2015 Stock assessment and fishery evaluation report for the Pribilof Island red king crab fishery of the Bering Sea and Aleutian Islands regions (DRAFT)

C.S. Szuwalski, R.J. Foy, B.J. Turnock
Alaska Fishery Science Center
National Marine Fishery Service
National Oceanic and Atmospheric Administration

Executive summary

1. Stock: Pribilof Islands red king crab, *Paralithodes camtschaticus*
2. Catches: Retained catches have not occurred since 1998/1999. Bycatch and discards have been increasing in recent years, but are still low relative to the OFL.
3. Stock biomass:
    a. According to a 3-year running average, mature male biomass decreased from 2007 to 2010 and increased during 2011 through 2014.
    b. According to an integrated length-based assessment, mature male biomass increased from 2007 to 2009 and decreased from 2010 through 2014.
4. Recruitment: Recruitment is episodic for PIRKC and has been low recently.
5. Recent management statistics:

Year	MSST	Biomass (MMB)	TAC	Retained Catch	Total Catch	OFL	ABC
2010/11	2,255	2,754^{A}	0	0	4.2	349	
2011/12	2,571	2,775^{B*}	0	0	5.4	393	307
2012/13	2,609	4,025^{C**}	0	0	13.1	569	455
2013/14	2,582	4,679^{D**}	0	0	2.25	903	718
2014/15	2,871	8894	0	0	1.06	1359	1019

Units are in tonnes.

Year	MSST	Biomass (MMB)	TAC	Retained Catch	Total Catch	OFL	ABC
2010/11	4.97	6.07^{A}	0	0	0.009	0.77	
2011/12	5.67	6.12^{B*}	0	0	0.011	0.87	0.68
2012/13	5.75	8.87^{C**}	0	0	0.029	1.25	1.00
2013/14	5.66	10.32^{D**}	0	0	0.005	1.99	1.58
2014/15	6.33	19.60	0	0	0.002	3.00	2.25

Units are in millions of lbs. The OFL is the total catch OFL for each year. The stock was above MSST in 2013/2014 according to both a 3-year average and a length-based assessment method and is hence not overfished.

Notes:

A – Based on survey data available to the Crab Plan Team in September 2010 and updated with 2010/2011 catches
B – Based on survey data available to the Crab Plan Team in September 2011 and updated with 2011/2012 catches
C – Based on survey data available to the Crab Plan Team in September 2012 and updated with 2012/2013 catches
D – Based on survey data available to the Crab Plan Team in September 2013
* – 2011/12 estimates based on 3 year running average
** –estimates based on weighted 3 year running average using inverse variance

6. 2015/2016 OFL projections:

Tier	Assessment Method	OFL	B_{MSY}	Current MMB	B/B_{MSY} (MMB)	γ	Years to define B_{MSY}	F_{MSY}	P*	ABC
4	Running Average	1997	5718	13065	2.28	1.0	1991/1992-2013/2014 (MMB)	0.18	0.49	1471
4	Integrated assessment	458	3887	3180	0.82	1.0	1991/1992-2013/2014 (MMB)	0.18	0.49	339
3	Integrated assessment	1015	1363	3180	2.62	1.0	1991/1992-2013/2014 (MMB)	0.45	0.49	752
4	Integrated assessment (males only)	741	4345	5161	1.19	1.0	1991/1992-2013/2014 (MMB)	0.18	0.49	532
3	Integrated assessment (males only)	1608	1560	5161	3.31	1.0	1983-present (recruitment)	0.44	0.49	1153

Units are in tonnes

Tier	Assessment Method	OFL	B_{MSY}	Current MMB	B/B_{MSY} (MMB)	γ	Years to define B_{MSY}	F_{MSY}	P*	ABC
4	Running Average	4.40	12.61	28.80	2.59	1.0	1991/1992-2013/2014 (MMB)	0.18	0.49	3.26
4	Integrated assessment	1.05	8.92	7.30	0.82	1.0	1991/1992-2013/2014 (MMB)	0.18	0.49	0.74
3	Integrated assessment	2.33	3.13	7.30	2.62	1.0	1983-present (recruitment)	0.52	0.49	1.65
4	Integrated assessment (males only)	1.70	9.97	11.85	1.19	1.0	1991/1992-2013/2014 (MMB)	0.18	0.49	1.11
3	Integrated assessment (males only)	3.69	3.58	11.85	3.31	1.0	1983-present (recruitment)	0.51	0.49	2.40

Units are in millions of pounds.

7. Probability distributions of the OFL for tier 4 methods were generated by bootstrapping values of MMB in the current year with an additional sigma of 0.3. The posterior of the OFL from the integrated assessment was used as the distribution for the OFL from which ABCs were calculated.
8. Basis for ABC: ABCs were identified as the 49th percentile of the distributions of the OFL given a p-star of 0.49.

Summary of Major Changes:

1. Management: None.
2. Input data: Survey (2015) and bycatch (2014) data were incorporated into the assessment. Methodology for calculating estimates of numbers from the survey data changed between 2014 and 2015.
3. Assessment methodology: A comparison of output when the only data for males is fit is presented based on concerns of 2014 model fits to survey estimates. Fishery selectivity is borrowed from BBRKC rather than knife-edge and incorporates discard mortality of 20%.
4. Assessment results: MMB estimates from the 3-year running average are the highest on record, but conflict with a lack of recruitment since the early 2000s.

CPT May 2015 requests (and SSC comments)

In response to the SSC comments about poor fits to male numbers from the survey data from 1990 forward, the CPT suggested a model run forcing a fit to the higher survey years and exploration of time-varying processes. The SSC also suggested truncating the time series to exclude the low abundances in the 1970s and 1980s.

The poor fits to survey numbers result from two data conflicts. First, males and females have opposite trends in recent years (apart from 2015; Figure 19): females are declining and males are increasing. Recruitment and catchability were identical for females and males in the 2014 integrated assessment, so the neither the male nor female numbers data were well fit for recent years. A model fitting to only males is presented here and fits male numbers (marginally) better than the 2014 assessment (Figure 27). Excluding the low abundances from the data (1970s-1980s) does not change the fits to the data starting in the 1990s. Forcing a fit to the high survey estimates during the 1990s results in large overestimates of numbers in the 2000s and after (i.e. the model can fit either the high abundances or the low, with a constant M or q because there is no fishing mortality; Figure 39). Large swings in abundance between the 1990s and 2000s are still poorly fit because the specified natural mortality and the inferred fishing mortality are not large enough to allow for such large yearly changes in abundance.

The second data conflict is apparent in the length frequencies, recruitment, and the most recent estimated MMB. Estimated MMB from the 3-year running average was the highest on record this year, but there has been no recruitment since the early 2000s (as seen through the length frequencies). This suggests that either catchability is varying or there has been large-scale immigration by large male crab.

The CPT also suggested time-blocking M and allowing time-varying selectivity or catchability to address the poor fits.

A switch allowing time-varying catchability was coded in the assessment method. Model fits to male numbers were much better when catchability was freely estimated (as expected; Figure 37), but there was no clear relationship between catchability and temperature (sea surface or bottom). Time-varying catchability analyses were only done when fitting males because: 1) trends in estimates of numbers are opposite for females and males in recent years and 2) male biomass (via survey numbers) are the important quantity to estimate for management.

The CPT suggested borrowing the total fishery selectivity from BBRKC for use with PIRKC so that some discard mortality could be applied when calculating target fishing mortalities.

This was incorporated and resulted in a reduction in $F_{35\%}$ by 0.08 (from 0.53 to 0.45) when both males and females were fit.

The SSC supports the author's suggestions to further investigate model sensitivity of different size bins on growth and management specifications.

A simulation framework was built to explore biases observed in 2014 by moving to 10mm length bins (Szuwalski, in press). Assessment methods using 5mm size bin data returned unbiased estimates of MMB, but 10mm size bins produced biased estimates of MMB. So, the estimates of MMB from the assessment method using 5mm size bins presented in 2014 are likely more reliable than the 10mm data. The bias was caused by the way the integral representing the probability of molting from one size to another was approximated. Assessment methods with 5mm length bins were used in all scenarios presented here based on the unbiased estimates of MMB in simulation.

Include more detail on the model
The code is now available on Github (github.com/szuwalski/PIRKC) and Appendix A (describing the model) is more detailed.

Unaddressed comments
Incorporate a mean-unbiased log normal likelihood for survey numbers
Next time.

Discuss the poisson vs. negative binomial for survey estimates of abundance and CVs
Currently all of the data in the model are those that are passed from Bob Foy and the Kodiak lab, but given the over-dispersion in the data, a negative binomial (or something similar) might be more appropriate, particularly for estimates of variance. The CVs sent by Bob are used in the assessment, but bootstrapped variances are much larger.

Consider ADFG pot survey data and retained catch size frequency data
These data area not yet incorporated, but may be useful in exploring the mechanics of time-varying catchability.

Employ an iterative reweighting scheme for setting the length frequency weights.
To be addressed.

1. Introduction

1.1 Distribution

Red king crabs, *Paralithodes camtschaticus,* (Tilesius, 1815) are anomurans in the family lithodidae and are distributed from the Bering Sea south to the Queen Charlotte Islands and to Japan in the western Pacific (Jensen 1995; Figure 1). Red king crabs have also been introduced and become established in the Barents Sea (Jørstad et al. 2002). The Pribilof Islands red king crab stock is located in the Pribilof District of the Bering Sea Management Area Q. The Pribilof District is defined as Bering Sea waters south of the latitude of Cape Newenham (58° 39' N lat.), west of 168° W long., east of the United States – Russian convention line of 1867 as amended in 1991, north of 54° 36' N lat. between 168° 00' N and 171° 00' W long and north of 55° 30'N lat. between 171° 00' W. long and the U.S.-Russian boundary (Figure 2).

1.2 Stock structure

Populations of red king crab in the eastern Bering Sea (EBS) for which genetic studies have been performed appear to be composed of four stocks: Aleutian Islands, Norton Sound, Southeast Alaska, and the rest of the EBS. Seeb and Smith (2005) reported micro-satellite samples from Bristol Bay, Port Moller, and the Pribilof Islands were divergent from the Aleutian Islands and Norton Sound. A more recent study describes the genetic distinction of Southeast Alaska red king crab compared to Kodiak and the Bering Sea; the latter two being similar (Grant and Cheng 2012).

1.3 Life history

Red king crabs reproduce annually and mating occurs between hard-shelled males and soft-shelled females. Red king crabs do not have spermathecae and cannot store sperm, therefore a female must mate every year to produce a fertilized clutch of eggs (Powell and Nickerson 1965). A pre-mating embrace is formed 3-7 days prior to female ecdysis, the female molts, and copulation occurs within hours. The male inverts the female so they are abdomen to abdomen and then the male extends his fifth pair of periopods to deposit sperm on the female's gonopores. Eggs are fertilized after copulation as they are extruded through the gonopores located at the ventral surface of the coxopides of the third periopods. The eggs form a spongelike mass, adhering to the setae on the pleopods where they are brooded until hatching (Powell and Nickerson 1965). Fecundity estimates are not available for Pribilof Islands red king crab, but range from 42,736 to 497,306 for Bristol Bay red king crab (Otto et al. 1990). The estimated size at 50 percent maturity of female Pribilof Islands red king crabs is approximately 102 mm carapace length (CL) which is larger than 89 mm CL reported for Bristol Bay and 71 mm CL for Norton Sound (Otto et al. 1990). Size at maturity has not been determined specifically for Pribilof Islands red king crab males, however, approximately 103 mm CL is reported for eastern Bering Sea male red king crabs (Somerton 1980). Early studies predicted that red king crab become mature at approximately age 5 (Powell 1967; Weber 1967); however, Stevens (1990) predicted mean age at recruitment in Bristol Bay to be 7 to 12 years, and Loher et al. (2001) predicted age to recruitment to be approximately 8 to 9 years after settlement. Based upon a long-term laboratory study, longevity of red king crab males is approximately 21 years and less for females (Matsuura and Takeshita 1990).

Natural mortality of Bering Sea red king crab stocks is poorly known (Bell 2006). Siddeek et al. (2002) reviewed natural mortality estimates from various sources. Natural mortality estimates based upon historical tag-recapture data range from 0.001 to 0.93 for crabs 80-169 mm CL with natural mortality increasing with size. Natural mortality estimates based on more recent tag-recovery data for Bristol Bay red king crab males range from 0.54 to 0.70, however, the authors noted that these estimates appear high considering the longevity of red king crab. Natural mortality estimates based on trawl survey data vary from 0.08 to 1.21 for the size range 85-169 mm CL, with higher mortality for crabs <125 mm CL. In an earlier analysis that utilized the same data sets, Zheng et al. (1995) concluded that natural mortality is dome shaped over length and varies over time. Natural mortality was set at 0.2 for Bering Sea king crab stocks (NPFMC 1998) and was changed to 0.18 with Amendment 24.

The reproductive cycle of Pribilof Islands red king crabs has not been established, however, in Bristol Bay, timing of molting and mating of red king crabs is variable and occurs from the end of January through the end of June (Otto et al. 1990). Primiparous (i.e. brooding their first egg clutch) Bristol Bay red king crab females extrude eggs on average 2 months earlier in the reproductive season and brood eggs longer than multiparous (i.e. brooding their second or subsequent egg clutch) females (Stevens and Swiney 2007a, Otto et al. 1990), resulting in incubation periods that are approximately eleven to twelve months in duration (Stevens and Swiney 2007a, Shirley et al. 1990). Larval hatching among red king crabs is relatively synchronous among stocks and in Bristol Bay occurs March through June with peak hatching in May and June (Otto et al. 1990), however larvae of primiparous females hatch earlier than multiparous females (Stevens and Swiney 2007b, Shirley and Shirley 1989). As larvae, red king crabs exhibit four zoeal stages and a glaucothoe stage (Marukawa 1933).

Growth parameters have not been examined for Pribilof Islands red king crabs; however they have been studied for Bristol Bay red king crab. A review by the Center for Independent Experts (CIE) reported that growth parameters are poorly known for all red king crab stocks (Bell 2006). Growth increments of immature southeastern Bering Sea red king crabs are approximately: 23% at 10 mm CL, 27% at 50 mm CL, 20% at 80 mm CL and 16 mm for immature crabs over 69 mm CL (Weber 1967). Growth of males and females is similar up to approximately 85 mm CL, thereafter females grow more slowly than males (Weber 1967; Loher et al. 2001). In a laboratory study, growth of female red king crabs was reported to vary with age; during their pubertal molt (molt to maturity) females grew on average 18.2%, whereas primiparous females grew 6.3% and multiparous females grew 3.8% (Stevens and Swiney, 2007a). Similarly, based upon tag-recapture data from 1955-1965 researchers observed that adult female growth per molt decreases with increased size (Weber 1974). Adult male growth increment averages 17.5 mm irrespective of size (Weber 1974).

