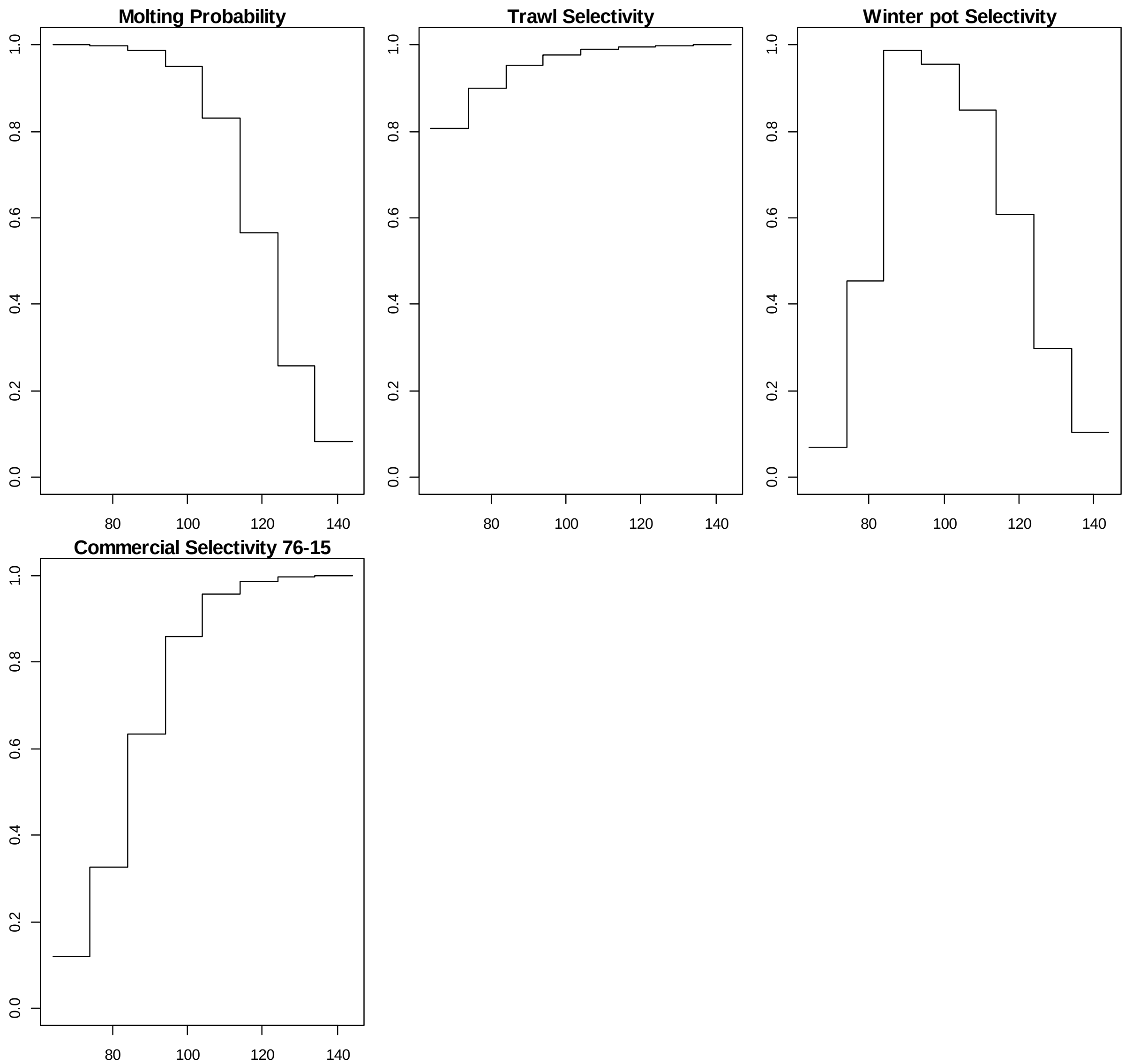


Figure C1-3. Annual Molting probability. X-axis is carapace length.

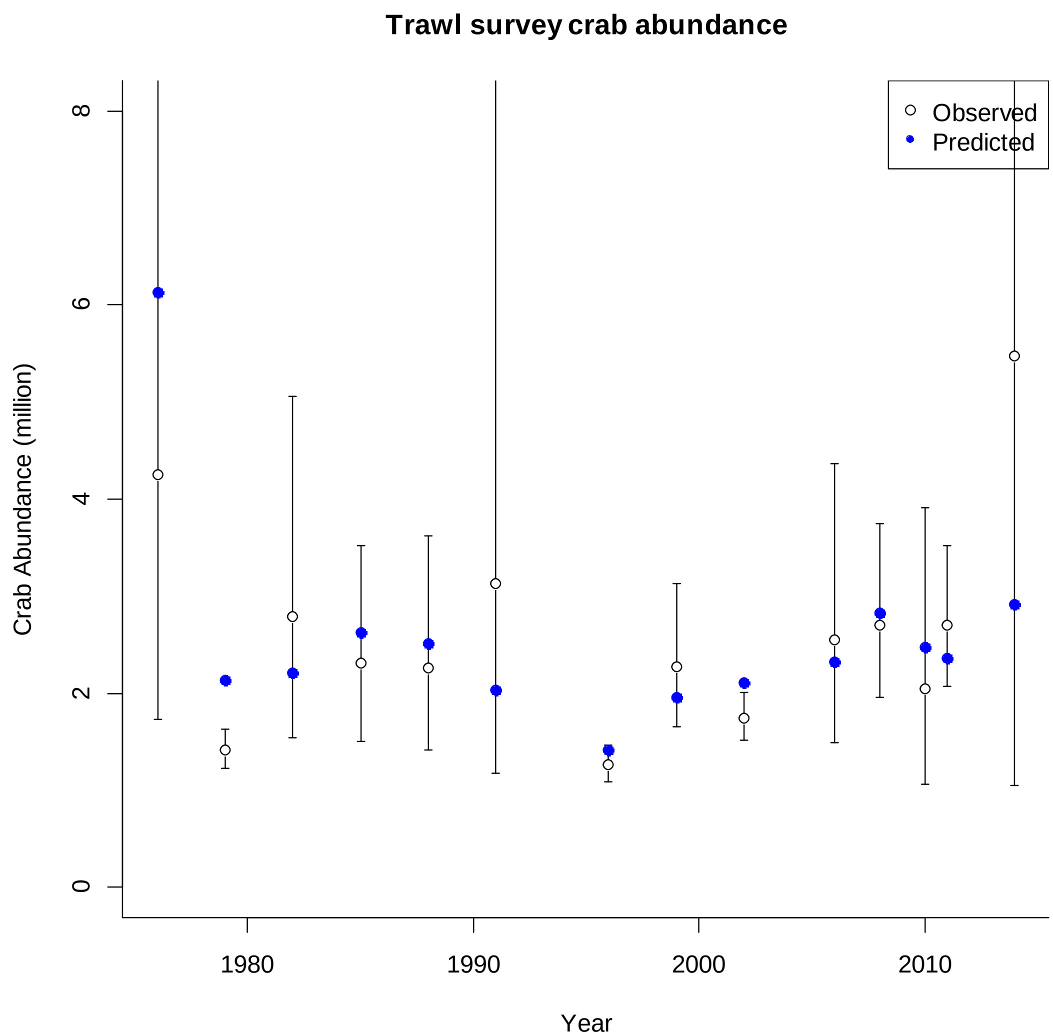


Figure C1-4. Estimated trawl survey male abundance (crab ≥ 74 mm CL).

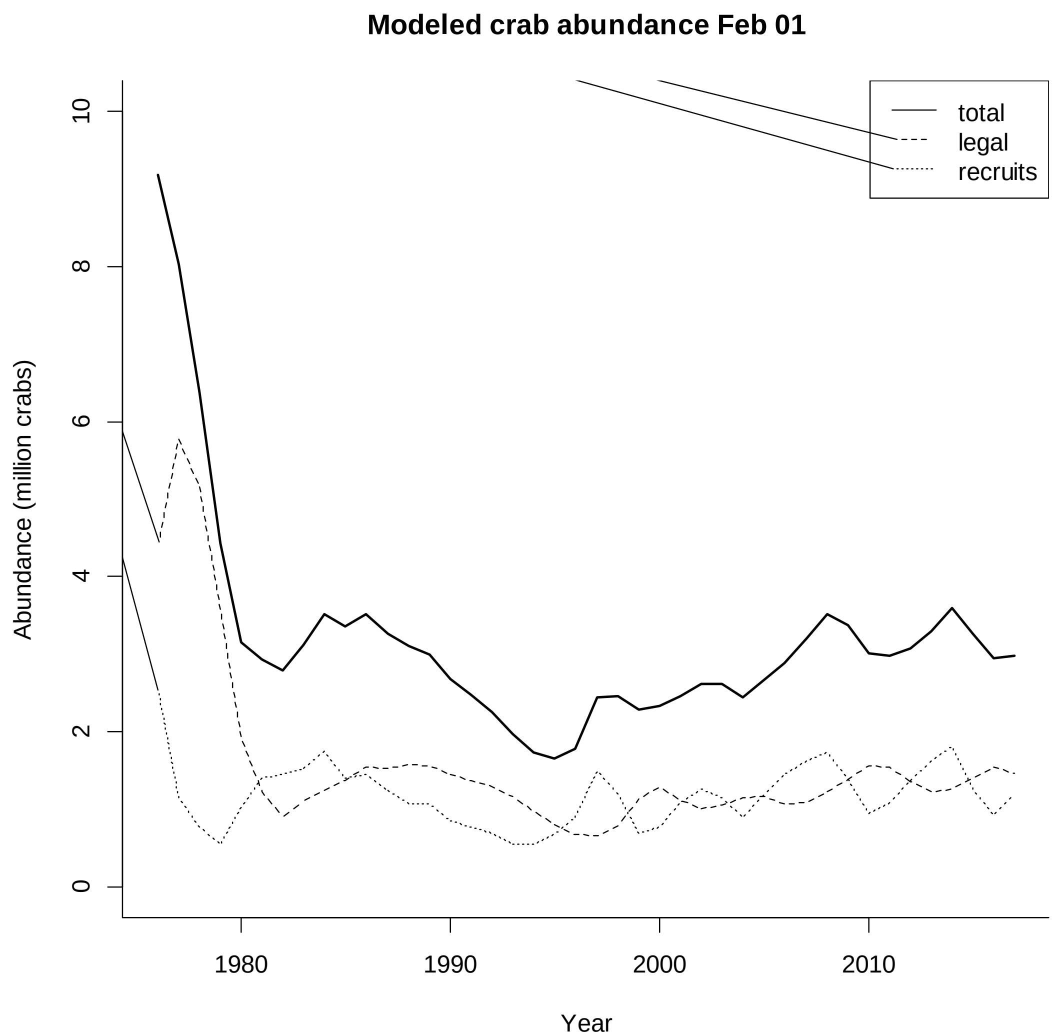


Figure C1-5. Estimated abundance of total, legal, and recruits males from 1976-2015.

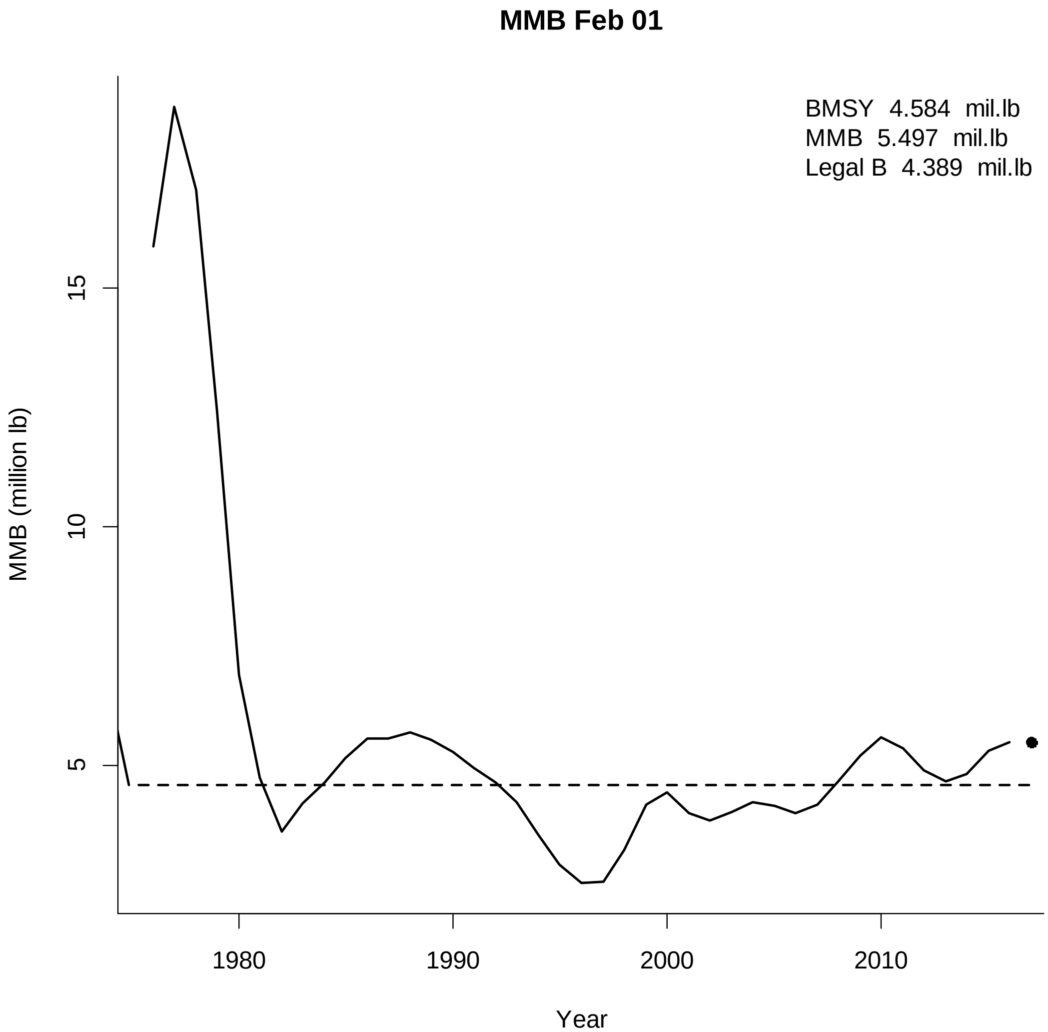


Figure C1-6. Estimated abundance of legal recruits from 1976-2016. Dash line shows B_{msy} (Average MMB of 1980-2016).

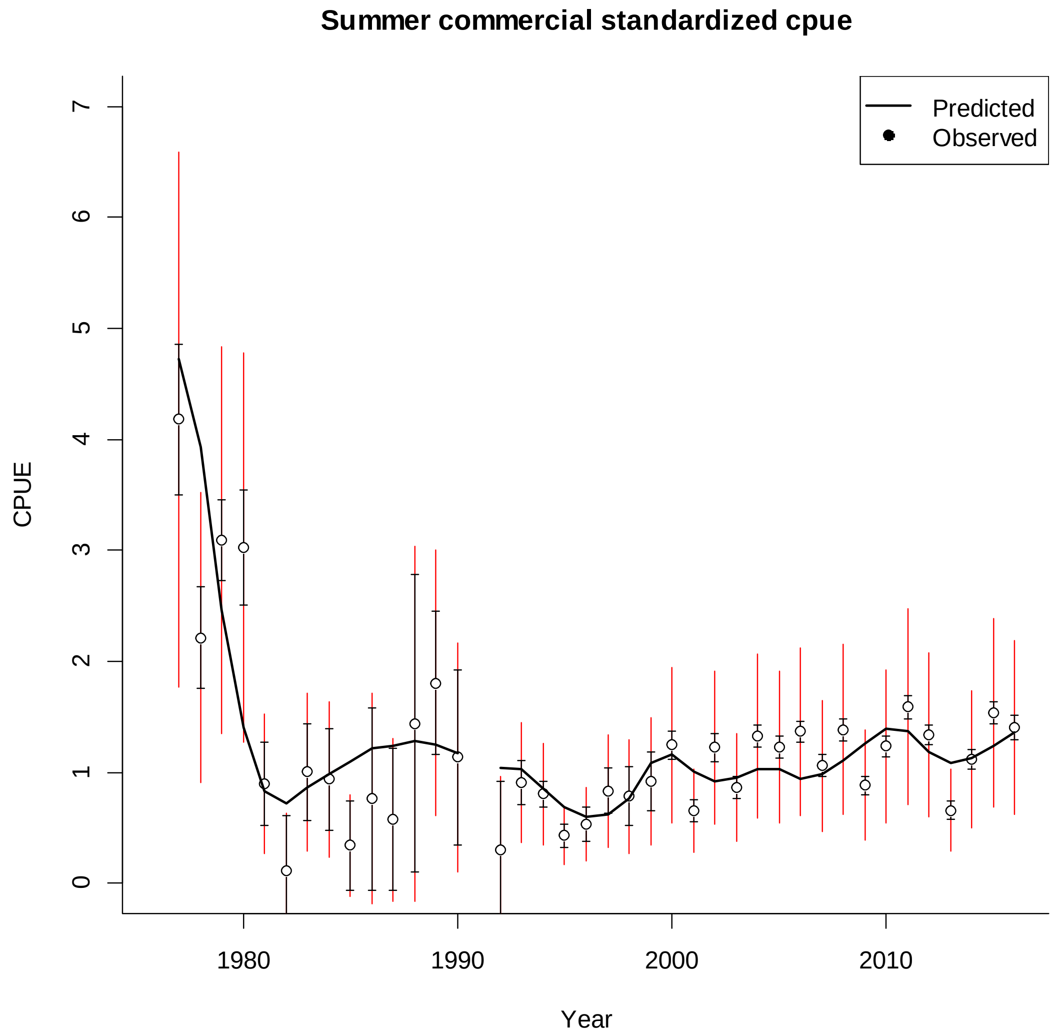


Figure C1-7. Summer commercial standardized cpue (1977-2016).

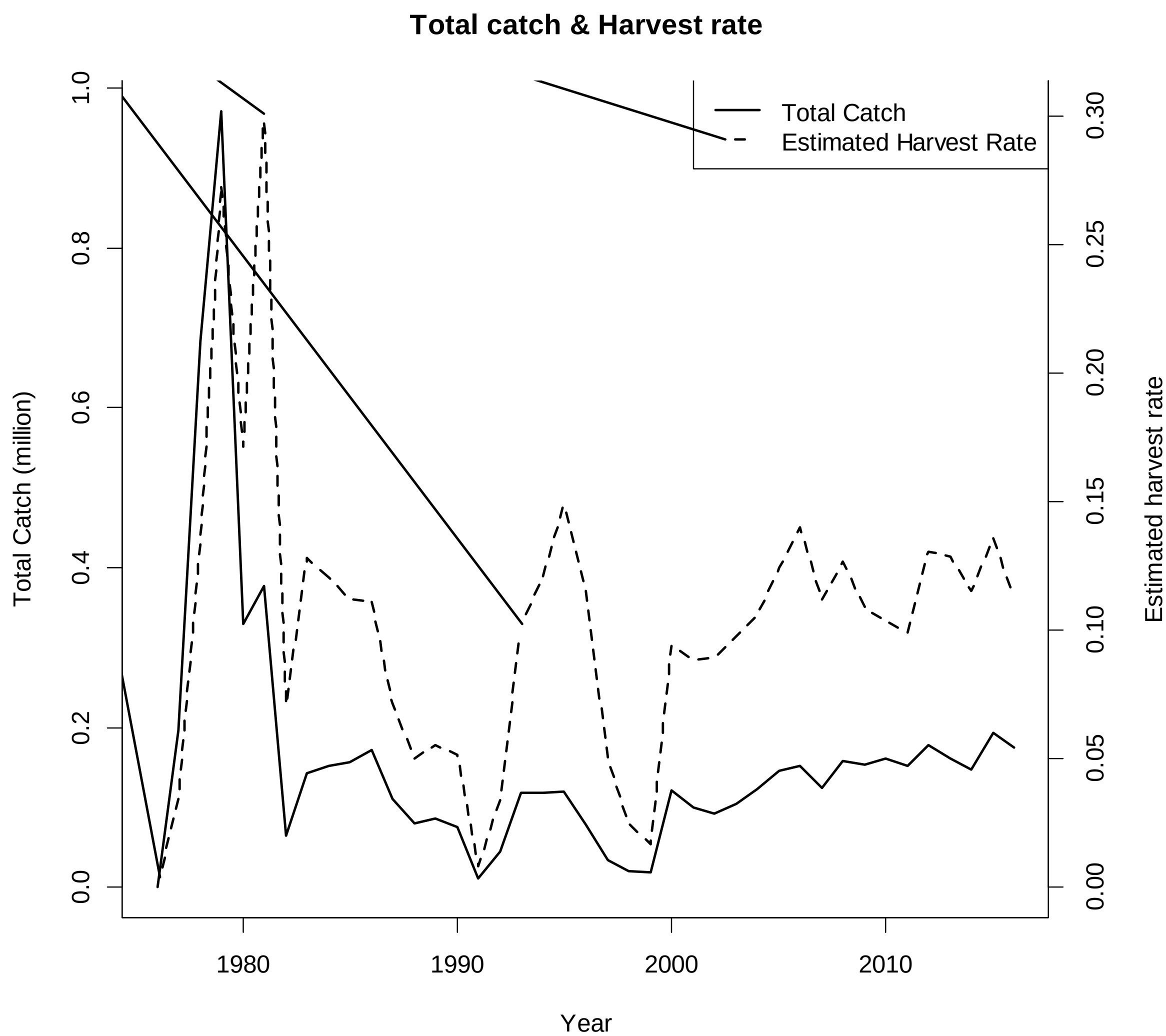


Figure C1-8. Total catch and estimated harvest rate 1976-2016.

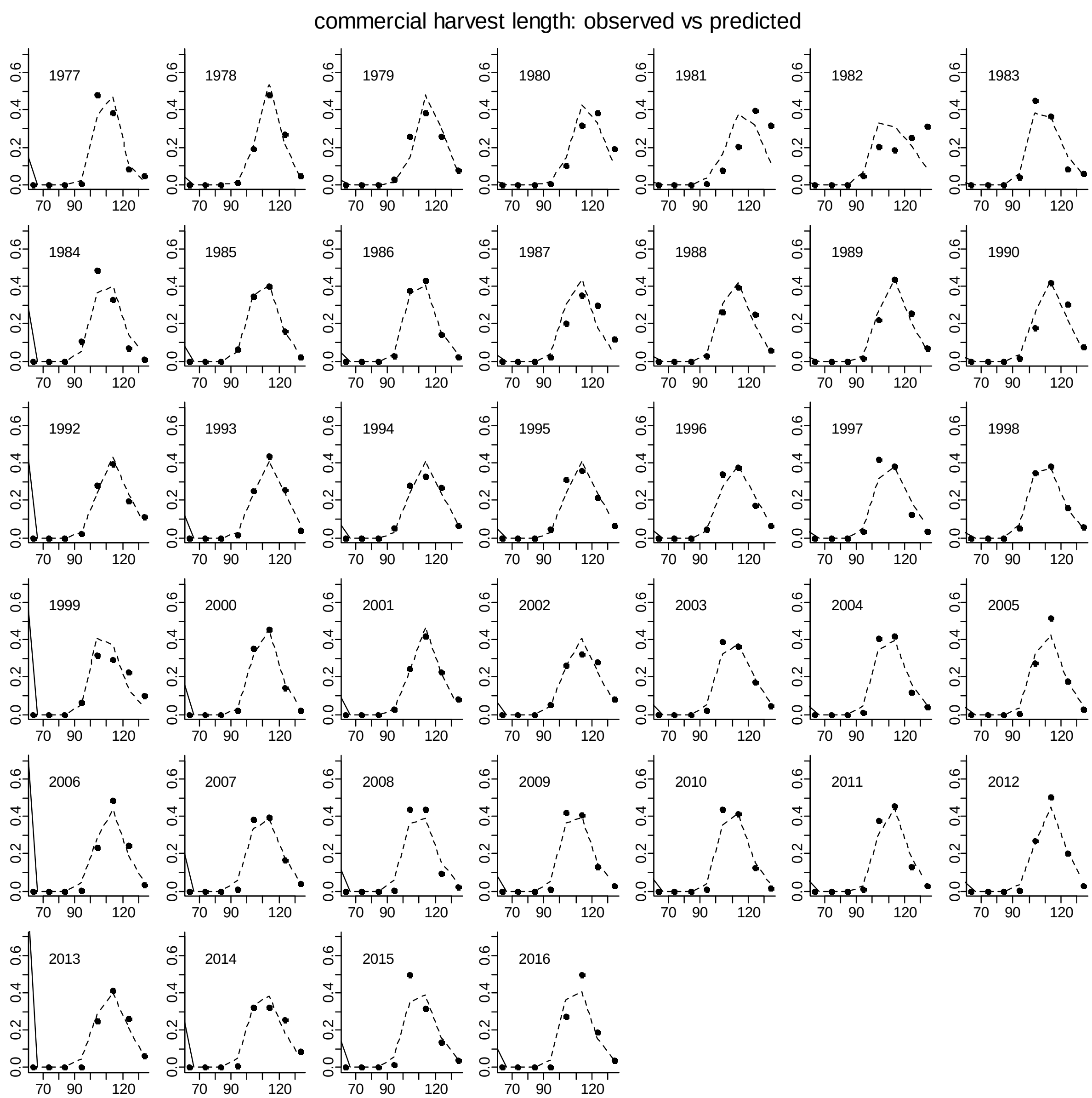


Figure C1-9. Predicted (dashed line) vs. observed (black dots) length class proportions for commercial catch.

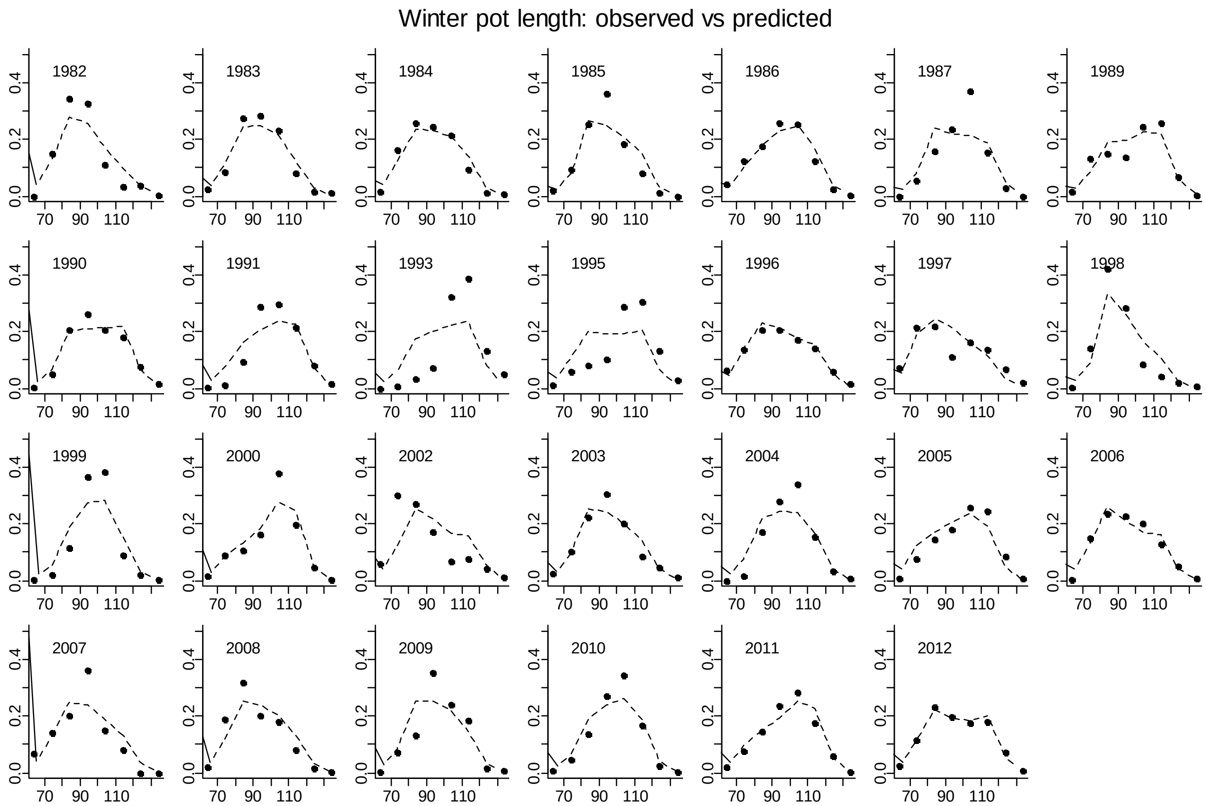


Figure C1-10. Predicted (dashed line) vs. observed (black dots) length class proportions for the winter pot survey.

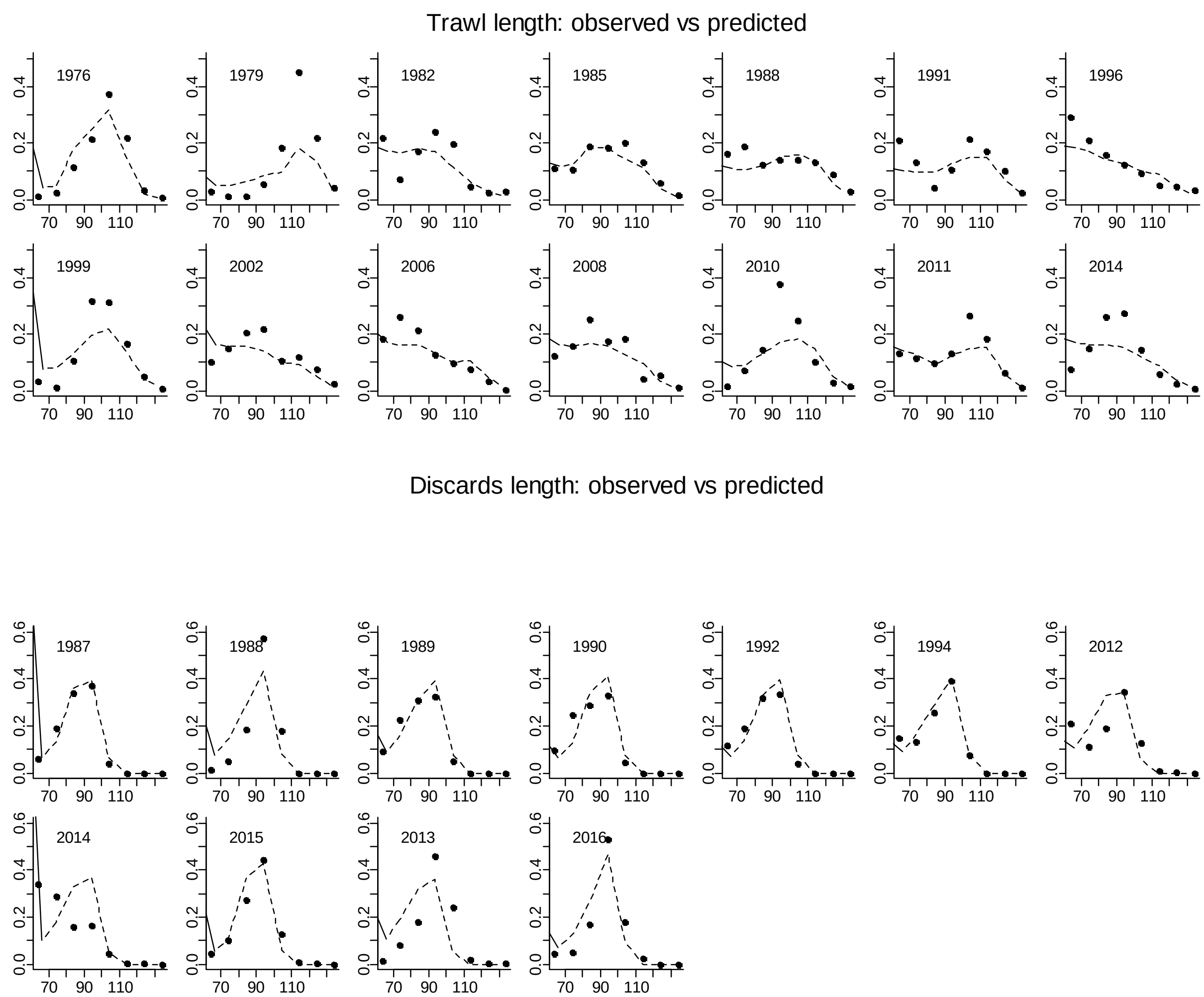


Figure C1-11. Predicted (dashed line) vs. observed (black dots) length class proportions for the trawl survey and observer survey.

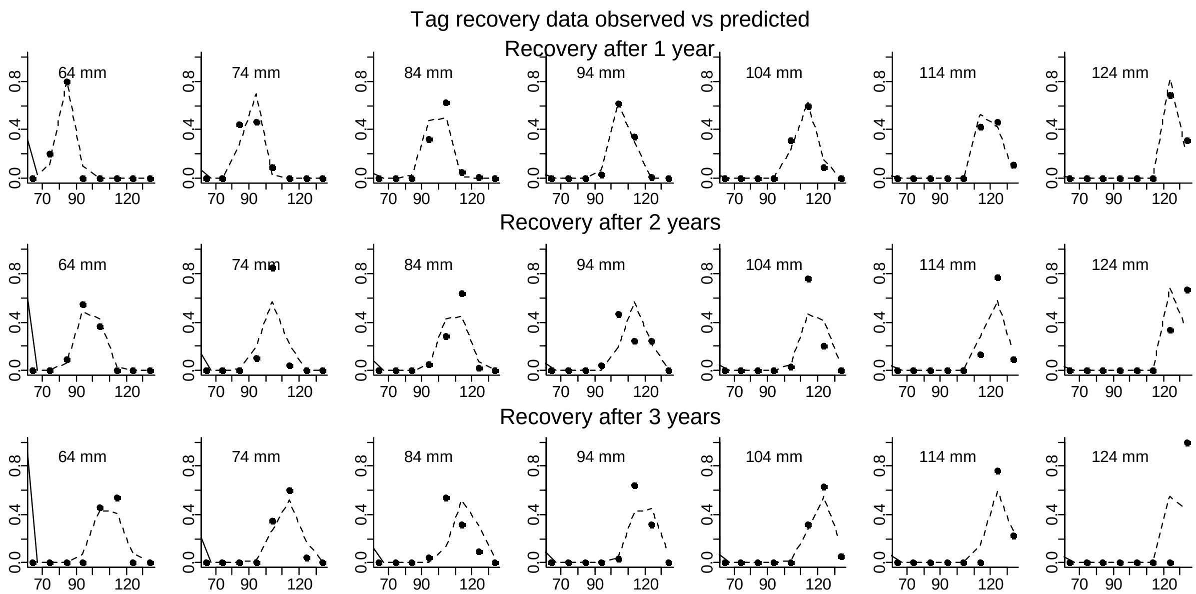


Figure C1-12. Predicted vs. observed length class proportions for tag recovery data.