Molting frequency has been studied for Alaskan red king crabs, but Pribilof Islands specific studies have not been conducted. Powell (1967) reports that the time interval between molts increases from a minimum of approximately three weeks for young juveniles to a maximum of four years for adult males. Molt frequency for juvenile males and females is similar and once mature, females molt annually and males molt annually for a few years and then biennially, triennially and quadrennial (Powell 1967). The periodicity of mature male molting is not well understood and males may not molt synchronously like females who molt prior to mating (Stevens 1990).

1.4 Management history

Red king crab stocks in the Bering Sea and Aleutian Islands are managed by the State of Alaska through the federal Fishery Management Plan (FMP) for Bering Sea/Aleutian Islands King and Tanner Crabs (NPFMC 1998). The Alaska Department of Fish and Game (ADF&G) has not published harvest regulations for the Pribilof district red king crab fishery. The king crab fishery in the Pribilof District began in 1973 with blue king crab *Paralithodes platypus* being targeted (Figure 3). A red king crab fishery in the Pribilof District opened for the first time in September 1993. Beginning in 1995, combined red and blue king crab GHLs were established. Declines in red and blue king crab abundance from 1996 through 1998 resulted in poor fishery performance during those seasons with annual harvests below the fishery GHL. The North Pacific Fishery Management Council (NPFMC) established the Bering Sea Community Development Quota (CDQ) for Bering Sea fisheries including the Pribilof Islands red and blue king crab fisheries which was implemented in 1998. From 1999 to present the Pribilof Islands fishery was not open due to low blue king crab abundance, uncertainty with estimated red king crab abundance, and concerns for blue king crab bycatch associated with a directed red king crab fishery. Pribilof Islands blue king crab was declared overfished in September of 2002 and is still considered overfished (see Bowers et al. 2011 for complete management history).

Amendment 21a to the BSAI groundfish FMP established the Pribilof Islands Habitat Conservation Area (Figure 4) which prohibits the use of trawl gear in a specified area around the Pribilof Islands year round (NPFMC 1994). The amendment went into effect January 20, 1995 and protects the majority of crab habitat in the Pribilof Islands area from impacts from trawl gear.

Pribilof Islands red king crab often occur as bycatch in the eastern Bering Sea snow crab (*Chionoecetes opilio*), eastern Bering Sea Tanner crab (*Chionoecetes bairdi*), Bering Sea hair crab (*Erimacrus isenbeckii*), and Pribilof Islands blue king crab fisheries (when there is one). Limited non-directed catch exists in crab fisheries and groundfish pot and hook and line fisheries (see bycatch and discards section below). However, bycatch is currently very low compared to historical levels.

2. Data

Two survey time series' (with accompanying CVs--both updated through 2014) are first presented for comparison (Figure 5). A change in the methodology used to produce estimates of biomass and numbers at length within these time series' produced small changes in some of the data used in the assessment methodology. The updated survey time series (through 2015) is used to present the final OFL and ABC.

The standard groundfish discards time series data (updated through 2014) were used in this assessment. The crab fishery retained and discard catch time series were updated with 2014/2015 data. The following sources and years of data are available:

Data source	Years available	Used in integrated assessment?
NMFS trawl survey	1975-2015	Yes
Retained catch	1993-2014	Yes
Trawl bycatch	1991-2014	Yes
Fixed gear bycatch	1991-2014	No
Pot discards	1998-2014	No

2.1 Retained catch

Red king crab were targeted in the Pribilof Islands District from the 1993/1994 season to 1998/1999. Live and deadloss landings data and effort data are available during that time period (Tables 1 and 2), but no retained catch has been allowed since 1999.

2.2 Bycatch and discards

Non-retained (directed and non-directed) pot fishery catches are provided for sub-legal males (≤138 mm CL), legal males (>138 mm CL), and females based on data collected by onboard observers. Catch weight was calculated by first determining the mean weight (g) for crabs in each of three categories: legal non-retained, sublegal, and female. Length to weight parameters were available for two time periods: 1973 to 2009 (males: A=0.000361, B=3.16; females: A=0.022863, B=2.23382) and 2010 to 2013 (males: A=0.000403, B=3.141; ovigerous females: A=0.003593, B=2.666; non-ovigerous females: A=0.000408, B=3.128). The average weight for each category was multiplied by the number of crabs at that CL, summed, and then divided by the total number of crabs (equation 2).

$$\text{Weight (g)} = A * \text{CL(mm)}^{B} \qquad (1)$$

$$\text{Mean Weight (g)} = \sum(\text{weight at size} * \text{number at size}) / \sum(\text{crabs}) \qquad (2)$$

Finally, weights, discards, and bycatch were the product of average weight, CPUE, and total pot lifts in the fishery. A 20% handling mortality rate was applied to these estimates.

Historical non-retained catch data are available from 1998/1999 to present from the snow crab, golden king crab (*Lithodes aequispina*), and Tanner crab fisheries (Table 3) although data may be incomplete for some of these fisheries. Limited observer data exists prior to 1998 for catcher-processor vessels only so non-retained catch before this date is not included here. In 2013/2014, there were no Pribilof Islands red king crab incidentally caught in the crab fisheries (Table 3).

2.3 Groundfish pot, trawl, and hook and line fisheries

The 2013/2014 NOAA Fisheries Regional Office (J. Gasper, NMFS, personal communication) assessments of non-retained catch from all groundfish fisheries are included in this SAFE report. Groundfish catches of crab are reported for all crab combined by federal reporting areas and by State of Alaska reporting areas since 2009/2010. Catches from observed fisheries were applied to non-observed fisheries to estimate a total catch. Catch counts were converted to biomass by applying the average weight measured from observed tows from July 2011 to June 2012. Prior to 2011/2012, Areas 513 and 521 were included in the estimate, a practice that likely resulted in an overestimate of the catch of Pribilof Islands red king crab due to the extent of Area 513 into the Bristol Bay District. In 2012/2013 these data were available in State of Alaska reporting areas that overlap specifically with stock boundaries so that the management unit for each stock can be more appropriately represented. To estimate sex ratios for 2012/2013 catches, it was assumed that the male to female ratio was one. To assess crab mortalities in these groundfish fisheries a 50% handling mortality rate was applied to pot and hook and line estimates and an 80% handling mortality rate was applied to trawl estimates.

Historical non-retained groundfish catch data are available from 1991/1992 to present (J. Mondragon, NMFS, personal communication) although sex ratios have not been determined (Table 3). Prior to 1991data are only available in INPFC reports. Between 1991 and December 2001 bycatch was estimated using the “blend method”. The blend method combined data from industry production reports and observer reports to make the best, comprehensive accounting of groundfish catch. For shoreside processors, Weekly Production Reports (WPR) submitted by industry were the best source of data for retained groundfish landings. All fish delivered to shoreside processors were weighed on scales, and these weights were used to account for retained catch. Observer data from catcher vessels provided the best data on at-sea discards of groundfish by vessels delivering to shoreside processors. Discard rates from these observer data were applied to the shoreside groundfish landings to estimate total at-sea discards from both observed and unobserved catcher vessels. For observed catcher/processors and motherships, the WPR and the Observer Reports recorded estimates of total catch (retained catch plus discards). If both reports were available, one of them was selected during the “blend method” for incorporation into the catch database. If the vessel was unobserved, only the WPR was available. From January 2003 to December 2007, a new database structure named the Catch Accounting System (CAS) led to large method change. Bycatch estimates were derived from a combination of observer and landing (catcher vessels/production data). Production data included CPs and catcher vessels delivering to motherships. To obtain fishery level estimates, CAS used a ratio estimator derived from observer data (counts of crab/kg groundfish) that is applied to production/landing information. (See http://www.afsc.noaa.gov/Publications/AFSC-TM/NOAA-TM-AFSC-205.pdf). Estimates of crab are in numbers because the PSC is managed on numbers. There were two issues with this dataset that required estimation work outside of CAS:

1) The estimated number of crab had to be converted to weights. An average weight was calculated using groundfish observer data. This weight was specific to crab year, crab species, and fixed or trawl gear. This average was applied to the estimated number of crab for crab year by federal reporting area.
2) In some situations, crab estimates were identified and grouped in the observed data to the genus level. These crabs were apportioned to the species level using the identified crab.

From January 2008 to 2012 the observer program changed the method in which they speciate crab to better reflect their hierarchal sampling method and to account for broken crab that in the past were only identified to genus. In addition, haul-level weights collected by the observers were used to estimate the weight of crab through CAS instead of applying an annual (global) weight factor. Spatial resolution was at federal reporting area.

Starting in 2013, a new data set based on the CAS system was made available for January 2009 to present. In 2009 reporting State statistical areas was required on groundfish production reports. The level of spatial resolution in CAS was formally federal reporting area since this the highest spatial resolution at which observer data is aggregated to create bycatch rates. The federal reporting area does not follow crab stock boundaries, in particular for species with small stock areas such as Pribilof Islands or St. Matthew Island stocks, so the new data was provided at the State reporting areas. This method uses ratio estimator (weight crab/weight groundfish) applied to the weight of groundfish reported on production/landing reports. Where possible, this dataset aggregates observer data to the stock area level to create bycatch estimates by stock area. There are instances where no observer data is available and aggregation may go outside of a stock area, but this practice is greatly reduced compared with the pre-2009 data, which at best was at the Federal reporting area level.

The new time series resulted in different estimates of red king crab bycatch biomass in 2009/2010-2012/2013 (Table 3). In 2012/2013, using the new database estimation, 16.46 t of male and female red king crab were caught in fixed gear (0.23 t) and trawl gear (16.23 t) groundfish fisheries which is 51% greater than was caught in 2011/2012 pot, trawl, and hook and line groundfish fisheries. The catch was mostly in non-pelagic trawls (99%) followed by longline (1%), and pot (<1%) fisheries (Table 4). The targeted species in these fisheries were Pacific cod (3%), flathead sole (18%), yellowfin sole (77%), and traces <1% found in the rockfish fisheries. Unlike previous years no bycatch was observed in Alaska plaice fisheries in 2011/2012 or 2012/2013.

2.4 Catch-at-length

Catch-at-length data are not available for this fishery.

2.5 Survey biomass and length frequencies

The 2015 NOAA Fisheries EBS bottom trawl survey results (Daly et al. in press) are included in this SAFE report. Data available for estimating the abundance of crab around the Pribilof Islands are relatively sparse. Red king crab have been observed at 35 unique stations in the Pribilof District (22 stations on the $400\ \text{nm}^2$ grid). The number of stations at which at least one crab was observed in a given year ranges from 0-14 over the period from 1975-present (Figure 6). Weight (equation 1) and maturity (equation 3) schedules are applied to calculated abundances and summed to calculate mature male, female, and legal male biomass for the Tier 4 analysis.

$$\begin{aligned} &\text{Proportion mature male} = 1/(1 + (5.842 * 10^{14}) * e^{((CL(mm)+2.5) * -0.288)}) \\ &\text{Proportion mature female} = 1/(1 + (1.416 * 10^{13}) * e^{((CL(mm)+2.5) * -0.297)}) \end{aligned} \tag{3}$$

Historical survey data are available from 1975 to the present (Tables 5 and 6), and survey data analyses were standardized in 1980 (Stauffer, 2004). Male and female abundance varies widely over the history of the survey time series' (Figure 7) and uncertainty around area-swept estimates of abundance are large due to relatively low sample sizes (Figure 6). Male crabs were observed at 9 of 35 stations in the Pribilof District during the 2015 NMFS survey (Figure 8); female crabs were observed at 5 (Figure 9). Two (possibly three) cohorts can be seen moving through the length frequencies over time (Figure 10 and Figure 11). Numbers at length vary dramatically from year to year, but the cohorts can nonetheless also be discerned in these data (Figure 12 and Figure 13). Methodologies for calculating estimated numbers at length and biomass changed slightly from 2014 to 2015 (see Daly et al., in press for description).

The centers of distribution for both males and females have moved within a 40 nm by 40 nm region around St. Paul Island. The center of the red king crab distribution moved to within 20 nm of the northeast side of St. Paul Island as the population abundance increased in the 1980's and remained in that region until the 1990's. Since then, the centers of distribution have been located closer to St. Paul Island the exception of 2000-2003 located towards the north east.

Survey length frequencies used in the 2014 assessment were calculated from the survey data for use in the integrated assessment. Occasionally, several hauls were taken at a single survey station (here a 'haul' does not refer to the high density sampling in which the 'corners' of a station are trawled—'haul' refers to multiple samples from a given location). Treating multiple hauls as independent measurements may introduce bias when calculating the population-wide length frequencies. Therefore, whenever multiple hauls were taken at a station, their contribution to the overall length frequency was weighted by the average number of individuals caught in a haul at that station. The length frequencies used in 2015 were provided by the Kodiak lab and exhibited only minor differences to 2014 input data.

3. Analytical approaches

3.1 History of modeling

An inverse-variance weighted 3-year running average of mature male biomass based on densities estimated from the NMFS summer trawl survey has been used in recent years to set allowable catches. The natural mortality rate has been used as a proxy for the fishing mortality at which maximum sustainable yield occurs (F_{MSY}) and target biomasses are set by identifying a range of years over which the stock was thought to be near B_{MSY} (i.e. a tier 4 control rule). A catch survey analysis has been used for assessing the stock in the past, although the data are not currently used in this assessment. This year (2015), biomass and derived management quantities are estimated both by a running-average method and by an integrated length-based assessment method (developed in 2014). Tier 3 and tier 4 harvest control rules (HCRs) are applied to the integrated assessment output and are compared to the OFLs calculated by a tier 4 HCR applied to the running-average estimates of MMB.

3.2 Model descriptions

3.2.1. Running average

A 3 year running average of mature male biomass (runAvg) was calculated using the function ‘weighted.mean’ in the R programming languages as:

```
for(t in 2:(length(MMB)-1))
 runAvg[t]<-weighted.mean(MMB[(t-1):(t+1)],w=1/σ²[(t-1):(t+1)])          (4)
```

Where,

? ? ?	Estimated mature male biomass from the survey data
σ^2	The variance associated with the estimate of MMB at time t

$?_?^?$ is calculated from the CVs of the estimates of MMB from the survey provided by the Kodiak lab as:

$$?_?^? \quad Ú\,A\!?_?^{?\ ?\ ?} * ??_?^{?\ ?\ ?\ \ ?} \tag{5}$$

Where,

$?_?^{?\ ?\ ?}$	estimated mature male biomass from the survey at time t
$??_?^{?\ ?\ ?}$	Coefficient of variation associated with the estimate of MMB at time t

3.2.2 Integrated assessment

A length-based integrated assessment method [coded in ADMB (Fournier et al. 2012)] was used to estimate trends in recruitment, fishing mortality (directed and bycatch in the non-pelagic trawl fishery) and male and female numbers in the survey (see appendix A for the model description, likelihood weightings, and estimated and fixed parameters). The assessment is initiated 5 years before data are available to avoid estimating initial numbers at length for both sexes. Males and females are tracked by 5 mm length bins ranging from 37.5-207.5mm in the base model. Fishing mortality from the directed fishery during 1993-1998 and bycatch in the non-pelagic trawl fishery from 1991-2013 were accounted for in the model, but discards from the pot fisheries for crab and the fixed gear fishery for cod are not incorporated into the model. The magnitude of the mortality imposed by discards on the population is very small compared to the directed fishery, so the impact of excluding them from the model should be relatively small. Samples were drawn from the posterior distributions for some quantities important in management (e.g. the OFL and MMB) using MCMC to characterize the uncertainty in parameter estimates and derived quantities. This involved conducting 5,000,000 cycles of the MCMC algorithm, implementing a 20% burn-in period and saving every 2000th draw. Several diagnostic statistics (e.g. checking for lack of autocorrelation and calculating Geweke statistics) were used to check for evidence of non-convergence of the MCMC algorithm.

Growth was estimated within the integrated assessment because there are no targeted studies on growth of Pribilof Island red king crab. The presence of a single, large cohort that established the population during the mid-1980s and then was subsequently relatively lightly fished (or not at all in the case of females) makes estimating growth tractable. The modes of the length frequency distributions were well fit by a linear relationship when translated to growth per molt (Figure 14).

Sensitivities to the bin width were performed in 2014 by fitting the assessment method with 10 mm length bins. Estimates of quantities important in management and model fits were not identical between 10 and 5 mm size bin scenarios. Fits to numbers at length and length frequencies were visually similar, but estimated MMB for 2014 was 16% higher when using the 10mm data. A simulation study was undertaken to explore these differences and showed that an assessment method with bin sizes of 5mm estimates MMB without bias (when the data were generated from the underlying population dynamics model), but the estimates from the assessment method fit data binned at 10mm exhibit positive biases compared to the true quantities (Figure 15). The details of this simulation study were presented at the CAPAM symposium on growth and have been accepted for publication in the special issue (Szuwalski, in press). As a result of this study, the assessment methods presented here use 5mm length bins.

The fits of the 2014 integrated assessment in the recent past were poor for both females and males (Figure 16). Male numbers were underestimated; female numbers were overestimated. An additional assessment method that fits only to male numbers and length frequencies in the survey is presented for comparison given the poor fits. An assessment method in which only males are fit and catchability is allowed to vary in each year is also presented to explore relationships between estimated catchability and environmental variables. Finally, an assessment method that decreases the CVs of the survey numbers during the 1990s (i.e. the first large cohort that produced large estimates of survey numbers) to force the model predictions to fit the 1990s data is presented.

4. Model Selection and Evaluation

The running average method with a tier 4 HCR was selected in 2014 by the SSC as the model to determine the TAC based on concerns around different trends in the last decade for the integrated model and the running average. This year (2015) three assessment methods are presented for comparison: a running average with a tier 4 HCR, an integrated assessment with tier 3 HCR, an integrated assessment with a tier 4 HCR. Each of these methods was fit to the new time series of estimated numbers from the summer survey. Data scenarios in which methods were fit to data for both sexes and data for only males are also presented.

There are trade-offs between using the running average method and the integrated assessment to estimate MMB. The running average methodology is simple to perform and interpret, but estimates of biomass can be sensitive to measurement errors, particularly when relatively few stations report observations of crab or very large tows are taken at a small number of stations. An integrated assessment can smooth over some of the error introduced by imperfect measurement, but it also smoothes over process error (e.g. time-varying population processes) that may be captured by a running average. Integrated assessments are also relatively data-hungry and some assumptions must be made about the underlying population processes (e.g. selectivity of the different fleets).

Non-convergence of the integrated models was checked for by examining the maximum gradient components and the ability to invert the Hessian matrix.

5. Results

5.1 Mature biomass

Estimated MMB from the integrated assessment peaked during 1992 at 5282 t using the 2015 survey data and fitting both males and females (Figure 17); estimates of MMB (i.e. carapace width >120mm) from a 3-year moving average peaked during 2015 at 13666 t. Estimated MMB in the year 2015 when only males were fit in the integrated assessment was 62% higher (5161 vs. 3180 t) than when females were also fit (Figure 17). MMB is higher for the data calculated using the new methodology because the survey estimates for females increased (Figure 5), estimated recruitment increased to compensate, and MMB is linked to FMB through recruitment.

Female mature biomass peaked during 2001 at 1541 t using the 2014 survey data; whereas estimates of FMB from the 3-year moving average peaked during 1994 at 5157 t. Estimated trajectories of biomass from the models are similar in that a large pulse of recruitment in the early 1980s translates to an initial rise in biomass which is fished down through the 1990s. However, estimates of biomass from the integrated assessment methods rebound to levels as high as or higher than the early 1990s levels after fishing pressure is ceased. Estimates from the 3-year moving average for MMB have recently returned to levels exceeding those estimated during the early 1990s. Given the similarities in mature biomass estimates between the 2015 and 2014 survey methodologies, only the results for the updated survey methodologies and the 2015 survey data will be presented from here forward.

5.2 Integrated assessment model fits

5.2.1 Both females and males fit

Estimated male survey numbers peaked during 1991 at 1.84 million (Figure 18), corresponding to an estimated mature male biomass at 5282 t. Estimated female survey numbers peaked during 1992 at 1.60 million, corresponding to an estimated mature female biomass of 2014 t. Catch and bycatch in the non-pelagic trawl fishery were well fit by the assessment method (Figure 18). Given a relatively low natural mortality, a short series of years in which there was a directed fishery, and the selectivity of the fishery, the assessment method was unable to track large year-to-year swings in estimated survey abundance. It is possible that yearly swings in estimates of abundance were attributable to sampling error, given the few data points available to inform these estimates. This was somewhat corroborated by noting the number of observations available to inform the estimates increased over time (Figure 6) and the extreme estimates of biomass were less often observed after the year 2000 (though 2014 and 2015 may be exceptions to this observation). The differences in interannual variability of estimates of mature biomass and numbers between the integrated assessment and running average represent a tradeoff between following data influenced by low sample sizes (running average) and the smoothing effects of assuming a constant natural mortality and catchability (integrated assessment).

Large estimated recruitment events during the mid-1980s translated to a large increase in mature biomass, but estimated recruitment events since that period have been much smaller (Figure 20). Estimated recruitment was very poor during recent years (2003-present) and there did not seem to be a relationship between female mature biomass and recruitment at 4, 5, or 6 year lags (Figure 22). Estimated fishing mortality peaked in 1993 (the first year of the directed fishery) at 0.38, which does not exceed the calculated $F_{35\%}$ of 0.44. Estimated survey selectivity gradually increased until ~150 mm length at which point 95% of crab are selected in the survey gear (Figure 20) and survey catchability is fixed at 1. The negative log likelihood decreases as survey catchability (q) increased, even beyond a value of 1 (Figure 23). However, catchability higher than 1 is difficult to justify, so fixing q at 1 was a reasonable practice here. Fishery selectivity was not estimated as there are no catch at length or discard at length data available.

Two (possibly three) cohorts moved through the male size classes throughout the history of the fishery and the resulting survey length frequencies are better fit in the 1980s than during the late 1990s and early 2000s (Figure 24 and Figure 25). During 1999 and 2001, two large peaks in small crab appeared but did not carry through to larger size classes. The appearance (1999), disappearance (2000), and reappearance (2001) of a “cohort” influenced the ability of the assessment method to fit the length frequencies in the 2000s. Capping the samples sizes at 200 provided slightly better fits to the length frequencies, but did not completely eliminate the poor fits. Female length frequencies were fit better than the male frequencies (table A3, Figure 25), but also displayed ‘disappearing’ crab (e.g. the year 2000).

The estimated growth relationships were similar to estimates for other red king crab in the EBS. For example, a 50 mm female would molt to 68 mm on average given the estimates produced here. Weber (1967) estimated the post-molt length for a 50 mm female at 63.5 and then 67.5 in 1974. An 80 mm female would molt to 93.8 mm given estimates from the integrated assessment which is less than Weber’s estimates (96m m and 97.5 mm), but corroborated the observation that female growth increment decreases compared to males as size increases. A 50 mm male would molt to 65 mm given the estimates from the assessment and an 80 mm male would molt to 99.5 mm. Posteriors for the growth parameters suggest growth was relatively well estimated (Figure 26). Estimated variability around the growth curve was larger for males than it was for females (1.12 vs. 0.30) and was apparent in the spread of the length frequencies throughout the 1990s (Figure 24 vs. Figure 25). There were slight changes in the estimated growth parameters from 2014 to 2015 due to changes in survey data methodologies.

5.2.2 Only males fit

Estimated male survey numbers peaked during 2009 at 2.2 million when fitting to only data for male crab, corresponding to an estimated mature male biomass at 7294 t, which is also the peak MMB (Figure 18 and Figure 27). Both of these figures are larger than the estimates when females were also fit and occur at a later time in the time series (2009 vs. 1992). Consequently, estimated recruitment was scaled up, but maintained similar patterns. Catch and bycatch in the non-pelagic trawl fishery were well fit by the assessment method. Estimated fishing mortality peaked in 1993 (the first year of the directed fishery) at 0.47, which was higher than the two sex model (Figure 28). Fits to the length frequencies were very similar to when both females and males were fit (Figure 29). Estimated survey selectivity shifted to the left slightly when males only are fit (sel95% = 147 and 145; both sexes and males only, respectively).

6. Calculation of reference points

6.1 Tier 4 OFL and B_{MSY}

Natural mortality was used as a proxy for F_{MSY} and a proxy for B_{MSY} was calculated by averaging the biomass of a predetermined period of time thought to represent the a time when the stock was at B_{MSY} in the tier 4 HCR. The OFL was calculated by applying a fishing mortality determined by equation 4 to the mature male biomass at the time of fishing.

$$?_{???} \begin{cases} ?????h??? & ⁇ \; \frac{?_{???}}{?_{? ?? ?????}} \leq ? \\ \frac{?? \; ?\frac{?_{???}}{?_{? ?? ?????}} - ??}{È - ?} & ⁇ \; ? \; \frac{?_{???}}{?_{? ?? ?????}} \; È \\ ?? & ⁇ \; ?_{???} \quad ?_{? ?? ?????} \end{cases} \qquad (4)$$

Where,

$?_{???}$	Current estimated mature male biomass
$?_{? ?? ?????}$	Average mature male biomass over the years 1991-present
?	Natural mortality
?	Determines the slope of the descending limb of the HCR (0.05)
?	Fraction of $B_{MSY\ proxy}$ below which directed fishing mortality is zero (here set to 0.25)

The F_{OFL} calculated from equation 4 was applied to the legal male population surviving to the time of the fishery (October 15).

6.2 Tier 3 OFL, $F_{35\%}$, and $B_{35\%}$

Proxies for biomass and fishing mortality reference points were calculated using spawner-per-recruit methods (e.g. Clarke, 1991) in the tier 3 HCR. After fitting the assessment model to the data and estimating population parameters, the model was projected forward 100 years using the estimated parameters under no exploitation to find virgin mature male biomass per recruit. Projections were repeated (again for 100 years) to determine the level of fishing mortality that reduced the mature male biomass per recruit to 35% of the virgin level (i.e. $F_{35\%}$ and $B_{35\%}$, respectively) by using the bisection method for identifying the target fishing mortality.

Calculated values of $F_{35\%}$ and $B_{35\%}$ were used in conjunction with a control rule to adjust the proportion of $F_{35\%}$ that is applied based on the status of the population relative to $B_{35\%}$ (Amendment 24, NPFMC).

$$?_{???} \begin{cases} ?\,????\,??h\,???? & ??\ \dfrac{?_{???}}{?_{??\%}} \leq ? \\ \dfrac{?_{??\%}\,?\dfrac{?_{???}}{?_{??\%}} - ??}{\grave{E} - ?} & ??\ ?\ \dfrac{?_{???}}{?_{??\%}}\ \grave{E} \\ ?_{??\%} & ??\ ?_{???}\ \ ?_{??\%} \end{cases} \qquad (5)$$

Where,

$?_{???}$	current estimated mature male biomass
$?_{??\%}$	mature male biomass at the time of mating resulting from fishing at $?_{??\%}$
$?_{??\%}$	Fishing mortality that reduce the spawners per recruit (measured here as mature male biomass at the time of mating) to 35% of the unfished level
$?$	Determines the slope of the descending limb of the HCR (0.05)
$?$	Fraction of $B_{35\%}$ below which directed fishing mortality is zero (here set to 0.25)

6.3 Acceptable biological catches

An acceptable biological catch (ABC) was set below the OFL by a proportion based a predetermined probability that the ABC would exceed the OFL (P*). Currently, P* is set at 0.49 and represents a proportion of the OFL distribution that accounts for within assessment uncertainty (σ_w) in the OFL to establish the maximum permissible ABC (ABC_{max}). Any additional uncertainty outside of the assessment methods (σ_b) will be considered as a recommended ABC below ABC_{max}. Additional uncertainty will be included in the application of the ABC by adding the uncertainty components as $\sigma_{\text{total}} = \sqrt{\sigma_b^2 + \sigma_w^2}$.

6.4 Specification of the distributions of the OFL used in the ABC

A distribution for the OFL associated with estimates of MMB from the running average method was constructed by bootstrapping values of MMB_{mating} (assuming that MMB is log-normally distributed) and calculating the OFL according to equation 4. Additional uncertainty (σ_b) equal to 0.3 was added when bootstrapping values of MMB while calculating the distribution for the OFL for the tier 4 HCR. The posterior distribution for the OFL generated from the integrated assessment was used for determining the ABC.