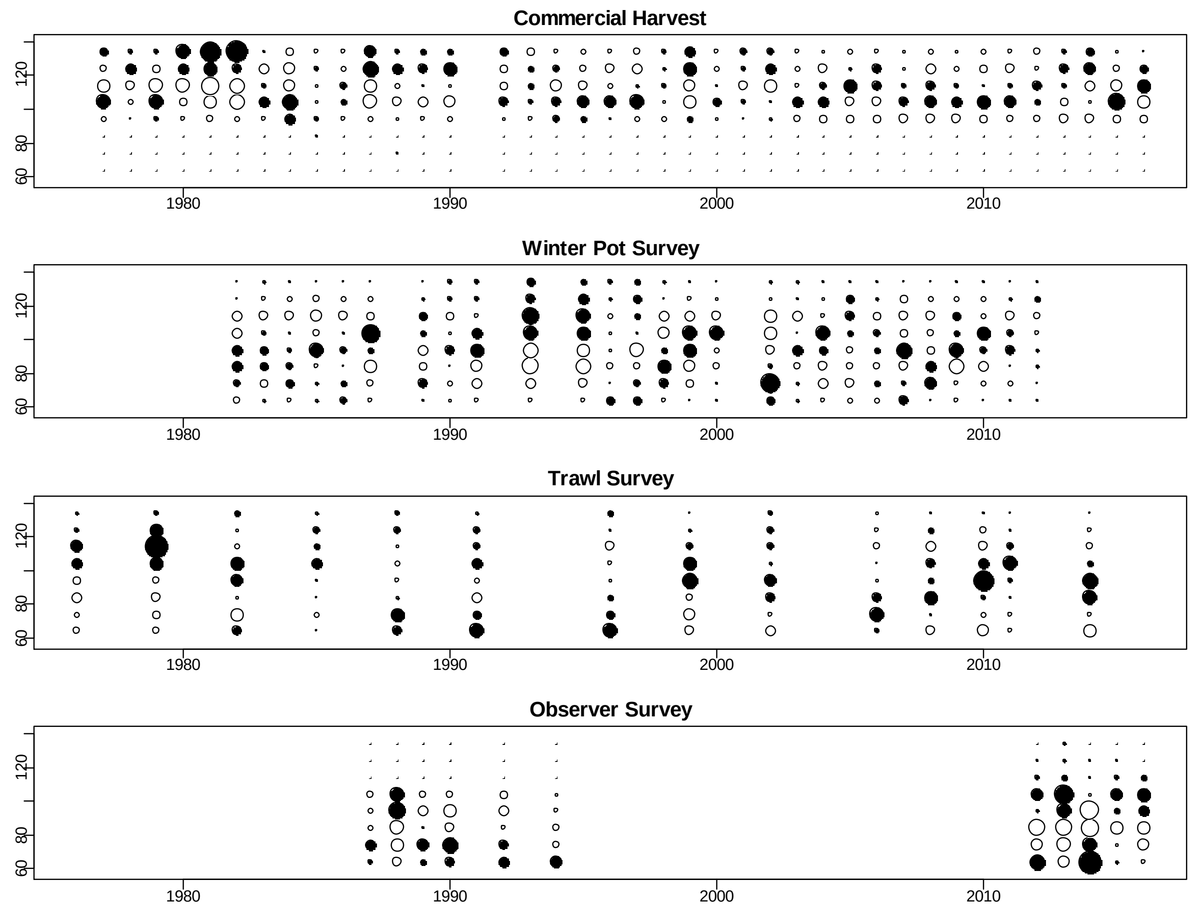


Figure C1-13. Bubble plots of predicted and observed length proportions. Black circle indicates model estimates lower than observed, white circle indicates model estimates higher than observed. Size of circle indicates degree of deviance (larger circle = larger deviance).

Table C1-1 . Summary of parameter estimates for a length-based stock synthesis population model of Norton Sound red king crab.

name	Estimate	std.dev
log_q_1	-6.9395	0.18833
log_q_2	-6.8143	0.10948
log_N_{76}	9.1246	0.14797
R_0	6.4935	0.08865
$log\_\sigma_R^2$	-0.0162	0.4391
log_R_{77}	-0.6033	0.36817
log_R_{78}	-0.7216	0.35405
log_R_{79}	0.23294	0.32136
log_R_{80}	0.32647	0.29744
log_R_{81}	0.31168	0.27337
log_R_{82}	0.38196	0.31749
log_R_{83}	0.5658	0.27964
log_R_{84}	0.06149	0.30856
log_R_{85}	0.41667	0.28325
log_R_{86}	-0.0194	0.30326
log_R_{87}	-0.0092	0.2615
log_R_{88}	0.01111	0.27207
log_R_{89}	-0.3943	0.29611
log_R_{90}	-0.2822	0.26239
log_R_{91}	-0.5337	0.28935
log_R_{92}	-0.7522	0.31345
log_R_{93}	-0.5989	0.29172
log_R_{94}	-0.3796	0.2679
log_R_{95}	-0.0663	0.23845
log_R_{96}	0.52664	0.21688
log_R_{97}	-0.2107	0.31331
log_R_{98}	-0.6575	0.31782
log_R_{99}	-0.1771	0.31252
log_R_{00}	0.14171	0.26825
log_R_{01}	0.19584	0.25364
log_R_{02}	-0.0097	0.31026
log_R_{03}	-0.3108	0.33407
log_R_{04}	0.28024	0.24704
log_R_{05}	0.3352	0.23962
log_R_{06}	0.47687	0.24966

name	Estimate	std.dev
log_R_{13}	0.56073	0.28843
log_R_{14}	-0.17762	0.41481
log_R_{15}	-0.16085	0.44217
a_1	2.5551	4.2362
a_2	2.5652	4.1878
a_3	3.9037	3.9797
a_4	4.1914	3.9639
a_5	4.4212	3.9568
a_6	3.6326	3.9831
a_7	2.0232	4.2066
r1	14.988	63.514
r2	14.614	63.514
log_α	-2.0188	0.01707
log_ϕ_{st1}	-2.5463	0.22276
log_ϕ_w	-2.0456	0.0502
Sw_7	0.07087	0.03399
Sw_8	0.45453	0.1092
log_ϕ_1	-2.0626	0.05424
w^2_t	0.07327	0.02264
q	0.77767	0.14252
ms	3.4889	0.30747
σ	4.231	0.24687
β_1	10.527	0.74631
β_2	8.0989	0.18995

log_R_{07}	0.50306	0.24441
log_R_{08}	0.09318	0.30158
log_R_{09}	-0.2974	0.30513
log_R_{10}	0.16769	0.24722
log_R_{11}	0.30805	0.2872
log_R_{12}	0.4813	0.28966

Appendix C2: Results Model 1

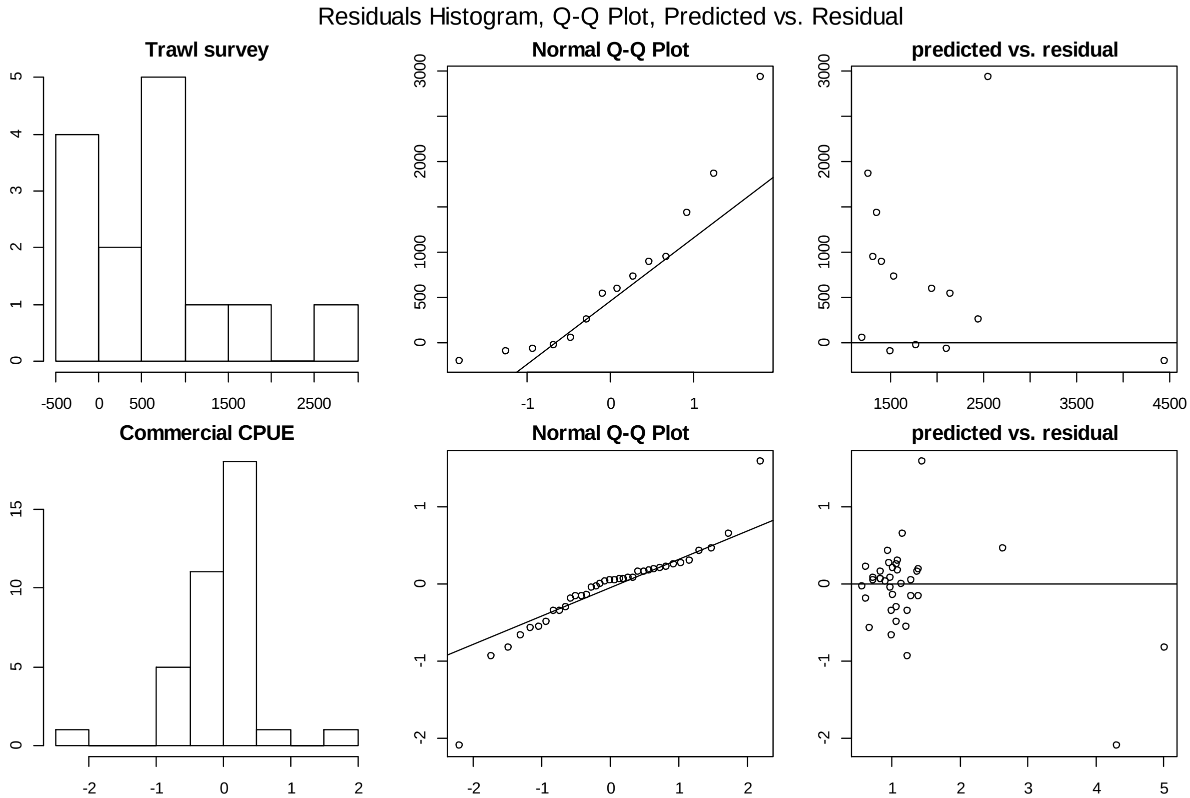


Figure C2-1. QQ Plot of Trawl survey and Commercial CPUE.

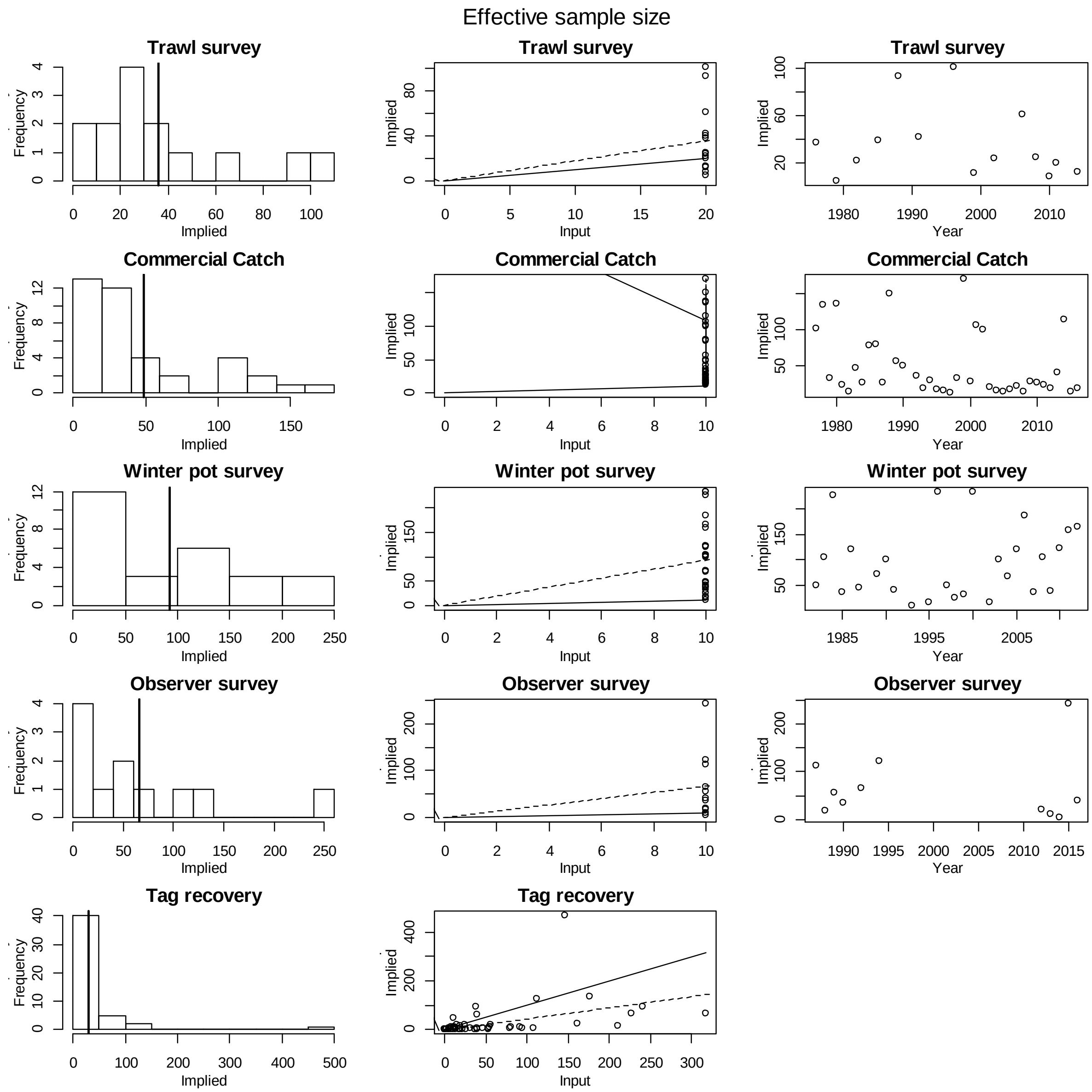


Figure C2-2: Implied effective samples. Figures in the first column show implied effective sample size (x-axis) vs. frequency (y-axis). Vertical solid line is the mean implied effective sample size. The second column show input sample size (x-axis) vs. implied effective sample size (y-axis). Dashed line indicates linear regression slope, and solid line is 1:1 line. The third column show year (x-axis) vs. implied effective sample size (y-axis).

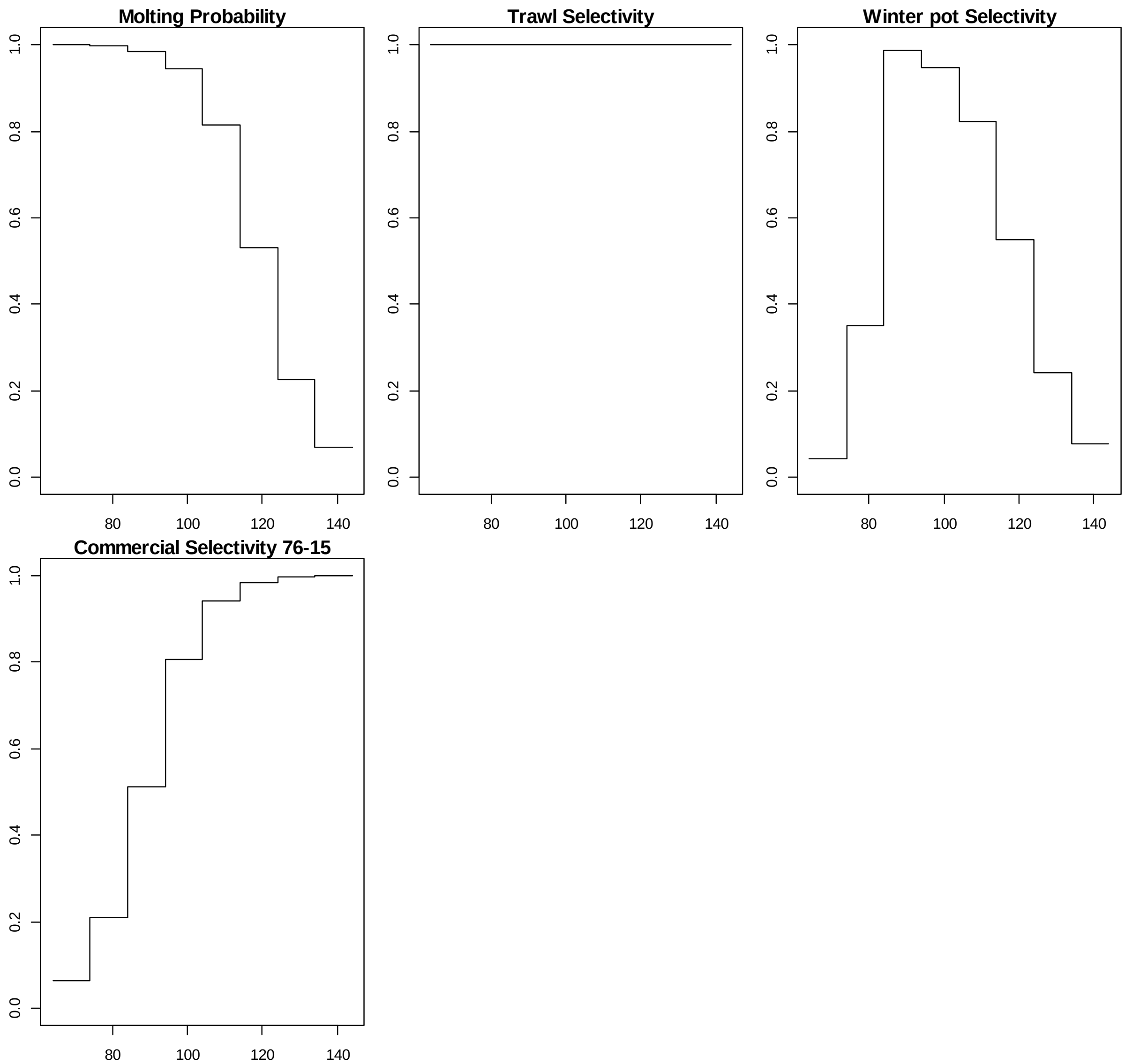


Figure C2-3. Molting probability and trawl/pot selectivity. X-axis is carapace length.

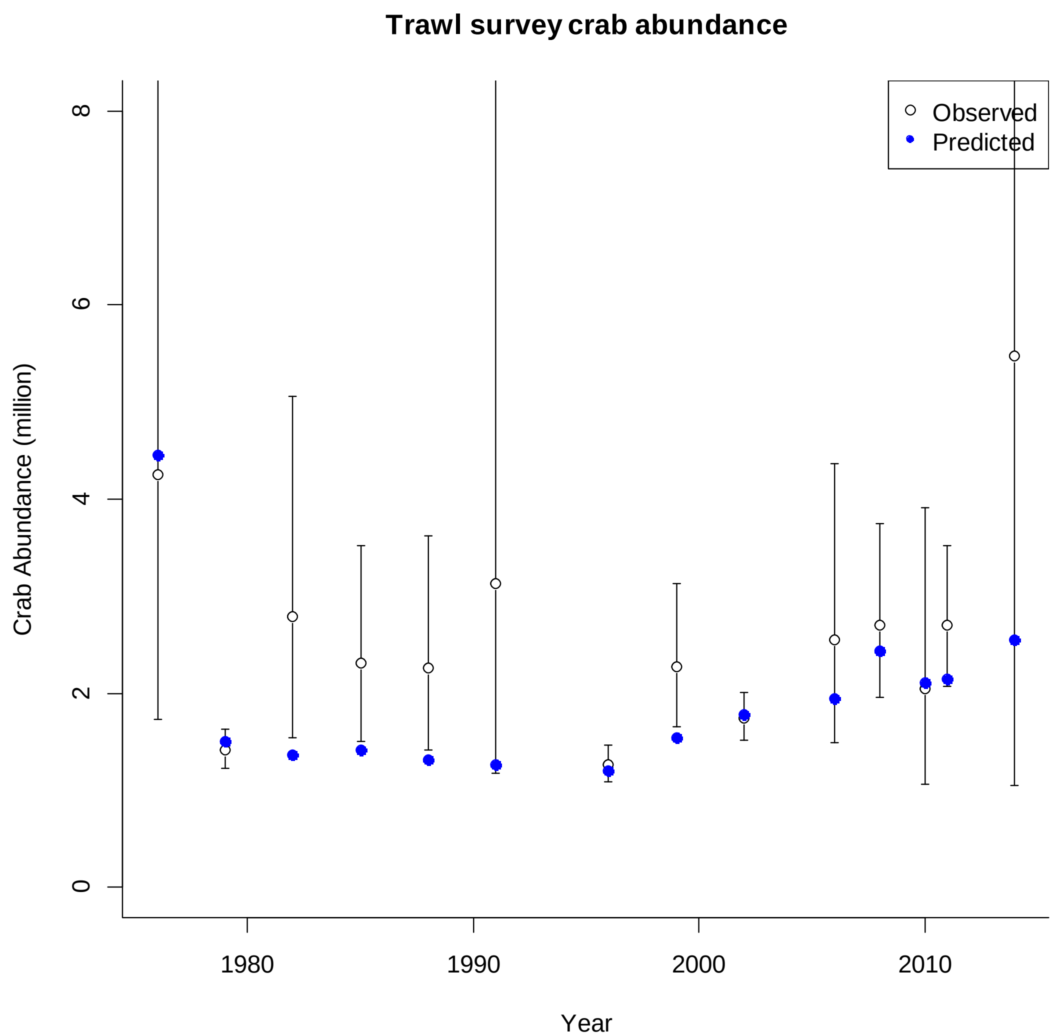


Figure C2-4. Estimated trawl survey male abundance (crab ≥ 74 mm CL).

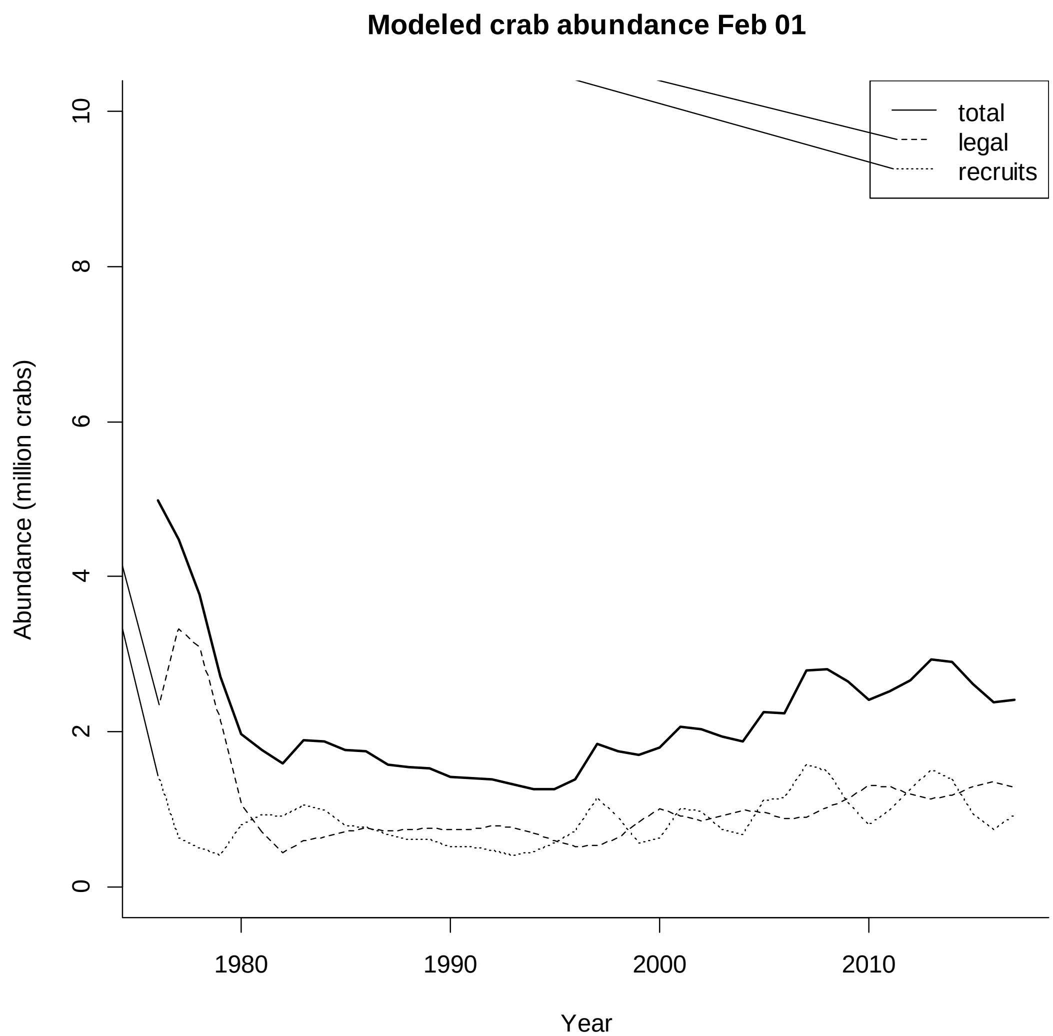


Figure C2-5. Estimated abundance of total, legal, and recruits males from 1976-2016.

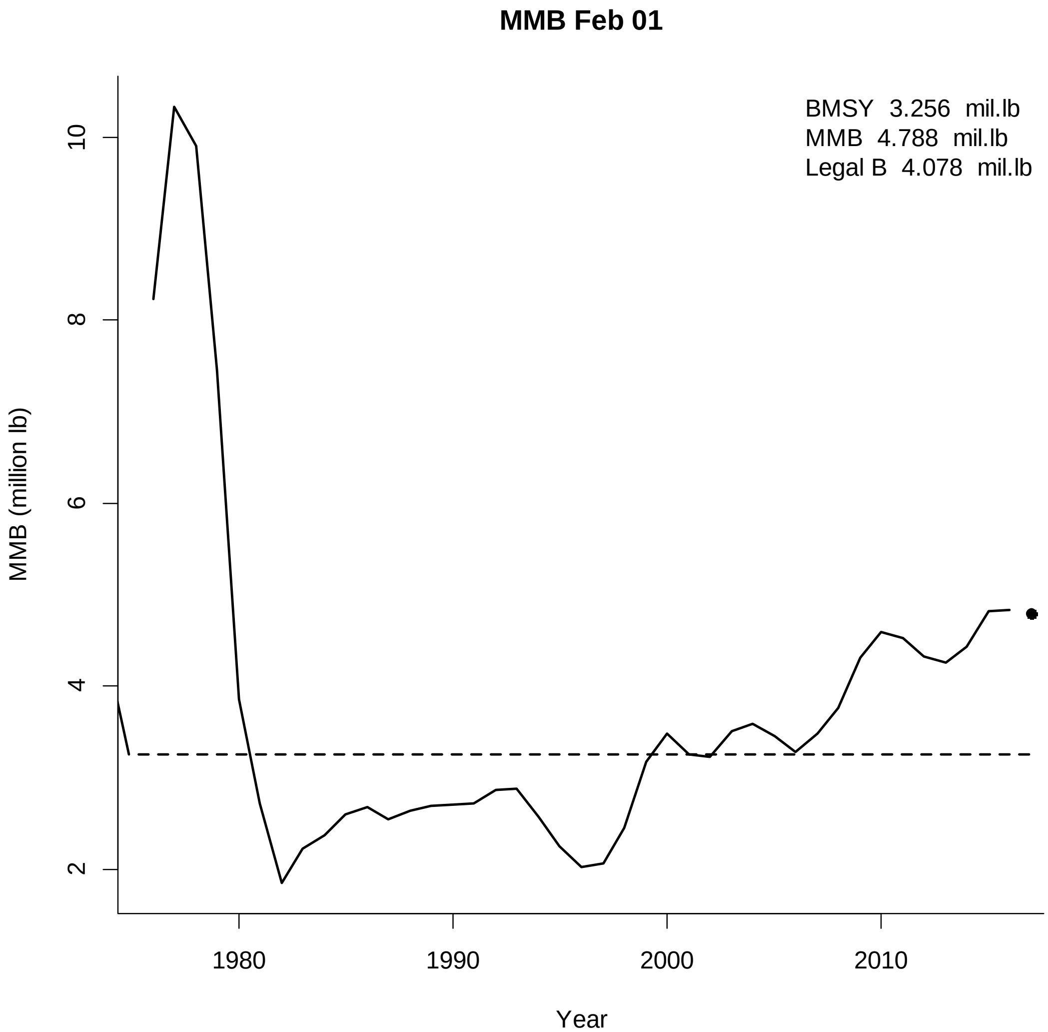


Figure C2-6. Estimated abundance of leg recruits from 1976-2016. Dash line shows B_{msy} (Average MMB of 1980-2016).

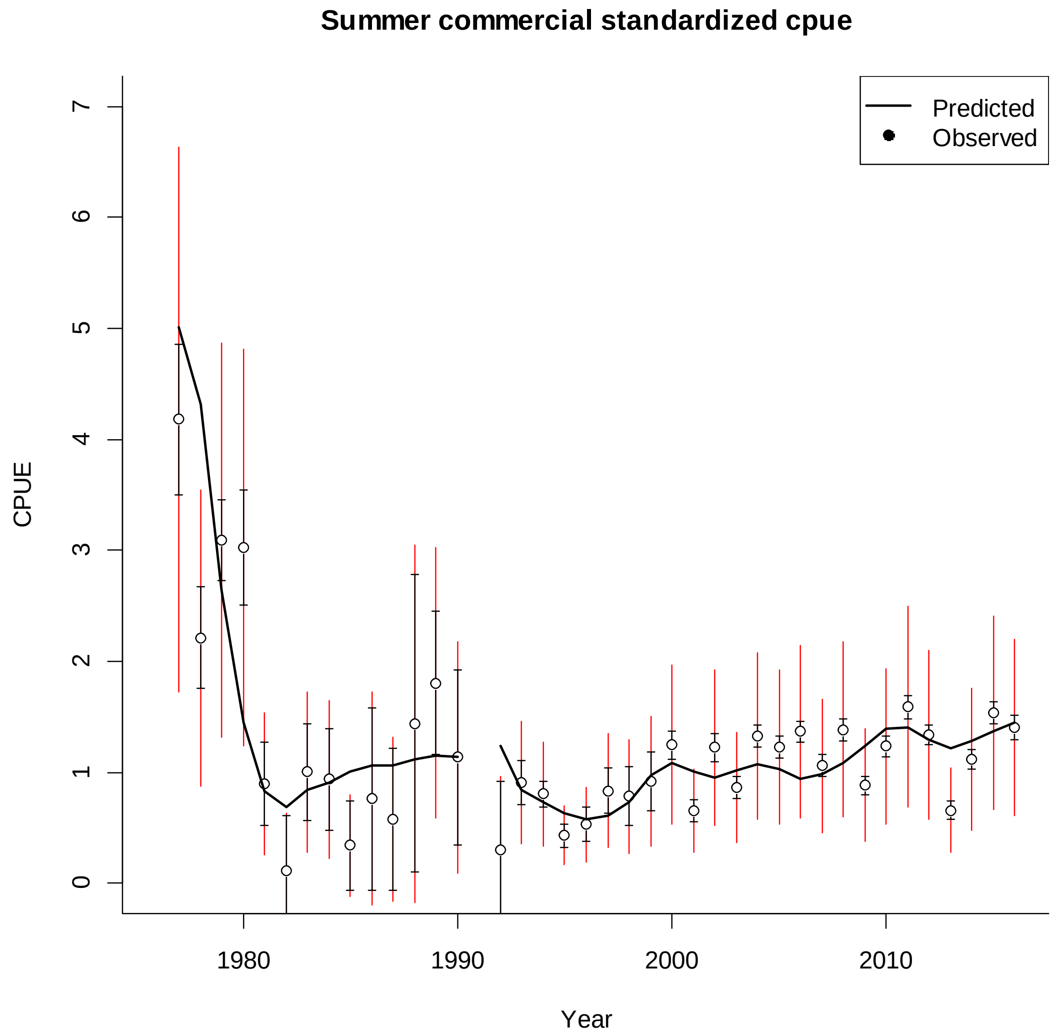


Figure C2-7. Summer commercial standardized cpue (1977-2016).

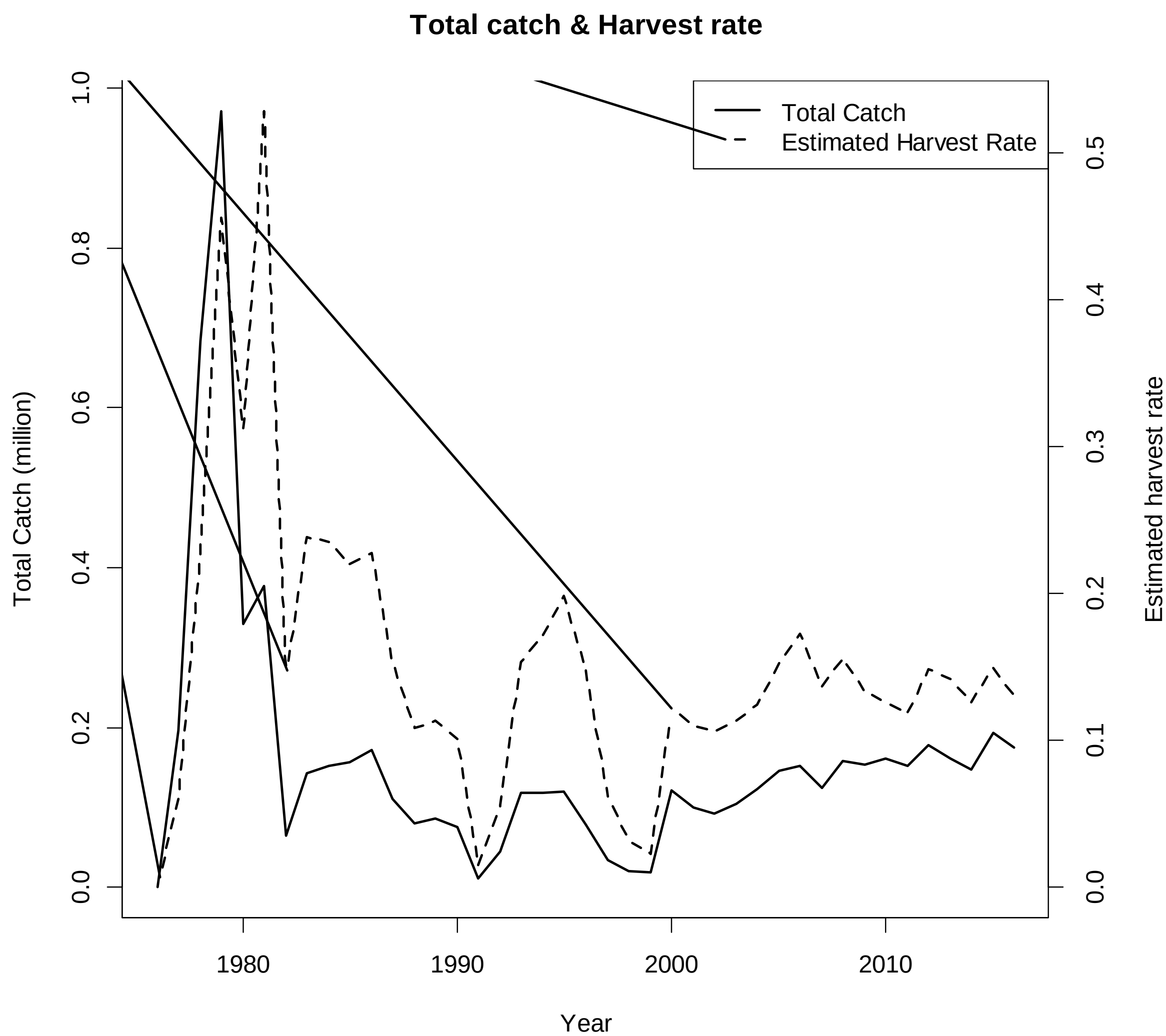


Figure C2-8. Total catch and estimated harvest rate 1976-2016.