6.5 Tier 3 and integrated assessment: Reference points and OFL

6.5.1 Fitting males and females

A large year class recruited to the survey gear during 1985 and, lagged to the year of fertilization, would have been produced near the timing of the late 1970s shift in environmental conditions in the North Pacific (Overland et al., 2008). Consequently, $B_{35\%}$ was calculated using only estimates of recruitment from 1983 forward to reflect current environmental conditions (DOC, 2007) and corresponds to a MMB of 1363 t. The corresponding $F_{35\%}$ was 0.45 and, given a ratio of the current biomass to $B_{35\%}$ of 2.62, the calculated F_{OFL} was also 0.45 which resulted in an OFL of 1015 t. $F_{35\%}$ was relatively high compared to natural mortality because a large fraction of MMB is protected by the 138mm size limit; $F_{35\%}$ in 2015 was less than the calculated value in 2014 (0.53) because discard mortality borrowed from BBRKC was incorporated into the assessment method. When only males were fit, $B_{35\%}$ was calculated as an MMB of 1560 t. The corresponding $F_{35\%}$ was 0.44 and, given a ratio of the current biomass to $B_{35\%}$ of 3.31, the calculated F_{OFL} was also 0.44 which resulted in an OFL of 1608 t.

The traces of the MCMCs performed were stationary for all data scenarios when thinned sufficiently. The 90% credibility interval of the posterior distribution of $B_{current}/B_{35\%}$ when both males and females were fit ranged from 2.42 to 2.79; the 90% credibility interval for the posterior for $F_{35\%}$ ranged from .449 to 0.457; and the 90% credibility interval for the OFL ranged from 894 to 1128 t (Figure 31). The 90% credibility interval of the posterior distribution of $B_{current}/B_{35\%}$ when only males were fit ranged from 3.06 to 4.40; the 90% credibility interval for the posterior for $F_{35\%}$ ranged from 0.438 to 0.445; and the 90% credibility interval for the OFL ranged from 1291 to 1857 t (Figure 32).

5.4 Tier 4 Reference points and OFL

Tier 4 reference points and management quantities were calculated simultaneously in the integrated assessment with the tier 3 reference points. B_{MSY} (based on the MMB over the years 1991-present) was calculated as 4615 t when fitting both males and females. F_{MSY} was set equal to natural mortality (0.18) and the resulting OFL was 1824 t. The 90% credibility interval of the posterior distribution of B_{MSY} for the tier 4 control rule ranged from 3861 to 5094 t, and the 90% credibility interval for the OFL ranged from 581 to 794 t (Figure 33). B_{MSY} (based on the MMB over the years 1991-present) was calculated as 4218 t when fitting only males; the associated 90% credibility interval of the posterior distribution ranged from 3342 to 5318 t, and the 90% credibility interval for the OFL ranged from 534 to 948 t (Figure 34).

B_{MSY} and current MMB calculated from the 3-year running averages were substantially higher than the estimates from the integrated assessment when both males and females were fit (e.g. MMB equal to 13065t vs 3180t for 3-year average and integrated assessment fit to males and females, respectively). Consequently, the calculated OFL was also much higher—1997 t. The OFL for the 3-year running average was the highest OFL from all methods, due to its reliance on the most recent survey estimate of male numbers and biomass, which is the highest estimate in the observed time series. The 90th quantiles of the bootstrapped distribution for the OFL ranged from 640 to 5176 t (Figure 35).

5.5 Recommended ABCs

All of the following ABCs are reported using a pstar of 0.49 and an additional buffer of 25%. Based on the distributions of the OFL calculated using the running-average method, the ABC for the tier 4 HCR was 1477 t. For the models in which both males and females were fit, the ABC for the tier 4 HCR using the posterior of the OFL from the integrated assessment was 339 t; the ABC for the tier 3 HCR was 752 t. For the models in which only males were fit, the ABC for the tier 4 HCR/integrated assessment and a p-star of 0.49 was 502 t; the ABC for the tier 3 HCR/integrated assessment was 1091 t.

5.6 Variables related to scientific uncertainty in the OFL probability distribution

Uncertainty in estimates of stock size and OFL for Pribilof Islands red king crab was relatively high due to small sample sizes. The coefficient of variation for the estimate of male abundance for 2015 was 0.72

and has ranged between 0.36 and 0.92 since the 1991 peak in numbers. These CVs were calculated by assuming the data are Poisson distributed, but the data are overdispersed. Using a negative binomial (or other distribution that can allow for overdispersion) would increase the CVs. Growth and survey selectivity were estimated within the integrated assessment (and therefore uncertainty in both processes is accounted for in the posterior distributions), but maturity, survey catchabillity, fishery selectivity, and natural mortality were fixed. F_{MSY} was assumed to be equal to natural mortality and B_{MSY} was somewhat arbitrarily set to the average MMB over a predetermined range of years for tier 4 HCRs; both of which were assumptions that had a direct impact on the calculated OFL. Sources of mortality from discard in the crab pot fishery and the fixed gear fishery were not included in the integrated assessment because of a lack of length data to apportion removals correctly. Including these sources of mortality may alter the estimated MMB.

A simulation test in which the assessment method was fit to data generated by the population dynamics model within the assessment method and subject to the same measurement error showed that the assessment method was capable of returning unbiased estimates of MMB band other quantities and parameters important in management when size bins were 5mm (Szuwalski, in press). Retrospective analyses have not yet been performed for the presented integrated assessment, but should be considered.

6. Author Recommendation

In the foreseeable future, low sample size will be a problem for the Pribilof Island red king crab, so extra precaution should be taken given the uncertainty associated with MMB estimates. In this respect, the tier 4 HCR is more precautionary in that it sets a higher MSST and a lower $F_{OFL,}$ OFL, and ABC for a given MMB. However, when used in concert with a running average method to estimate MMB, it can be less conservative than the tier 3 HCR that uses estimates from the integrated assessment. If there is a particularly high estimate of MMB from the survey (which are often uncertain–see 2015 for an example), the OFL can be much higher for the tier 4/running average combination than the tier3/integrated assessment combination. The integrated assessment can be useful in these years because it smoothes over fluctuations in estimates of biomass and numbers, which often appear to be the result of measurement error. The integrated assessment method also provides increased biological realism, allows for the incorporation of multiple data streams into the assessment, and facilitates the use of MCMC to characterize uncertainty in management quantities. MCMC is a cleaner way to account for uncertainty than arbitrarily inflating the variance around survey estimates, particularly when data are available to inform estimation of important population processes.

Females and male experienced similar increases in abundance in the early 1990s, and only in recent years did trends in their abundances deviate from previously correlated trajectories. This suggests that some population process (e.g. natural mortality or catchability) has changed for males or females, but it is difficult to say if the change in trends was a result of a population process for females or for males (or both) changing. It is generally inadvisable to invoke time-varying population processes within an assessment for the sake of improving fits without a hypothesis behind the changes and data to corroborate it. Consequently, it is difficult to make a recommendation on which data scenario to use—the male only scenario did fit the male data better, but that should be expected.

Although it is inadvisable to invoke time-varying processes to produce estimates of MMB without some underlying mechanism, allowing survey catchability to vary in each year can be useful in looking for relationships between estimated catchability and environmental variables (to find such a mechanism). An assessment method fit to only males and allowing catchability to vary yearly improved fits to the male numbers (as expected; Figure 37). The utility of this exercise is not to fit the data better, but compare the variability in estimated catchability and environmental variables (Figure 36). However, no relationship was apparent between sea surface temperature at the Pribilof Islands during winter or summer bottom temperature (Figure 38). More in-depth analyses incorporating temperature observations at specific stations for which large hauls occurred may be useful in further exploring how catchability may vary with environmental conditions. For the most recent cohorts, catchability seems to increase as the cohort begins to die out. For example, during 2015 the 3-year average estimated the largest biomass in the history of the time series, but there has been no recruitment since the early 2000s as seen through the length frequencies. So, either there has been immigration of large crab (less likely) or there has been a change in catchability (more likely). This suggests another potential avenue of research to understand changes in catchability over time (in addition to temperature mediated response); a relationship between density of crab and their movement or preferred habitat may exist. An increasing biomass estimate as a cohort ages and dies off through natural mortality may suggest higher mobility or a change in habitat preference as population density decreases. Although considering time-varying catchability is potentially interesting, ultimately the small sample sizes used to produce estimates of biomass will continue to make precise assessment for PIRKC difficult.

Forcing the model to fit the high estimates of survey numbers during the 1990s (the first cohort seen in the length frequencies) results in a trajectory that is completely unable to fit the most recent numbers estimates (i.e. cohorts 2 and 3; Figure 39).

7. Data gaps and research priorities

The largest data gap is the number of observations from which the population size and biomass is extrapolated. Catch-at-length data for the trawl fishery would allow trawl fishery selectivity to be estimated and discard mortality specific to PIRKC to be incorporated into the model. Simulation studies designed to prioritize research on population processes for which additional information would be beneficial in achieving more accurate estimates of management quantities could be useful for this stock (e.g. Szuwalski and Punt, 2012). Research on the probability of molting at length for males would allow the use of data specific to PIRKC in specifying molting probability in the assessment. Research aimed at the catchability and availability of PIRKC may shed some light on divergent changes in abundance in recent years.

7. Ecosystem Considerations

The impact of a directed fishery for Pribilof Islands red king crab on the population of Pribilof island blue king crab will likely continue to be the largest ecosystem consideration facing this fishery and preclude the possibility of a directed fishery for red king crab. Linking changes in productivity as seen in the 1980s with environmental influences is a potential avenue of research useful in selecting management strategies for crab stocks around the Pribilof Islands (e.g. Szuwalski and Punt, 2013a). It is possible that the large year class in the mid-1980s reflected changing environmental conditions, similar to proposed relationships between the Pacific Decadal Oscillation snow crab recruitment in the EBS (Szuwalski and Punt, 2013b). Ocean acidification also appears to have a large detrimental effect on red king crab (Long et al., 2012), which may impact the productivity of this stock in the future.

All code for this assessment can be found at github.com/szuwalski/pirkc.

8. Literature cited

Bell, M. C. 2006. Review of Alaska crab overfishing definitions: Report to University of Miami Independent System for peer reviews. April 24-28, 2006 Seattle, Washington, 35 p.

Bowers, F., M. Schwenzfeier, K. Herring, M. Salmon, H. Fitch, J. Alas, B. Baechler. 2011. Annual management report for the commercial and subsistence shellfish fisheries of the Aleutian Islands, Bering Sea, and the Westward Region’s Shellfish Observer Program, 2009/2010.

Daly, B.J., Foy R.J. and C.E. Armistead. In press. The 2014 Eastern Bering Sea Continental Shelf Bottom Trawl Survey: Results for Commercial Crab Species. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-XXX, 143 pp.

Department of Commerce (DOC). 2007. Magnuson-Stevens Fishery Conservation and Management Act. U.S.A. Public Law 94-265.

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

Jensen, G.C. 1995. Pacific Coast Crabs and Shrimps. Sea Challengers, Monterey, California, 87p.

Jørstad, K.E., E. Farestveit, H. Rudra, A-L. Agnalt, and S. Olsen. 2002. Studies on red king crab (*Paralithodes camtschaticus*) introduced to the Barents Sea, p. 425-438. *In* A. J. Paul, E. G. Dawe, R. Elner, G. S. Jamieson, G. H. Kruse, R. S. Otto, B. Sainte-Marie, T. C. Shirley and D. Woodby (editors), Crabs in cold water regions: biology, management, and economics. Alaska Sea Grant College Program Report No. AK-SG-02-01, University of Alaska, Fairbanks, AK.

Livingston, P. A., A. Ward, G. M. Lang, and M.S. Yang. 1993. Groundfish food habits and predation on commercially important prey species in the eastern Bering Sea from 1987 to 1989. United States Department of Commerce, NOAA Technical Memorandum. NMFD-AFSC-11, 192 p.

Livingston, P.A. 1989. Interannual trends in Pacific cod, *Gadus macrocephalus*, predation on three commercially important crab species in the Eastern Bering Sea. Fishery Bulletin 87:807-827.

Loher, T. and D.A. Armstrong. 2005. Historical changes in the abundance and distribution of ovigerous red king crabs (*Paralithodes camtschaticus*) in Bristol Bay (Alaska), and potential relationship with bottom temperature. Fisheries Oceanography 14:292-306.

Loher, T., D.A. Armstrong, and B. G. Stevens. 2001. Growth of juvenile red king crab (*Paralithodes camtschaticus*) in Bristol Bay (Alaska) elucidated from field sampling and analysis of trawl-survey data. Fishery Bulletin 99:572-587.

Long WC, Swiney KM, Harris C, Page HN, Foy RJ (2013) Effects of Ocean Acidification on Juvenile Red King Crab (*Paralithodes camtschaticus*) and Tanner Crab (*Chionoecetes bairdi*) Growth, Condition, Calcification, and Survival. PLoS ONE 8(4): e60959.

Marukawa, H. 1933. Biological and fishery research on Japanese king crab *Paralithodes camtschatica* (Tilesius). Fish. Exp. Stn, Tokyo 4:1-152.

Matsuura, S. and Takeshita, K. 1990. Longevity of red king crab, *Paralithodes camtschatica*, revealed by long-term rearing study, p. 65-90. *In* B. Melteff (editor) International Symposium on King and Tanner crabs. Alaska Sea Grant College Program Report No. 90-04, University of Alaska Fairbanks, AK.

NMFS. 2000. Endangered Species Act Section 7 Consultation – Biological Assessment: Crab fisheries authorized under the Fishery Management Plan for Bering Sea/Aleutian Islands king and Tanner crabs. National Marine Fisheries Service, Alaska Region, 14 p.

NMFS. 2002. Endangered Species Act Section 7 Consultation – Biological Assessment: Crab fisheries authorized under the Fishery Management Plan for Bering Sea/Aleutian Islands king and Tanner crabs. National Marine Fisheries Service, Alaska Region, 59 p.

NMFS. 2004. Final Environmental Impact Statement for Bering Sea and Aleutian Islands Crab Fisheries. National Marine Fisheries Service, Alaska Region

NPFMC (North Pacific Fishery Management Council). 1994. Environmental Assessment/Regulatory Impact/Review/Initial Regulatory Flexibility analysis for Amendment 21a to the Fishery Management Plan for Bering Sea and Aleutian Islands Groundfish. Anchorage, Alaska.

NPFMC (North Pacific Fishery Management Council). 1998. Fishery Management Plan for the Bering Sea/Aleutian Islands king and Tanner crabs. Anchorage, Alaska 105 p.