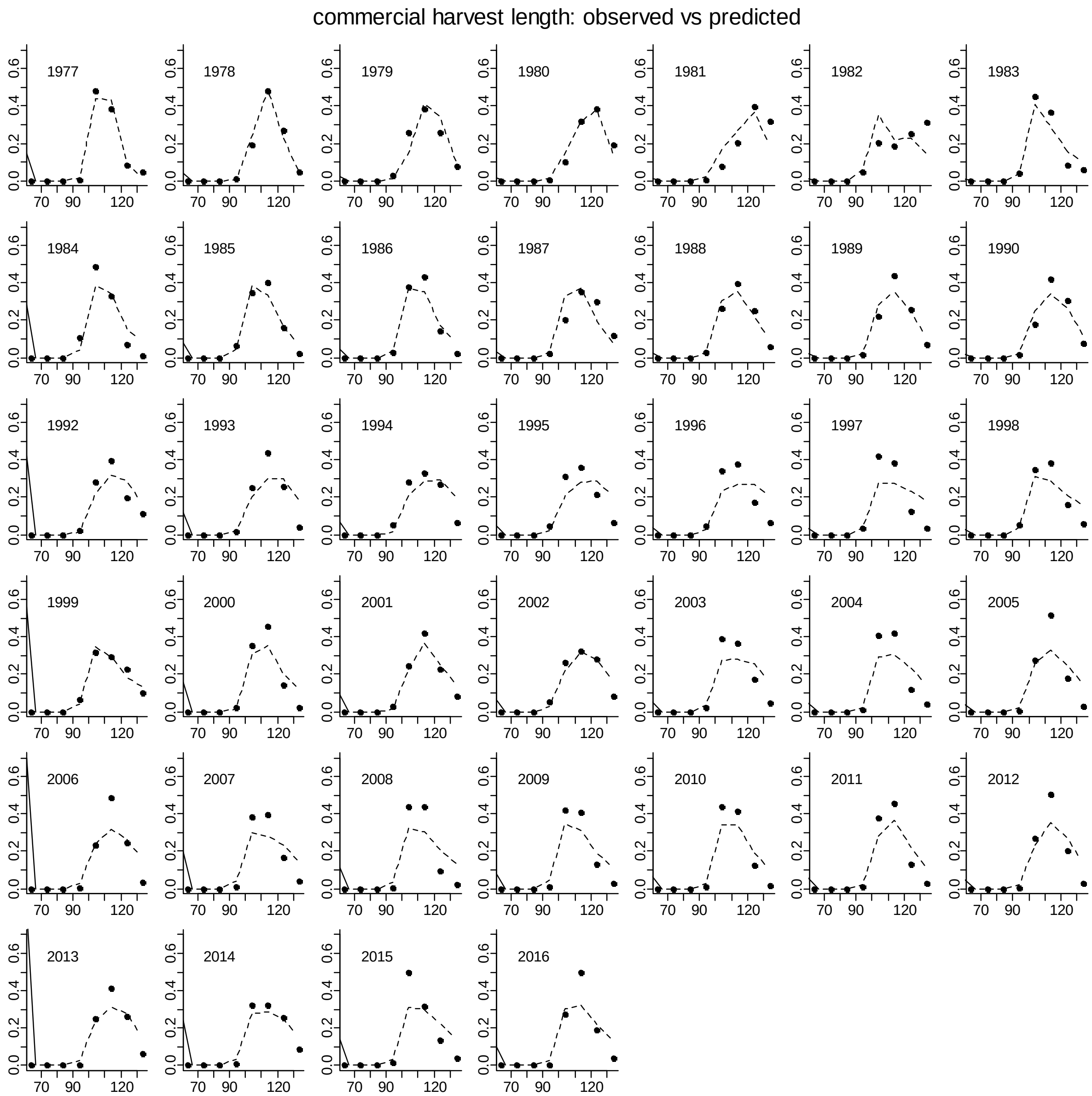


Figure C2-9. Predicted (dashed line) vs. observed (black dots) length class proportions for commercial catch.

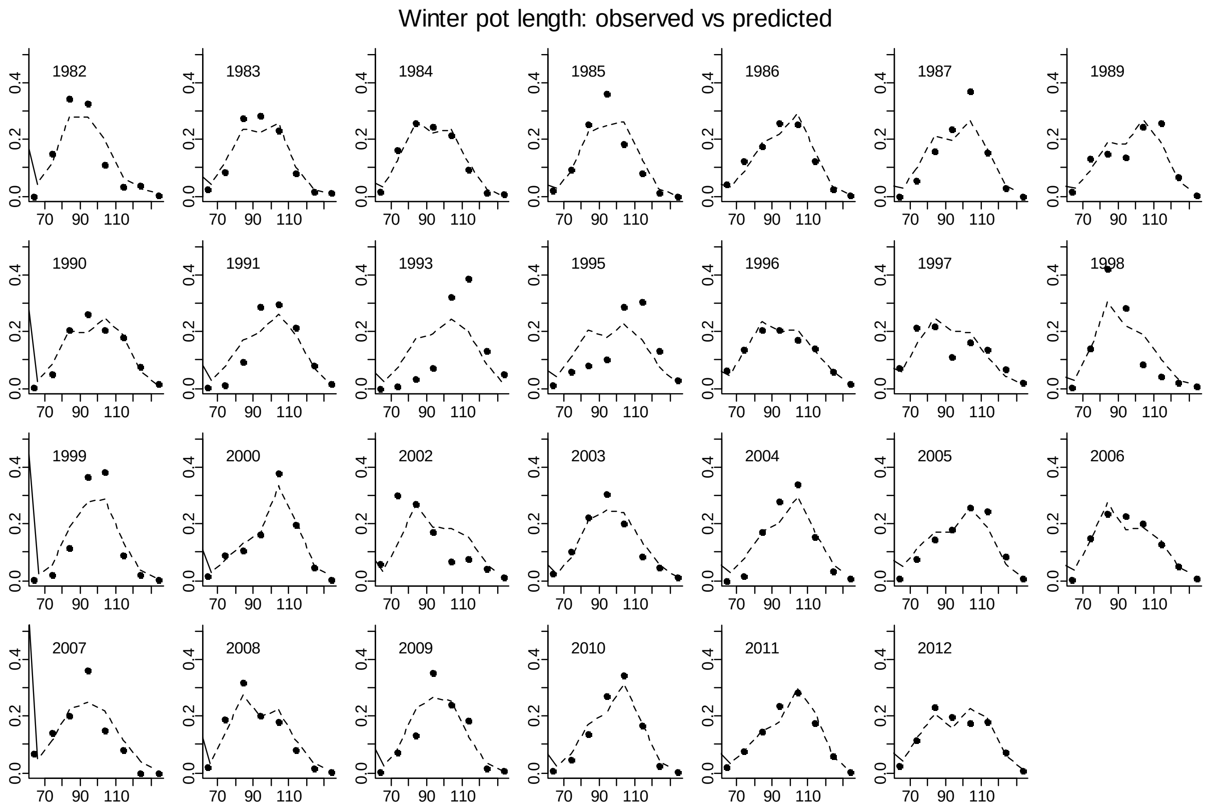


Figure C2-10. Predicted (dashed line) vs. observed (black dots) length class proportions for the winter pot survey.

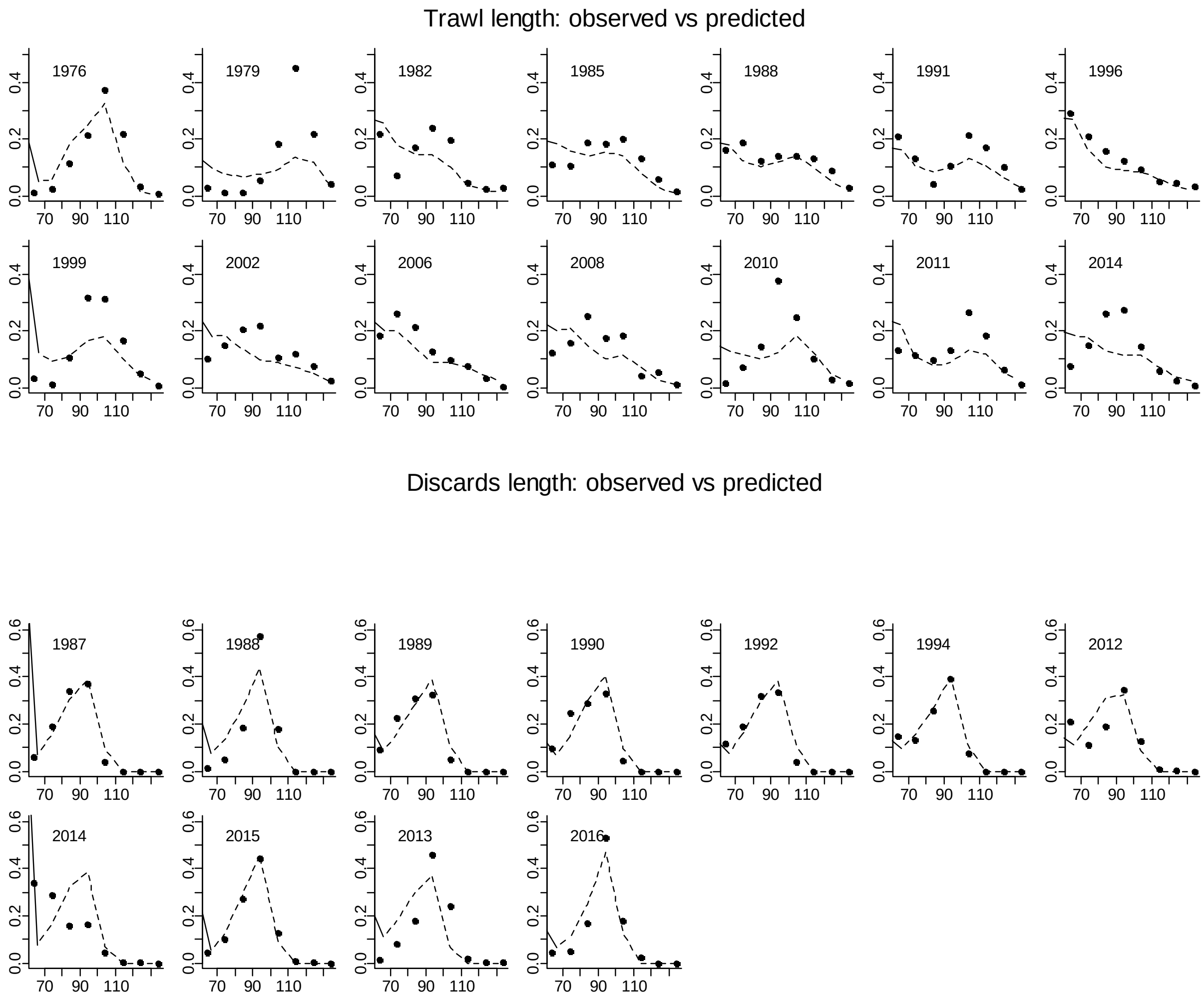


Figure C2-11. Predicted (dashed line) vs. observed (black dots) length class proportions for the trawl survey and observer survey.

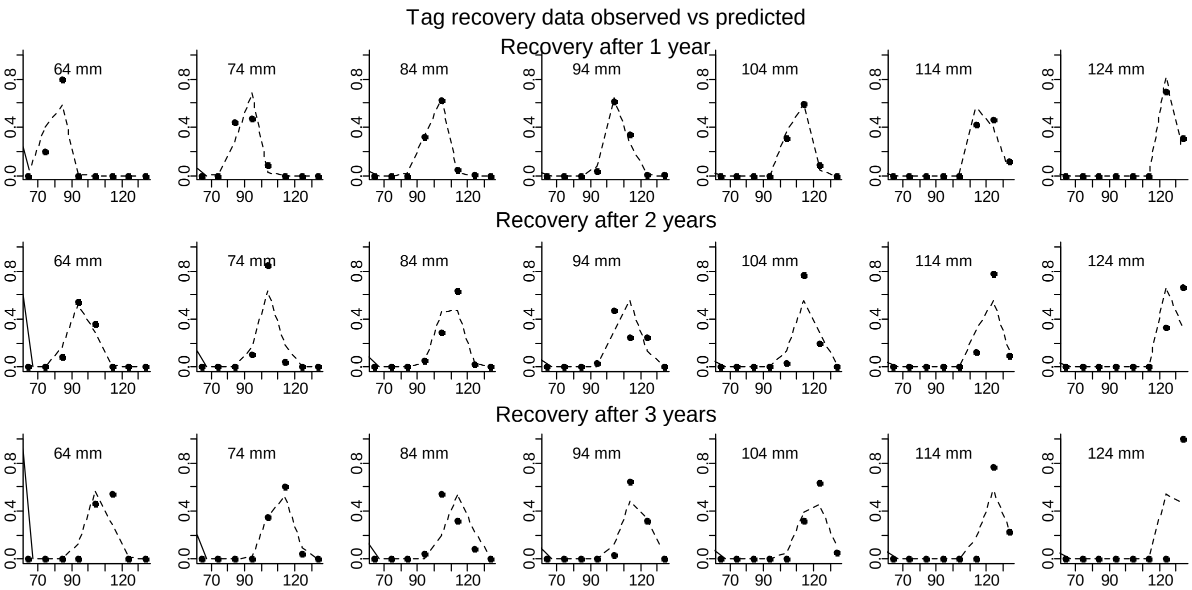


Figure C2-12. Predicted vs. observed length class proportions for tag recovery data.

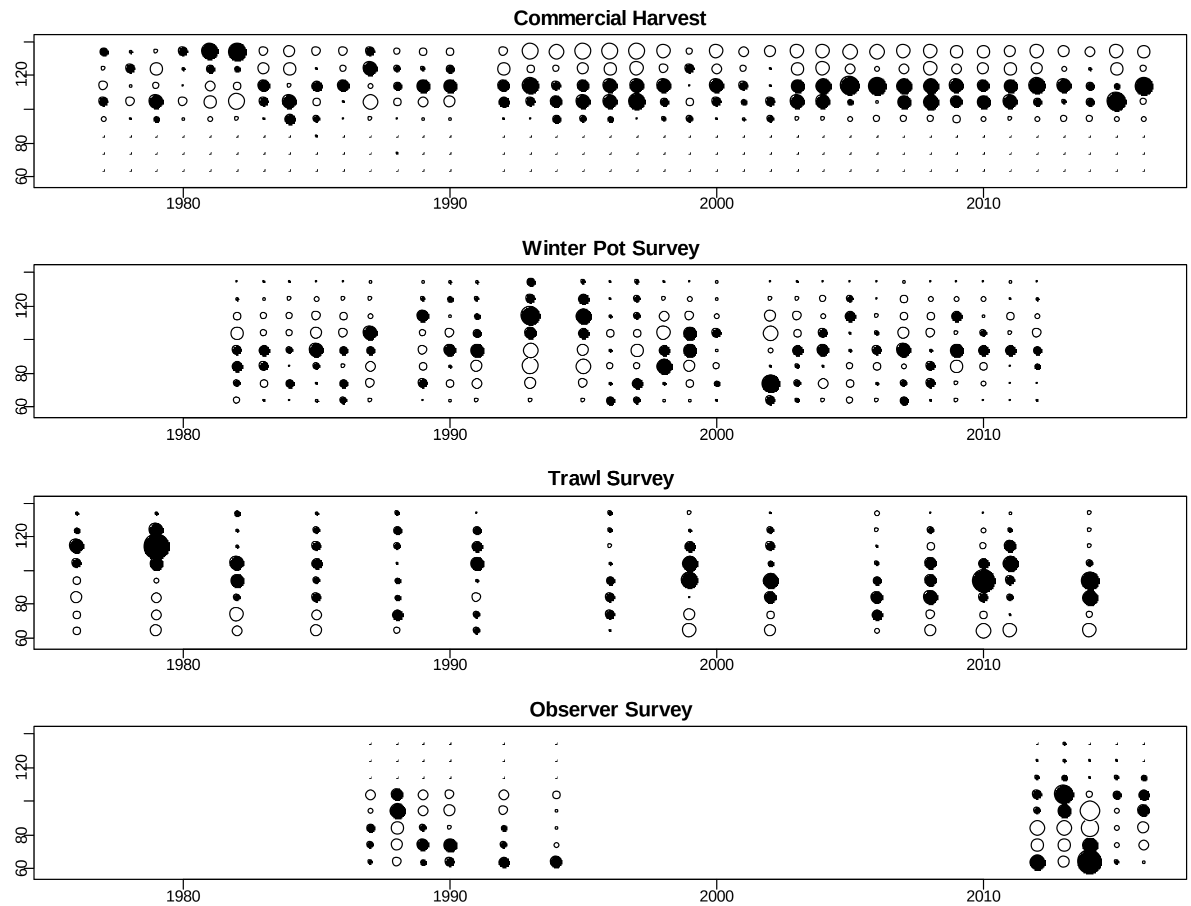


Figure C2-13. Bubble plots of predicted and observed length proportions. Black circle indicates model estimates lower than observed, white circle indicates model estimates higher than observed. Size of circle indicates degree of deviance (larger circle = larger deviance).

Table C2-1 . Summary of parameter estimates for a length-based stock synthesis population model of Norton Sound red king crab.

name	Estimate	std.dev
log_q_1	-6.3127	0.12861
log_q_2	-6.6425	0.11552
log_N_{76}	8.5132	0.045654
R_0	6.0115	0.055367
$log\_\sigma_R^2$	-0.23488	0.41209
log_R_{77}	-0.65987	0.36052
log_R_{78}	-0.69039	0.35451
log_R_{79}	0.41026	0.28341
log_R_{80}	0.078735	0.33746
log_R_{81}	0.17457	0.2862
log_R_{82}	0.42854	0.29594
log_R_{83}	0.086939	0.33753
log_R_{84}	-0.14673	0.3029
log_R_{85}	0.076389	0.27497
log_R_{86}	-0.35052	0.30499
log_R_{87}	-0.21213	0.26402
log_R_{88}	-0.22319	0.2833
log_R_{89}	-0.57374	0.31377
log_R_{90}	-0.33386	0.2703
log_R_{91}	-0.61857	0.31258
log_R_{92}	-0.69348	0.32864
log_R_{93}	-0.42064	0.3091
log_R_{94}	-0.22067	0.29868
log_R_{95}	0.085322	0.27098
log_R_{96}	0.63557	0.23027
log_R_{97}	-0.49925	0.36594
log_R_{98}	-0.45966	0.33749
log_R_{99}	-0.03149	0.35768
log_R_{00}	0.50596	0.26315
log_R_{01}	-0.00475	0.32477
log_R_{02}	-0.19311	0.35181
log_R_{03}	-0.13198	0.37741
log_R_{04}	0.67736	0.2439
log_R_{05}	0.19451	0.3289
log_R_{06}	0.96771	0.24

name	Estimate	std.dev
log_R_{13}	0.39845	0.35761
log_R_{14}	-0.15903	0.43752
log_R_{15}	-0.052849	0.46291
a_1	3.5034	4.9963
a_2	3.7424	4.9669
a_3	4.8637	4.8171
a_4	5.1519	4.8042
a_5	5.4344	4.7953
a_6	4.4165	4.8191
a_7	2.2708	5.0191
r1	14.996	22.694
r2	13.317	22.71
log_α	-1.9983	0.019238
log_ϕ_{st1}	-14.921	303.45
log_ϕ_w	-2.0085	0.041859
Sw_7	0.044032	0.021908
Sw_8	0.35143	0.084349
log_ϕ_I	-1.9866	0.046104
w^2_t	0.076205	0.022317
q	1	3.89E-05
ms		
σ	4.228	0.21096
β_1	13.548	0.98015
β_2	12.667	0.9774
β_3	10.167	0.84032
β_4	6.1268	0.623
β_5	5.5323	0.63649
β_6	10.837	0.78165
β_7	10.095	2.662

log_R_{07}	0.40104	0.32756
log_R_{08}	0.13349	0.34482
log_R_{09}	-0.14066	0.35046
log_R_{10}	0.47983	0.27371
log_R_{11}	0.54266	0.34934
log_R_{12}	0.77409	0.3298

Appendix C3: Results Model 2

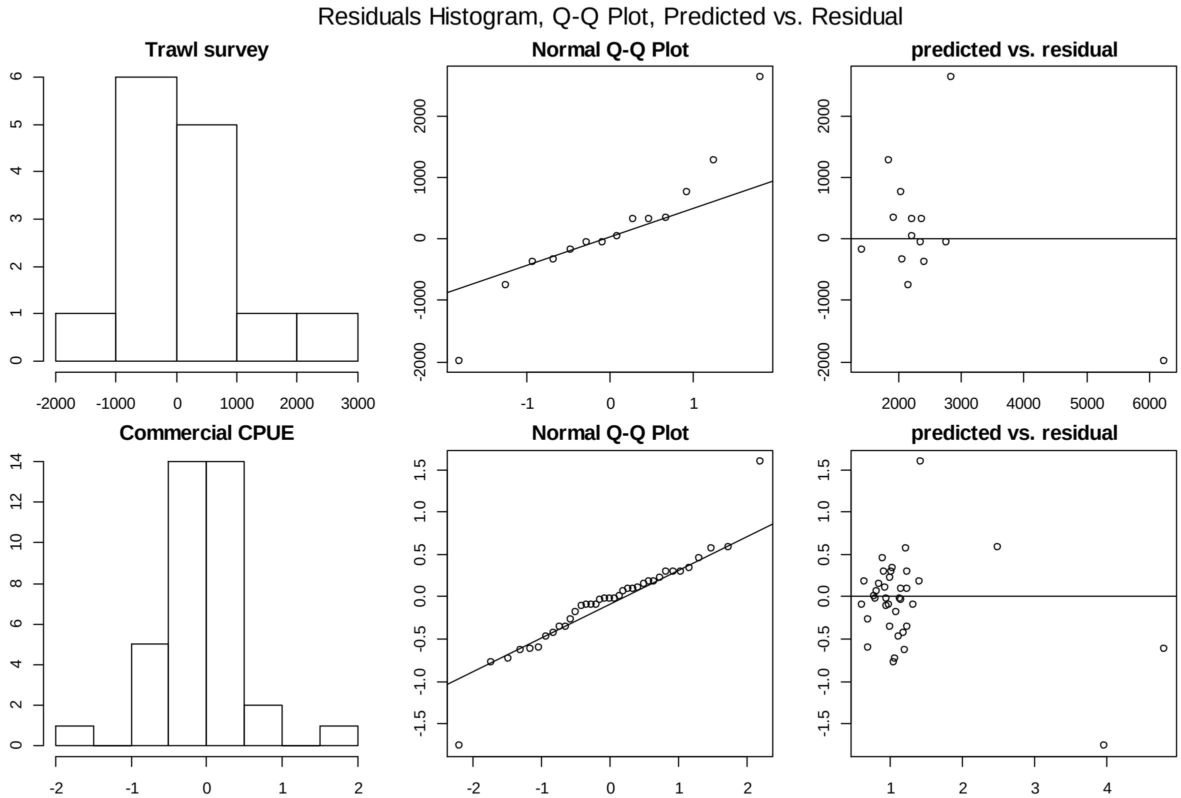


Figure C3-1. QQ Plot of Trawl survey and Commercial CPUE.

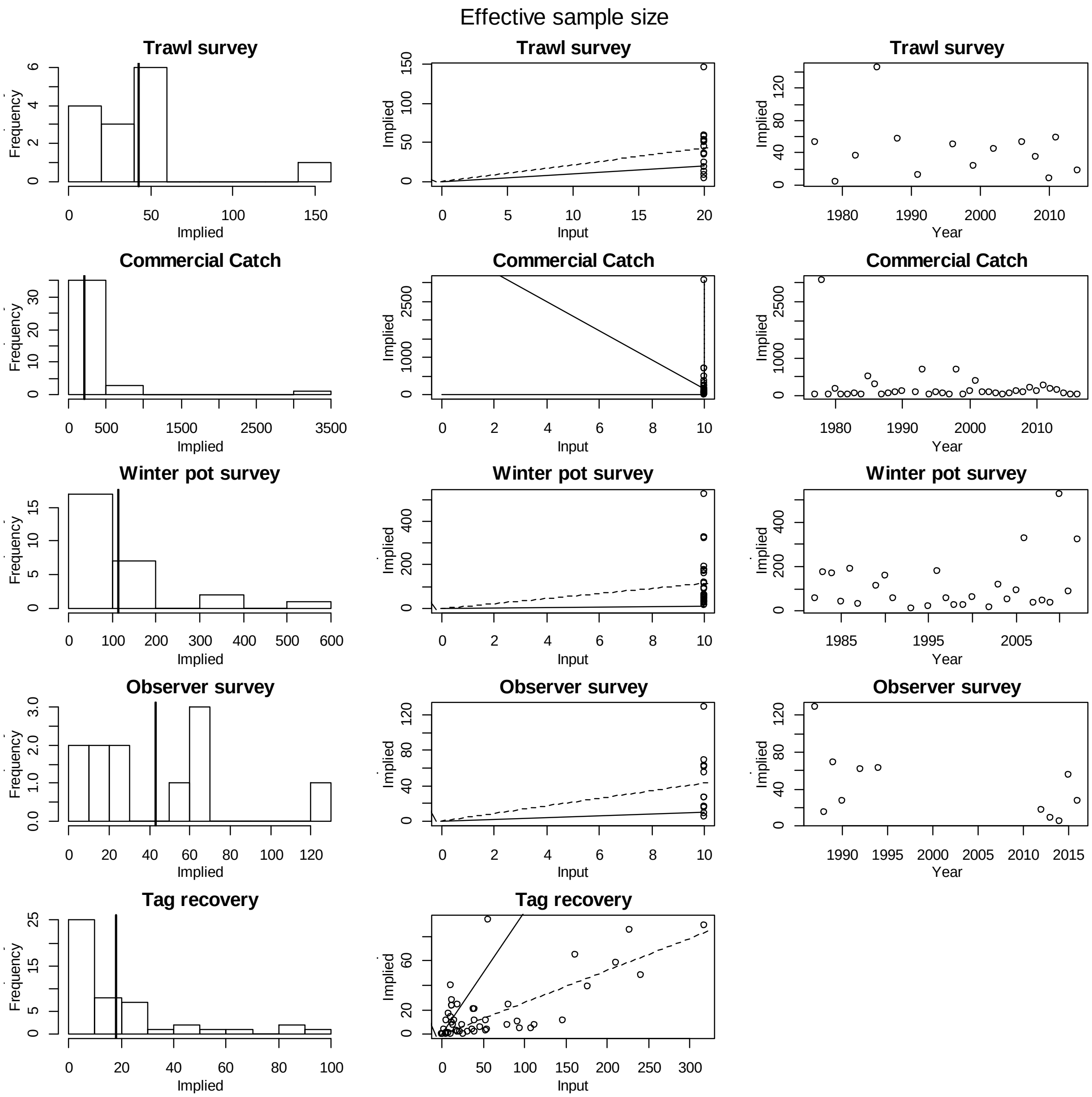
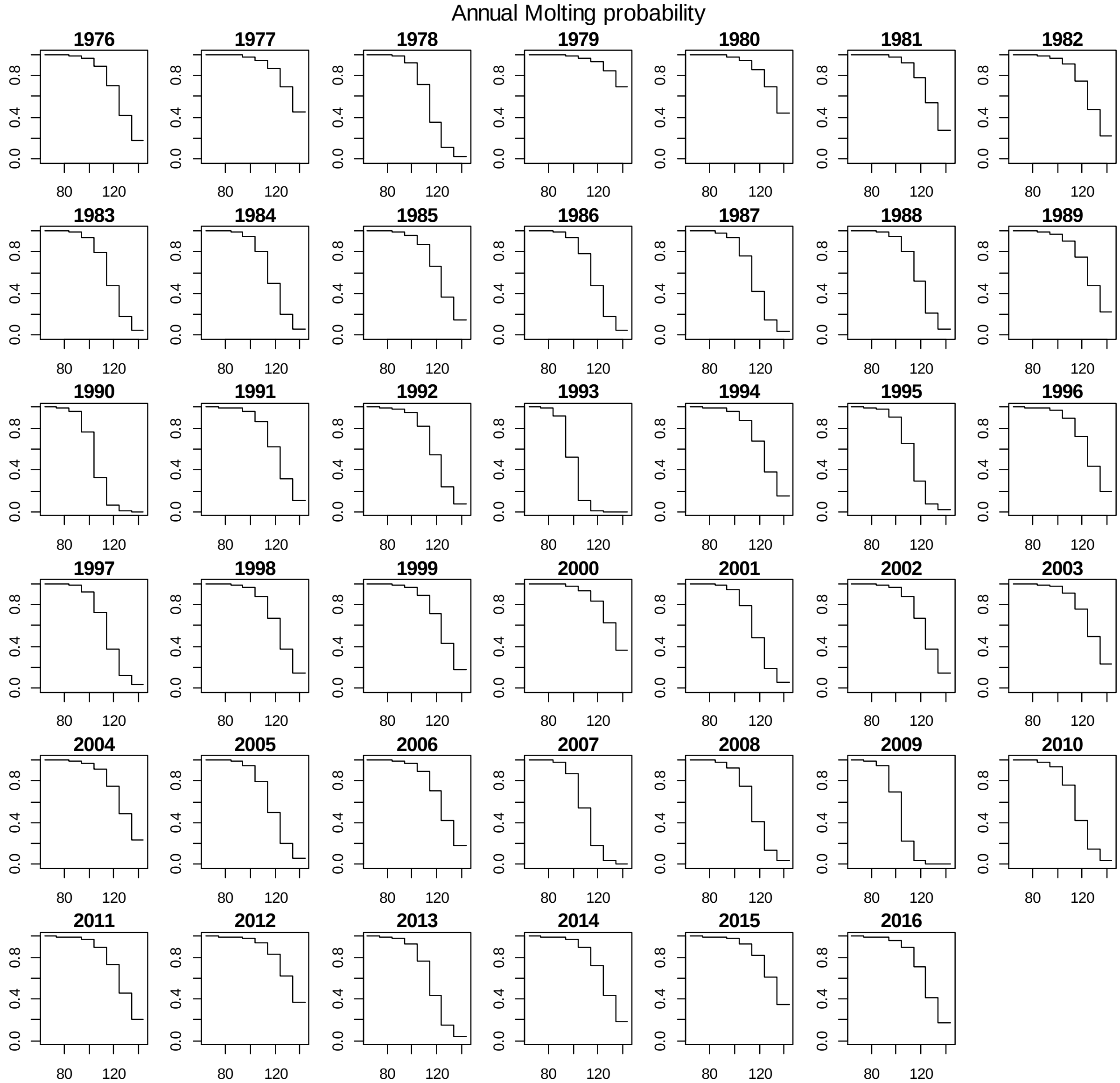


Figure C3-2: Implied effective samples. Figures in the first column show implied effective sample size (x-axis) vs. frequency (y-axis). Vertical solid line is the mean implied effective sample size. The second column show input sample size (x-axis) vs. implied effective sample size (y-axis). Dashed line indicates linear regression slope, and solid line is 1:1 line. The third column show year (x-axis) vs. implied effective sample size (y-axis).

Annual Molting probability



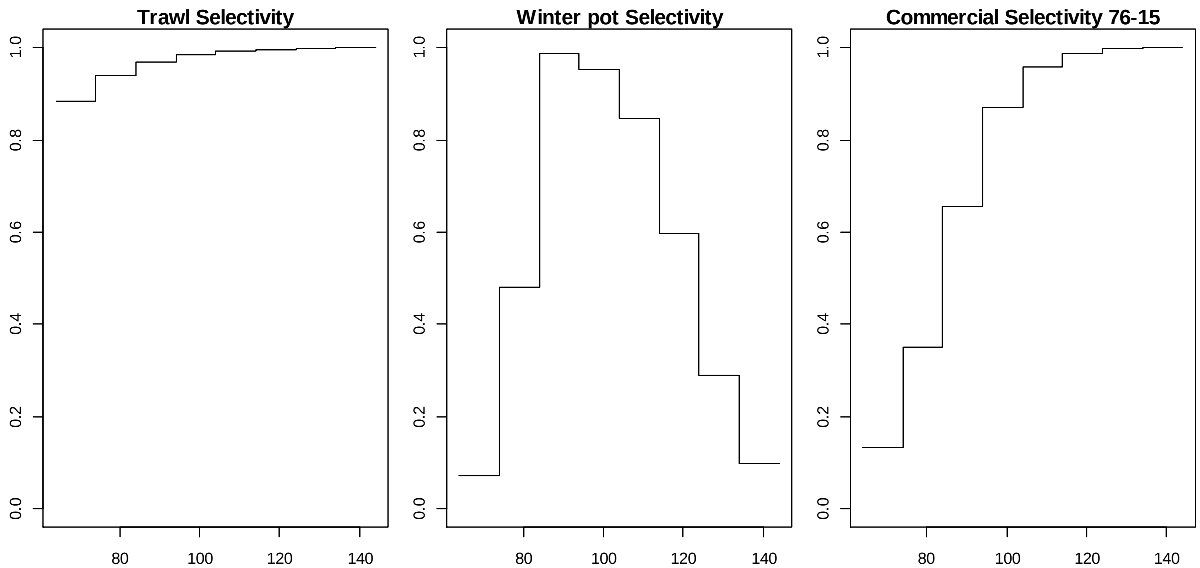


Figure C3-3. Molting probability and trawl/pot selectivity. X-axis is carapace length.

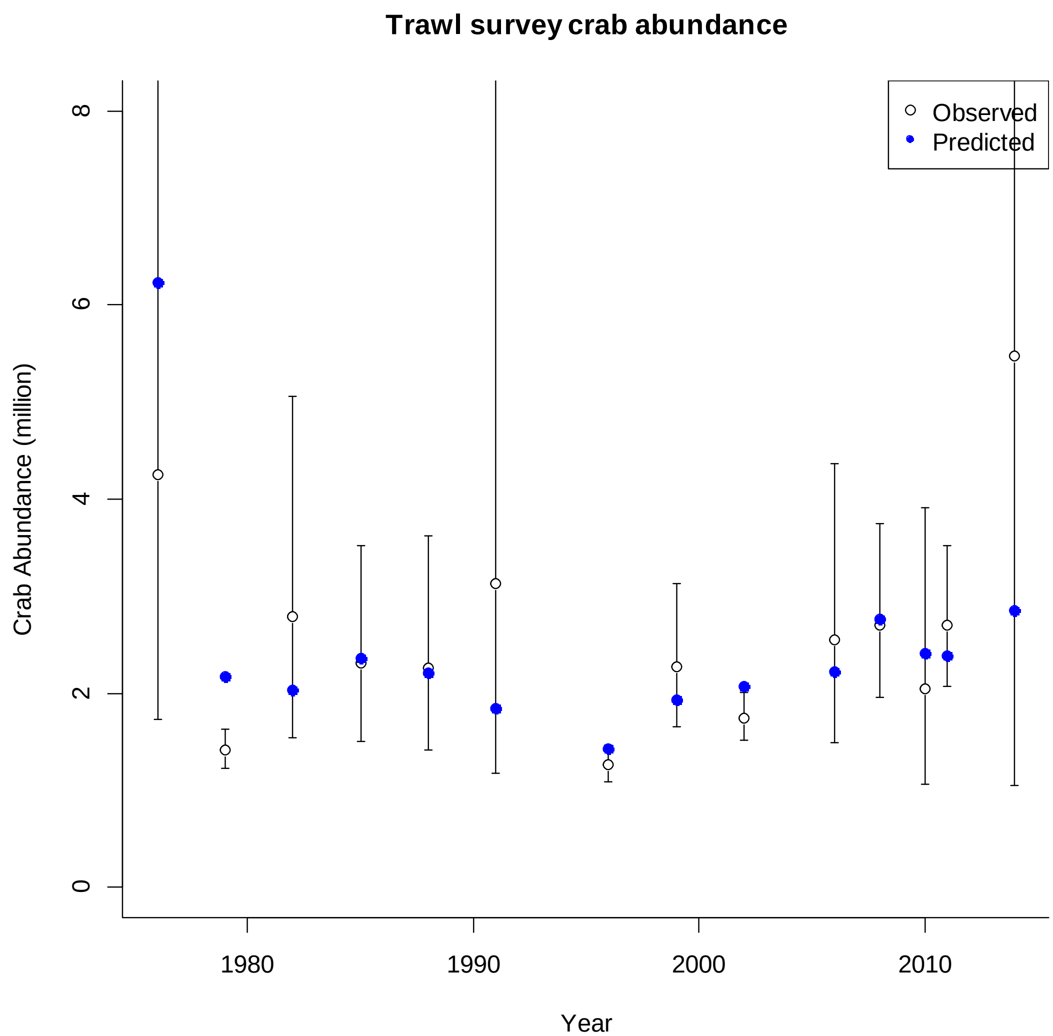


Figure C3-4. Estimated trawl survey male abundance (crab ≥ 74 mm CL).

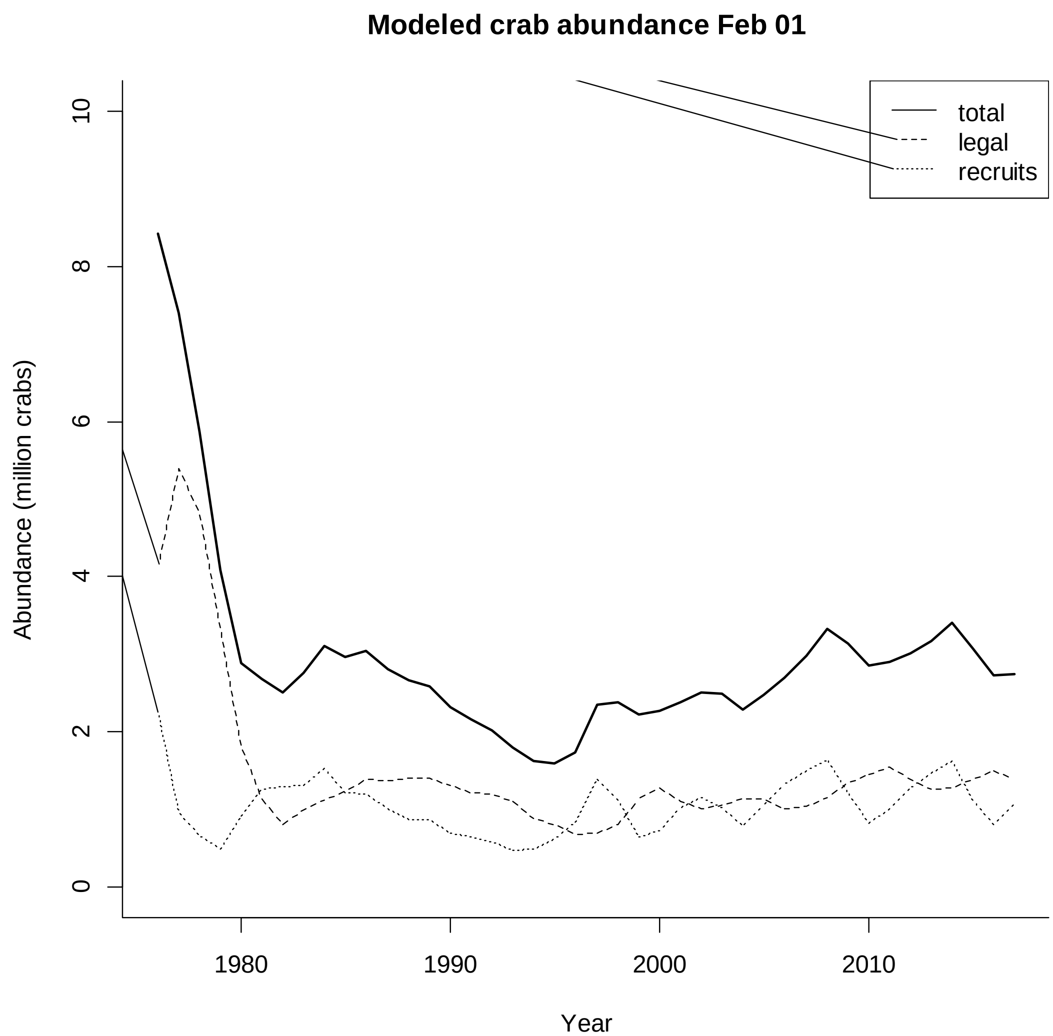


Figure C3-5. Estimated abundance of total, legal, and recruits males from 1976-2016.

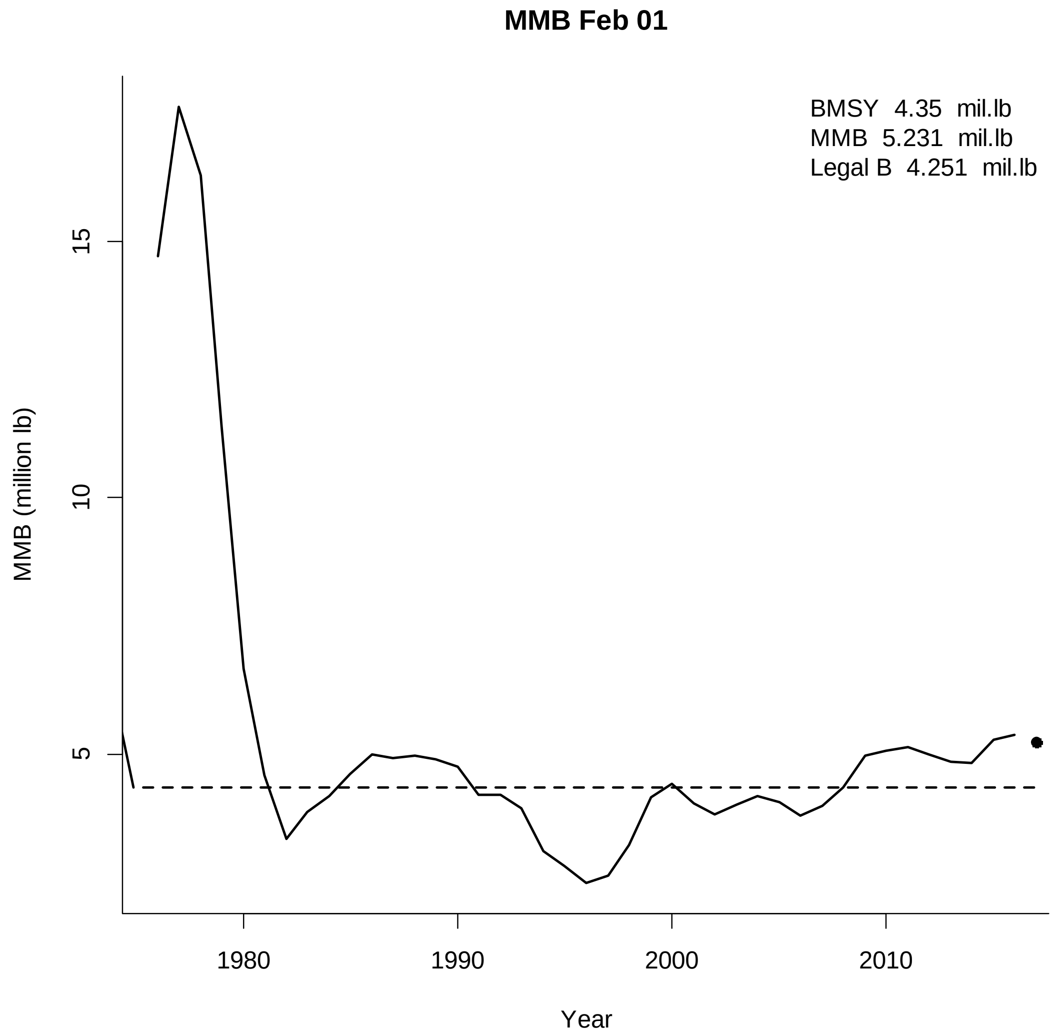


Figure C3-6. Estimated abundance of leg recruits from 1976-2016. Dash line shows B_{msy} (Average MMB of 1980-2016).

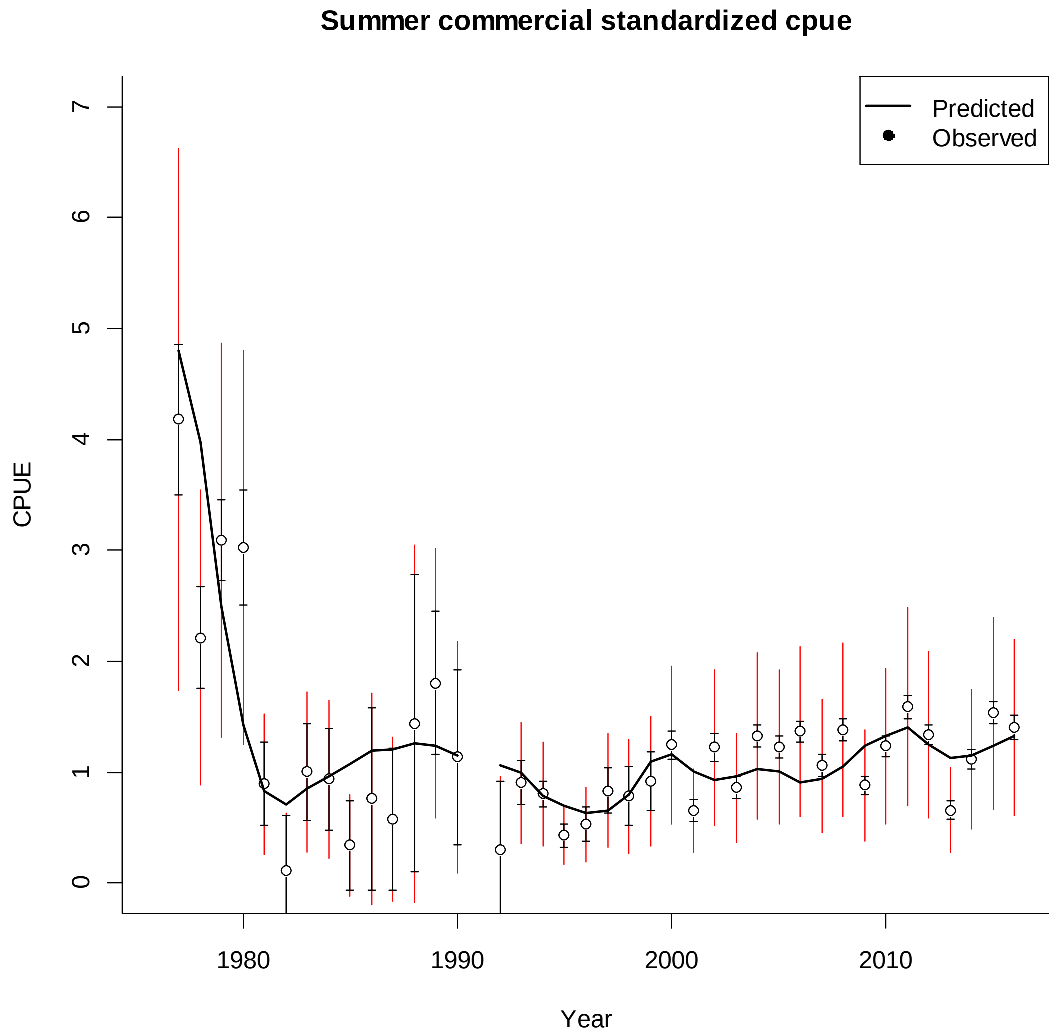


Figure C3-7. Summer commercial standardized cpue (1977-2016).

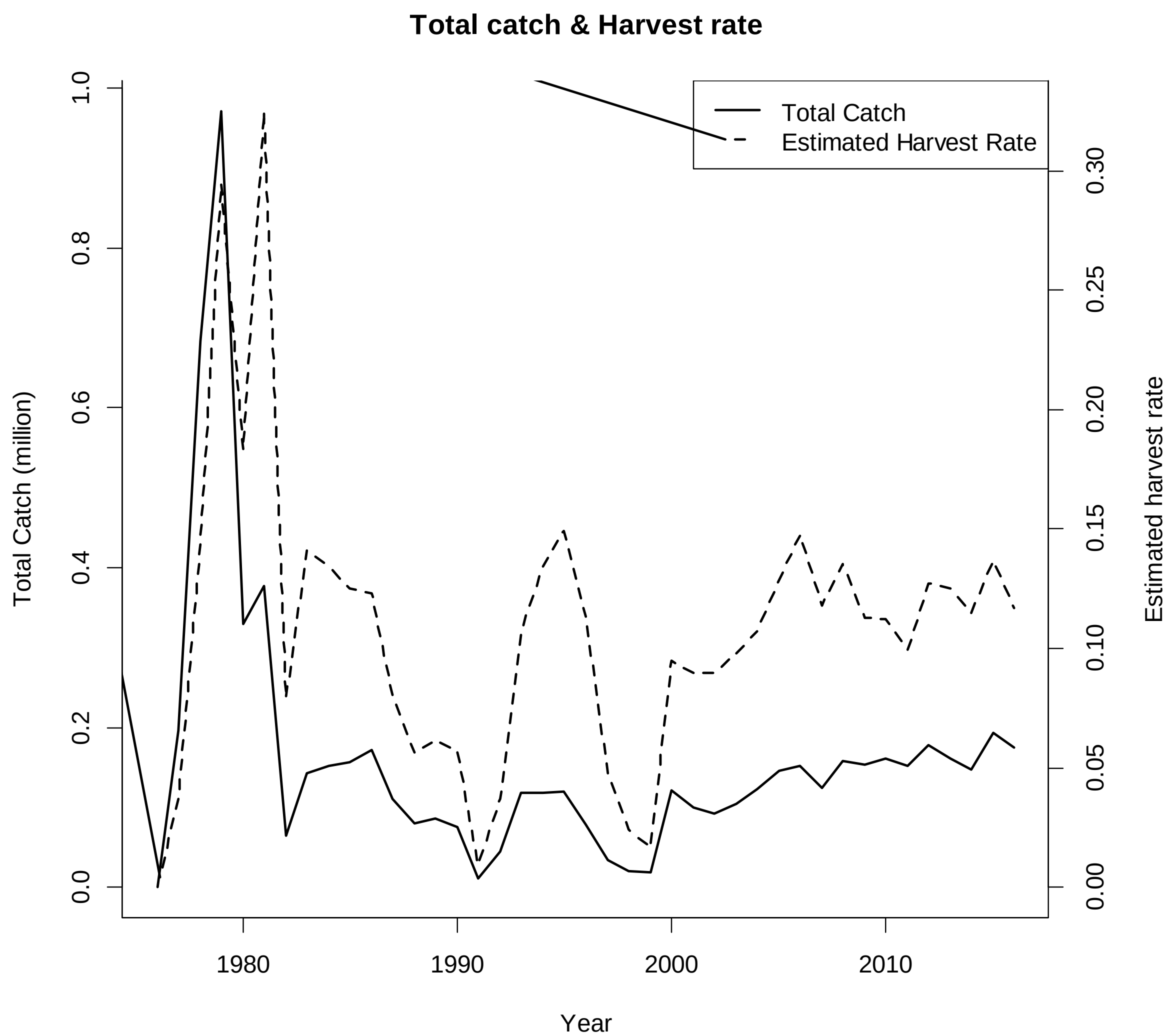


Figure C3-8. Total catch and estimated harvest rate 1976-2016.

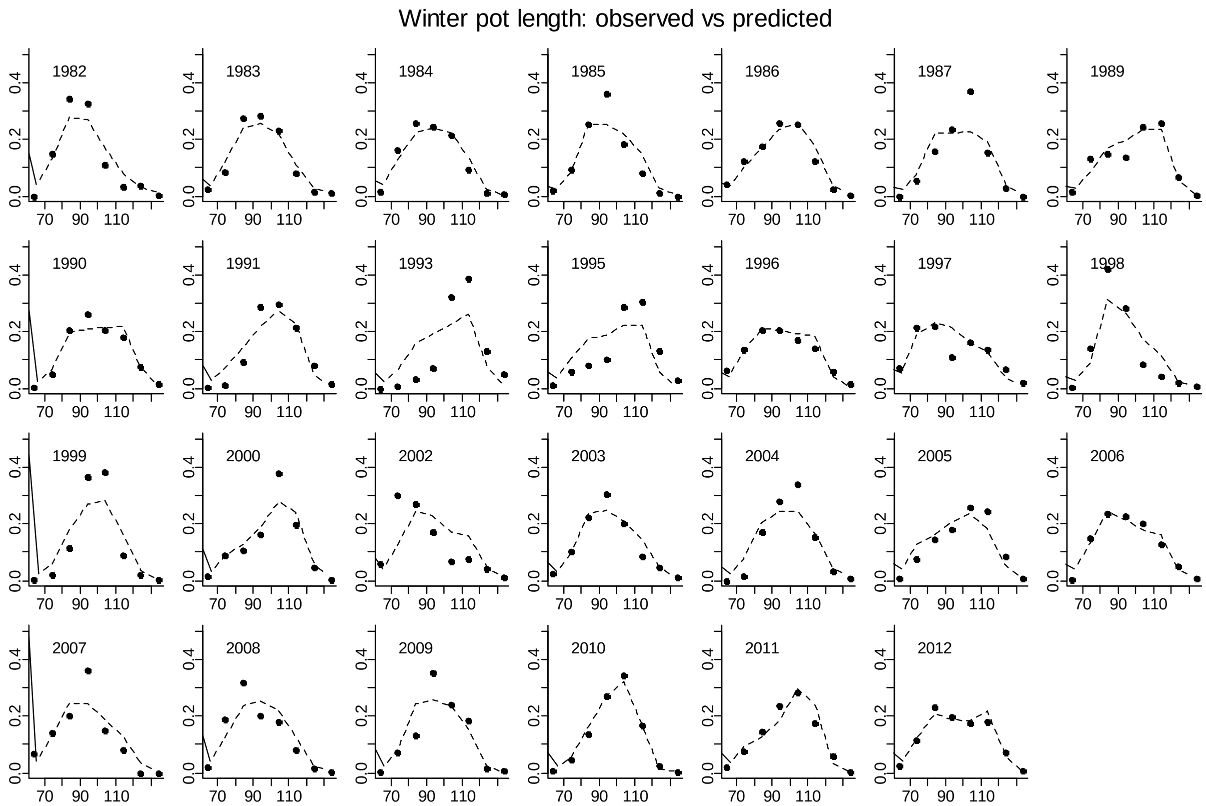


Figure C3-9. Predicted (dashed line) vs. observed (black dots) length class proportions for commercial catch.

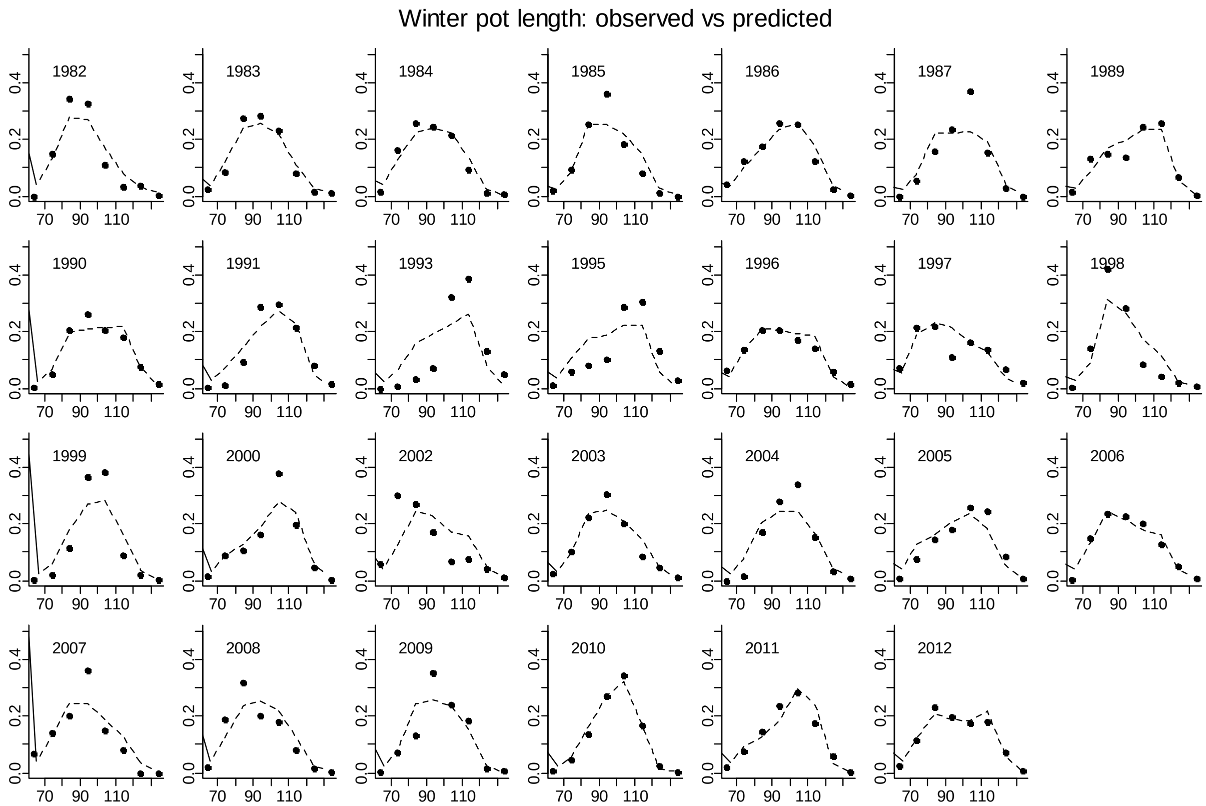


Figure C3-10. Predicted (dashed line) vs. observed (black dots) length class proportions for the winter pot survey.

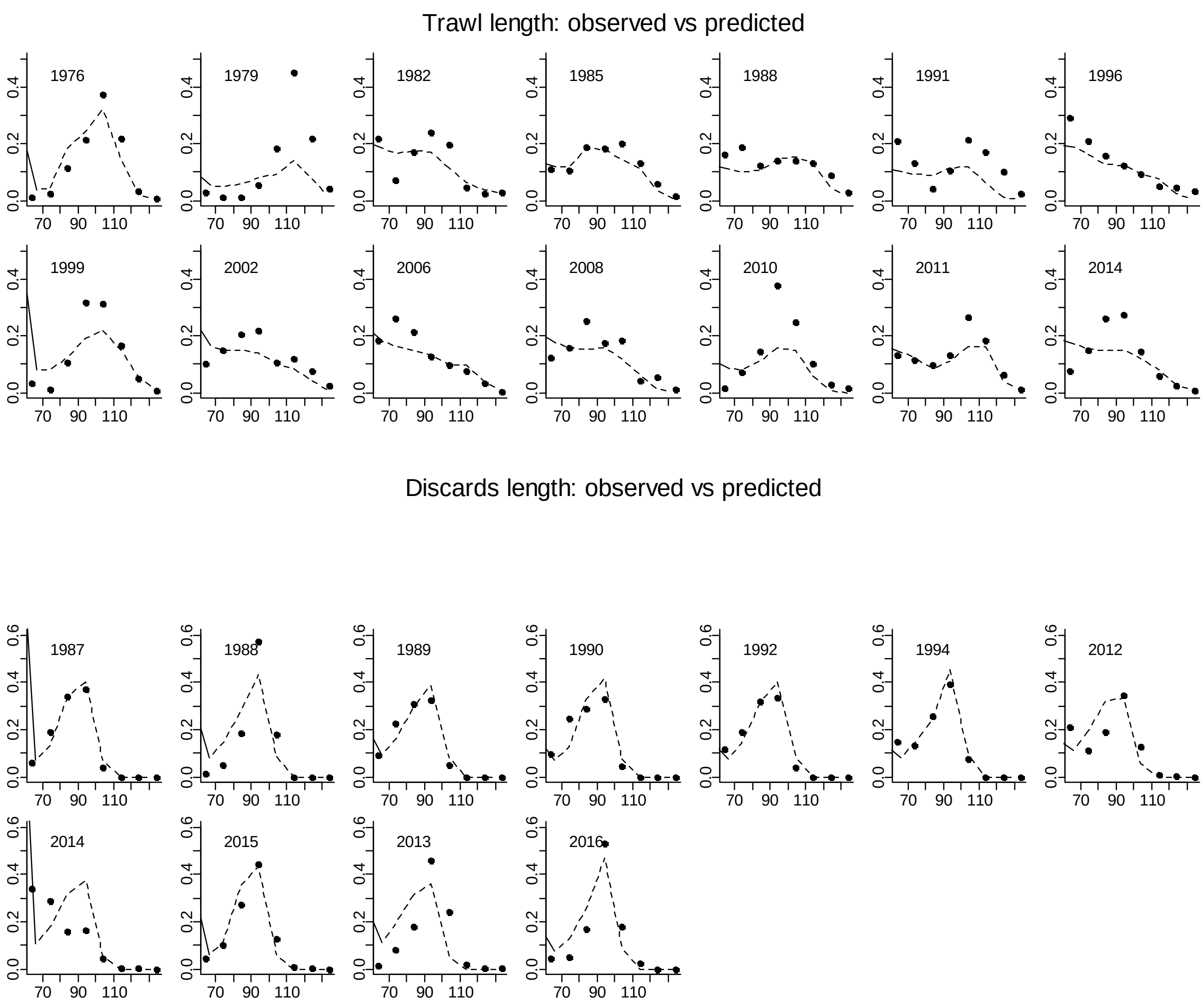


Figure C3-11. Predicted (dashed line) vs. observed (black dots) length class proportions for the trawl survey and observer survey.

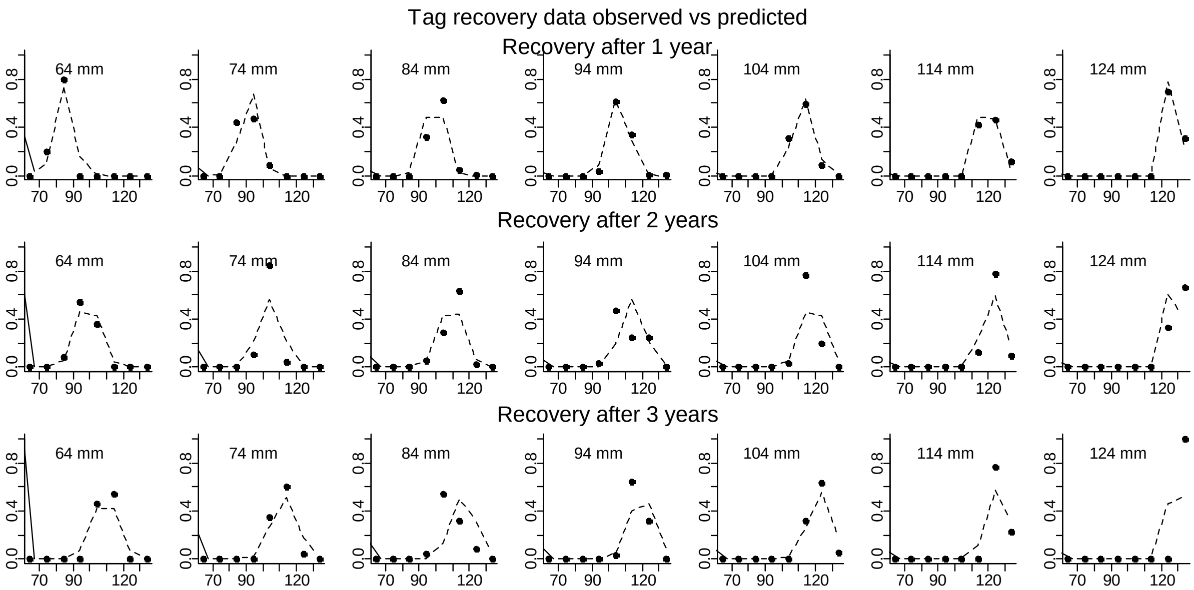


Figure C3-12. Predicted vs. observed length class proportions for tag recovery data.

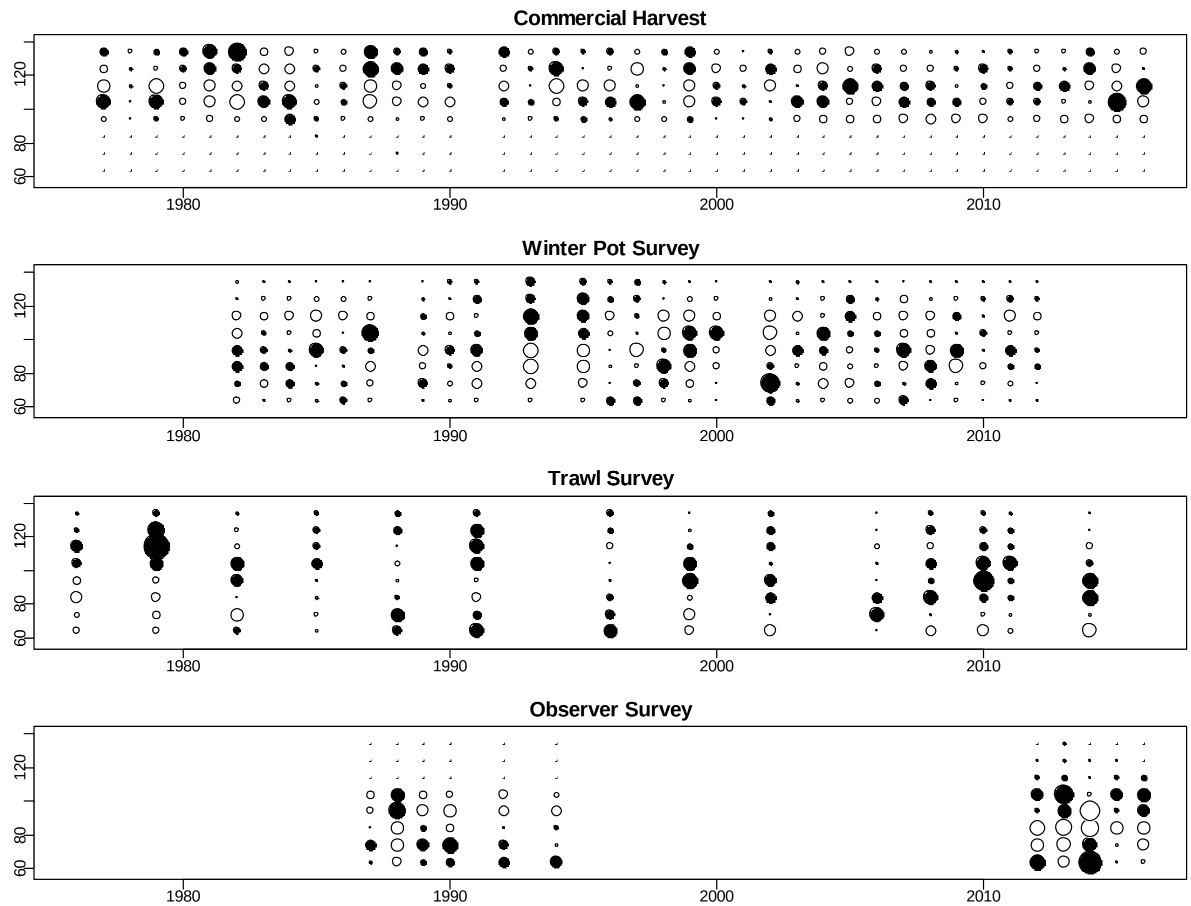


Figure C3-13. Bubble plots of predicted and observed length proportions. Black circle indicates model estimates lower than observed, white circle indicates model estimates higher than observed. Size of circle indicates degree of deviance (larger circle = larger deviance).

Table C3-1 . Summary of parameter estimates for a length-based stock synthesis population model of Norton Sound red king crab.

name	Estimate	std.dev
log_q_1	-6.8583	0.18397
log_q_2	-6.8053	0.113
log_N_{76}	9.0385	0.14549
R_0	6.3851	0.093581
log_σ_R^2	-0.02934	0.43855
log_R_{77}	-0.59451	0.37109
log_R_{78}	-0.72245	0.35641
log_R_{79}	0.22171	0.33078
log_R_{80}	0.36214	0.29911
log_R_{81}	0.30562	0.27501
log_R_{82}	0.34076	0.32462
log_R_{83}	0.55418	0.27834
log_R_{84}	0.02244	0.30842
log_R_{85}	0.32588	0.28853
log_R_{86}	-0.1002	0.30062
log_R_{87}	-0.091858	0.25979
log_R_{88}	-0.065353	0.27097
log_R_{89}	-0.47546	0.2972
log_R_{90}	-0.34257	0.26475
log_R_{91}	-0.56521	0.29376
log_R_{92}	-0.79635	0.32116
log_R_{93}	-0.59856	0.30042
log_R_{94}	-0.33692	0.2729
log_R_{95}	-0.009389	0.2432
log_R_{96}	0.56497	0.22654
log_R_{97}	-0.14316	0.31811
log_R_{98}	-0.60908	0.32381
log_R_{99}	-0.10668	0.3217
log_R_{00}	0.20028	0.27578
log_R_{01}	0.2162	0.26082
log_R_{02}	0.008416	0.31662
log_R_{03}	-0.32715	0.3405
log_R_{04}	0.29394	0.25205
log_R_{05}	0.39062	0.24289
log_R_{06}	0.50726	0.26182

name	Estimate	std.dev
log_R_{13}	0.57828	0.29178
log_R_{14}	-0.17835	0.41491
log_R_{15}	-0.17747	0.44038
a_1	2.4484	4.4508
a_2	2.7157	4.3115
a_3	4.0391	4.1132
a_4	4.3201	4.0962
a_5	4.5837	4.088
a_6	3.778	4.1157
a_7	2.0618	4.3458
r1	14.98	104.23
r2	14.595	104.23
log_α	-2.1128	0.054509
dev_log_α	-0.17195	0.19472
dev_log_α	0.392	0.19429
dev_log_α	-0.54516	0.21378
dev_log_α	0.15608	0.16555
dev_log_α	0.098333	0.21973
dev_log_α	0.035522	0.16978
dev_log_α	0.18223	0.13402
dev_log_α	-0.013735	0.13231
dev_log_α	-0.10518	0.14577
dev_log_α	0.12224	0.15445
dev_log_α	0.028036	0.13402
dev_log_α	-0.05434	0.13231
dev_log_α	-0.15861	0.14577
dev_log_α	0.48973	0.15445
dev_log_α	-0.39657	0.15659
dev_log_α	0.050505	0.14867
dev_log_α	0.52088	0.17082
dev_log_α	-0.60772	0.17362
dev_log_α	0.2344	0.14589
dev_log_α	-0.27015	0.16773
dev_log_α	0.22005	0.18391
dev_log_α	-0.18355	0.1633

name	Estimate	std.dev
dev_log_α	-0.13989	0.16644
dev_log_α	0.33544	0.16915
dev_log_α	-0.149	0.18079
dev_log_α	0.33733	0.1673
dev_log_α	-0.34113	0.15872
dev_log_α	-0.20129	0.11728
dev_log_α	-0.10364	0.15316
dev_log_α	0.29929	0.20177
dev_log_α	-0.18434	0.19564
dev_log_α	-0.10611	0.20188
dev_log_α	0.11698	0.23437
log_ϕ_{st1}	-2.6629	0.18513
log_ϕ_w	-2.0391	20627
Sw_7	0.072994	0.051463
Sw_8	0.4803	0.035034
log_ϕ_1	-2.0768	353.55
w^2_t	0.075548	20482
q	0.8506	0.023259
ms	2.9815	0.15336
σ	4.6761	0.33564
β_1	11.617	0.2647
β_2	7.7011	0.15336

log_R_{07}	0.57575	0.24945
log_R_{08}	-0.002374	0.32726
log_R_{09}	-0.29474	0.31064
log_R_{10}	0.23332	0.24985
log_R_{11}	0.36734	0.29378
log_R_{12}	0.49808	0.29925

dev_log_α	-0.028803	0.17267
dev_log_α	-0.11736	0.20509
dev_log_α	0.26928	0.18738
dev_log_α	-0.12295	0.16818
dev_log_α	-0.065131	0.20634
dev_log_α	-0.000259	0.20505
dev_log_α	0.17855	0.16644

Appendix C4: Results Model 3

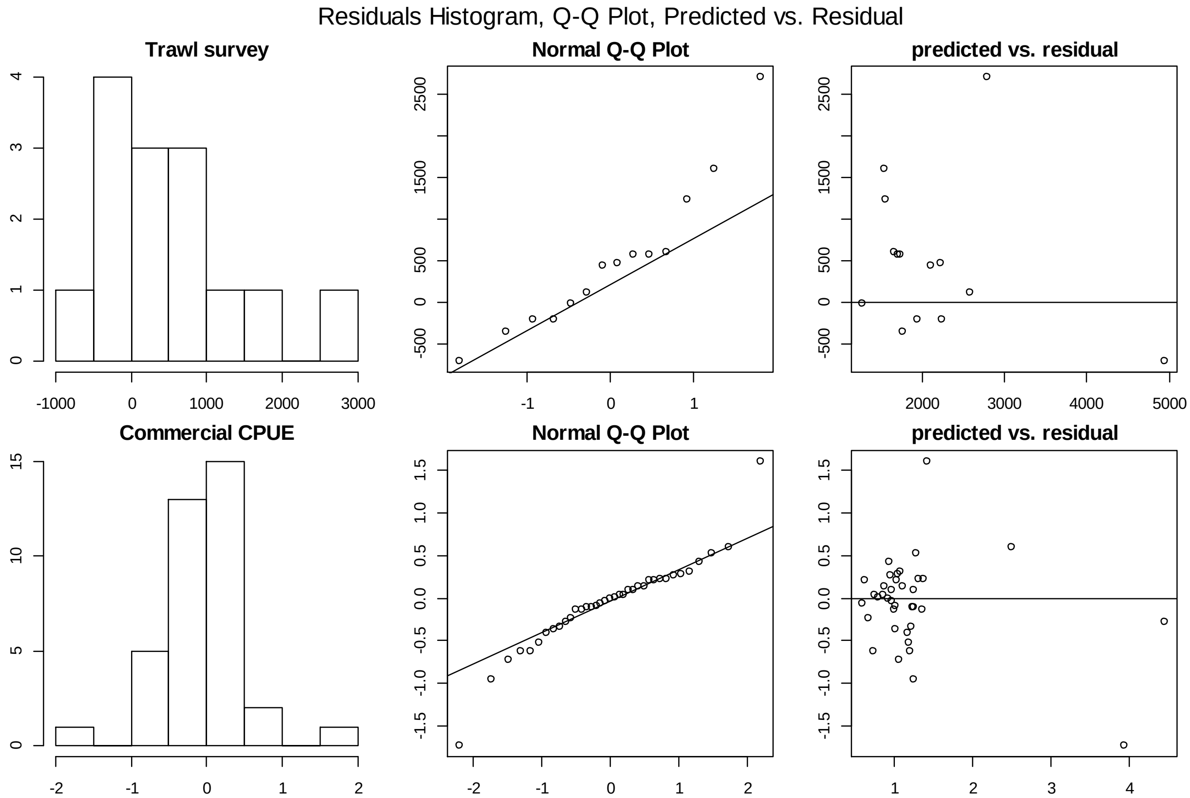


Figure C4-1. QQ Plot of Trawl survey and Commercial CPUE.