NPFMC (North Pacific Fishery Management Council). 2003. Environmental Assessment for Amendment 17 to the Fishery Management Plan for the king and Tanner crab fisheries in the Bering Sea/Aleutian Islands: A rebuilding plan for the Pribilof Islands blue king crab stock. Anchorage, Alaska 87 p.

NPFMC (North Pacific Fishery Management Council). 2008. Environmental Assessment for Amendment 24 to the Fishery Management Plan for the king and Tanner crab fisheries in the Bering Sea/Aleutian Islands: to revise overfishing definitions. Anchorage, Alaska 194 p.

Otto R.S., R.A. MacIntosh, and P.A. Cummiskey. 1990. Fecundity and other reproductive parameters of female red king crab (*Paralithodes camtschatica*) in Bristol Bay and Norton Sound, Alaska, p. 65-90 *In* B. Melteff (editor) Proceedings of the International Symposium on King and Tanner crabs. Alaska Sea Grant College Program Report No. 90-04, University of Alaska Fairbanks, AK.

Overland, J., Rodionov, S., Minobe, S., and Bond, N. 2008. North Pacific regime shifts: definitions, issues, and recent transitions. Progress in Oceanography, 77: 92–102.

Powell G.C. and R.B. Nickerson. 1965. Reproduction of king crabs, *Paralithodes camtschatica* (Tilesius). Journal of Fisheries Research Board of Canada 22:101-111.

Powell, G.C. 1967. Growth of king crabs in the vicinity of Kodiak Island, Alaska. Informational Leaflet 92, Alaska Department of Fish and Game, 58 p.

Punt, A.E., Szuwalski, C.S., and Stockhausen, W. 2014. An evaluation of stock-recruitment proxies and environmental change points for implementing the US Sustainable Fisheries Act. Fish. Res., 157: 28-40.

Shirley, S. M. and T. C. Shirley. 1989. Interannual variability in density, timing and survival of Alaskan red king crab *Paralithodes camtschatica* larvae. Marine Ecology Progress Series 54:51-59.

Shirley, T. C., S. M. Shirley, and S. Korn. 1990. Incubation period, molting and growth of female red king crabs: effects of temperature, p. 51-63. *In* B. Melteff (editor) Proceedings of the International Symposium on King and Tanner Crabs. Alaska Sea Grant College Program Report No. 90-04, University of Alaska Fairbanks, AK.

Siddeek, M.S.M, L. J. Watson, S. F. Blau, and H. Moore. 2002. Estimating natural mortality of king crabs from tag recapture data, p. 51-75. *In* A. J. Paul, E. G. Dawe, R. Elner, G. S. Jamieson, G. H. Kruse, R. S. Otto, B. Sainte-Marie, T. C. Shirley and D. Woodby (editors), Crabs in cold water regions: biology, management, and economics. Alaska Sea Grant College Program Report No. AK-SG-02-01, University of Alaska, Fairbanks, AK.

Somerton, D. A. 1980. A computer technique for estimating the size of sexual maturity in crabs. Canadian Journal of Fisheries and Aquatic Science 37: 1488-1494.

Stauffer, D.A., 2004. NOAA protocols for groundfish bottom trawl surveys of the Nation's fishery resources U.S. Department of Commerce, NOAA Technical Memorandum NMFS-F/SPO-65, 205.

Stevens, B.B. 1990. Temperature-dependent growth of juvenile red king crab (*Paralithodes camtschatica*), and its effects on size-at-age and subsequent recruitment in the eastern Bering Sea. Canadian Journal of Fisheries and Aquatic Sciences 47:1307-1317.

Stevens, B.G. and K. M. Swiney. 2007b. Growth of female red king crabs *Paralithodes camtshaticus* during pubertal, primiparous, and multiparous molts. Alaska Fisheries Research Bulletin 12:263-270.

Stevens, B.G. and K.M. Swiney. 2007a. Hatch timing, incubation period, and reproductive cycle for primiparous and multiparous red king crab *Paralithodes camtschaticus*. Journal of Crustacean Biology 27:37-48.

Szuwalski, C.S. (2015) Biases in biomass estimates and selecting bind width in size-structured assessment methods. Fisheries Research.

Szuwalski, C.S. and Punt, A.E. 2013a Regime shifts and recruitment dynamics of snow crab, *Chionoecetes opilio*, in the eastern Bering Sea. Fish. Ocean., 22(5): 345-354.

Szuwalski, C. S., and Punt, A. E. 2013b Fisheries management for regime-based ecosystems: a management strategy evaluation for the snow crab fishery in the eastern Bering Sea. ICES J. Mar. Sci.,70: 955-967.

Szuwalski, C. S., and Punt, A. E. 2012 Identifying research priorities for management under uncertainty: The estimation ability of the stock assessment method used for eastern Bering Sea snow crab (*Chionoecetes opilio*). Fish. Res., 134–136: 82–94.

Weber, D. D. 1967. Growth of the immature king crab Paralithodes camtschatica (Tilesius). Bulletin No. 21, North Pacific Commission, 53 p.

Weber, D.D. 1974. Observations on growth of southeastern Bering Sea king crab, *Paralithodes camtschatica*, from a tag-recovery study, 1955-65. Data Report 86, National Marine Fisheries Service, 122 p.

Wilderbuer, T.K. D.G. Nichol and J. Ianelli. Chapter 4: Yellowfin sole. Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Bering Sea/Aleutian Islands Regions, North Pacific Fishery Management Council, Anchorage 447-512 p.

Zheng, J. and G. H. Kruse. 2000. Recruitment patterns of Alaskan crabs in relation to decadal shifts in climate and physical oceanography. ICES Journal of Marine Science 57:438-451.

Zheng, J. M.C. Murphy, and G.H. Kruse. 1995. A length-based population model and stock-recruitment relationships for red king crab, *Paralithodes camtschaticus*, in Bristol Bay, Alaska. Canadian Journal of Fisheries and Aquatic Science 52:1229-1246.

Zheng, J. and Siddeek, M.S.M. 2015. Bristo Bay red king crab stock assessment.

8. Appendix 1: Population dynamics model for the integrated assessment

An integrated length-based assessment that tracks biannual dynamics of numbers of male and female Pribilof Island red king crabs is used here to provide estimates for quantities used in management. See table A1 for a list of estimated and fixed parameters, table A2 for a list of estimates of parameters, and table A3 for contributions of likelihood components to the objective function and their relative weights. The mode date of the hauls performed in the NMFS trawl survey was June 15th, so this date is used as the beginning of the 'model year'. Survey to fishery dynamics are described by equation A1:

$$?_{???} \quad ?_{???}?^{???\ \ ??} \qquad \text{(A1)}$$

where $?_{???}$ is the number of animals of sex *s* in length-class *l* at time step *y,* and $-3M/12$ decrements the population by three months of natural mortality. A pulse fishery is modeled three month after the survey (the fishery lasted on average two weeks, so a pulse fishery is a reasonable assumption) in which numbers are updated as in equation A2. Historically, the fishery occurred in September, but the opening day for all crab fisheries is October 15th now. Consequently, the calculated OFL is based on numbers at length decremented by 4 months of natural mortality.

$$?_{???} \quad ?_{???}?^{?\,Æ?\,???\,?\,??\,?\,????\,??\,?} \qquad \text{(A2)}$$

Molting, growth, and recruitment occur after the fishery (in that order, equation A3):

$$?_{???} \quad \overset{?}{}Æ\grave{E} - ?_{?}\ ?_{???}\ \overset{?_{?}?_{???}X_{???}}{} \quad ??_{?}?_{?} \qquad \text{(A3)}$$

Where $?_{?}$ is the probability of an animal molting at length *l*, $?_{???}$, is the number of animals in sex *s* in length-class *l* at time step *y*, $X_{???}$ is the size transition matrix, R_y is recruitment during year *y* and Pr_l is the proportion recruiting to length-class *l.*

Mature biomass at the time of mating (which is used in calculation of reference points) is calculated by decrementing the population by 5 months of natural mortality after the fishery. The remaining 4 months of natural mortality are applied to the population between the mating and the survey:

$$?_{?????} \quad ?_{???}?^{???\ \ ??} \qquad \text{(A4)}$$

Fishing mortality and selectivity

Historical fishing mortality was primarily caused by landings in the directed fishery. No length frequency data are available to allocate discards from the directed fishery, so discard mortality is assumed to be zero and knife-edge selectivity is specified for the fishery with the 'edge' occurring at the minimum legal size—138mm carapace length (Figure 21). Fishing mortality is calculated by:

$$?_{?????} \quad ?_{????}?^{???????\ ??} \qquad \text{(A5)}$$

where $S_{l,dir}$ is the selectivity of the fishery on animals in length-class l, ???? is the average (over time) ln-scale fully-selected fishing mortality, and $?_?$ is the ln-scale deviation in fishing mortality for year y from the average fishing mortality. Average fishing mortality and the yearly deviations are estimated parameters.

Fishery selectivity is assumed to be a logistic function of size and constant over time:

$$?_{????} \quad ?\grave{E} \qquad ? - \frac{Ŭ\ (\grave{E}\ )??_? - ?_{?????}?}{?_{?????} - ?_{?????}}??^{??} \qquad \text{(A6)}$$

where $L_{50,\mathrm{dir}}$ is the length at which 50% of animals are selected, $?_?$ is the midpoint of length-class l, and $L_{95,\mathrm{dir}}$ is the length at which 95% of animals are selected.

A switch that allows mortality due to discarding in the fishery to be modeled based on the Bristol Bay red king crab assessment (Zheng et al., 2014) is included in the code. Discard selectivity, $S_{l,\mathrm{disc}}$ is defined as:

$$?_{?????} \quad ? \quad ? * ?_? \qquad ??\ ?_? \leq \grave{E}\hat{E} \qquad \text{(A7)}$$

$$?_{?????} \quad ?_{???????} \quad \ddot{E} * ? \qquad ??\ ?_? \quad \grave{E}\hat{E} \qquad \text{(A8)}$$

$$?_{?????} \qquad ??\ ?_{?????} \qquad \text{(A9)}$$

Where θ, φ, and δ are parameters borrowed from the 2014 BBRKC assessment and L_l is the carapace width of an individual crab. Discard mortality is assumed to be 0.2.

Bycatch in the non-pelagic trawl for groundfish is the second largest historical source of mortality, but it only comprised 3% (on average) of the catch when the directed fishery was operating. Fishing mortality at length attributed to bycatch in the trawl fishery is modeled by equation A7:

$$?_{???????} \quad ?_{??????}\, ?^{???????????\ ??} \qquad \text{(A10)}$$

Selectivity, $?_{??????}$, in the non-pelagic trawl fishery for groundfish is assumed to be a logistic function of size and constant over time:

$$?_{??????} \quad ?\grave{E} \qquad ? - \frac{Ŭ\ (\grave{E}\ )??_? - ?_{????????}?}{?_{???????} - ?_{???????}}??^{??} \qquad \text{(A11)}$$

where $L_{50,\mathrm{trawl}}$ is the length at which 50% of animals are selected, $?_?$ is the midpoint of length-class l, and $L_{95,\mathrm{trawl}}$ is the length at which 95% of animals are selected. Parameters are fixed to those reported in the Bristol Bay red king crab assessment because there are no length frequency data available to inform estimation for Pribilof Island red king crab (Figure 21).

Survey selectivity is assumed to be a logistic function of size and constant over time. :

$$?_{?????} \quad ????_? * ?\grave{E} \qquad ? - \frac{Ŭ\ (\grave{E}\ )??_? - ?_{??????}?}{?_{??????} - ?_{??????}}??^{??} \qquad \text{(A12)}$$

where $????_?$ is the catchability coefficient for the survey gear, $L_{50,\mathrm{surv}}$ is the length at which 50% of animals are selected, $?_?$ is the midpoint of length-class l, and $L_{95,\mathrm{surv}}$ is the length at which 95% of animals are selected. Survey selectivity parameters are estimated, except for $????_?$, which is fixed to a value of 1. A switch has been added to the code to allow $????_?$ to be estimated annually. This is to be used as an exploratory tool, not to provide estimated of numbers during the survey.

Survey numbers at length

The model prediction of the number of male crab at length at the time of the survey, ? ?? ?? ? ? ? is given by:

? ?? ?? ? ? ?   ? ?? ?? ? ? ? ? (A13)

Catch

The model prediction of the directed catch at length is given by:

??? ?? ? ?   ? ?? ?? ? ? ? ? ??? ?? ? ?ÉÈ − ? ? ? ? ? (A14)

where ??? ?? ? ? is the model estimate of the total catch of animals in length-class *l* during year *y* in numbers, $N_{s,y=fishtime,l}$ is the number of animals of sex *s* in length-class *l* when the fishery occurs during year *y*. ($1-e^{-F_{y,l}}$) is the proportion of crab taken by the fishery during year *y*.

Growth

Molting and growth occur before the survey. Female crab are assumed to molt every year, but the probability of molting for male crab is a declining logistic function of length. The parameters are fixed based on Powell (1967) such that the probability of molting is 1 until approximately the age of maturity at which time it steadily declines (Figure 21):

?? È − ? È   ? − Ûİ (È) ??? − ?? ? ? ??? / ??? ? ?? − ??? ? ?? ?? ? ? (A15)

where $L_{50,\mathrm{molt}}$ is the length at which 50% of animals molt, and $L_{95,\mathrm{molt}}$ is the length at which 95% of animals molt. The growth increment for animals that do molt is based on a gamma distribution, i.e.:

? ? ??   ? ? ?? ? ? ? ?? (A16)

? ? ??   ÉΔ? ?? É? ?? (?? ? ?(?) ? ?? Δ? ?? ? ?? (A17)

where L_l is the expected length for an animal in length-class *l* given that it moults:

?? ?? ???? (A18)

?? ?? are the parameters of the relationship between length and growth increment, $\Delta_{l,l'}$ is the difference in length between midpoints of length-classes *i* and *j*:

Δ? ?? ? ?? É(Ë − ?? (A19)

β is the parameter which defines the variability in growth increment and was set to 0.75 for this analysis. The constant “2.5” is half a length bin’s length. The size transition matrix can be seen in Figure 21.

Recruitment

The fraction of the annual recruitment in an area which recruits to length-class *l* is based on a gamma function, i.e.:

? ?? ÉΔ? ?? ? ? ? ? ? ? Δ? ?? ? ? ? ÉΔ? ?? ? ? ? ? ? ? Δ? ?? ? ? ?? (A20)

Where ?? and ?? are the parameters that define the recruitment fractions. Mean recruitment, annual recruitments and fraction recruiting are treated as estimable parameters, resulting 42 total estimated parameters related to recruitment (Table A1). The fraction recruiting was estimated and changes depending on whether both males and females are fit or if only males are fit (compare Figure 21 and Figure 30).