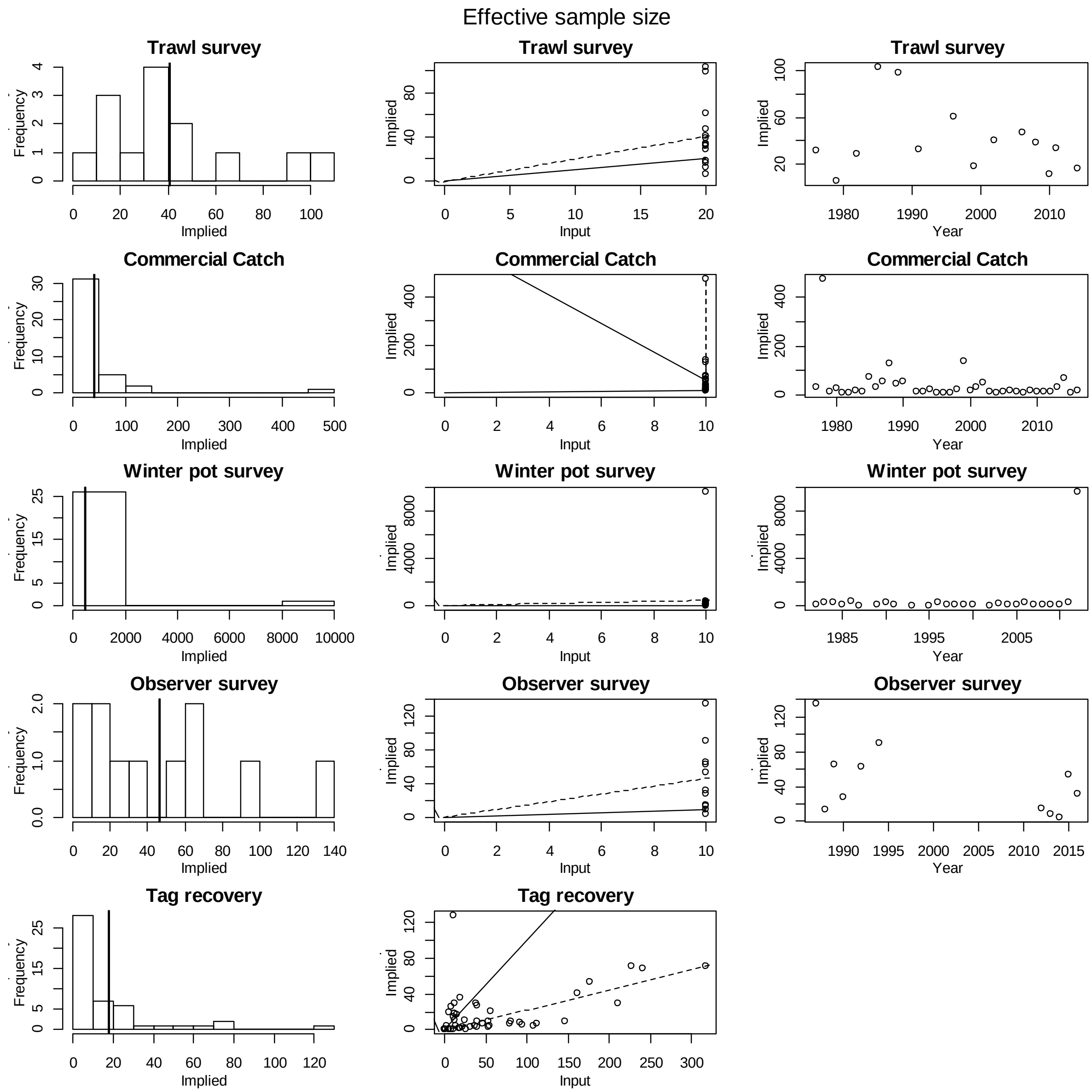


Figure C4-2: Implied effective samples. Figures in the first column show implied effective sample size (x-axis) vs. frequency (y-axis). Vertical solid line is the mean implied effective sample size. The second column show input sample size (x-axis) vs. implied effective sample size (y-axis). Dashed line indicates linear regression slope, and solid line is 1:1 line. The third column show year (x-axis) vs. implied effective sample size (y-axis).

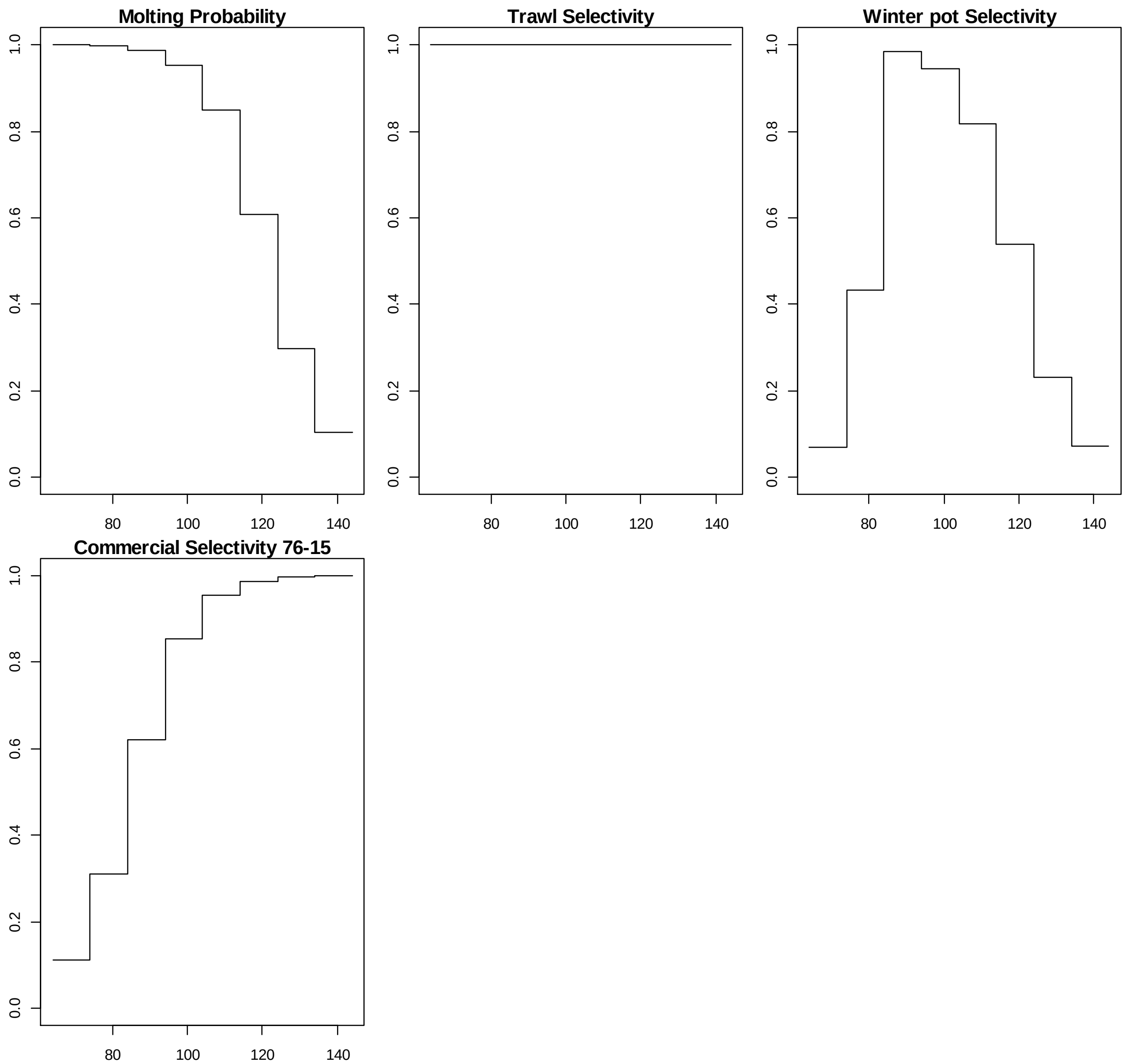


Figure C4-3. Molting probability and trawl/pot selectivity. X-axis is carapace length.

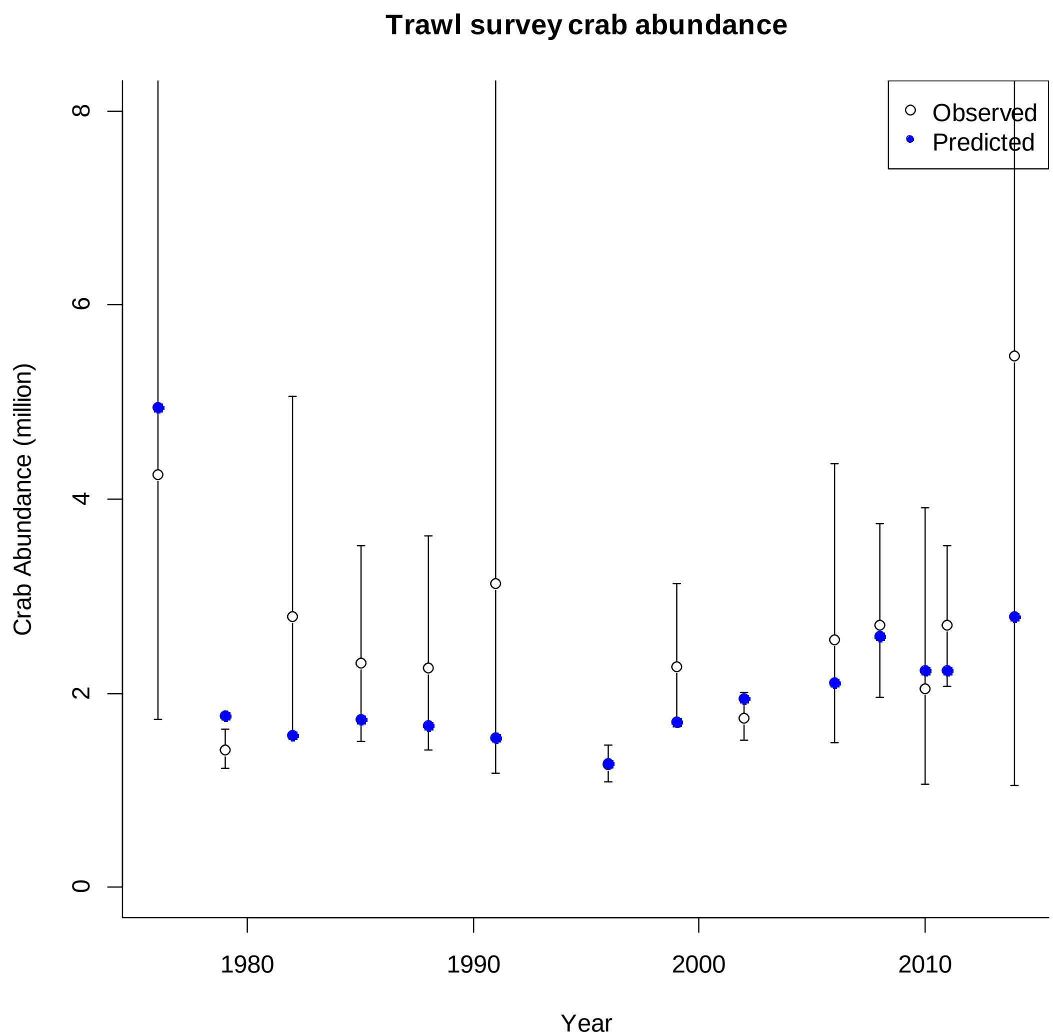


Figure C4-4. Estimated trawl survey male abundance (crab ≥ 74 mm CL).

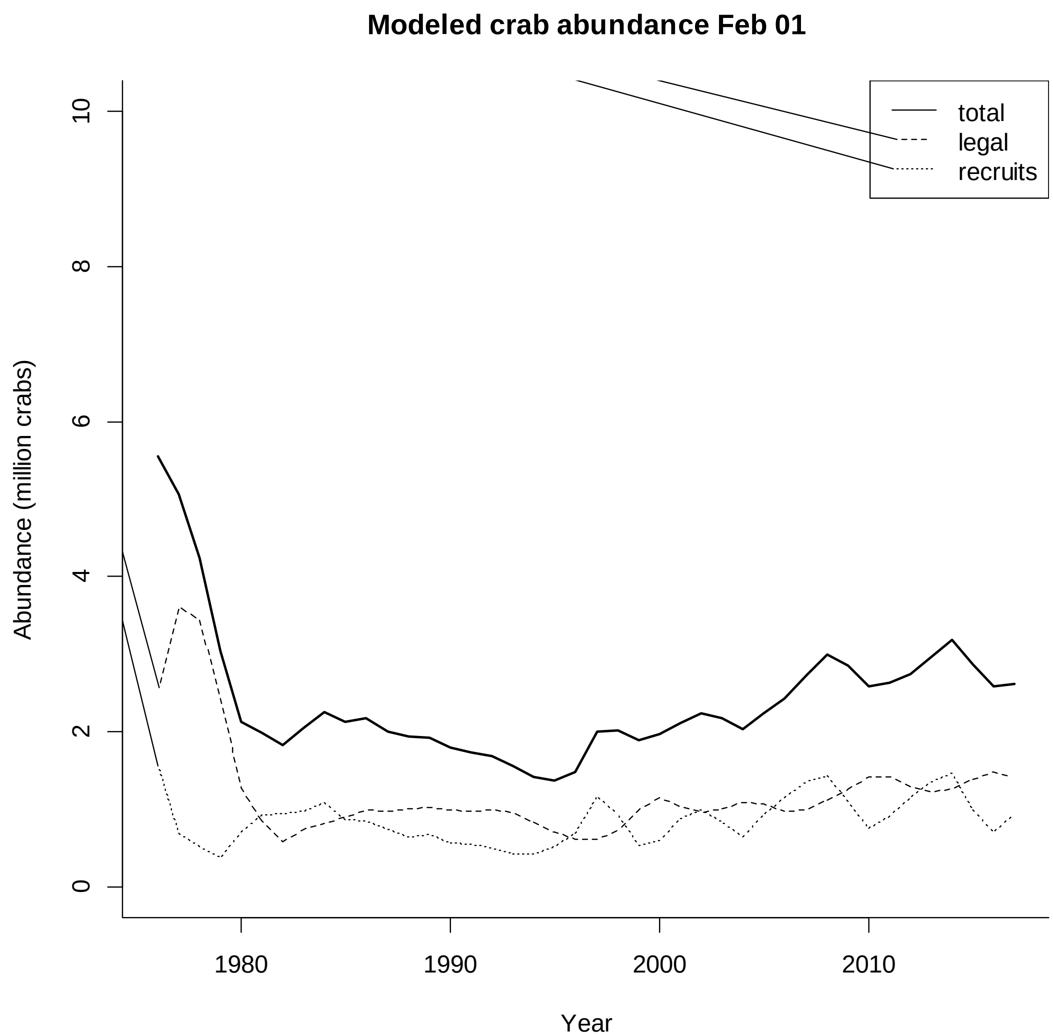


Figure C4-5. Estimated abundance of total, legal, and recruit males from 1976-2016.

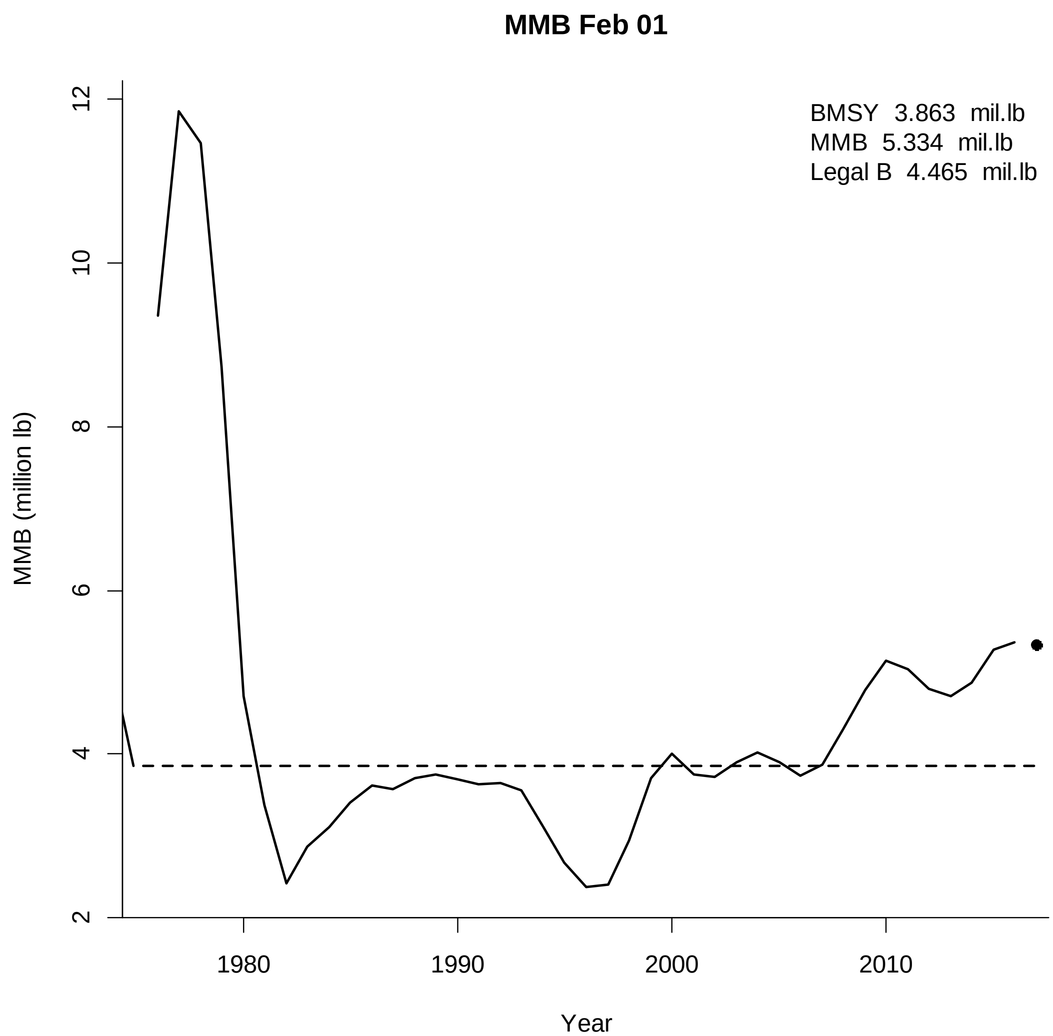


Figure C4-6. Estimated abundance of leg recruits from 1976-2016. Dash line shows B_{msy} (Average MMB of 1980-2016).

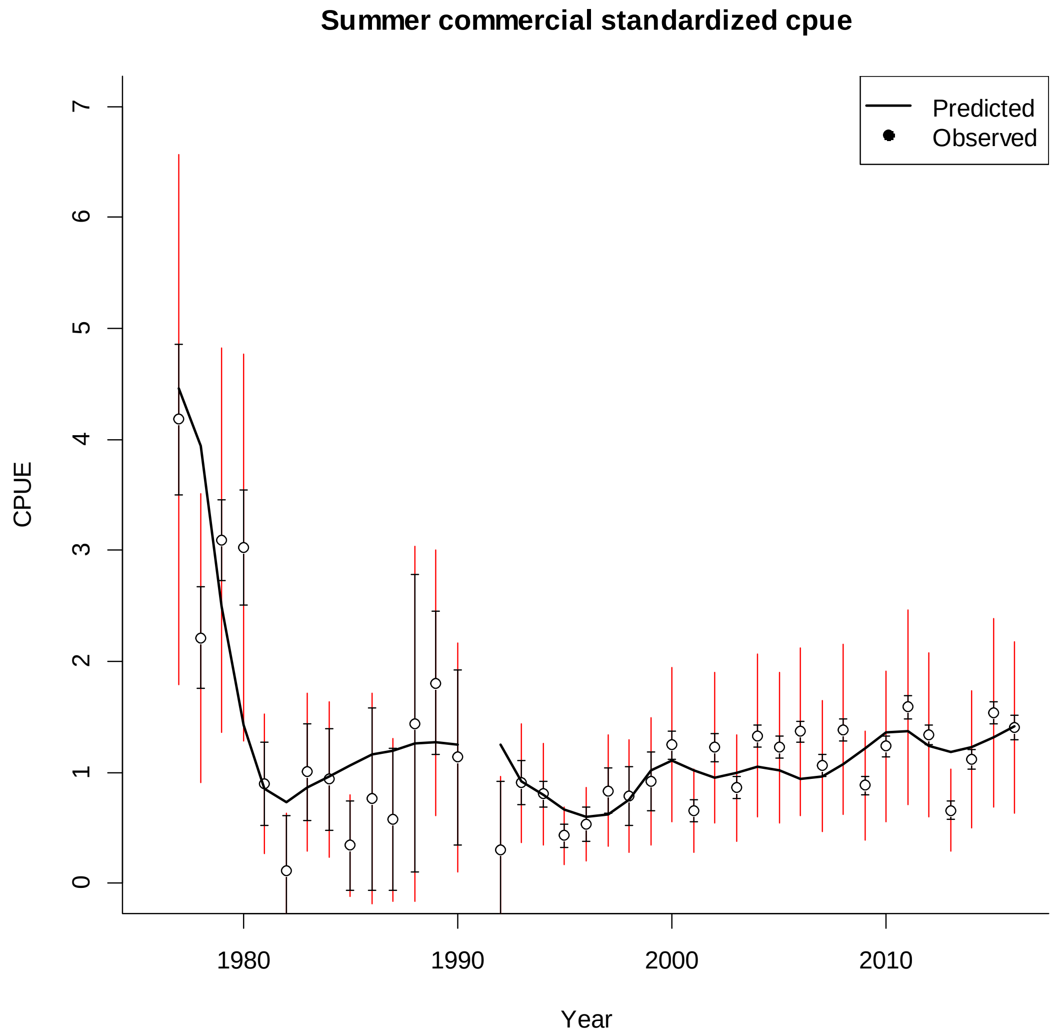


Figure C4-7. Summer commercial standardized cpue (1977-2016).

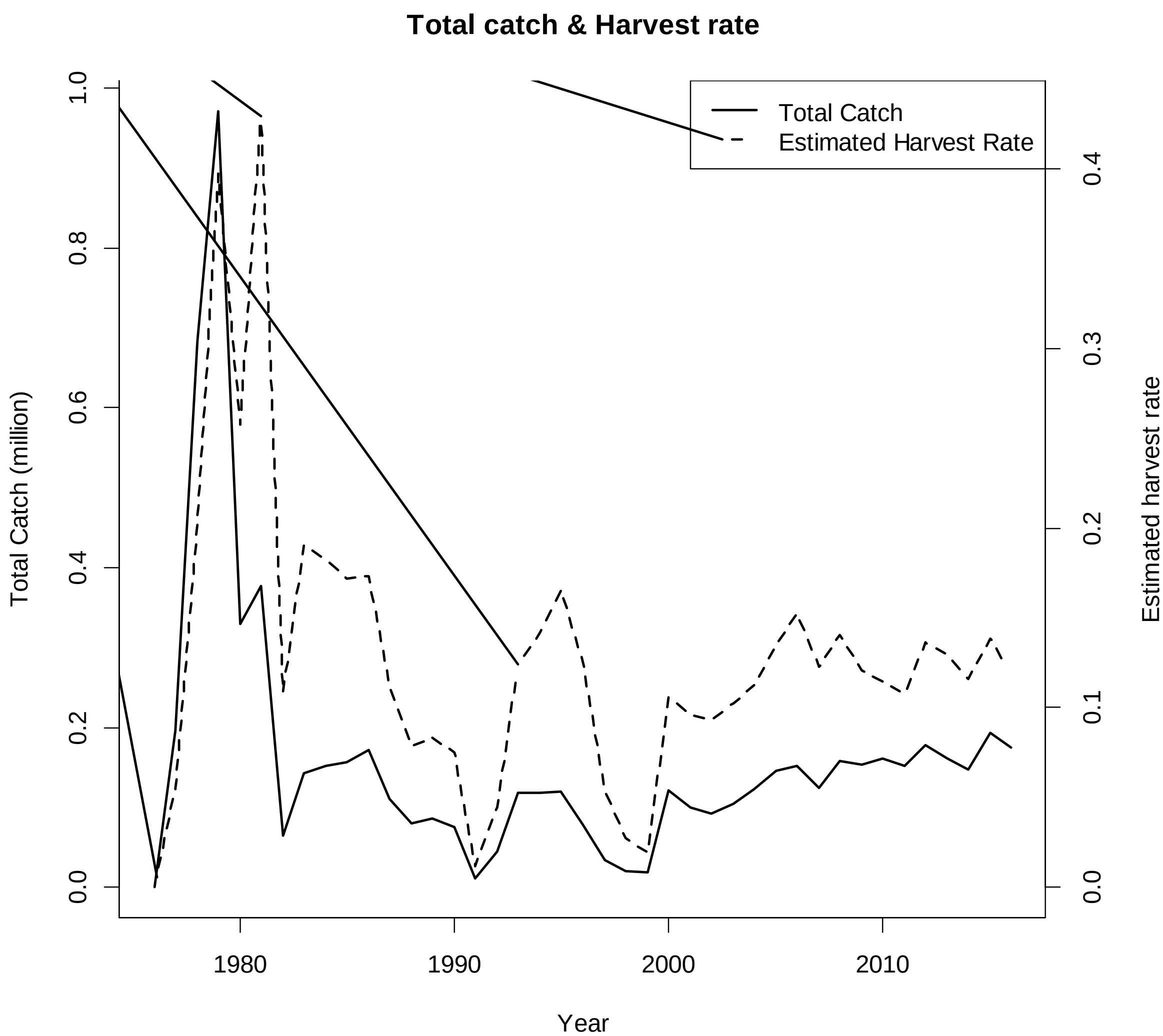


Figure C4-8. Total catch and estimated harvest rate 1976-2016.

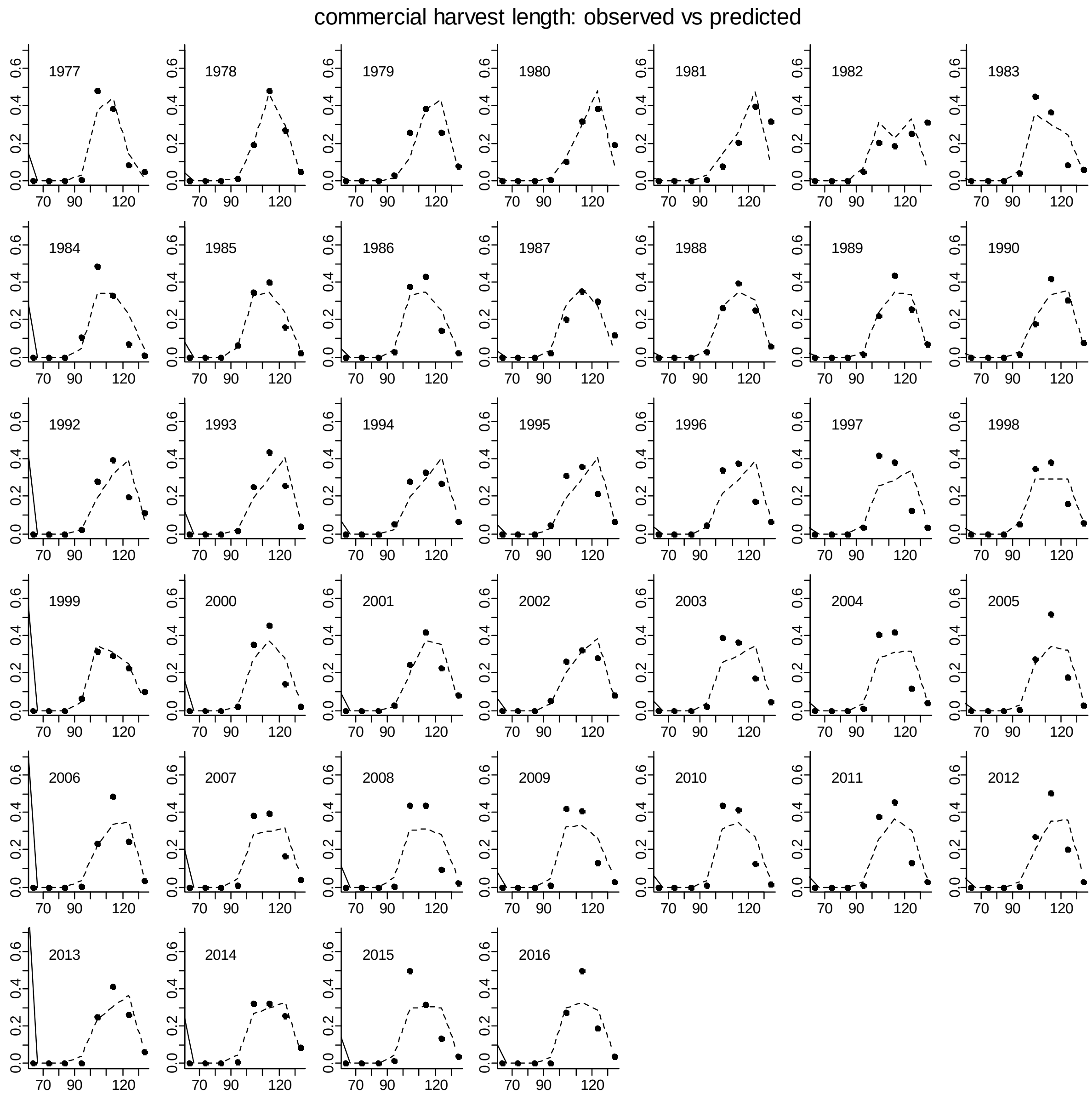


Figure C4-9. Predicted (dashed line) vs. observed (black dots) length class proportions for commercial catch.

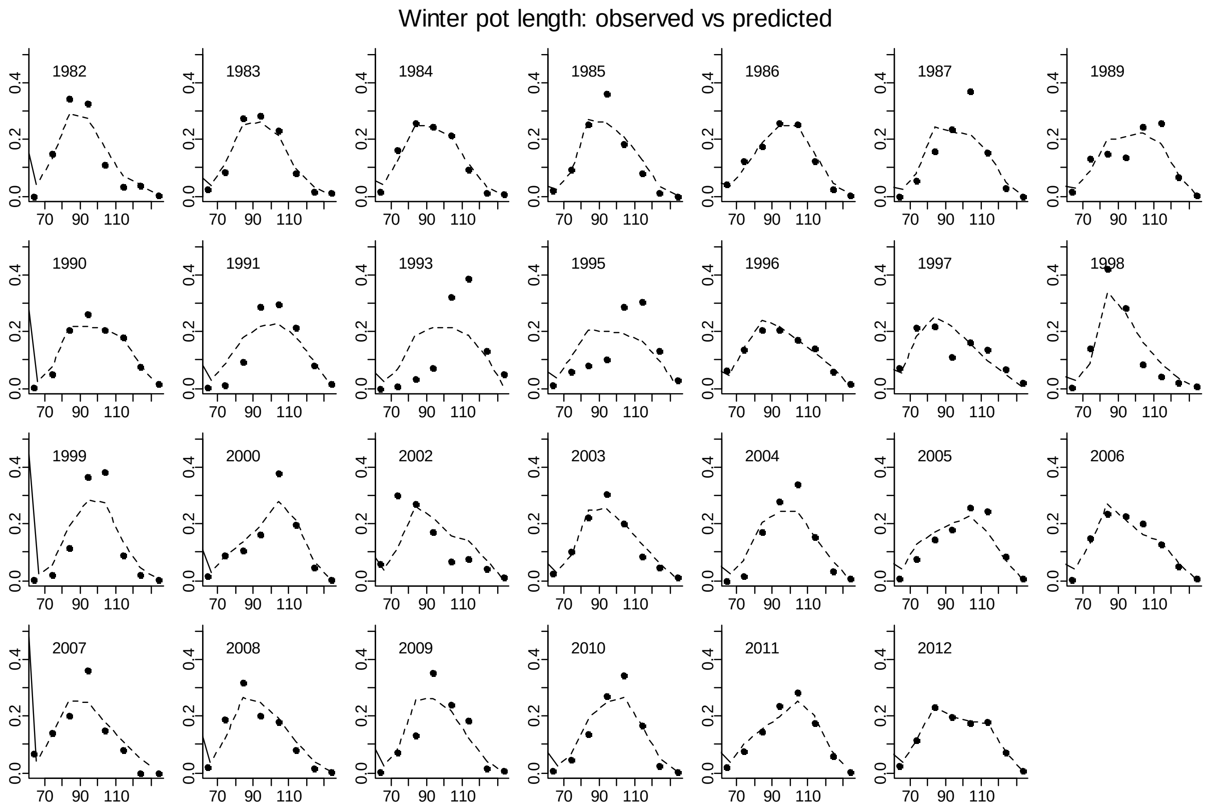


Figure C4-10. Predicted (dashed line) vs. observed (black dots) length class proportions for the winter pot survey.

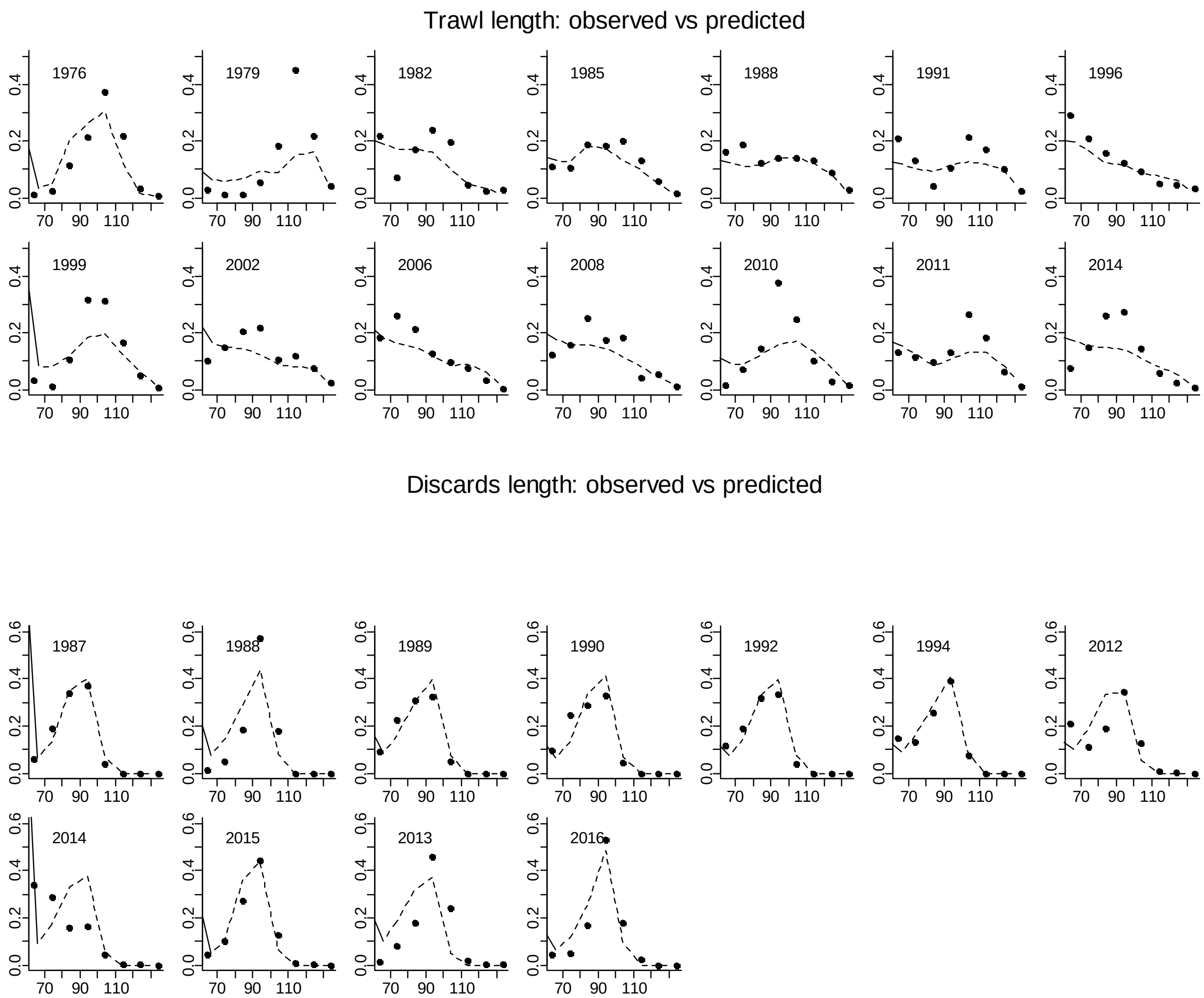


Figure C4-11. Predicted (dashed line) vs. observed (black dots) length class proportions for the trawl survey and observer survey.

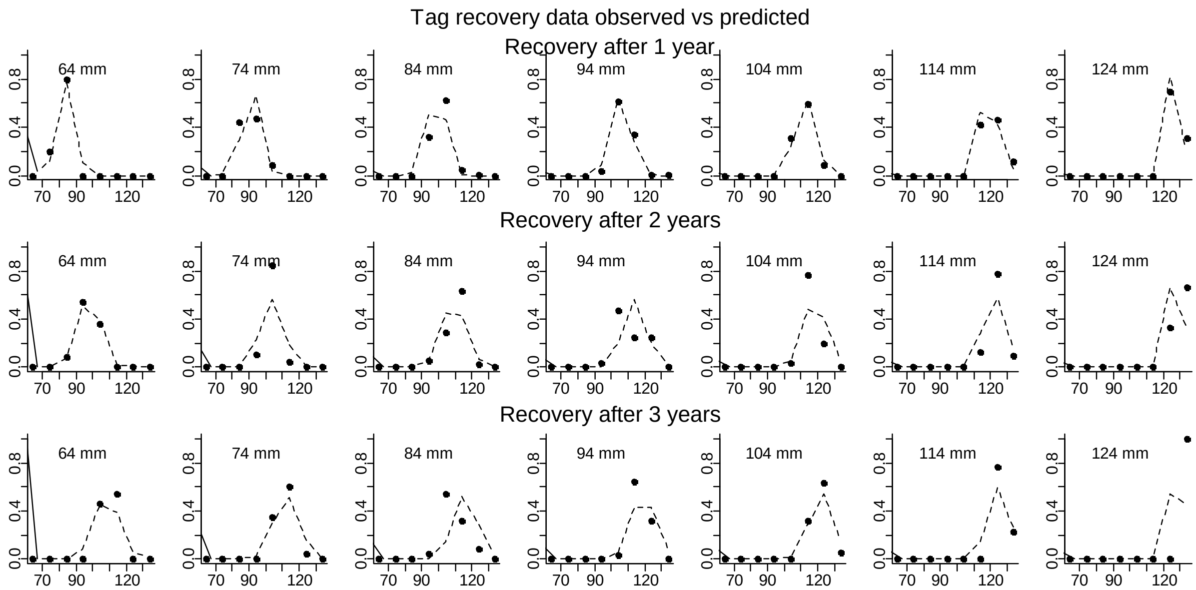


Figure C4-12. Predicted vs. observed length class proportions for tag recovery data.

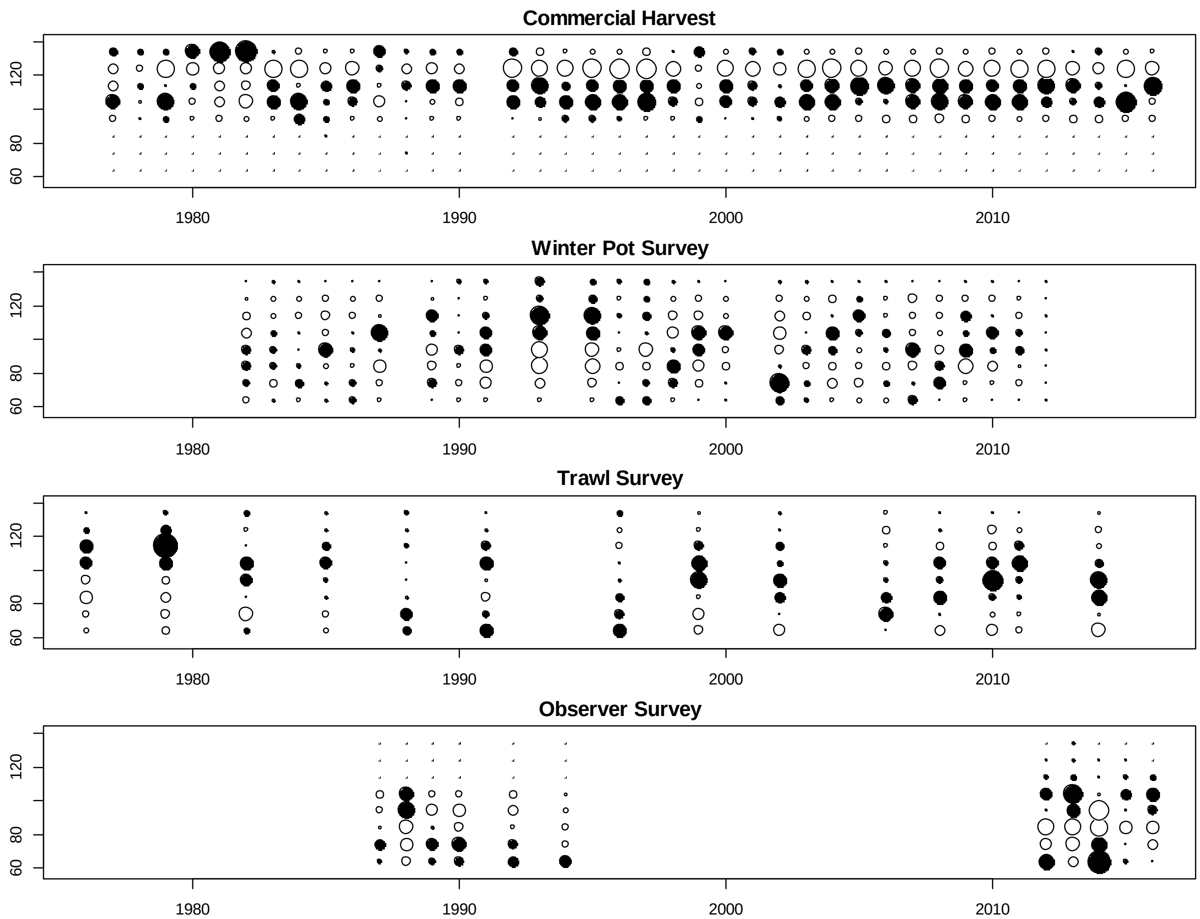


Figure C4-13. Bubble plots of predicted and observed length proportions. Black circle indicates model estimates lower than observed, white circle indicates model estimates higher than observed. Size of circle indicates degree of deviance (larger circle = larger deviance).

Table C4-1 . Summary of parameter estimates for a length-based stock synthesis population model of Norton Sound red king crab.

name	Estimate	std.dev
log_q_1	-6.5356	0.13691
log_q_2	-6.7661	0.10242
log_N_{76}	8.6216	0.071289
R_0	6.1728	0.060268
$log\_\sigma_R^2$	-0.070438	0.41689
log_R_{77}	-0.65897	0.36104
log_R_{78}	-0.7895	0.34423
log_R_{79}	0.17136	0.30644
log_R_{80}	0.21027	0.29008
log_R_{81}	0.19289	0.26078
log_R_{82}	0.25152	0.30692
log_R_{83}	0.38914	0.26745
log_R_{84}	-0.10486	0.29313
log_R_{85}	0.1818	0.27564
log_R_{86}	-0.19642	0.29296
log_R_{87}	-0.18507	0.2535
log_R_{88}	-0.13107	0.26835
log_R_{89}	-0.45984	0.29419
log_R_{90}	-0.31643	0.2636
log_R_{91}	-0.51306	0.29222
log_R_{92}	-0.70822	0.32106
log_R_{93}	-0.54853	0.3003
log_R_{94}	-0.32071	0.27559
log_R_{95}	0.009511	0.23608
log_R_{96}	0.5943	0.2207
log_R_{97}	-0.17398	0.32579
log_R_{98}	-0.58621	0.32431
log_R_{99}	-0.11391	0.32867
log_R_{00}	0.2552	0.27728
log_R_{01}	0.23873	0.25335
log_R_{02}	-0.063146	0.32305
log_R_{03}	-0.28026	0.34357
log_R_{04}	0.38026	0.25361
log_R_{05}	0.41843	0.24809
log_R_{06}	0.62268	0.2561

name	Estimate	std.dev
log_R_{13}	0.64842	0.29826
log_R_{14}	-0.14501	0.42093
log_R_{15}	-0.12872	0.44553
a_1	1.5545	3.9787
a_2	2.0523	3.7806
a_3	3.44	3.5564
a_4	3.6967	3.5395
a_5	3.8457	3.5319
a_6	2.9585	3.5655
a_7	0.96949	3.8341
r1	14.991	50.669
r2	14.613	50.669
log_α	-2.0444	0.019886
log_ϕ_{st1}	-14.909	367.26
log_ϕ_w	-2.0019	0.039445
Sw_7	0.068806	0.032955
Sw_8	0.43364	0.10289
log_ϕ_1	-2.0534	0.054963
w^2_t	0.072189	0.021541
q	1	8.21E-05
ms	4.0297	0.6532
σ	4.4792	0.23254
β_1	10.534	0.75922
β_2	7.9747	0.19286

log_R_{07}	0.60445	0.25248
log_R_{08}	0.15002	0.3198
log_R_{09}	-0.21559	0.31766
log_R_{10}	0.33631	0.24973
log_R_{11}	0.43576	0.3049
log_R_{12}	0.61894	0.30805

Appendix C5: Results Model 4

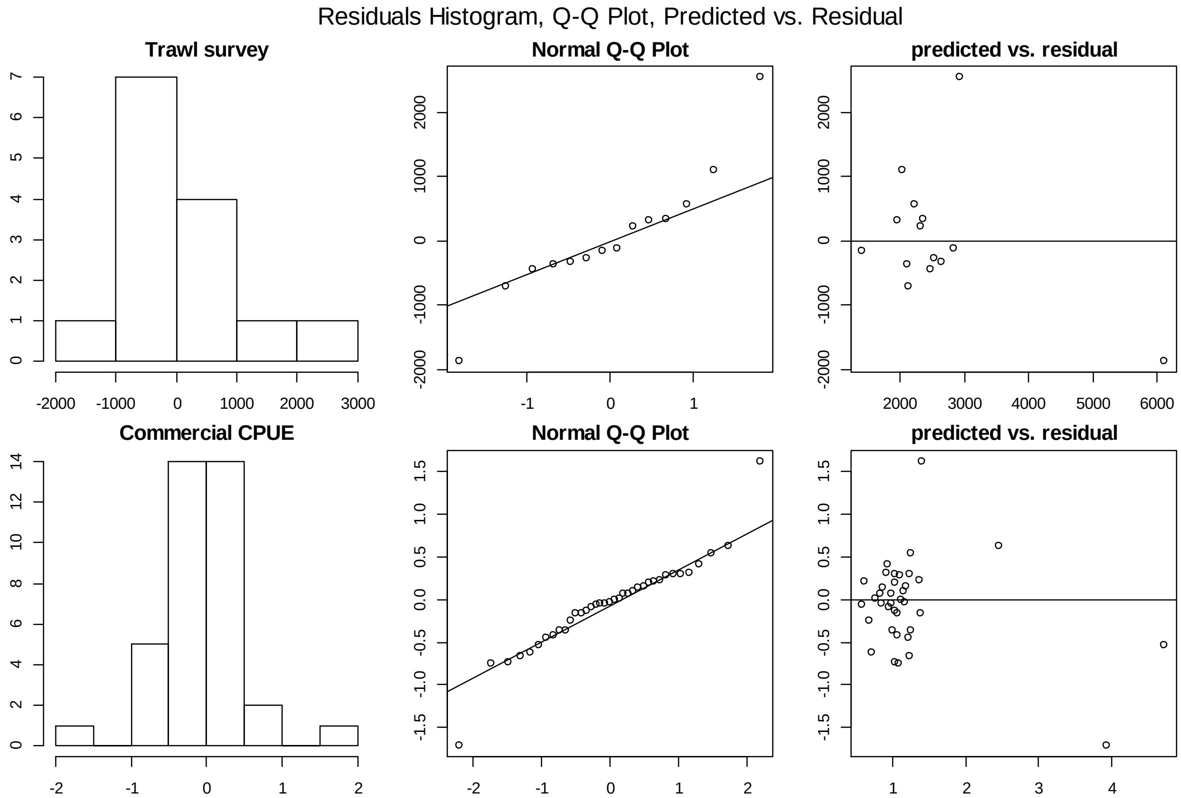


Figure C5-1. QQ Plot of Trawl survey and Commercial CPUE.

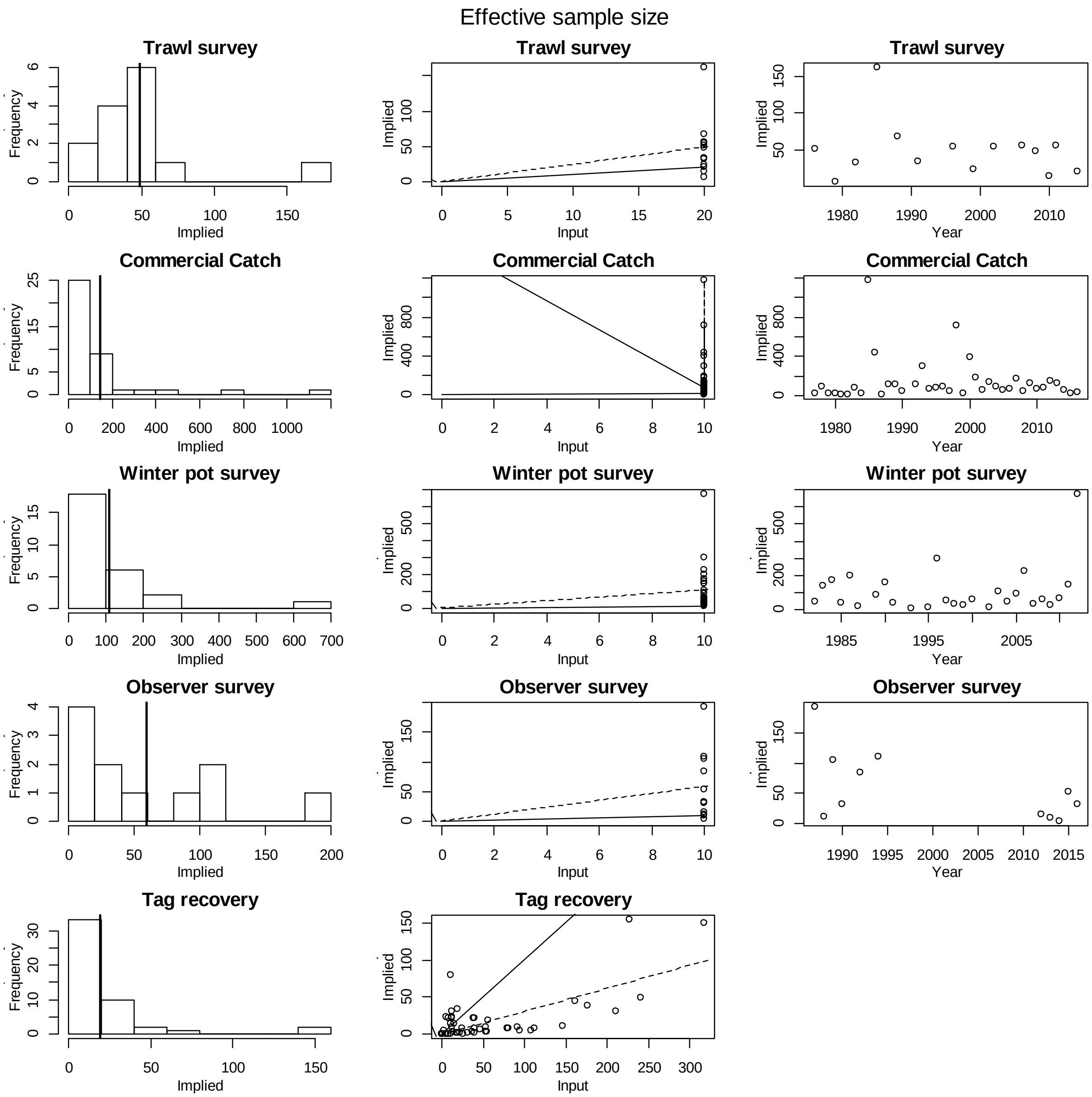


Figure C5-2: Implied effective samples. Figures in the first column show implied effective sample size (x-axis) vs. frequency (y-axis). Vertical solid line is the mean implied effective sample size. The second column show input sample size (x-axis) vs. implied effective sample size (y-axis). Dashed line indicates linear regression slope, and solid line is 1:1 line. The third column show year (x-axis) vs. implied effective sample size (y-axis).

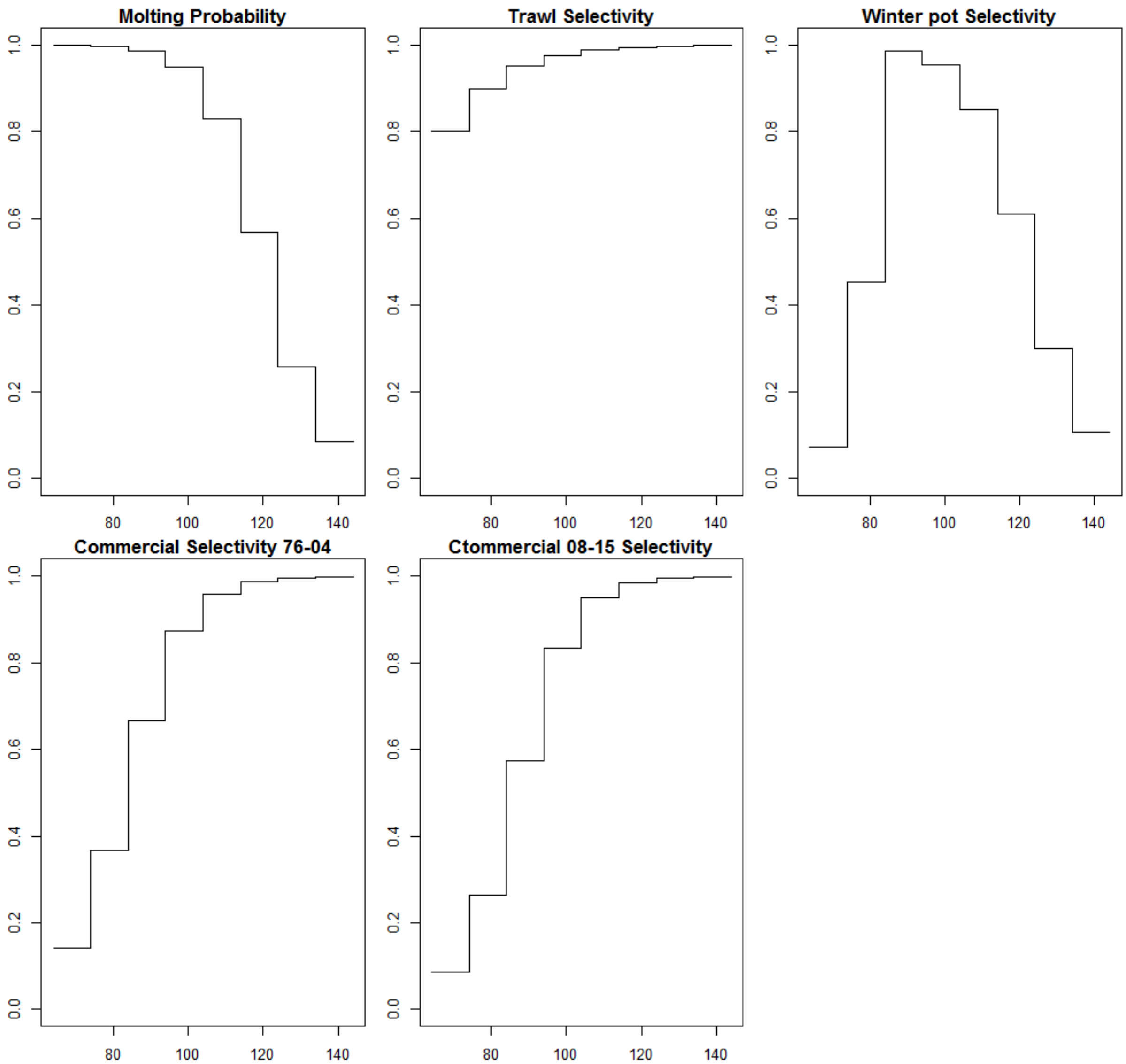


Figure C5-3. Molting probability and trawl/pot selectivity. X-axis is carapace length.

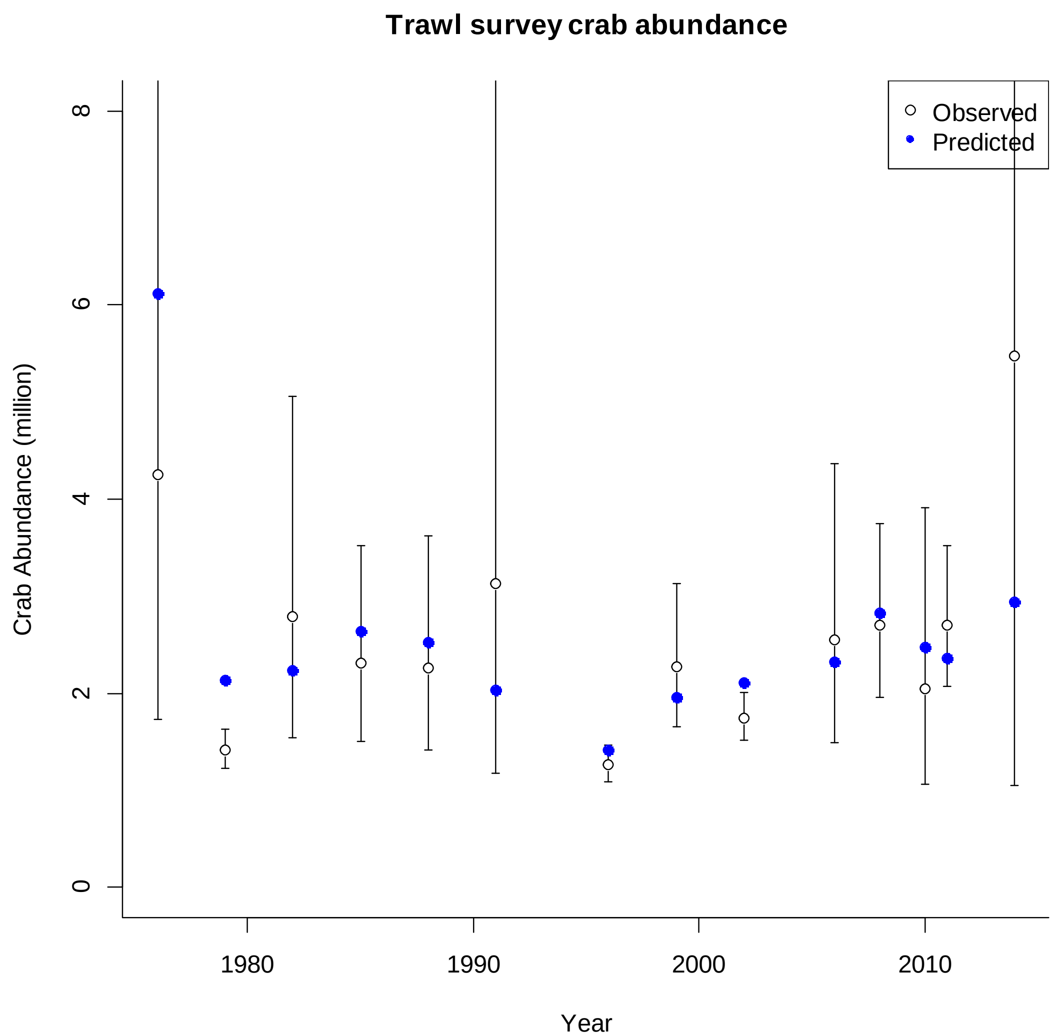


Figure C5-4. Estimated trawl survey male abundance (crab ≥ 74 mm CL).

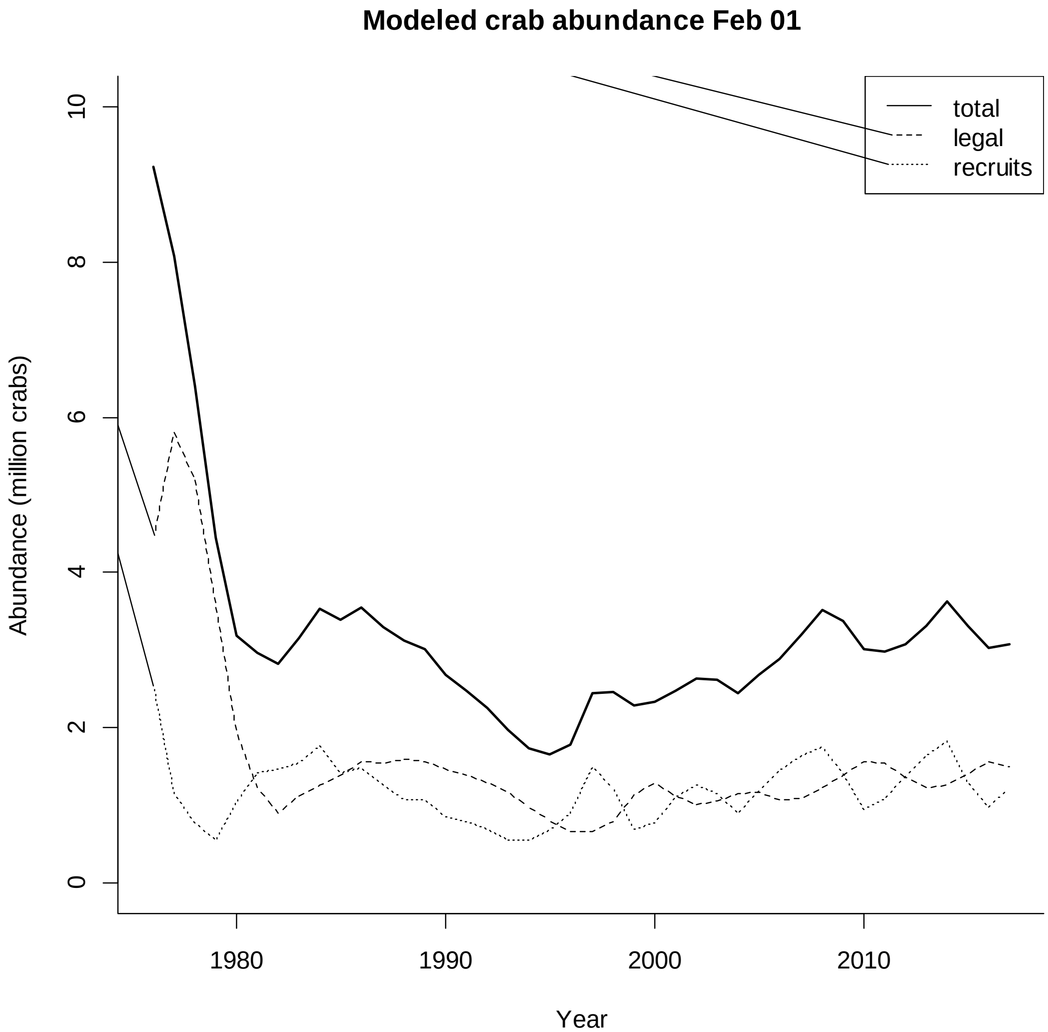


Figure C5-5. Estimated abundance of total, legal, and recruit males from 1976-2016.

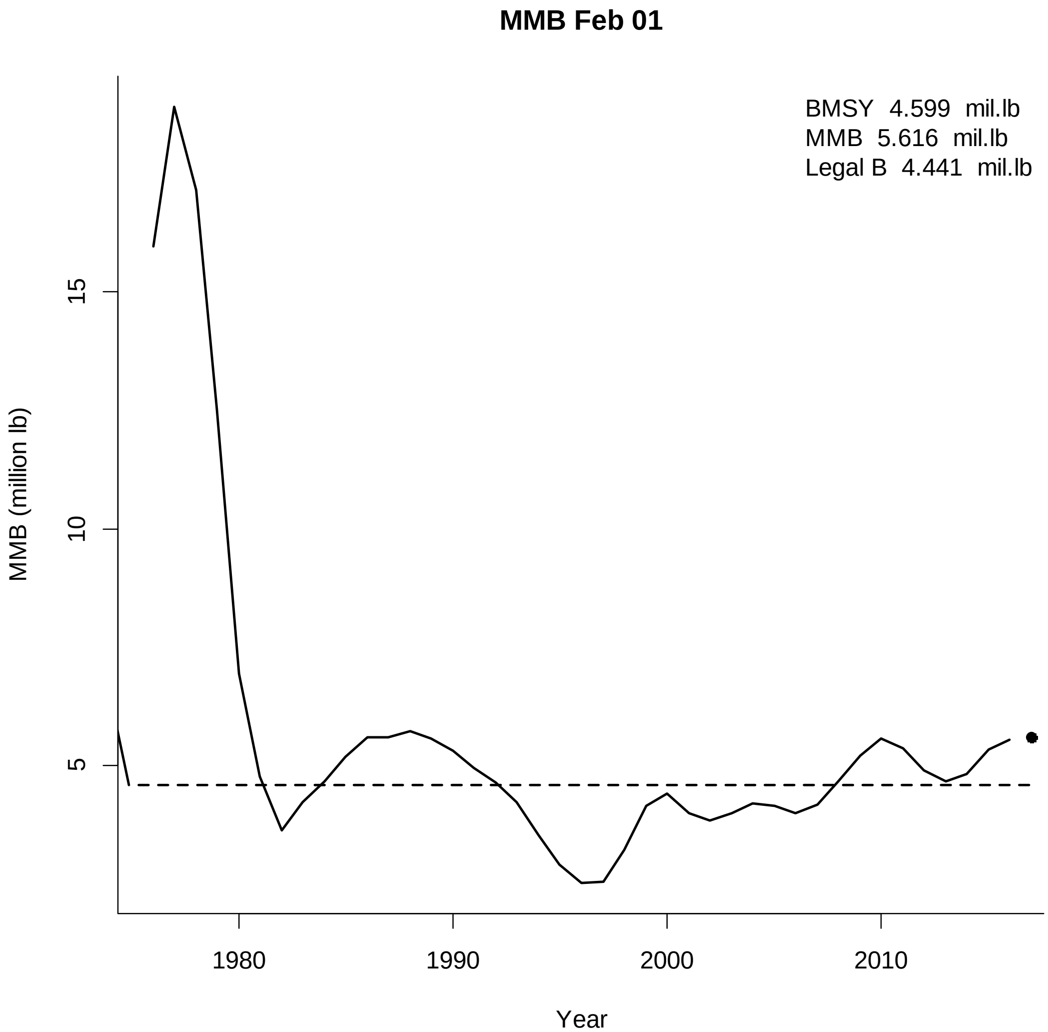


Figure C5-6. Estimated abundance of leg recruits from 1976-2016. Dash line shows B_{msy} (Average MMB of 1980-2016).

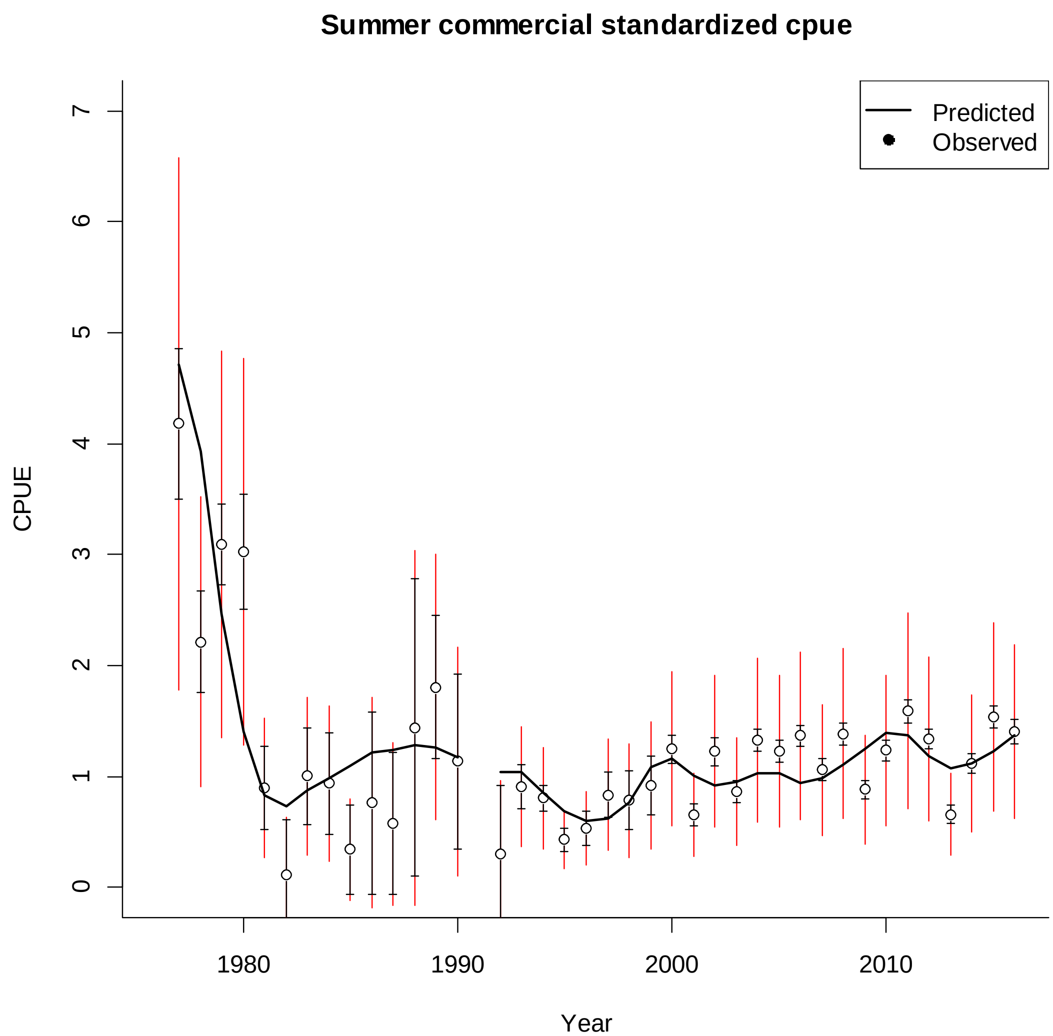


Figure C5-7. Summer commercial standardized cpue (1977-2015).