Likelihood components

The model is fit to survey length frequencies (L1, A21), a survey index of abundance (L2, A22), directed catch (L3, A23) and non-pelagic trawl bycatch (L4, A24).

$$?_? \quad ? \; ? \; ? \; ? \; ? \quad -?_? ?^{???}_{?????\,??\,?} \acute{U} ??^{????}_{????\,??\,?} \quad ?? \quad ?? \; ?^{???}_{????\,??\,?} \geq \; (\; \grave{E} \qquad ?? \; ?^{???}_{????\,??\,?} \; (\; \grave{E} \qquad \text{(A21)}$$

where L_l is the contribution to the objective function of the fit to survey length frequencies; $?_?$ is the sample size for year y, $?^{????}_{????\,??\,?}$ is the model-estimate of the length-frequency for sex s for length-class l in year y; $?^{???}_{????\,??\,?}$ is the observed survey length-frequency for sex s for length-class l during year y; κ is a small number (0.001 here) added to all log calculations. Fits to the observed length frequencies only contribute to the objective function if the observed proportion is greater than 0.01. The reported number of samples used to calculate the length frequencies were used to weight the survey length frequency likelihoods unless they exceeded 200, at which point they were set to 200.

$$?_? \quad \sum_{?} \sum_{?} \frac{\acute{A}\acute{U}\, ??^{????}_{?\,?} \quad ?? - \acute{U}\, ??^{???}_{?\,?} \quad ??^{\;?}}{\acute{U}\, \acute{A}??\, ?_{?\,?} ?^{?} \quad \grave{E}} \qquad \text{(A22)}$$

where $?^{????}_{?\,?}$ is the model-estimate of the number of crab of sex s caught in the survey in during year y, $?^{???}_{?\,?}$ is the observed number of crab of sex s in the survey in during year y, and $CV_{y,s}$ is the observed coefficient of variation for $?^{???}_{?\,?}$. κ is a small number (equal to 0.001 here) added to avoid taking the log of zero. Historically calculated CVs were used to fit the survey numbers

$$?_? \quad \sum_{?} \frac{\acute{A}\acute{U}\, ??^{????}_{?} \quad ?? - \acute{U}\, ??^{???}_{?} \quad ??^{\;?}}{\acute{U}\, \acute{A}??\, ?_?^{???} ?^{?} \quad \grave{E}} \qquad \text{(A23)}$$

where $?^{????}_{?}$ is the catch in numbers predicted by the model for year y, $?^{???}_{?}$ is the observed catch in numbers for year y, $??_?^{???}$ is the assumed coefficient of variation for the observed data for year y, and κ is a small number added to avoid taking the log of zero when catches do not occur (here 0.001 is used).

$$?_? \quad \sum_{?} \frac{\acute{A}\acute{U}\, ?\sum_? ???^{????}_{?\,?} \quad ?? - \acute{U}\, ????^{???}_{?\,?} \quad ??^{\;?}}{\acute{U}\, \acute{A}??\, ?_?^{???????} ?^{?} \quad \grave{E}} \qquad \text{(A24)}$$

where $???^{????}_{?\,?}$ is the bycatch in tonnes of sex s from the non-pelagic trawl fishery predicted by the model for year y, $???^{???}_{?}$ is the observed bycatch in tonnes for during year y, $??_?^{???????}$ is the assumed coefficient of variation for the observed data for year y, and κ is a small number added to avoid taking the log of zero when catches do not occur (here 0.001 is used).

Penalty components

A penalty is placed on the between year deviations in estimated recruitment deviates and fishing mortality deviates (both directed and trawl) of the form:

$$?_? \quad ?_? \sum_{?} \acute{A}\acute{U}\,(\eta_?) - \acute{U}\,(\eta_{??\,?}) \quad \acute{E} \qquad \text{(A25)}$$

where, η_l, is the quantity in question (e.g. recruitment deviations) and γ_w is the weighting factor (equal to 1 in the assessment presented for all quantities).

9. Tables

Table 1. Total retained catches from directed fisheries for Pribilof Islands District red king crab (Bowers et al. 2011; D. Pengilly, ADF&G, personal communications).

Year	Catch (count)	Catch (t)	Avg CPUE (legal crab count pot^{-1})
1973/1974	0	0	0
1974/1975	0	0	0
1975/1976	0	0	0
1976/1977	0	0	0
1977/1978	0	0	0
1978/1979	0	0	0
1979/1980	0	0	0
1980/1981	0	0	0
1981/1982	0	0	0
1982/1983	0	0	0
1983/1984	0	0	0
1984/1985	0	0	0
1985/1986	0	0	0
1986/1987	0	0	0
1987/1988	0	0	0
1988/1989	0	0	0
1989/1990	0	0	0
1990/1991	0	0	0
1991/1992	0	0	0
1992/1993	0	0	0
1993/1994	380,286	1183.02	11
1994/1995	167,520	607.34	6
1995/1996	110,834	407.32	3
1996/1997	25,383	90.87	<1
1997/1998	90,641	343.29	3
1998/1999	68,129	246.91	3
1999/2000 to 2014/2015	0	0	0

Table 2. Fishing effort during Pribilof Islands District commercial red king crab fisheries, (Bowers et al. 2011).

Season	Number of Vessels	Number of Landings	Number of Pots Registered	Number of Pots Pulled
1993	112	135	4,860	35,942
1994	104	121	4,675	28,976
1995	117	151	5,400	34,885
1996	66	90	2,730	29,411
1997	53	110	2,230	28,458
1998	57	57	2,398	23,381
1999-2013/14	Fishery Closed			

Table 3. Non-retained total catch mortalities from directed and non-directed fisheries for Pribilof Islands District red king crab. Handling mortalities (pot and hook/line= 0.5, trawl = 0.8) were applied to the catches. (Bowers et al. 2011; D. Pengilly, ADF&G; J. Mondragon, NMFS). **** NEW 2013 calculation of bycatch using AKRO Catch Accounting System with data reported from State of Alaska reporting areas that encompass the Pribilof Islands red king crab district.**

	Crab pot fisheries			Groundfish fisheries	
Year	Legal male (t)	Sublegal male (t)	Female (t)	All fixed (t)	All trawl (t)
1991/1992				0.48	45.71
1992/1993				16.12	175.93
1993/1994				0.60	131.87
1994/1995				0.27	15.29
1995/1996				4.81	6.32
1996/1997				1.78	2.27
1997/1998				4.46	7.64
1998/1999	0.00	0.91	11.34	10.40	6.82
1999/2000	1.36	0.00	8.16	12.40	3.13
2000/2001	0.00	0.00	0.00	2.08	4.71
2001/2002	0.00	0.00	0.00	2.71	6.81
2002/2003	0.00	0.00	0.00	0.50	9.11
2003/2004	0.00	0.00	0.00	0.77	9.83
2004/2005	0.00	0.00	0.00	3.17	3.52
2005/2006	0.00	0.18	1.81	4.53	24.72
2006/2007	1.36	0.14	0.91	6.99	21.35
2007/2008	0.91	0.05	0.09	1.92	2.76
2008/2009	0.09	0.00	0.00	1.64	6.94
2009/2010	0.00	0.00	0.00	0.33	2.45
**2009/2010				0.19	1.05
2010/2011	0.00	0.00	0.00	0.30	3.87
**2010/2011				0.45	6.25
2011/2012	0.00	0.00	0.00	0.62	4.78
**2011/2012				0.35	4.47
**2012/2013	0.00	0.00	0.00	0.12	12.98
2013/2014	0.00	0.00	0.00	0.25	1.99
2014/2015	0.00	0.00	0.00	0.82	0.24

Table 4. Proportion by weight of the Pribilof Islands red king crab bycatch using the new 2014 calculation of bycatch using AKRO Catch Accounting System with data reported from State of Alaska reporting areas that encompass the Pribilof Islands red king crab district.

Crab fishing season	hook and line %	non-pelagic trawl %	pot %	pelagic trawl %	TOTAL (# crabs)
2009/10	19	77	3	1	813
2010/11	10	90	<1	<1	3,026
2011/12	10	89	1		2,167
2012/13	1	99	<1		4,517
2013/14	11	89	0	0	640
2014/2015	68	32	0	0	439

Table 5. 2016 Pribilof Islands District red king crab male abundance, male biomass, and female biomass estimated based on the NMFS annual EBS bottom trawl survey with no running average.

Year	Total Male Abundance	Total males at survey (t)	Total females at survey (t)
1975/1976	0	0	11
1976/1977	50778	165	102
1977/1978	228477	213	148
1978/1979	367140	1250	52
1979/1980	279707	556	93
1980/1981	400513	1269	262
1981/1982	80928	312	35
1982/1983	352166	1482	933
1983/1984	144735	553	309
1984/1985	64331	317	112
1985/1986	16823	61	0
1986/1987	38419	138	79
1987/1988	18611	54	31
1988/1989	1963775	525	836
1989/1990	1844076	1720	2251
1990/1991	6354076	8019	2723
1991/1992	3100675	4979	5032
1992/1993	1861538	3361	3432
1993/1994	3787997	10156	6478
1994/1995	3669755	9538	3964
1995/1996	7693368	18417	5149
1996/1997	683611	2378	2007
1997/1998	3155556	7254	1962
1998/1999	1192015	2655	1719
1999/2000	9102898	5751	5418
2000/2001	1674067	4477	995
2001/2002	6157584	10186	5774
2002/2003	1910263	7037	787
2003/2004	1506201	5373	2269
2004/2005	2196795	3622	1292
2005/2006	302997	1262	3118
2006/2007	1459278	7097	2183
2007/2008	1883489	5371	1811
2008/2009	1721467	5603	3017
2009/2010	923133	2545	826
2010/2011	927825	4449	840
2011/2012	1052228	3878	817
2012/2013	1609444	4753	663
2013/2014	1831377	7854	169
2014/2015	3036807	12129	1093
2015/2016	3662609	15252	3859

Table 6. 2016 Pribilof Islands District male red king crab abundance CV and total male and female biomass CVs estimated from the NMFS annual EBS bottom trawl survey data.

Year	Total Male Abundance CV	Total male at survey (t) CV	Total female at survey (t) CV
1975/1976	0.00	0.00	1.00
1976/1977	1.00	1.00	0.78
1977/1978	1.00	1.00	1.00
1978/1979	0.83	0.83	1.00
1979/1980	0.49	0.52	1.00
1980/1981	0.40	0.38	0.73
1981/1982	0.57	0.58	1.00
1982/1983	0.70	0.70	0.77
1983/1984	0.64	0.55	0.48
1984/1985	0.48	0.55	0.57
1985/1986	1.00	1.00	0.00
1986/1987	0.70	0.70	1.00
1987/1988	1.00	1.00	1.00
1988/1989	0.74	0.56	0.67
1989/1990	0.69	0.77	0.68
1990/1991	0.87	0.89	0.72
1991/1992	0.78	0.80	0.60
1992/1993	0.68	0.61	0.91
1993/1994	0.93	0.92	0.72
1994/1995	0.81	0.78	0.88
1995/1996	0.57	0.60	0.66
1996/1997	0.37	0.37	0.74
1997/1998	0.56	0.54	0.57
1998/1999	0.42	0.37	0.77
1999/2000	0.79	0.58	0.82
2000/2001	0.40	0.38	0.63
2001/2002	0.90	0.83	0.99
2002/2003	0.67	0.69	0.52
2003/2004	0.66	0.66	0.91
2004/2005	0.83	0.60	0.53
2005/2006	0.53	0.57	0.78
2006/2007	0.39	0.38	0.61
2007/2008	0.61	0.51	0.77
2008/2009	0.52	0.50	0.68
2009/2010	0.70	0.64	0.53
2010/2011	0.45	0.43	0.71
2011/2012	0.63	0.64	0.73
2012/2013	0.65	0.59	0.55
2013/2014	0.58	0.61	0.58
2014/2015	0.71	0.78	0.94
2015/2016	0.72	0.74	0.96

Table 9. Estimated recruitment (numbers), female mature biomass (t), male mature biomass (t), total female abundance and total male abundance (1000s) from the integrated assessment method when females and males are fit.

Year	Recruitment	FMB (t)	MMB (t)	Female abundance	Male abundance
1975	14878	85	145	91.6	89.6
1976	15602	127	255	114.5	121.1
1977	18528	157	372	128.1	144.3
1978	10050	168	443	131.7	151.5
1979	6575	168	458	127.5	144.3
1980	7715	162	440	119	130.6
1981	16246	154	411	108.6	116.5
1982	72094	144	379	97.7	103.7
1983	413692	132	345	88.7	93.1
1984	142532	120	310	90.1	92
1985	4598343	112	278	103.3	96.3
1986	835610	127	259	225.7	209.6
1987	241773	193	306	441.4	354.3
1988	498254	425	522	777.6	614
1989	197221	1114	1108	1158.6	1055
1990	112964	1734	3547	1450.5	1582.3
1991	130316	1966	5035	1591.7	1876
1992	1080215	2014	5282	1596.5	1837.3
1993	578885	1780	3775	1527.7	1674.1
1994	312839	1526	3030	1321.9	1159.1
1995	2179664	1304	2425	1173.1	941.7
1996	1067346	1315	2259	1113.8	899.4
1997	78360	1232	2241	1179.2	1016.4
1998	28431	1233	2324	1219.7	1085.5
1999	38865	1545	2707	1308.6	1205.3
2000	212285	1852	3819	1411.1	1430.8
2001	362669	1936	4681	1417	1540.2
2002	1797022	1859	4779	1348.3	1463.4
2003	1045487	1733	4471	1279.7	1334.1
2004	270685	1624	4059	1254.2	1234.8
2005	122624	1600	3714	1294.8	1217.1
2006	151155	1769	3650	1373.8	1307.3
2007	286966	1974	4339	1432	1467.3
2008	317137	2024	4957	1431.2	1560.1
2009	115741	1948	5040	1374.1	1506.5
2010	43303	1832	4771	1286.8	1374.2
2011	29841	1727	4411	1189.7	1240.1
2012	16937	1632	4105	1088.9	1129.8
2013	13945	1519	3859	981.8	1027
2014	13267	1380	3548	871.5	915.1
2015	13267	1233	3180	762.2	795.1

Table 10. Estimated recruitment (numbers), female mature biomass (t), male mature biomass (t), total female abundance and total male abundance (1000s) from the integrated assessment method when males are fit.