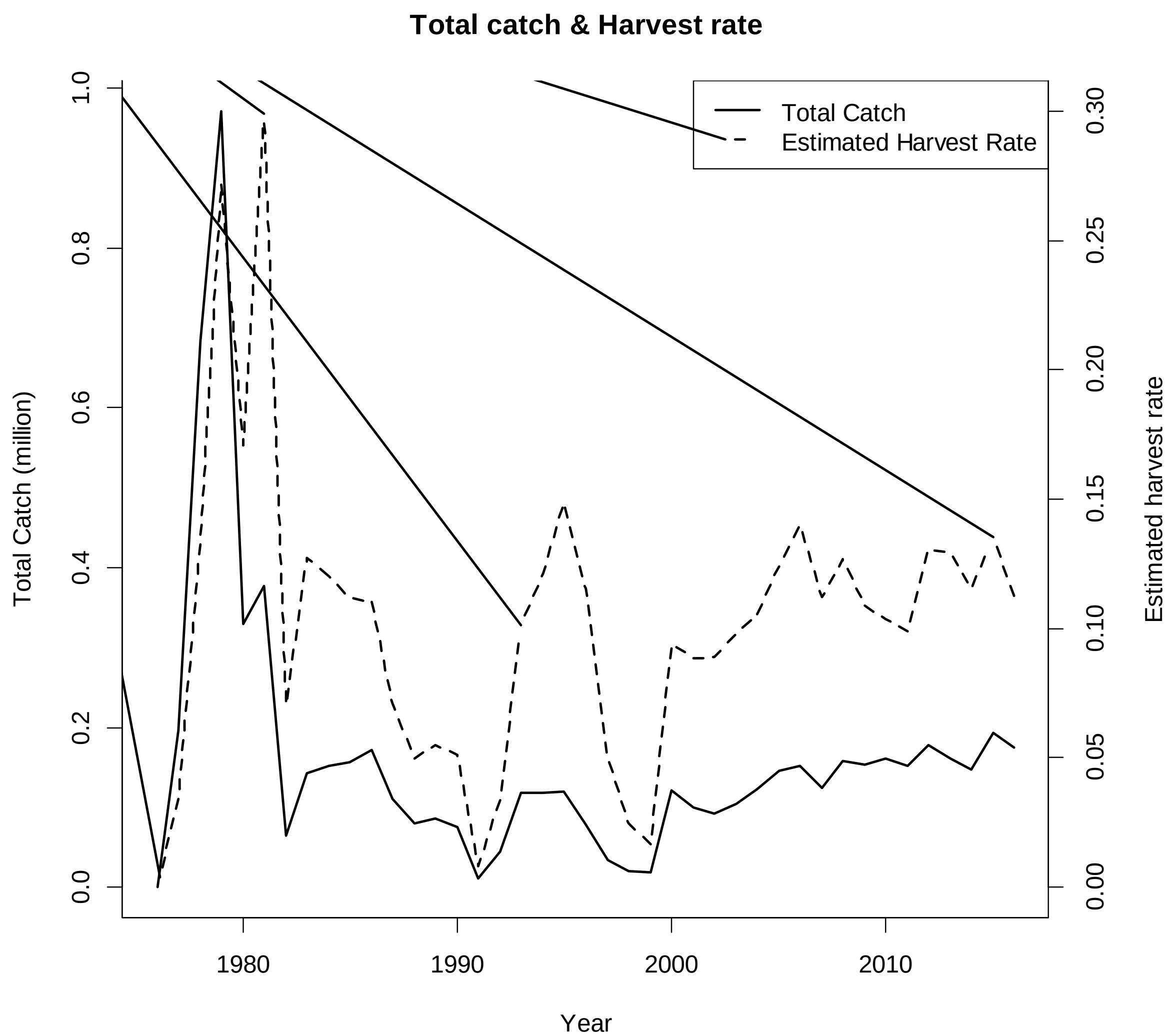


Figure C5-8. Total catch and estimated harvest rate 1976-2015.

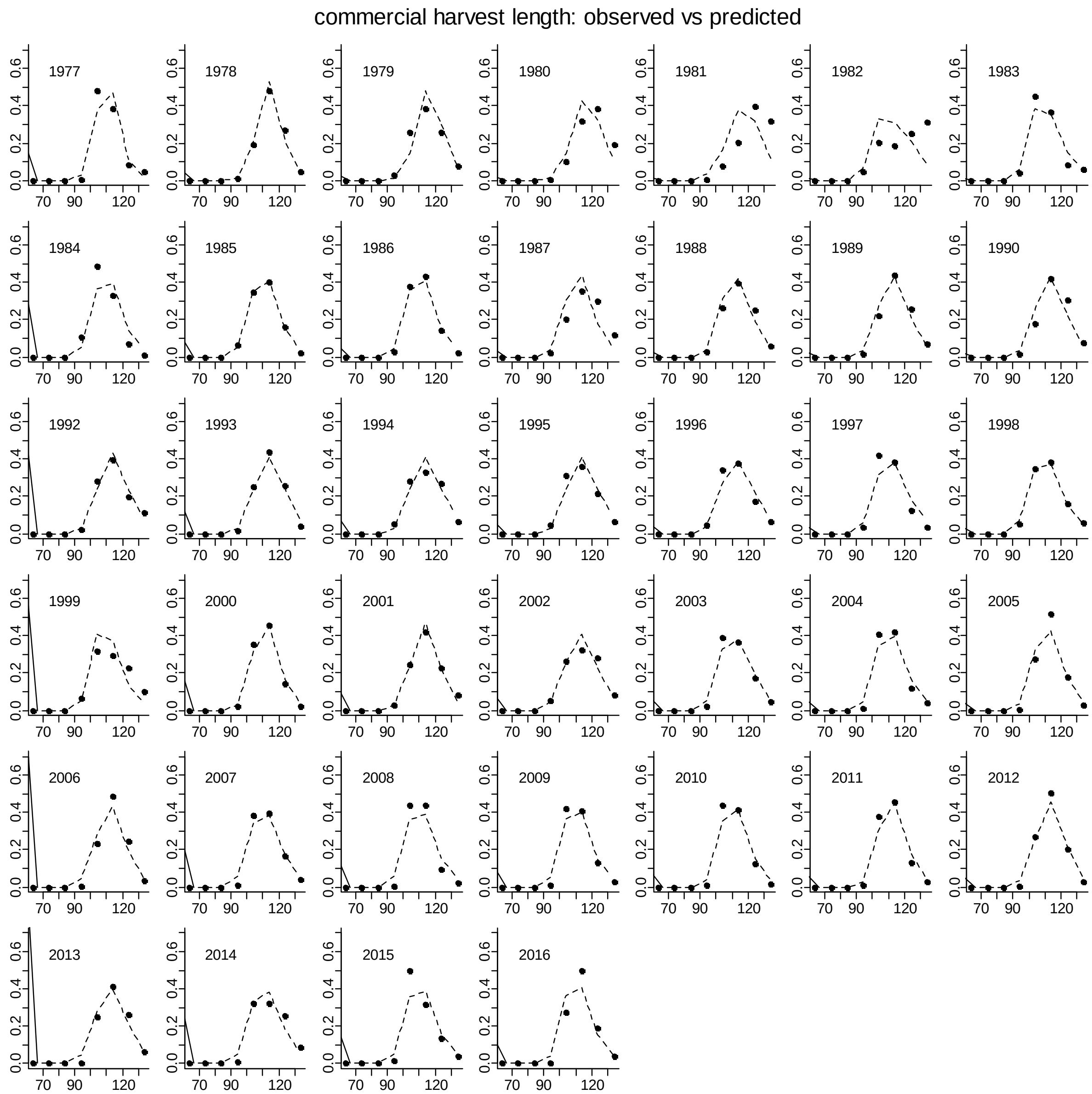


Figure C5-9. Predicted (dashed line) vs. observed (black dots) length class proportions for commercial catch.

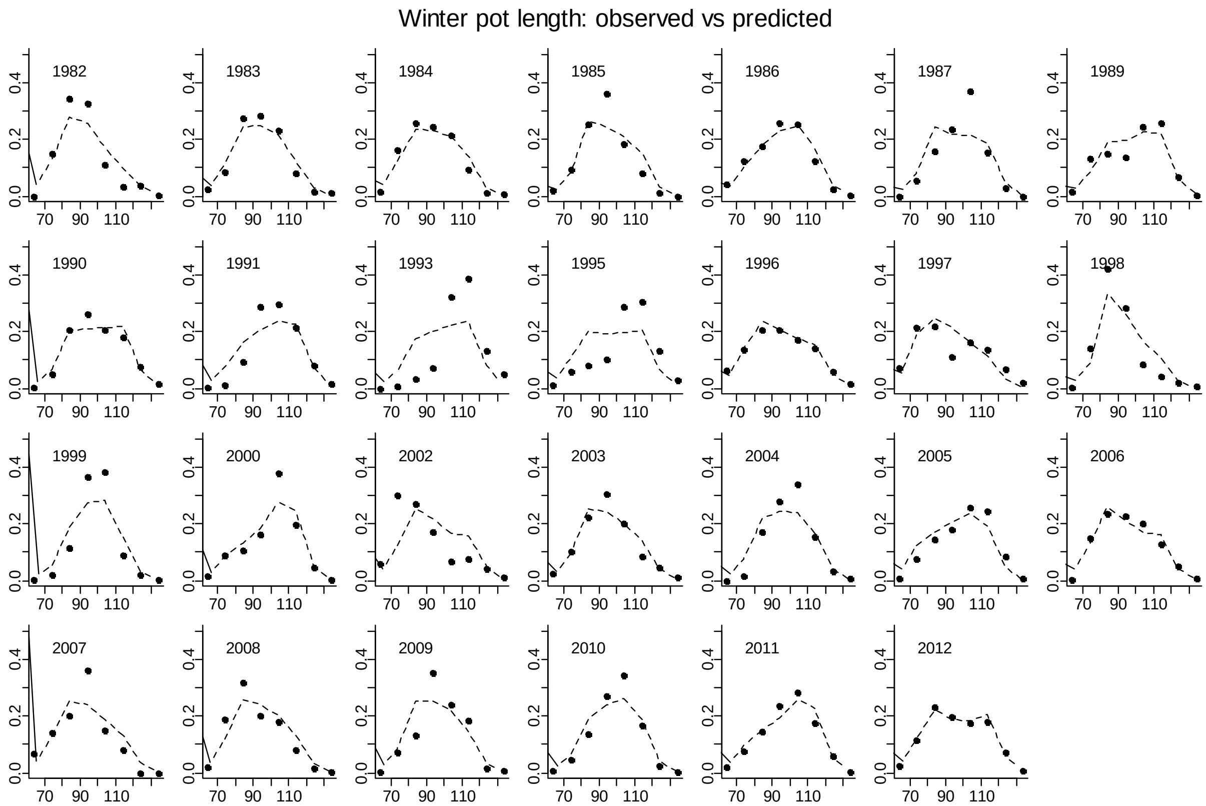


Figure C5-10. Predicted (dashed line) vs. observed (black dots) length class proportions for the winter pot survey.

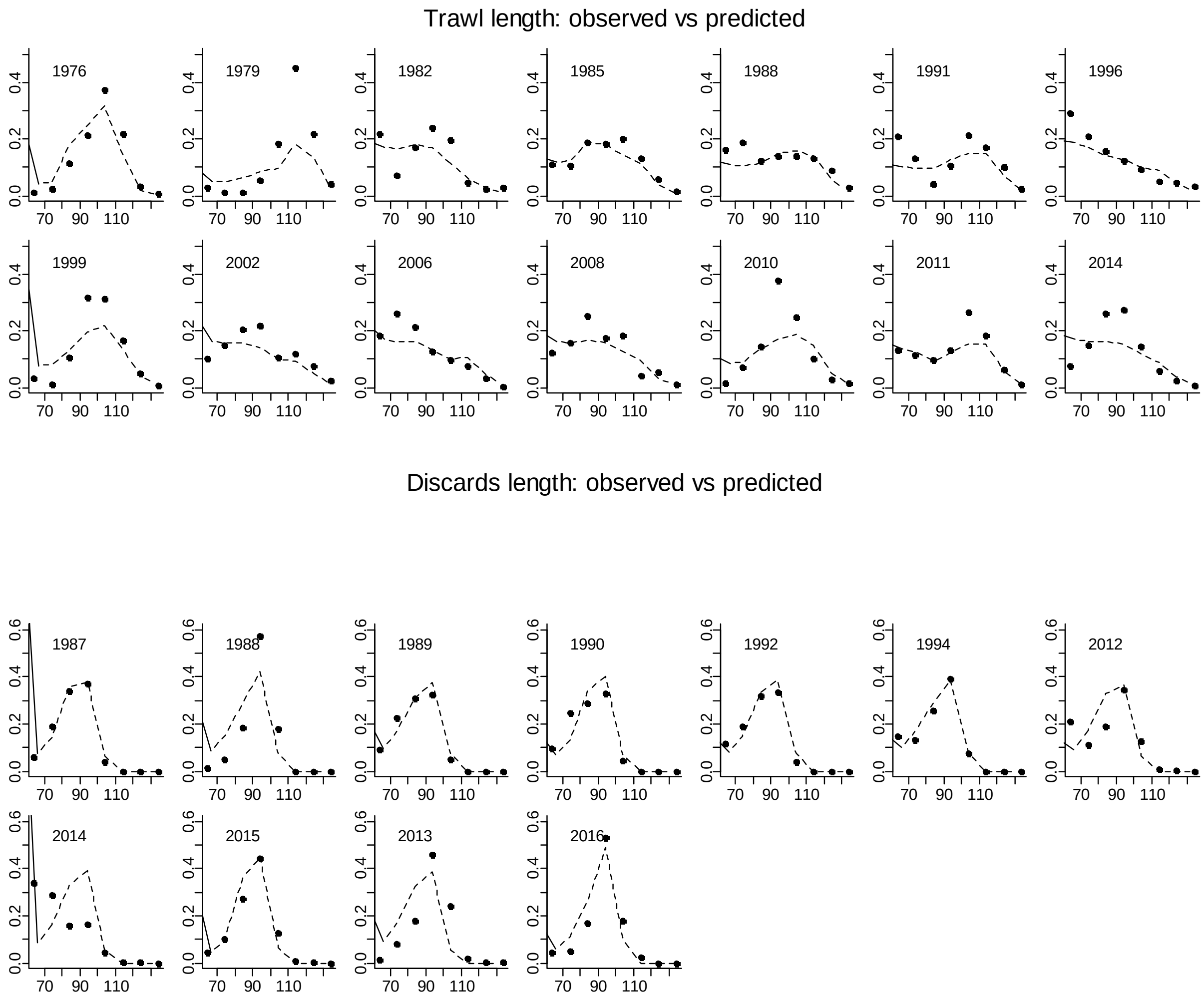


Figure C5-11. Predicted (dashed line) vs. observed (black dots) length class proportions for the trawl survey and observer survey.

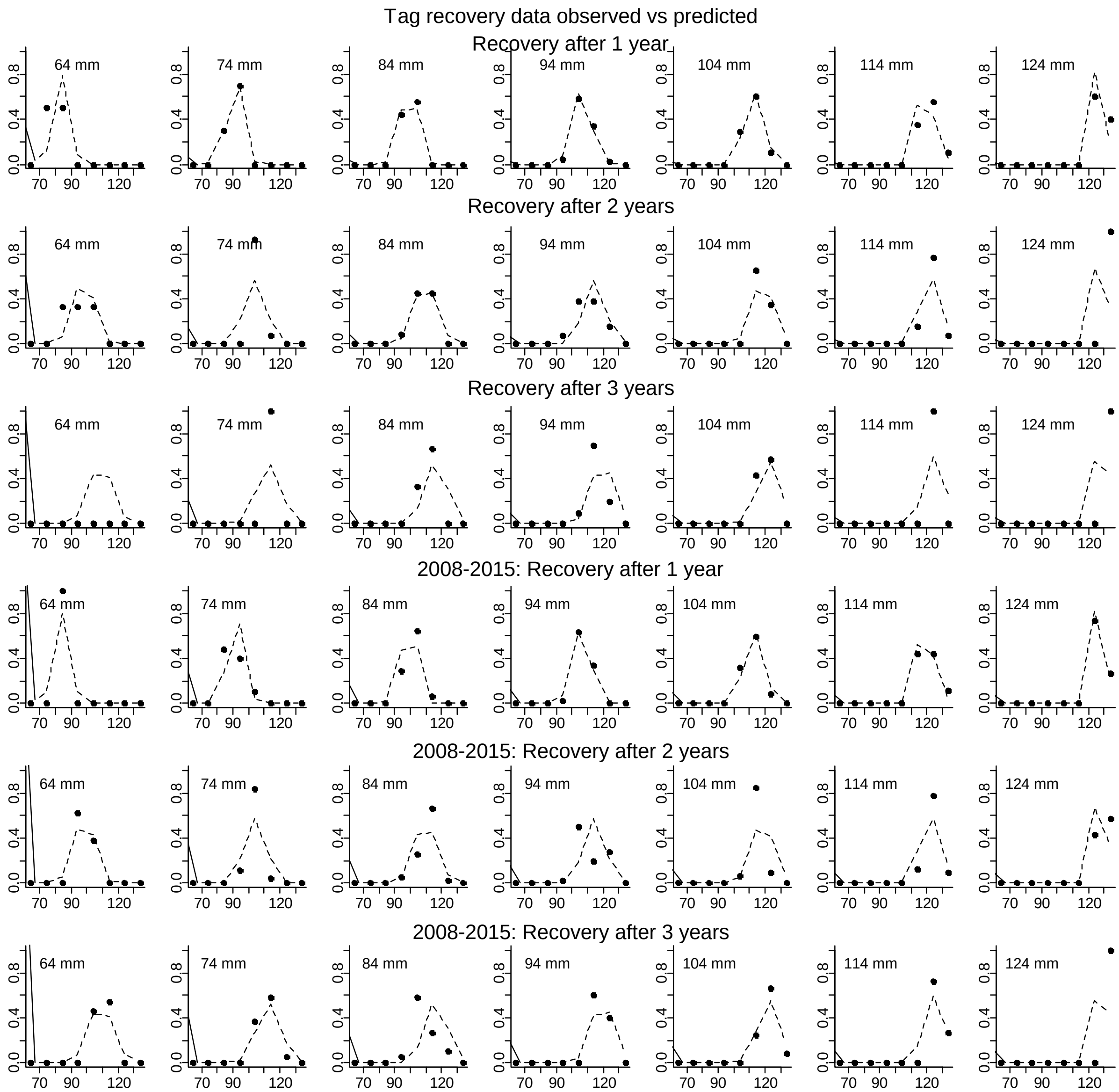


Figure C5-12. Predicted vs. observed length class proportions for tag recovery data.

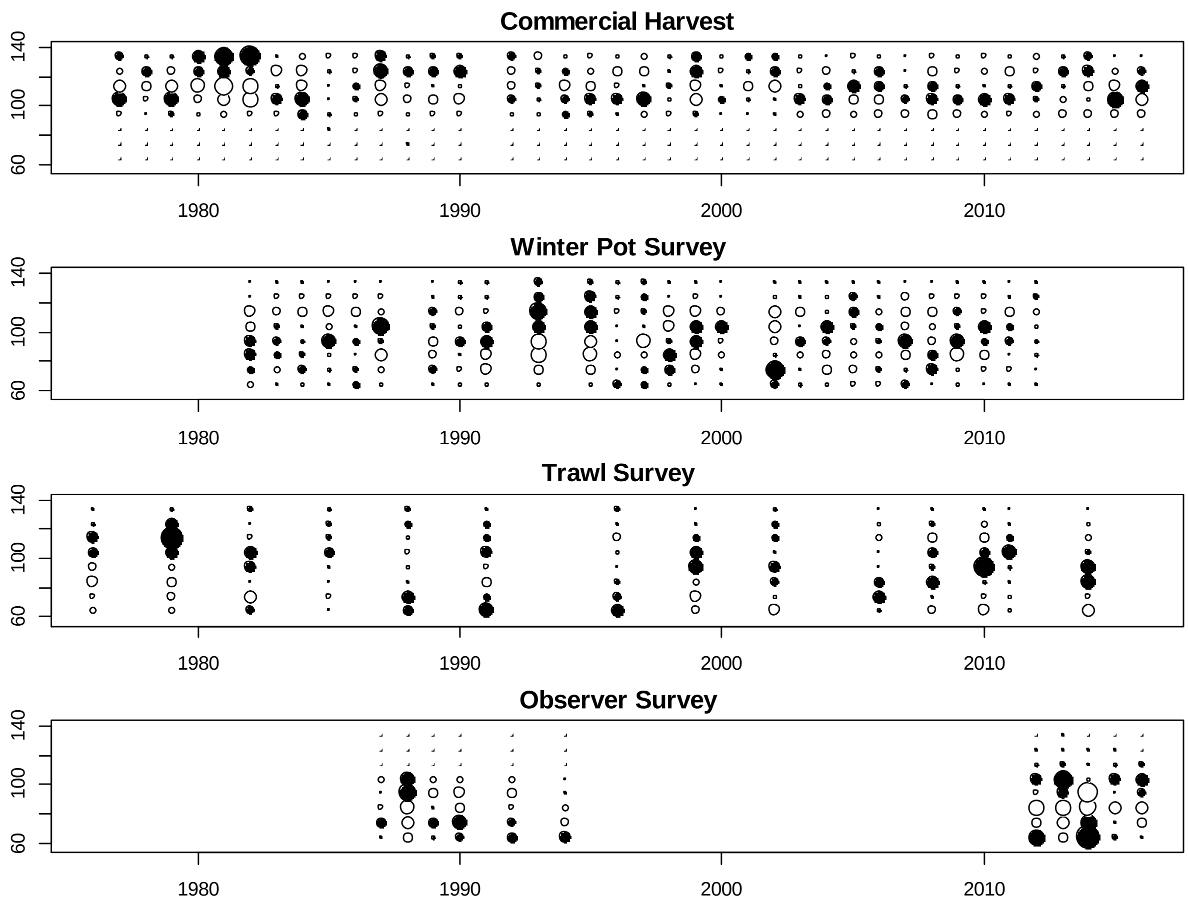


Figure C5-13. Bubble plots of predicted and observed length proportions. Black circle indicates model estimates lower than observed, white circle indicates model estimates higher than observed. Size of circle indicates degree of deviance (larger circle = larger deviance).

Table C5-1 . Summary of parameter estimates for a length-based stock synthesis population model of Norton Sound red king crab.

name	Estimate	std.dev
log_q_1	-6.9474	0.18897
log_q_2	-6.8138	0.10936
log_N_{76}	9.1299	0.14868
R_0	6.499	0.08912
$log\_\sigma_R^2$	-0.021582	0.4392
log_R_{77}	-0.60339	0.36841
log_R_{78}	-0.7184	0.35467
log_R_{79}	0.24292	0.32215
log_R_{80}	0.32661	0.29918
log_R_{81}	0.31454	0.27427
log_R_{82}	0.38607	0.3187
log_R_{83}	0.56497	0.28125
log_R_{84}	0.067198	0.30972
log_R_{85}	0.42872	0.28383
log_R_{86}	-0.027087	0.30475
log_R_{87}	-0.009808	0.26152
log_R_{88}	0.00016	0.27322
log_R_{89}	-0.40455	0.29705
log_R_{90}	-0.28143	0.26223
log_R_{91}	-0.54574	0.29078
log_R_{92}	-0.74853	0.31326
log_R_{93}	-0.61301	0.29393
log_R_{94}	-0.38116	0.26823
log_R_{95}	-0.067781	0.23891
log_R_{96}	0.52355	0.21688
log_R_{97}	-0.22331	0.3156
log_R_{98}	-0.66038	0.31801
log_R_{99}	-0.17771	0.31278
log_R_{00}	0.14041	0.26892
log_R_{01}	0.19071	0.25487
log_R_{02}	-0.014399	0.31106
log_R_{03}	-0.31204	0.33456
log_R_{04}	0.27971	0.24765
log_R_{05}	0.3315	0.24077
log_R_{06}	0.47889	0.25018

name	Estimate	std.dev
log_R_{13}	0.57103	0.2908
log_R_{14}	-0.14459	0.42292
log_R_{15}	-0.10962	0.4554
a_1	2.5567	4.2403
a_2	2.5676	4.1927
a_3	3.9044	3.9848
a_4	4.1958	3.9689
a_5	4.4256	3.9619
a_6	3.6364	3.9881
a_7	2.0252	4.2111
r1	14.989	61.07
r2	14.606	61.071
log_α	-2.0189	0.017065
log_ϕ_{st1}	-2.5417	0.21766
log_ϕ_w	-2.0463	0.050332
Sw_7	0.070648	0.03389
Sw_8	0.45406	0.10913
log_ϕ_1	-2.0854	0.069554
log_ϕ_2	-2.0231	0.084819
w^2_t	0.072799	0.022524
q	0.77256	0.14205
ms	3.4913	0.30739
σ	4.2447	0.24827
β_1	10.447	0.76932
β_2	8.1125	0.19273

log_R_{07}	0.49927	0.24551
log_R_{08}	0.085111	0.30276
log_R_{09}	-0.30983	0.30646
log_R_{10}	0.14871	0.2505
log_R_{11}	0.31101	0.28821
log_R_{12}	0.48325	0.29162

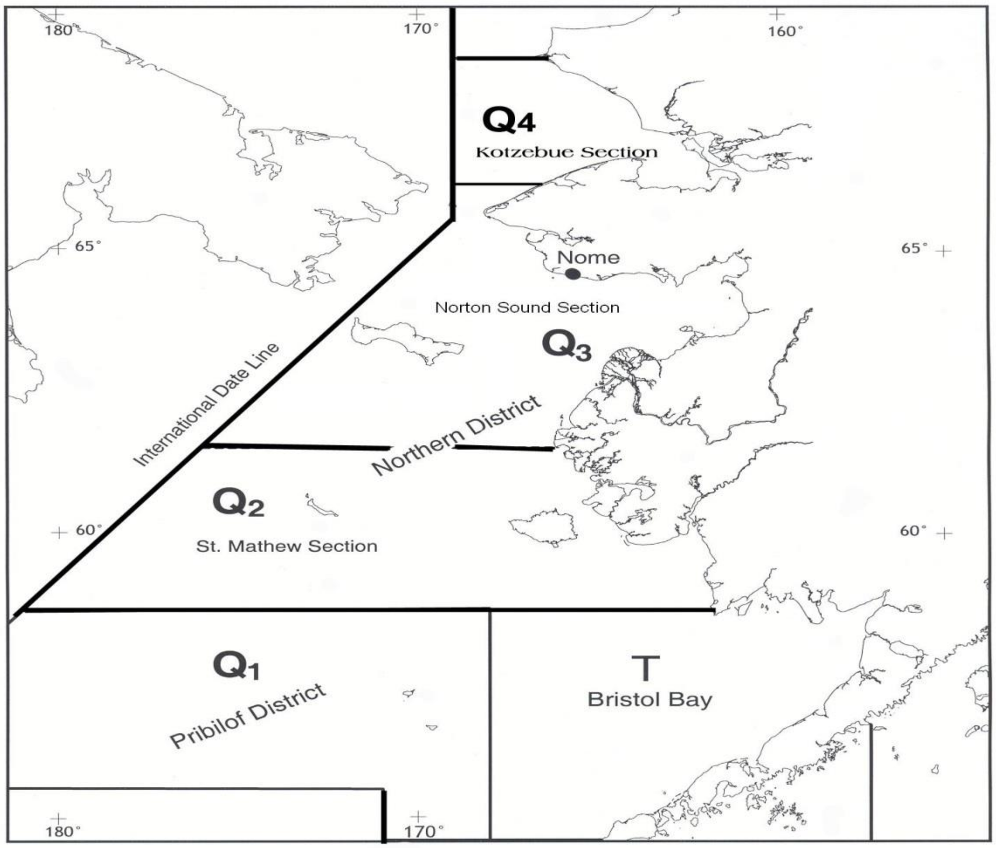


Figure 1. King crab fishing districts and sections of Statistical Area Q.

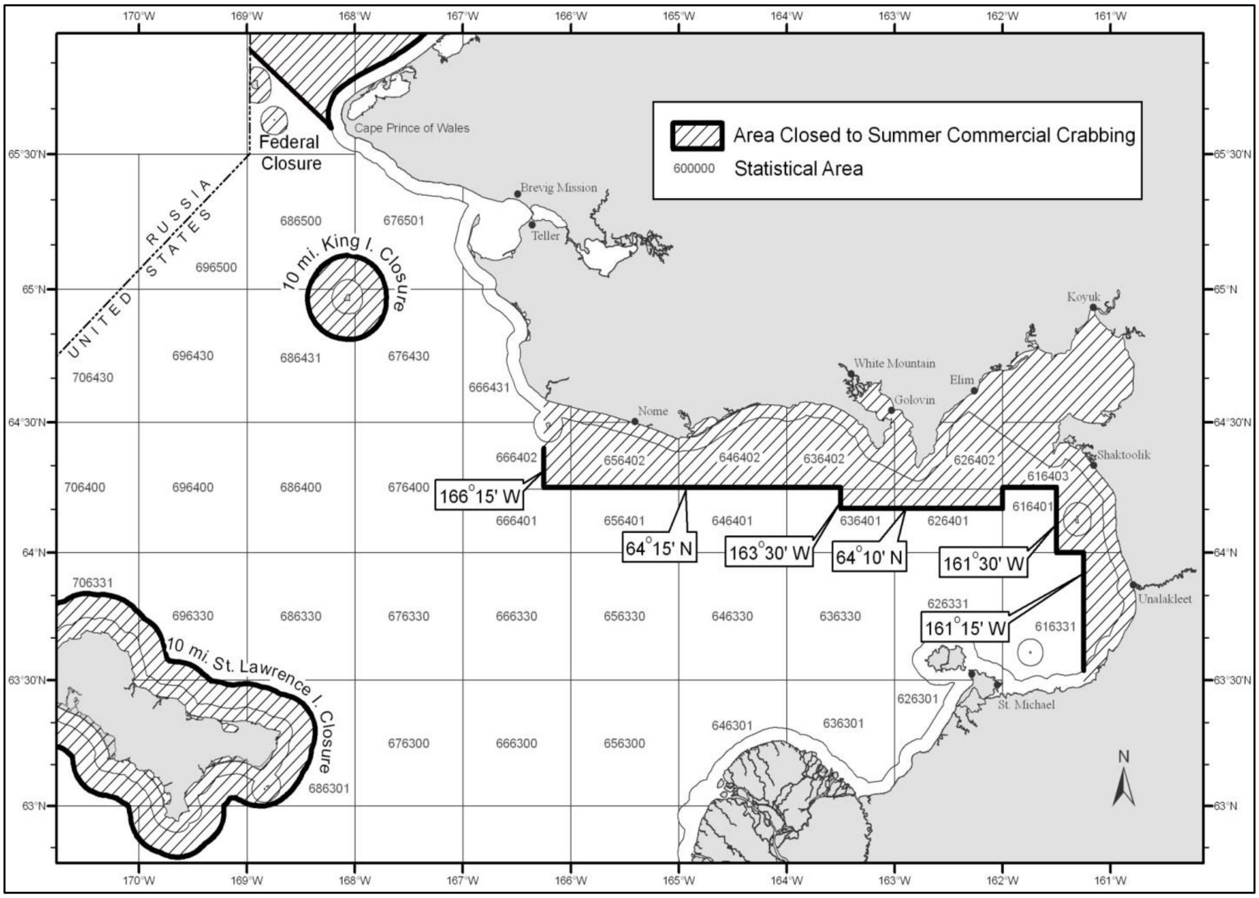


Figure 2. Closed water regulations in effect for the Norton Sound commercial crab fishery. Line around the coastline delineates the 3-mil3 state waters zone.

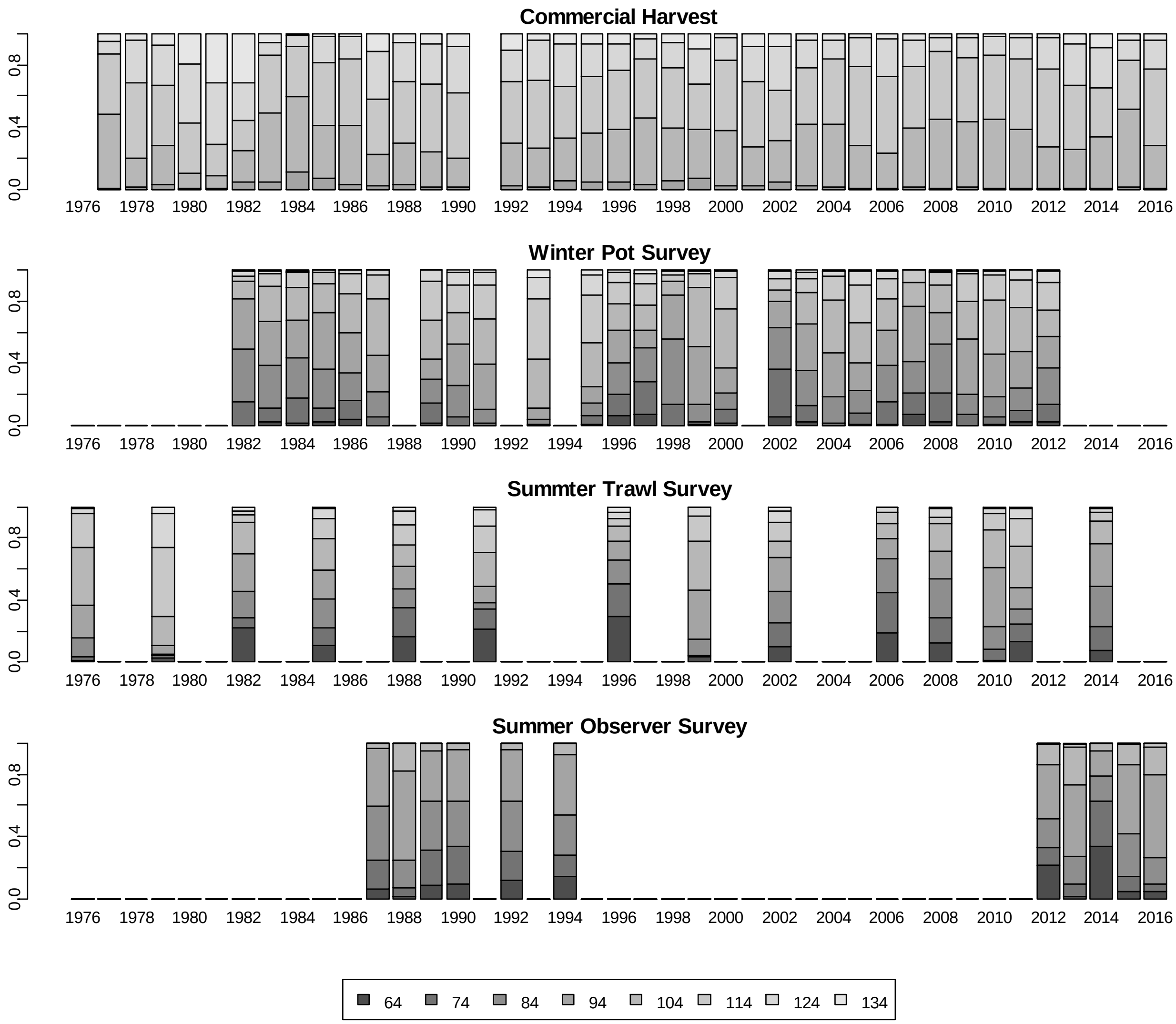


Figure 3. Observed length compositions 1976-2016.

Figure 4. Effective sample size vs. implied sample size. Figures in the first column show effective sample size (x-axis) vs. frequency (y-axis). Vertical solid line is the implied sample size. Figures in the second column show implied sample size (x-axis) vs. effective sample size (y-axis). Dashed line indicates linear regression slope, and solid line is 1:1 line. Figures in the third column show year (x-axis) vs. effective sample size (y-axis).

Figure 5. Molting probability and trawl/pot selectivity.

Figure 6. Estimated trawl survey male abundance with 95% lognormal Confidence Interval (crab ≥ 74 mm CL).

Figure 7. Estimated abundances of legal and recruits males from 1976-2015.

Figure 8. Estimated MMB from 1976-2015. Dash line shows Bmsy (Average MMB of 1980-2016). Black points indicate projected MMB of 2016.

Figure 9. Summer commercial standardized cpue. Black line is input SD and red line is input and estimated additional SD.

Figure 10. Commercial Catch and estimated harvest rate of legal male.

Figure 11. Residual and QQ plot.

Figure 12. Bubble plot of predicted and observed length proportion (Alternative model 0). Black circle indicates model estimates lower than observed, white circle indicates model estimates higher than observed. Size of circle indicate degree of deviance (larger circle = larger deviance).

Figure 13. Predicted (dashed line) vs. observed (black dots) length class proportion for the summer commercial catch.

Figure 14. Predicted vs. observed length class proportion for winter pot survey.