Year	Recruitment	MMB (t)	Male abundance
1975	14681	95	53.7
1976	21030	208	85.1
1977	12543	296	105
1978	8614	341	109.7
1979	9146	347	103.9
1980	15132	332	94.1
1981	48544	310	84.4
1982	323491	288	76.2
1983	178587	265	70.8
1984	4823576	241	66.3
1985	650956	218	95.6
1986	435730	202	125.1
1987	617317	223	193.6
1988	232138	354	346.6
1989	118534	829	654.4
1990	154506	2794	1136
1991	1157155	4169	1496.9
1992	571461	4486	1535.6
1993	433932	3070	1416.5
1994	2875288	2433	939.5
1995	1226401	1914	749.5
1996	132122	1797	673.7
1997	64580	1747	760.3
1998	92980	1839	828
1999	430421	2289	956.2
2000	761735	3487	1242.5
2001	2580435	4505	1455.9
2002	3152752	4756	1458.7
2003	605901	4536	1350.9
2004	244048	4185	1253.8
2005	256801	3940	1257.7
2006	622266	4054	1414.6
2007	676978	5058	1743.3
2008	229647	6578	2093.1
2009	116479	7294	2205.2
2010	99699	7188	2074.2
2011	61775	6768	1883
2012	50875	6391	1728.6
2013	47031	6100	1600.2
2014	45958	5689	1453.9
2015	45958	5161	1281.8

Table 11. Estimates of female and male abundance (1000s individuals) and female and male biomass (t) from a 3-year running average. NAs result from years in which no individuals were captured of a given sex.

Year	Female abundance	Male abundance	Female biomass	Male biomass
1977	108	216	81	429
1978	100	238	87	561
1979	96	347	137	1005
1980	81	274	122	789
1981	208	315	291	973
1982	195	165	308	606
1983	170	149	291	594
1984	103	86	NA	332
1985	49	56	NA	193
1986	31	27	NA	90
1987	621	480	NA	103
1988	1603	1229	NA	324
1989	2687	3188	1366	719
1990	3662	3633	3000	2347
1991	3736	3610	3560	3017
1992	4262	2687	5018	4779
1993	3498	2783	4719	6034
1994	3517	4637	5157	13371
1995	2295	2017	3503	5850
1996	1828	2112	2638	5540
1997	1203	1272	1788	2800
1998	2589	2760	1586	3501
1999	2381	2173	1259	3477
2000	3312	3339	1672	5114
2001	929	2219	1277	5380
2002	1071	2531	1588	6765
2003	834	1820	1121	5076
2004	1425	960	1796	2996
2005	1239	1148	1847	4460
2006	1044	1102	2285	4853
2007	1159	1558	2268	6078
2008	797	1432	1500	4575
2009	705	1463	1268	4281
2010	420	1253	819	3761
2011	480	1410	748	4295
2012	295	1502	454	5236
2013	284	2066	453	7092
2014	434	2661	702	10945
2015	778	3344	2219	13666

Table A1. List of estimated and fixed parameters.

Fixed parameters (14)	Number
Natural mortality	1
Molting probability	3
Fishery selectivity	2
Discard selectivity	3
Weight	4
Survey catchability	1
Estimated parameters (89)	
Growth	6
Proportion recruiting	2
Log recruitment deviations	46
Log average fishing mortality (directed)	1
Log fishing mortality deviations (directed)	6
Log average fishing mortality (trawl)	1
Log fishing mortality deviations (trawl)	26
Survey selectivity	2

Table A2. List of estimated parameter values from 2014 and 2015.

Parameter	2014	2015
srv_q	1	1
fish_sel50	138	138
fish_sel95	138.05	138.05
srv_sel50	102.15	100.3
srv_sel95	141.06	147.88
log_avg_fmort_dir	-0.98	-1.72
log_avg_fmort_trawl	-4.88	-5.5
mean_log_rec	11.21	11.62
A_f (growth)	25.42	25.3
A_m (growth)	9.77	7.76
B_f (growth)	0.86	0.86
B_m (growth)	1.13	1.15
growth_beta_males	0.72	1.12
alpha_rec	0.86	5.56
beta_rec	0.16	1.53

Table A3. Likelihood component contribution to the likelihood and associated weights for males and female and males only.

Likelihood component	negLogLike (both)	negLogLike (males only)	Weighting
Survey numbers (males)	185.9	52.7	.36 -1 (CVs)
Survey numbers (females)	178.6	n/a	.36-1 (CVs)
Survey length frequencies (male)	9175.2	9218.9	18-200 (sample size)
Survey length frequencies (female)	5824.9	n/a	18-200 (sample size)
Catch	1.9	0.4	.005(CV)
Trawl	206.5	206.6	.05 (CV)
Smoothness penalties			
Trawl fishing mortality	28.9	28.9	1 (CV)
Fishing mortality	4.3	4.2	1 (CV)
Recruitment	57.1	49.6	1 (CV)

10. Figures

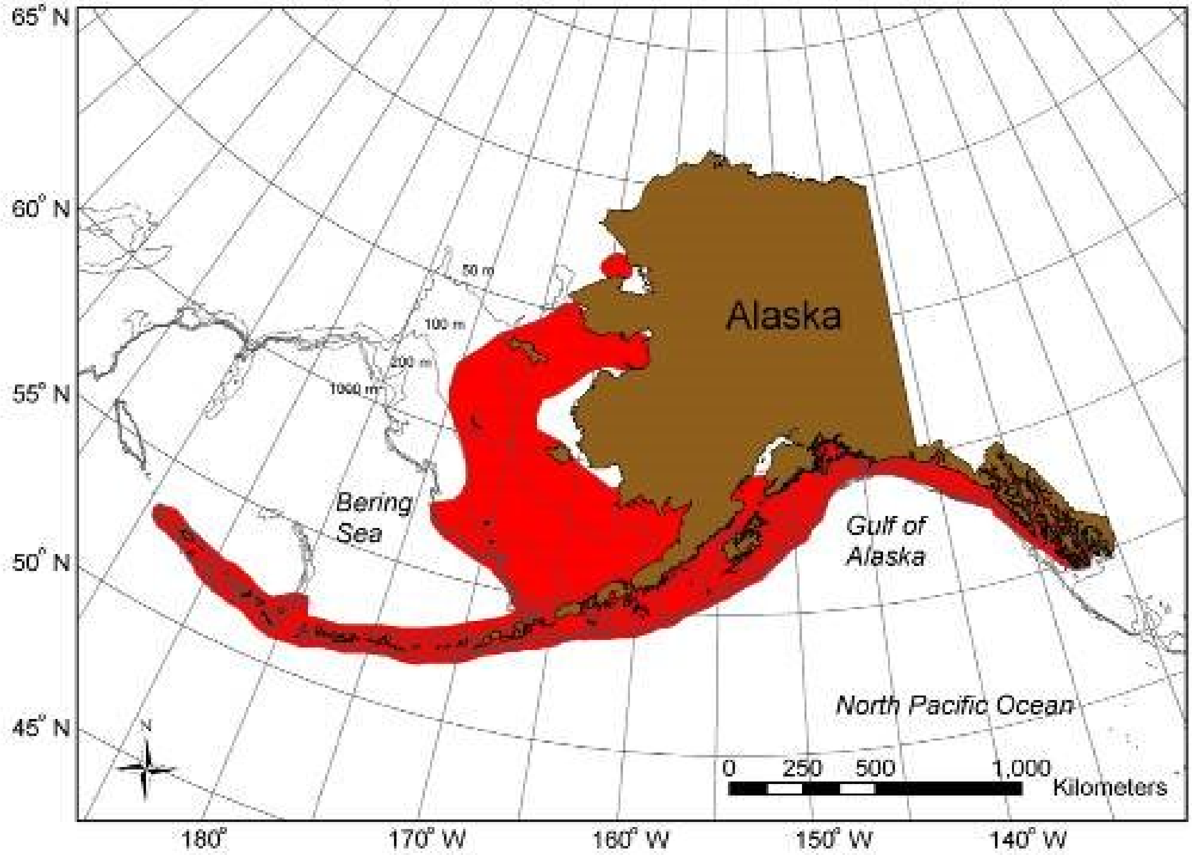

Figure 1. Red king crab distribution.

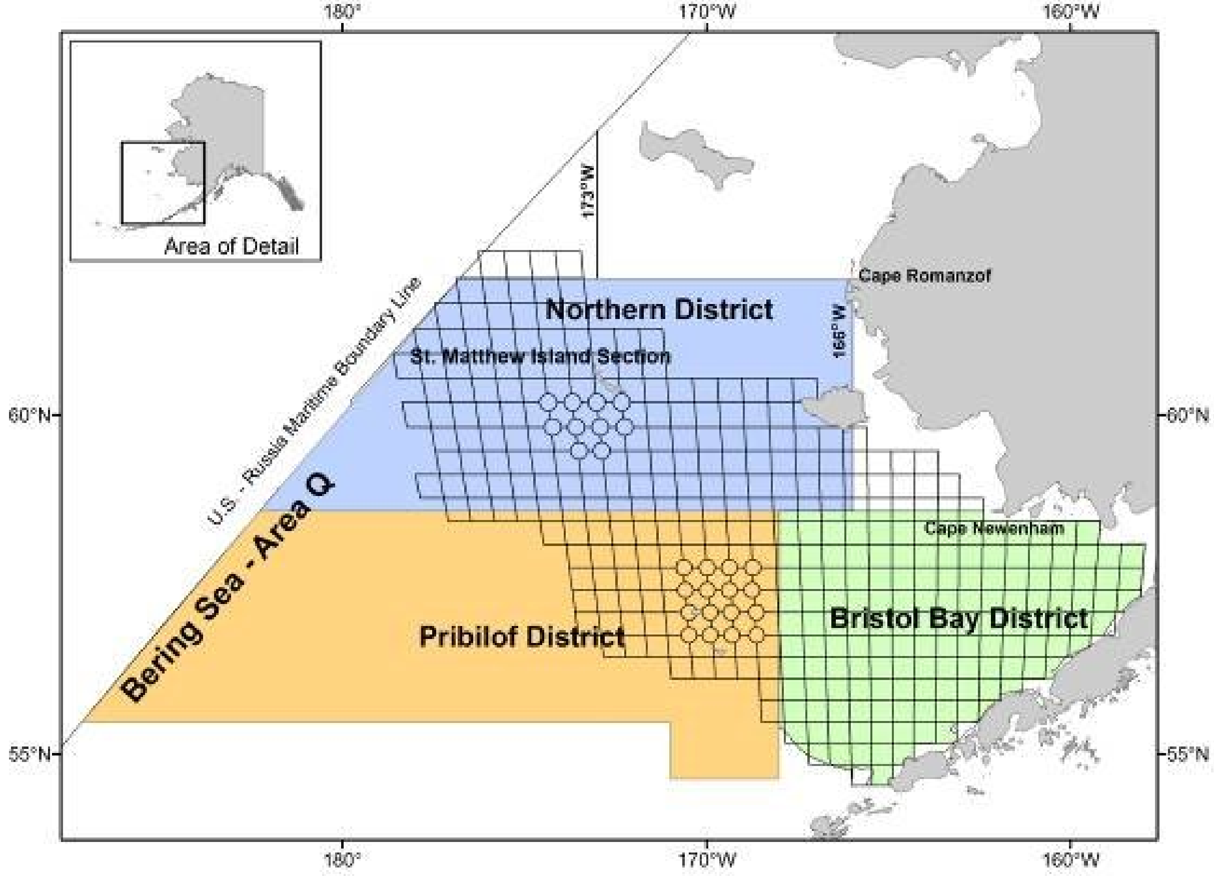

Figure 2. King crab registration area Q (Bering Sea) showing the Pribilof District.

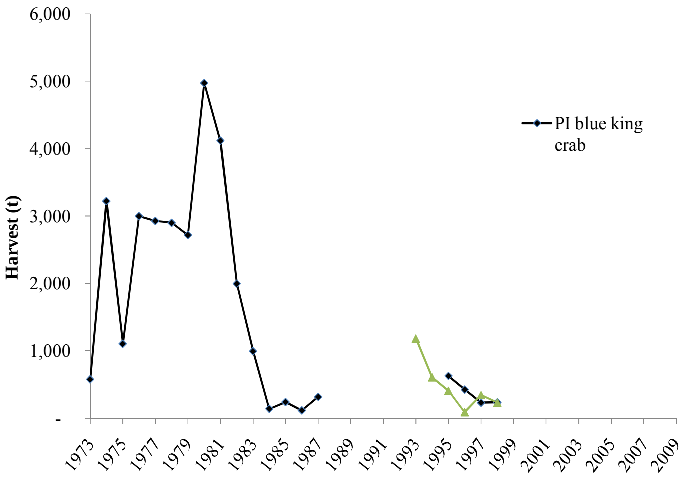

Figure 3. Historical harvests and GHLs for Pribilof Island blue (diamonds) and red king crab (triangles) (Bowers et al. 2011).

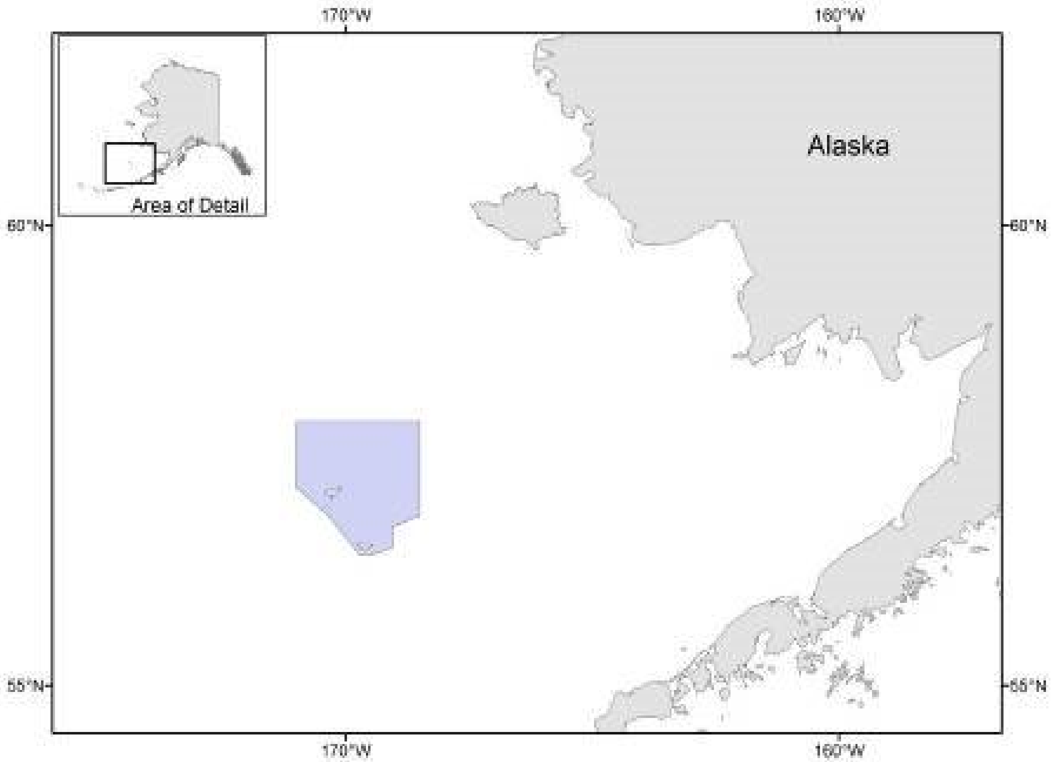

Figure 4. The shaded area shows the Pribilof Islands Habitat Conservation area.