Figure 15. Predicted vs. observed length class proportion for trawl survey and commercial observer.

Figure 16. Predicted vs. observed length class proportion for tag recovery data 1980-1992, and 1993-2014.

Figure 17. Retrospective analyses. Each line shows retrospective MMB.

Table 1. Historical summer commercial red king crab fishery economic performance, Norton Sound Section, eastern Bering Sea, 1977-2014. Bold type shows data that are used for the assessment model.

Year	Guideline Harvest Level (lb) [b]	Commercial Harvest (lb) [a, b] Open Access	CDQ	Harvest	Total Number (Open Access) Vessels	Permits	Landings	Total Pots Registered	Pulls	ST CPUE CPUE	SD	Season Length Days	Dates	Mid-day from July
1977	[c]	517.787		**195,877**	7	7	13		5,457	**4.18**	**0.34**	60	[c]	**0.049**
1978	3,000.000	2,091.961		**660,829**	8	8	54		10,817	**2.21**	**0.23**	60	6/07-8/15	**0.142**
1979	3,000.000	2,931.672		**970,962**	34	34	76		34,773	**3.09**	**0.18**	16	7/15-7/31	**0.088**
1980	1,000.000	1,186.596		**329,778**	9	9	50		11,199	**3.03**	**0.26**	16	7/15-7/31	**0.066**
1981	2,500.000	1,379.014		**376,313**	36	36	108		33,745	**0.89**	**0.19**	38	7/15-8/22	**0.096**
1982	500.000	228.921		**63,949**	11	11	33		11,230	**0.11**	**0.25**	23	8/09-9/01	**0.151**
1983	300.000	368.032		**132,205**	23	23	26	3,583	11,195	**1.00**	**0.22**	3.8	8/01-8/05	**0.096**
1984	400.000	387.427		**139,759**	8	8	21	1,245	9,706	**0.94**	**0.23**	13.6	8/01-8/15	**0.110**
1985	450.000	427.011		**146,669**	6	6	72	1,116	13,209	**0.34**	**0.20**	21.7	8/01-8/23	**0.118**
1986	420.000	479.463		**162,438**	3	3		578	4,284	**0.76**	**0.41**	13	8/01-8/25	**0.153**
1987	400.000	327.121		**103,338**	9	9		1,430	10,258	**0.57**	**0.32**	11	8/01-8/12	**0.107**
1988	200.000	236.688		**76,148**	2	2		360	2,350	**1.44**	**0.67**	9.9	8/01-8/11	**0.110**
1989	200.000	246.487		**79,116**	10	10		2,555	5,149	**1.80**	**0.32**	3	8/01-8/04	**0.096**
1990	200.000	192.831		**59,132**	4	4		1,388	3,172	**1.13**	**0.40**	4	8/01-8/05	**0.099**
1991	340.000			**0**	No Summer Fishery									
1992	340.000	74.029		**24,902**	27	27		2,635	5,746	**0.30**	**0.31**	2	8/01-8/03	**0.093**
1993	340.000	335.790		**115,913**	14	20	208	560	7,063	**0.90**	**0.10**	52	7/01-8/28	**0.093**
1994	340.000	327.858		**108,824**	34	52	407	1,360	11,729	**0.80**	**0.06**	31	7/01-7/31	**0.044**
1995	340.000	322.676		**105,967**	48	81	665	1,900	18,782	**0.43**	**0.05**	67	7/01-9/05	**0.093**
1996	340.000	224.231		**74,752**	41	50	264	1,640	10,453	**0.53**	**0.08**	57	7/01-9/03	**0.101**
1997	80.000	92.988		**32,606**	13	15	100	520	2,982	**0.83**	**0.10**	44	7/01-8/13	**0.074**
1998	80.000	29.684	0.00	**10,661**	8	11	50	360	1,639	**0.78**	**0.13**	65	7/01-9/03	**0.110**
1999	80.000	23.553	0.00	**8,734**	10	9	53	360	1,630	**0.92**	**0.13**	66	7/01-9/04	**0.104**
2000	336.000	297.654	14.87	**111,728**	15	22	201	560	6,345	**1.25**	**0.06**	91	7/01- 9/29	**0.126**
2001	303.000	288.199	0	**98,321**	30	37	319	1,200	11,918	**0.65**	**0.05**	97	7/01- 9/09	**0.104**
2002	248.000	244.376	15.226	**86,666**	32	49	201	1,120	6,491	**1.22**	**0.06**	77	6/15-9/03	**0.060**
2003	253.000	253.284	13.923	**93,638**	25	43	236	960	8,494	**0.86**	**0.05**	68	6/15-8/24	**0.058**
2004	326.500	314.472	26.274	**120,289**	26	39	227	1,120	8,066	**1.33**	**0.05**	51	6/15-8/08	**0.033**
2005	370.000	370.744	30.06	**138,926**	31	42	255	1,320	8,867	**1.23**	**0.05**	73	6/15-8/27	**0.058**
2006	454.000	419.191	32.557	**150,358**	28	40	249	1,120	8,867	**1.36**	**0.05**	68	6/15-8/22	**0.052**
2007	315.000	289.264	23.611	**110,344**	38	30	251	1,200	9,118	**1.06**	**0.05**	52	6/15-8/17	**0.036**
2008	412.000	364.235	30.9	**143,337**	23	30	248	920	8,721	**1.38**	**0.05**	73	6/23-9/03	**0.079**
2009	375.000	369.462	28.125	**143,485**	22	27	359	920	11,934	**0.88**	**0.04**	98	6/15-9/20	**0.090**
2010	400.000	387.304	30	**149,822**	23	32	286	1,040	9,698	**1.23**	**0.04**	58	6/28-8/24	**0.074**
2011	358.000	373.990	26.851	**141,626**	24	25	173	1,040	6,808	**1.59**	**0.05**	33	6/28-7/30	**0.038**
2012	465.450	441.080	34.91	**161,113**	40	29	312	1,200	10,041	**1.34**	**0.04**	72	6/29-9/08	**0.093**
2013	495.600	373.278	18.585	**130,603**	37	33	460	1,420	15,058	**0.66**	**0.04**	74	7/3-9/14	**0.110**
2014	382.800	360.860	28.148	**129,657**	52	33	309	1,560	10,127	**1.12**	**0.05**	52	6/25-8/15	**0.052**
2015	394.600	371.520	29.595	**144,255**	42	36	251	1,480	8,356	**1.53**	**0.05**	26	6/29-7/24	**0.033**
2016	517.200	416.576	3.583	**138,997**	36	37	220	1,520	7,891	**1.40**	**0.06**	25	6/27-7/21	**0.025**

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

Table 2. Historical winter commercial and subsistence red king crab fisheries, Norton Sound Section, eastern Bering Sea, 1977-2015. Bold typed data are used for the assessment model.

		Commercial			Subsistence				
Model Year	Year[a]	# of Fishers	# of Crab Harvested	Winter[b]	Permits			Total Crab	
					Issued	Returned	Fished	Caught[c]	Retained[d]
1978	1978	37	**9,625**	1977/78	290	206	149	**NA**	**12,506**
1979	1979	1[f]	**221**[f]	1978/79	48	43	38	**NA**	**224**
1980	1980	1[f]	**22**[f]	1979/80	22	14	9	**NA**	**213**
1981	1981	0	**0**	1980/81	51	39	23	**NA**	**360**
1982	1982	1[f]	**17**[f]	1981/82	101	76	54	**NA**	**1,288**
1983	1983	5	**549**	1982/83	172	106	85	**NA**	**10,432**
1984	1984	8	**856**	1983/84	222	183	143	**15,923**	**11,220**
1985	1985	9	**1,168**	1984/85	203	166	132	**10,757**	**8,377**
1986	1985/86	5	**2,168**	1985/86	136	133	107	**10,751**	**7,052**
1987	1986/87	7	**1,040**	1986/87	138	134	98	**7,406**	**5,772**
1988	1987/88	10	**425**	1987/88	71	58	40	**3,573**	**2,724**
1989	1988/89	5	**403**	1988/89	139	115	94	**7,945**	**6,126**
1990	1989/90	13	**3,626**	1989/90	136	118	107	**16,635**	**12,152**
1991	1990/91	11	**3,800**	1990/91	119	104	79	**9,295**	**7,366**
1992	1991/92	13	**7,478**	1991/92	158	105	105	**15,051**	**11,736**
1993	1992/93	8	**1,788**	1992/93	88	79	37	**1,193**	**1,097**
1994	1993/94	25	**5,753**	1993/94	118	95	71	**4,894**	**4,113**
1995	1994/95	42	**7,538**	1994/95	166	131	97	**7,777**	**5,426**
1996	1995/96	9	**1,778**	1995/96	84	44	35	**2,936**	**1,679**
1997	1996/97	2[f]	**83**[f]	1996/97	38	22	13	**1,617**	**745**
1998	1997/98	5	**984**	1997/98	94	73	64	**20,327**	**8,622**
1999	1998/99	5	**2,714**	1998/99	95	80	71	**10,651**	**7,533**
2000	1999/00	10	**3,045**	1999/00	98	64	52	**9,816**	**5,723**
2001	2000/01	3	**1,098**	2000/01	50	27	12	**366**	**256**
2002	2001/02	11	**2,591**	2001/02	114	61	45	**5,119**	**2,177**
2003	2002/03	13	**6,853**	2002/03	107	70	61	**9,052**	**4,140**
2004	2003/04	2[f]	**522** [f]	2003/04[g]	96	77	41	**1,775**	**1,181**
2005	2004/05	4	**2,091**	2004/05	170	98	58	**6,484**	**3,973**
2006	2005/06	1[f]	**75**[f]	2005/06	98	97	67	**2,083**	**1,239**
2007	2006/07	8	**3,313**	2006/07	129	127	116	**21,444**	**10,690**
2008	2007/08	9	**5,796**	2007/08	139	137	108	**18,621**	**9,485**
2009	2008/09	7	**4,951**	2008/09	105	105	70	**6,971**	**4,752**
2010	2009/10	10	**4,834**	2009/10	125	123	85	**9,004**	**7,044**
2011	2010/11	5	**3,365**	2010/11	148	148	95	**9,183**	**6,640**
2012	2011/12	35	**9,157**	2011/12	204	204	138	**11,341**	**7,311**
2013	2012/13	26	**22,639**	2012/13	149	148	104	**21,524**	**7,622**
2014	2013/14	21	**14,986**	2013/14	103	103	75	**5,421**	**3,252**
2015	2014/15	44	**41,062**	2014/15	155	153	107	**9,840**	**7,651**
2016	2015/16	25	**29,792**	2015/16	139	97	64	**6,468**	**5,340**

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.

f 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.

Table 3. 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).

Year	Dates	Survey Agency	Survey method	Survey coverage			Abundance ≥74 mm	
				surveyed stations	Stations w/ NSRKC	n mile^2 covered		CV
1976	9/02 – 9/25	NMFS	Trawl	103	62	10260	**4247.5**	**0.31**
1979	7/26 - 8/05	NMFS	Trawl	85	22	8421	**1417.2**	**0.20**
1980	7/04 - 7/14	ADFG	Pots				2092.3	N/A
1981	6/28 - 7/14	ADFG	Pots				2153.4	N/A
1982	7/06 - 7/20	ADFG	Pots				1140.5	N/A
1982	9/05 - 9/11	NMFS	Trawl	58	37	5721	**2791.7**	**0.29**
1985	7/01 - 7/14	ADFG	Pots				2320.4	0.083
1985	9/16 -10/01	NMFS	Trawl	78	49	7688	**2306.3**	**0.25**
1988	8/16 - 8/30	NMFS	Trawl	78	41	7721	**2263.4**	**0.29**
1991	8/22 - 8/30	NMFS	Trawl	52	38	5183	**3132.5**	**0.43**
1996	8/07 - 8/18	ADFG	Trawl	50	30	4938	**1264.7**	**0.317**
1999	7/28 - 8/07	ADFG	Trawl	53	31	5221	**2276.1**	**0.194**
2002	7/27 - 8/06	ADFG	Trawl	57	37	5621	**1747.6**	**0.125**
2006	7/25 - 8/08	ADFG	Trawl	101	45	10008	**2549.7**	**0.288**
2008	7/24 - 8/11	ADFG	Trawl	74	44	7330	**2707.1**	**0.164**
2010[a]	7/27 - 8/09	NMFS	Trawl	35	15	13749	**2041.0**	**0.455**
2011	7/18 - 8/15	ADFG	Trawl	65	34	6447	**2701.7**	**0.133**
2014	7/18 - 7/30	ADFG	Trawl	47	34	4700	**5481.5**	**0.486**

Table 4. Summer commercial catch size/shell compositions. Sizes in this and Tables 5-10 and 12 are mm carapace length. Legal size (4.75 inch carapace width is approximately equal to 124 mm carapace length.

		New Shell								Old Shell							
Year	Sample	64-73	74-83	84-93	94-103	104-113	114-123	124-133	134+	64-73	74-83	84-93	94-103	104-113	114-123	124-133	134+
1977	1549	0	0	0	0.00	0.42	0.34	0.08	0.05	0	0	0	0.00	0.06	0.04	0.01	0.00
1978	389	0	0	0	0.01	0.19	0.47	0.26	0.04	0	0	0	0.00	0.01	0.01	0.01	0.00
1979	1660	0	0	0	0.03	0.23	0.38	0.26	0.07	0	0	0	0.00	0.03	0.00	0.00	0.01
1980	1068	0	0	0	0.00	0.10	0.31	0.37	0.18	0	0	0	0.00	0.00	0.01	0.02	0.01
1981	1784	0	0	0	0.00	0.07	0.15	0.28	0.23	0	0	0	0.00	0.00	0.05	0.12	0.09
1982	1093	0	0	0	0.04	0.19	0.16	0.22	0.29	0	0	0	0.00	0.01	0.02	0.03	0.03
1983	802	0	0	0	0.04	0.41	0.36	0.06	0.03	0	0	0	0.00	0.04	0.01	0.02	0.02
1984	963	0	0	0	0.10	0.42	0.28	0.06	0.01	0	0	0	0.01	0.07	0.05	0.01	0.00
1985	2691	0	0	0.00	0.06	0.31	0.37	0.15	0.02	0	0	0	0.00	0.03	0.03	0.01	0.00
1986	1138	0	0	0	0.03	0.36	0.39	0.12	0.02	0	0	0	0.00	0.02	0.04	0.02	0.00
1987	1985	0	0	0	0.02	0.18	0.29	0.27	0.11	0	0	0	0.00	0.03	0.06	0.03	0.01
1988	1522	0	0.00	0	0.02	0.20	0.30	0.18	0.04	0	0	0	0.01	0.06	0.10	0.07	0.02
1989	2595	0	0	0	0.01	0.16	0.32	0.17	0.05	0	0	0	0.00	0.06	0.12	0.09	0.02
1990	1289	0	0	0	0.01	0.14	0.35	0.26	0.07	0	0	0	0.00	0.04	0.07	0.05	0.01
1991																	
1992	2566	0	0	0	0.02	0.20	0.27	0.14	0.09	0	0	0	0.00	0.08	0.13	0.06	0.02
1993	17804	0	0	0	0.01	0.23	0.39	0.23	0.03	0	0	0	0.00	0.02	0.04	0.03	0.01
1994	404	0	0	0	0.02	0.09	0.08	0.07	0.02	0	0	0	0.02	0.19	0.25	0.20	0.05
1995	1167	0	0	0	0.04	0.26	0.29	0.15	0.05	0	0	0	0.01	0.05	0.07	0.06	0.01
1996	787	0	0	0	0.03	0.22	0.24	0.09	0.05	0	0	0	0.01	0.12	0.14	0.08	0.02
1997	1198	0	0	0	0.03	0.37	0.34	0.10	0.03	0	0	0	0.00	0.06	0.04	0.03	0.01
1998	1055	0	0	0	0.03	0.23	0.24	0.08	0.03	0	0	0	0.02	0.11	0.14	0.08	0.03
1999	562	0	0	0	0.06	0.29	0.24	0.18	0.09	0	0	0	0.00	0.02	0.05	0.04	0.00
2000	17213	0	0	0	0.02	0.30	0.39	0.11	0.02	0	0	0	0.00	0.05	0.07	0.04	0.01
2001	20030	0	0	0	0.02	0.22	0.37	0.21	0.07	0	0	0	0.00	0.02	0.05	0.02	0.01
2002	5219	0	0	0	0.04	0.23	0.28	0.25	0.07	0	0	0	0.00	0.03	0.04	0.03	0.01
2003	5226	0	0	0	0.02	0.37	0.32	0.12	0.03	0	0	0	0.00	0.02	0.05	0.05	0.01
2004	9606	0	0	0	0.01	0.38	0.39	0.11	0.03	0	0	0	0.00	0.03	0.03	0.01	0.01
2005	5360	0	0	0	0.00	0.25	0.47	0.16	0.02	0	0	0	0.00	0.02	0.05	0.02	0.01
2006	6707	0	0	0	0.00	0.18	0.35	0.17	0.02	0	0	0	0.00	0.05	0.14	0.07	0.01
2007	6125	0	0	0	0.01	0.36	0.34	0.14	0.03	0	0	0	0.00	0.02	0.06	0.03	0.01
2008	5766	0	0	0	0.00	0.35	0.35	0.06	0.01	0	0	0	0.00	0.09	0.09	0.04	0.01
2009	6026	0	0	0	0.01	0.34	0.33	0.11	0.02	0	0	0	0.00	0.08	0.08	0.02	0.01
2010	5902	0	0	0	0.01	0.39	0.36	0.10	0.01	0	0	0	0.00	0.05	0.05	0.02	0.00
2011	2552	0	0	0	0.00	0.32	0.40	0.12	0.02	0	0	0	0.00	0.06	0.06	0.02	0.00
2012	5056	0	0	0	0.00	0.24	0.46	0.18	0.02	0	0	0	0.00	0.03	0.04	0.02	0.00
2013	6072	0	0	0	0.00	0.24	0.37	0.24	0.06	0	0	0	0.00	0.01	0.04	0.02	0.00
2014	4682	0	0	0	0.01	0.28	0.24	0.18	0.07	0	0	0	0.00	0.04	0.09	0.07	0.02
2015	4173	0	0	0	0.01	0.48	0.28	0.10	0.03	0	0	0	0.00	0.02	0.03	0.03	0.01
2016	1542	0	0	0	0.00	0.25	0.47	0.16	0.03	0	0	0	0.00	0.02	0.02	0.03	0.01

Table 5. Summer Trawl Survey size/shell compositions.

		New Shell								Old Shell							
Year	Sample	64-73	74-83	84-93	94-103	104-113	114-123	124-133	134+	64-73	74-83	84-93	94-103	104-113	114-123	124-133	134+
1976	1326	0.01	0.02	0.10	0.19	0.34	0.18	0.02	0.00	0.00	0.00	0.01	0.02	0.03	0.04	0.01	0.01
1979	220	0.01	0.01	0.00	0.02	0.05	0.05	0.03	0.01	0.01	0.00	0.01	0.04	0.14	0.40	0.19	0.03
1982	327	0.22	0.07	0.16	0.23	0.17	0.03	0.00	0.00	0.00	0.00	0.01	0.02	0.03	0.02	0.02	0.03
1985	350	0.11	0.11	0.19	0.17	0.16	0.06	0.01	0.00	0.00	0.00	0.00	0.02	0.05	0.08	0.05	0.01
1988	366	0.16	0.19	0.12	0.13	0.11	0.06	0.03	0.00	0.00	0.00	0.01	0.01	0.03	0.07	0.05	0.03
1991	340	0.18	0.08	0.02	0.03	0.06	0.03	0.01	0.01	0.03	0.06	0.02	0.08	0.16	0.14	0.09	0.02
1996	269	0.29	0.21	0.13	0.09	0.05	0.00	0.00	0.01	0.00	0.00	0.03	0.03	0.04	0.04	0.04	0.03
1999	283	0.03	0.01	0.10	0.29	0.26	0.13	0.03	0.01	0.00	0.00	0.00	0.03	0.05	0.04	0.02	0.00
2002	244	0.09	0.12	0.14	0.11	0.02	0.03	0.02	0.01	0.01	0.03	0.07	0.10	0.09	0.09	0.05	0.02
2006	373	0.18	0.26	0.21	0.11	0.06	0.04	0.02	0.00	0.00	0.00	0.00	0.02	0.04	0.04	0.01	0.00
2008	275	0.12	0.15	0.21	0.11	0.10	0.03	0.02	0.01	0.00	0.01	0.04	0.06	0.08	0.01	0.04	0.00
2010	69	0.01	0.04	0.06	0.17	0.06	0.03	0.00	0.00	0.00	0.03	0.09	0.20	0.19	0.07	0.03	0.01
2011	315	0.13	0.11	0.09	0.11	0.18	0.14	0.03	0.01	0.00	0.00	0.01	0.02	0.09	0.04	0.03	0.00
2014	391	0.08	0.15	0.24	0.18	0.09	0.02	0.01	0.01	0.00	0.00	0.03	0.10	0.05	0.04	0.01	0.00

Table 6. Winter pot survey size/shell compositions.

			New Shell								Old Shell							
Year	CPUE	Sample	64-73	74-83	84-93	94-103	104-113	114-123	124-133	134+	64-73	74-83	84-93	94-103	104-113	114-123	124-133	134+
1981/82	NA	719	0.00	0.10	0.23	0.21	0.07	0.02	0.02	0.00	0.00	0.05	0.11	0.11	0.04	0.02	0.02	0.00
1982/83	24.2	2583	0.03	0.08	0.28	0.28	0.21	0.07	0.01	0.00	0.00	0.00	0.00	0.00	0.02	0.01	0.01	0.01
1983/84	24.0	1677	0.01	0.16	0.26	0.23	0.15	0.06	0.01	0.00	0.00	0.00	0.00	0.02	0.06	0.03	0.01	0.01
1984/85	24.5	789	0.02	0.09	0.25	0.35	0.16	0.06	0.01	0.00	0.00	0.00	0.00	0.01	0.03	0.02	0.00	0.00
1985/86	19.2	594	0.04	0.12	0.17	0.24	0.19	0.08	0.01	0.00	0.00	0.00	0.00	0.01	0.06	0.04	0.01	0.00
1986/87	5.8	144	0.00	0.06	0.15	0.19	0.07	0.04	0.00	0.00	0.00	0.00	0.01	0.04	0.30	0.11	0.03	0.00
1987/88																		
1988/89	13.0	500	0.02	0.13	0.15	0.13	0.19	0.17	0.03	0.00	0.00	0.00	0.00	0.00	0.05	0.08	0.03	0.00
1989/90	21.0	2076	0.00	0.05	0.21	0.26	0.18	0.12	0.06	0.01	0.00	0.00	0.00	0.00	0.03	0.06	0.02	0.00
1990/91	22.9	1283	0.00	0.01	0.09	0.29	0.27	0.10	0.01	0.00	0.00	0.00	0.00	0.00	0.03	0.12	0.07	0.02
1992/93	5.5	181	0.00	0.01	0.03	0.06	0.13	0.12	0.03	0.00	0.00	0.00	0.00	0.02	0.19	0.27	0.10	0.05
1993/94																		
1994/95	6.2	858	0.01	0.06	0.08	0.10	0.26	0.23	0.07	0.01	0.00	0.00	0.00	0.00	0.03	0.07	0.06	0.02
1995/96	9.9	1580	0.06	0.14	0.20	0.19	0.11	0.07	0.03	0.00	0.00	0.00	0.00	0.01	0.06	0.07	0.03	0.01
1996/97	2.9	398	0.07	0.21	0.22	0.11	0.15	0.11	0.05	0.01	0.00	0.00	0.00	0.00	0.02	0.03	0.01	0.01
1997/98	10.9	881	0.00	0.14	0.41	0.27	0.05	0.02	0.00	0.00	0.00	0.00	0.01	0.02	0.03	0.02	0.02	0.01
1998/99	10.7	1307	0.00	0.02	0.12	0.36	0.36	0.08	0.01	0.00	0.00	0.00	0.00	0.01	0.02	0.01	0.01	0.00
1999/00	6.2	575	0.02	0.09	0.10	0.16	0.33	0.18	0.03	0.00	0.00	0.00	0.00	0.00	0.05	0.02	0.01	0.00
2000/01	3.1	44																
2001/02	13.0	828	0.05	0.29	0.26	0.17	0.06	0.06	0.04	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.00	0.00
2002/03	9.6	824	0.02	0.10	0.22	0.28	0.18	0.06	0.02	0.00	0.00	0.01	0.01	0.02	0.02	0.03	0.02	0.01
2003/04	3.7	296	0.00	0.02	0.16	0.26	0.32	0.14	0.01	0.00	0.00	0.00	0.01	0.02	0.02	0.01	0.02	0.01
2004/05	4.4	405	0.00	0.07	0.14	0.18	0.22	0.19	0.07	0.00	0.00	0.00	0.00	0.00	0.04	0.06	0.01	0.00
2005/06	6.0	512	0.00	0.14	0.23	0.21	0.16	0.05	0.02	0.00	0.00	0.01	0.01	0.02	0.04	0.07	0.03	0.01
2006/07	7.3	159	0.07	0.14	0.19	0.35	0.13	0.04	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.04	0.00	0.00
2007/08	25.0	3552	0.01	0.14	0.25	0.17	0.14	0.07	0.01	0.00	0.01	0.04	0.07	0.03	0.03	0.01	0.01	0.00
2008/09	21.9	525	0.00	0.07	0.13	0.35	0.20	0.08	0.01	0.00	0.00	0.00	0.00	0.00	0.04	0.10	0.00	0.00
2009/10	25.3	578	0.01	0.05	0.13	0.21	0.24	0.11	0.02	0.00	0.00	0.00	0.01	0.06	0.10	0.05	0.01	0.00
2010/11	22.1	596	0.02	0.08	0.13	0.20	0.17	0.13	0.05	0.00	0.00	0.00	0.01	0.03	0.11	0.05	0.01	0.00
2011/12	29.4	675	0.03	0.11	0.23	0.19	0.12	0.13	0.04	0.00	0.00	0.00	0.00	0.01	0.05	0.05	0.03	0.00

Table 7. Summer commercial1987-1994, 2012-2016 observer discards size/shell compositions

		New Shell								Old Shell							
Year	Sample	64-73	74-83	84-93	94-103	104-113	114-123	124-133	134+	64-73	74-83	84-93	94-103	104-113	114-123	124-133	134+
1987	1146	0.06	0.19	0.32	0.33	0.03	0.00	0.00	0.00	0.00	0.00	0.02	0.04	0.00	0.00	0.00	0.00
1988	722	0.01	0.04	0.15	0.48	0.14	0.00	0.00	0.00	0.00	0.01	0.03	0.10	0.04	0.00	0.00	0.00
1989	1000	0.07	0.19	0.24	0.22	0.03	0.00	0.00	0.00	0.02	0.03	0.07	0.11	0.03	0.00	0.00	0.00
1990	507	0.08	0.23	0.27	0.27	0.04	0.00	0.00	0.00	0.02	0.02	0.02	0.05	0.01	0.00	0.00	0.00
1992	580	0.11	0.17	0.30	0.29	0.03	0.00	0.00	0.00	0.01	0.02	0.02	0.04	0.01	0.00	0.00	0.00
1994	850	0.07	0.06	0.11	0.15	0.02	0.00	0.00	0.00	0.07	0.07	0.15	0.24	0.05	0.00	0.00	0.00
2012	939	0.21	0.11	0.19	0.32	0.10	0.01	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.00	0.00	0.00
2013	2617	0.34	0.29	0.16	0.16	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2014	1755	0.05	0.10	0.26	0.41	0.12	0.01	0.00	0.00	0.00	0.00	0.01	0.03	0.01	0.00	0.00	0.00
2015	824	0.01	0.08	0.18	0.44	0.23	0.02	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.00	0.00	0.00
2016	426	0.04	0.05	0.17	0.50	0.17	0.02	0.00	0.00	0.00	0.00	0.00	0.03	0.01	0.00	0.00	0.00

Table 8 The number of tagged data released and recovered after 1 year (Y1) – 3 year (Y3) during 1980-1992 and 1993-2016 periods.

Release Length Class	Recap Length Class	1980-2004			2005-2016		
		Y1	Y2	Y3	Y1	Y2	Y3
64 – 73	64 – 73						
64 – 73	74 - 83	1					
64 – 73	84 - 93	1	1		3		
64 – 73	94 - 103		1			5	
64 – 73	104 – 113		1			3	6
64 – 73	114 – 123						7
64 – 73	124 – 133						
64 – 73	134+						
74 - 83	74 - 83						
74 - 83	84 - 93	3			18		
74 - 83	94 - 103	7			15	11	
74 - 83	104 – 113		13		4	79	14
74 - 83	114 – 123		1	2		4	22
74 - 83	124 – 133						2
74 - 83	134+						
84 - 93	84 - 93						
84 - 93	94 - 103	15	1		34	4	1
84 - 93	104 – 113	19	5	1	72	21	11
84 - 93	114 – 123		5	2	7	53	5
84 - 93	124 – 133				1	2	2
84 - 93	134+						
94 - 103	94 - 103	4	1		6	1	
94 - 103	104 – 113	53	5	1	143	20	
94 - 103	114 – 123	31	5	7	77	8	9
94 - 103	124 – 133	2	2	2		11	6
94 - 103	134+				1		
104 – 113	104 – 113	18			57	2	
104 – 113	114 – 123	38	15	3	105	27	3
104 – 113	124 – 133	7	8	4	15	3	8
104 – 113	134+						1
114 – 123	114 – 123	17	2		71	5	
114 – 123	124 – 133	27	10	2	71	31	8
114 – 123	134+	5	1		19	4	3
124 – 133	124 – 133	15			41	6	
124 – 133	134+	10	4	2	15	8	6
134+	134+	15	6	1	11		

Table 9. Summary of initial input parameter values and bounds for a length-based population model of Norton Sound red king crab. Parameters with "log_" indicate log scaled parameters.

Parameter	Parameter description	Equation Number in Appendix A	Lower	Upper
log_q_1	Commercial fishery catchability (1977-92)	(20)	-32.5	8.5
log_q_2	Commercial fishery catchability (1993-2014)	(20)	-32.5	10.0
log_N_{76}	Initial abundance	(1)	2.0	15.0
R_0	Mean Recruit	(13)	2.0	12.0
$log\_\sigma_R^2$	Recruit standard deviation	(13)	-20.0	20.0
a_1	Parameter for intimal length proportion	(2)	-5.0	5.0
a_2	Parameter for intimal length proportion	(2)	-5.0	5.0
a_3	Parameter for intimal length proportion	(2)	-5.0	5.0
a_4	Parameter for intimal length proportion	(2)	-5.0	5.0
a_5	Parameter for intimal length proportion	(2)	-5.0	5.0
a_6	Parameter for intimal length proportion	(2)	-5.0	5.0
a_7	Parameter for intimal length proportion	(2)	-5.0	5.0
R	Proportion of length class 1 for recruit	(14)	0.5	0.9
log_α	Inverse logistic molting parameter	(15)	-5.5	-2.0
log_ϕ_{st1}	Logistic trawl selectivity parameter (NMFS)	(16)	-15.0	-1.0
log_ϕ_{st2}	Logistic trawl selectivity parameter (ADF&G)	(16)	-15.0	-1.0
log_ϕ_w	Inverse logistic winter pot selectivity parameter	(15,16)	-10.0	10.0
Sw_1	Winter pot selectivity of length class 1	(15,16)	0.1	1.0
Sw_2	Winter pot selectivity of length class 2	(15,16)	0.1	1.0
log_ϕ_1	Logistic commercial catch selectivity parameter (1977-2004)	(16)	-5.0	-1.0
log_ϕ_2	Logistic commercial catch selectivity parameter (2005-2016)	(16)	-5.0	-1.0
w^2_t	Additional variance for standard CPUE	(31)	0.0	6.0
q	Survey q for NMFS trawl 1976-91	(31)	0.1	1.0
σ	Growth transition sigma	(17)	0.0	30.0
β_1	Growth transition mean	(17)	0.0	20.0
β_2	Growth transition increment	(17)	0.0	20.0

Table 10 . Summary of parameter estimates and standard deviations of Norton Sound red king crab.

Table 11. Estimated selectivities, molting probabilities, and proportions of legal crab by length (mm CL) class for Norton Sound male red king crab.

Length Class	Legal Proportion	Mean weight (lb)	Selectivity ADFG/ NOAA	Selectivity Winter Pot	Selectivity Summer Fishery	Molting Probability
64 - 73						
74 - 83						
84 - 93						
94 - 103						
104 - 113						
114 - 123						
124 - 133						
134+						

Table 12: Estimated molting probability incorporated transition matrix.

Without molting probability

Pre-molt Length Class	Post-molt Length Class							
	64-73	74-83	84-93	94-103	104-113	114-123	124-133	134+
64 – 73								
74 - 83								
84 - 93								
94 - 103								
104 – 113								
114 – 123								
124 – 133								
134+								

With molting probability

Pre-molt Length Class	Post-molt Length Class							
	64-73	74-83	84-93	94-103	104-113	114-123	124-133	134+
64 - 73								
74 - 83								
84 - 93								
94 - 103								
104 - 113								
114 - 123								
124 - 133								
134+								

Table 13. Annual abundance estimates (million crab) and mature male biomass (MMB, million lb) for Norton Sound red king crab estimated by a length-based analysis from 1976 to 2016

	Abundance			Legal (≥ 104 mm)				MMB	
Year	Recruits	Total (≥ 74 mm)	Mature (≥ 94 mm)	Abundance	S.D	Biomass	S.D	Biomass	S.D.
1976									
1977									
1978									
1979									
1980									
1981									
1982									
1983									
1984									
1985									
1986									
1987									
1988									
1989									
1990									
1991									
1992									
1993									
1994									
1995									
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2004									
2005									
2006									
2007									
2008									
2009									
2010									
2011									
2012									
2013									
2014									
2015									
2016									

Table 14. Summary of catch and estimated discards (million lb) for Norton Sound red king crab. Assumed average crab weight is 2.5 lb for the winter commercial catch, 2.0 lb for the subsistence catch, and 1.0 lb for Winter subsistence discards. Summer and winter commercial discards were estimated from the model.

Year	Summer Com	Winter Com	Winter Sub	Discards Summer	Discards Winter Sub	Discards Winter com	Total	Catch/ MMB
1977	0.52	0.000	0.000		0.000			
1978	2.09	0.024	0.025		0.008			
1979	2.93	0.001	0.000		0.000			
1980	1.19	0.000	0.000		0.000			
1981	1.38	0.000	0.001		0.000			
1982	0.23	0.000	0.003		0.001			
1983	0.37	0.001	0.021		0.006			
1984	0.39	0.002	0.022		0.005			
1985	0.43	0.003	0.017		0.002			
1986	0.48	0.005	0.014		0.004			
1987	0.33	0.003	0.012		0.002			
1988	0.24	0.001	0.005		0.001			
1989	0.25	0.001	0.012		0.002			
1990	0.19	0.009	0.024		0.004			
1991	0	0.010	0.015		0.002			
1992	0.07	0.019	0.023		0.003			
1993	0.33	0.004	0.002		0.000			
1994	0.32	0.014	0.008		0.001			
1995	0.32	0.019	0.011		0.002			
1996	0.22	0.004	0.003		0.001			
1997	0.09	0.000	0.001		0.001			
1998	0.03	0.002	0.017		0.012			
1999	0.02	0.007	0.015		0.003			
2000	0.3	0.008	0.011		0.004			
2001	0.28	0.003	0.001		0.000			
2002	0.25	0.006	0.004		0.003			
2003	0.26	0.017	0.008		0.005			
2004	0.34	0.001	0.002		0.001			
2005	0.4	0.005	0.008		0.003			
2006	0.45	0.000	0.002		0.001			
2007	0.31	0.008	0.021		0.011			
2008	0.39	0.014	0.019		0.009			
2009	0.4	0.012	0.010		0.002			
2010	0.42	0.012	0.014		0.002			
2011	0.4	0.008	0.013		0.003			
2012	0.47	0.023	0.015		0.004			
2013	0.35	0.057	0.015		0.014			
2014	0.39	0.037	0.007		0.002			
2015	0.40	0.103	0.019		0.005			
2016	0.42	0.080	0.011		0.001			