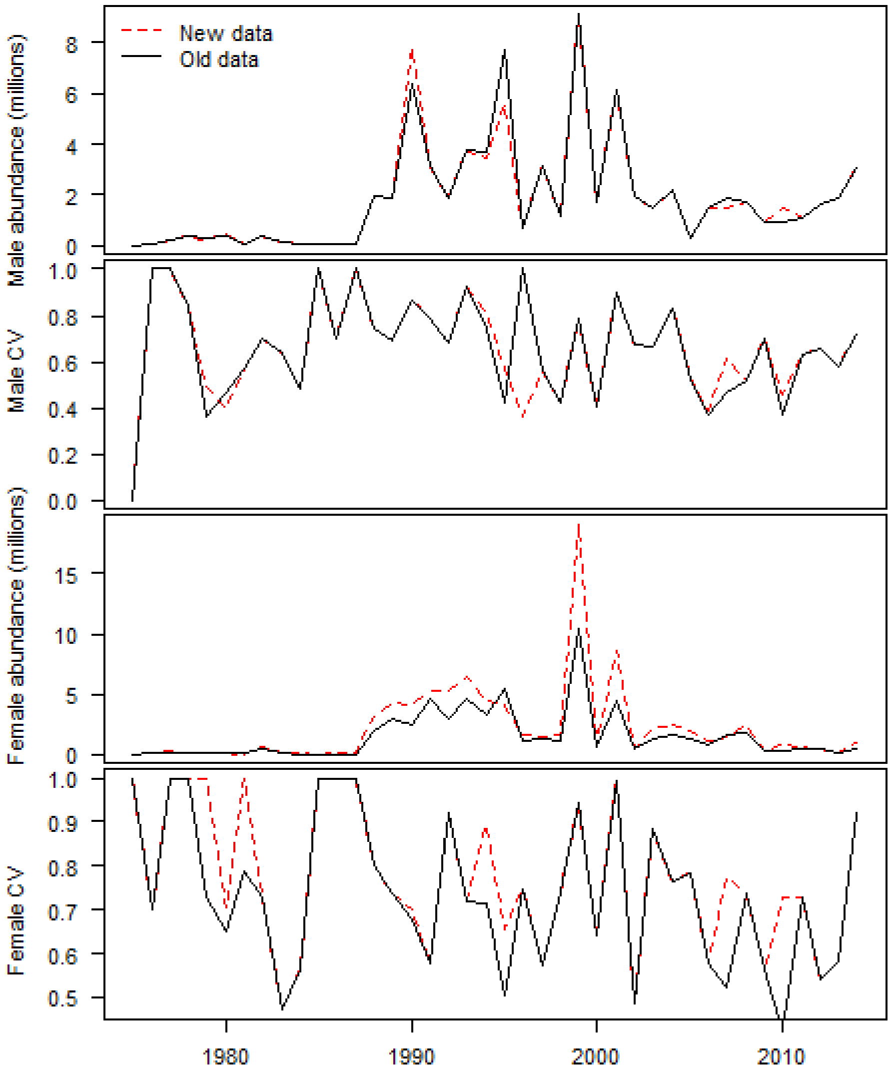

Figure 5. Comparison of data calculated using 2014 and 2015 methodologies.

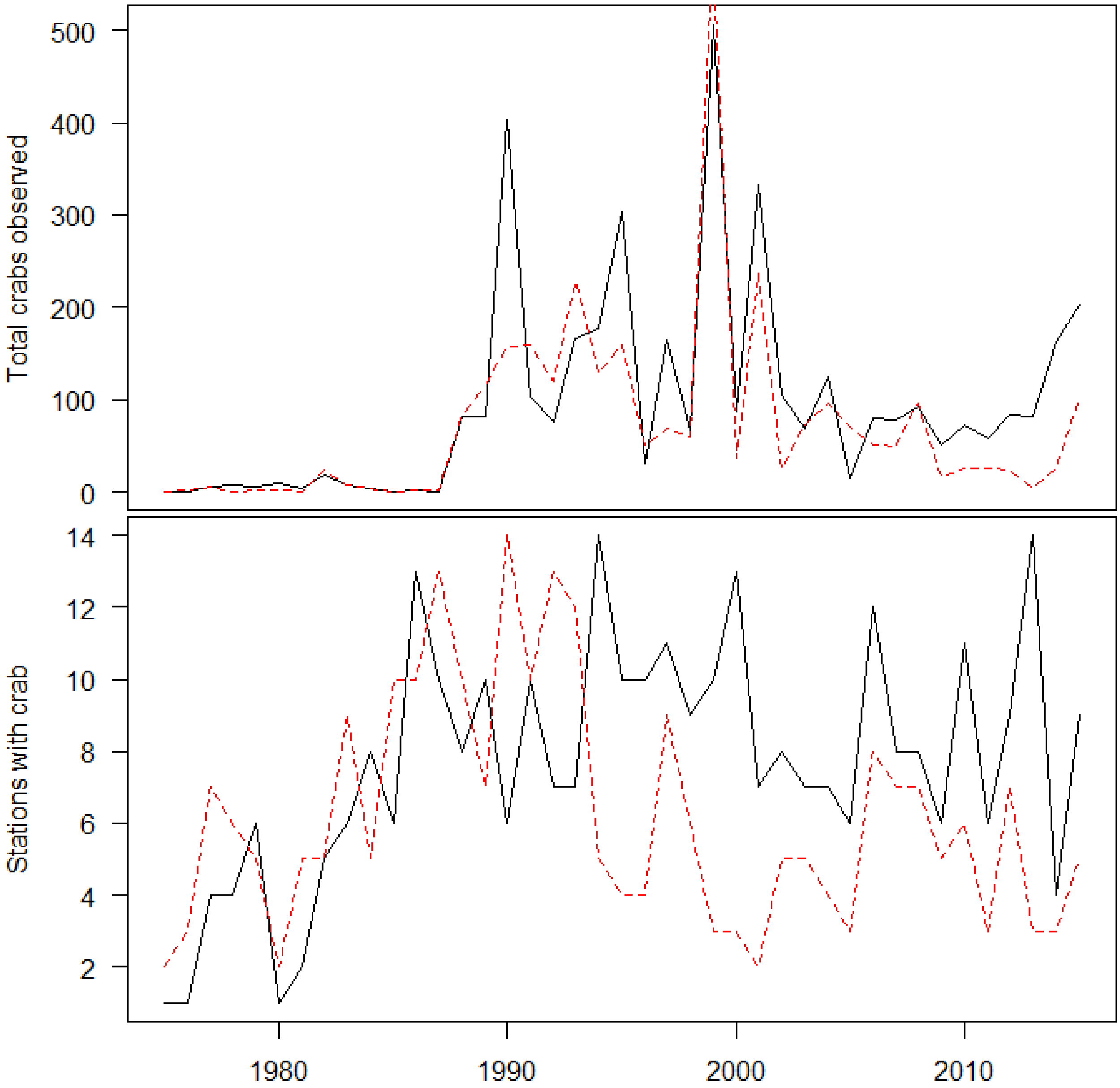

Figure 6. Total number of observed crab (top) and the number of stations that reported observations of crab (female = dashed line, male = solid line) from 1975-2014.

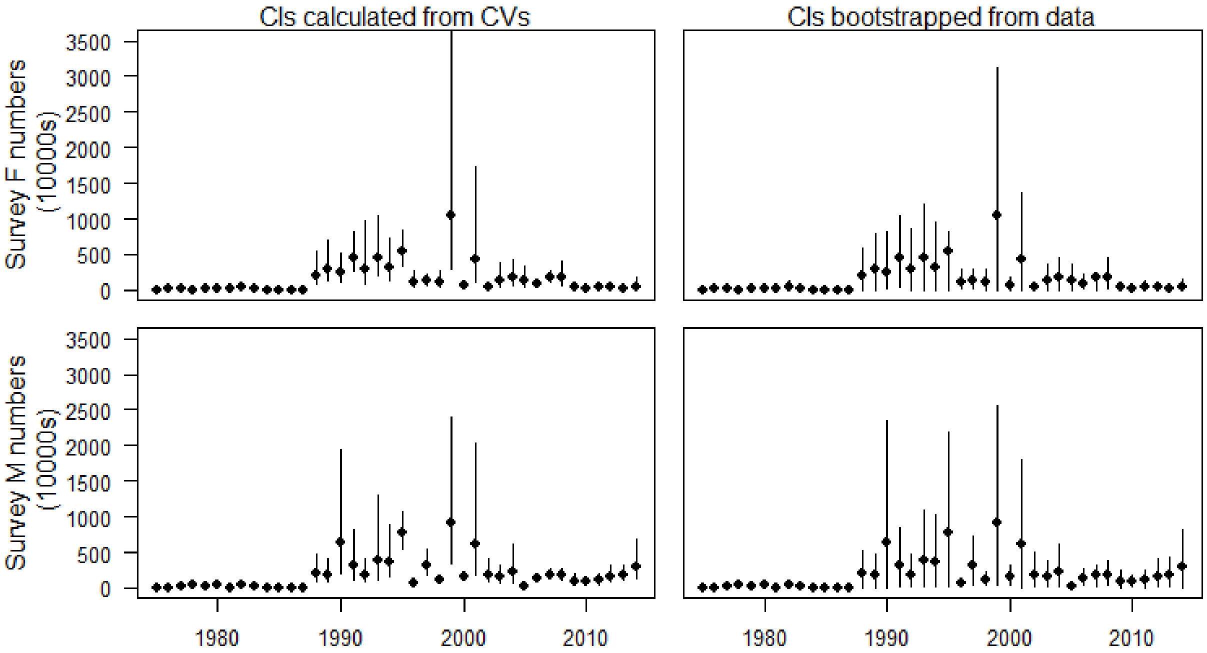

Figure 7. Time series of Pribilof Islands red king crab estimated from the NMFS annual EBS bottom trawl survey. CIs for the left column are based on back calculations from the CVs provided from Kodiak, CIs in the right column are based on bootstraps from the NMFS.

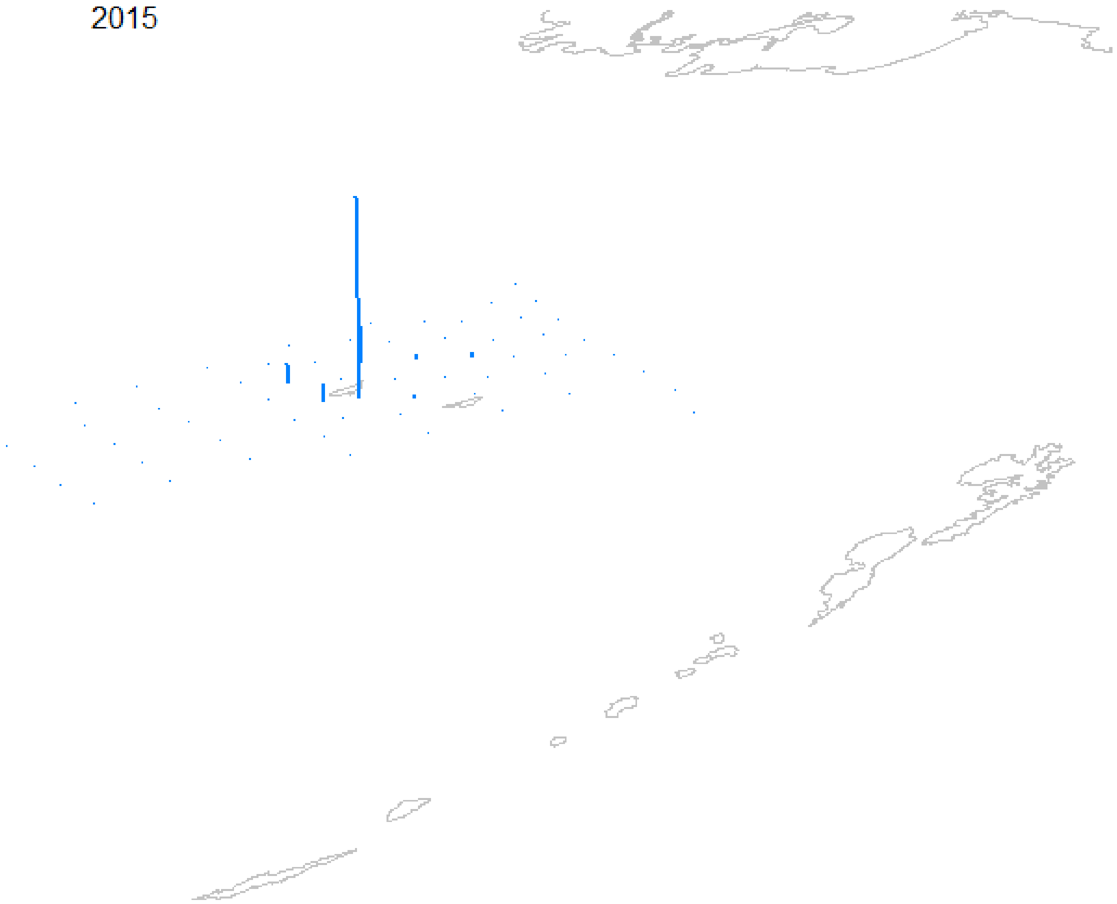

Figure 8. Male red king crab relative density by station in the Pribilof Island district in 2015. Blue bars represent the relative magnitude of the density calculated from the NMFS trawl survey.

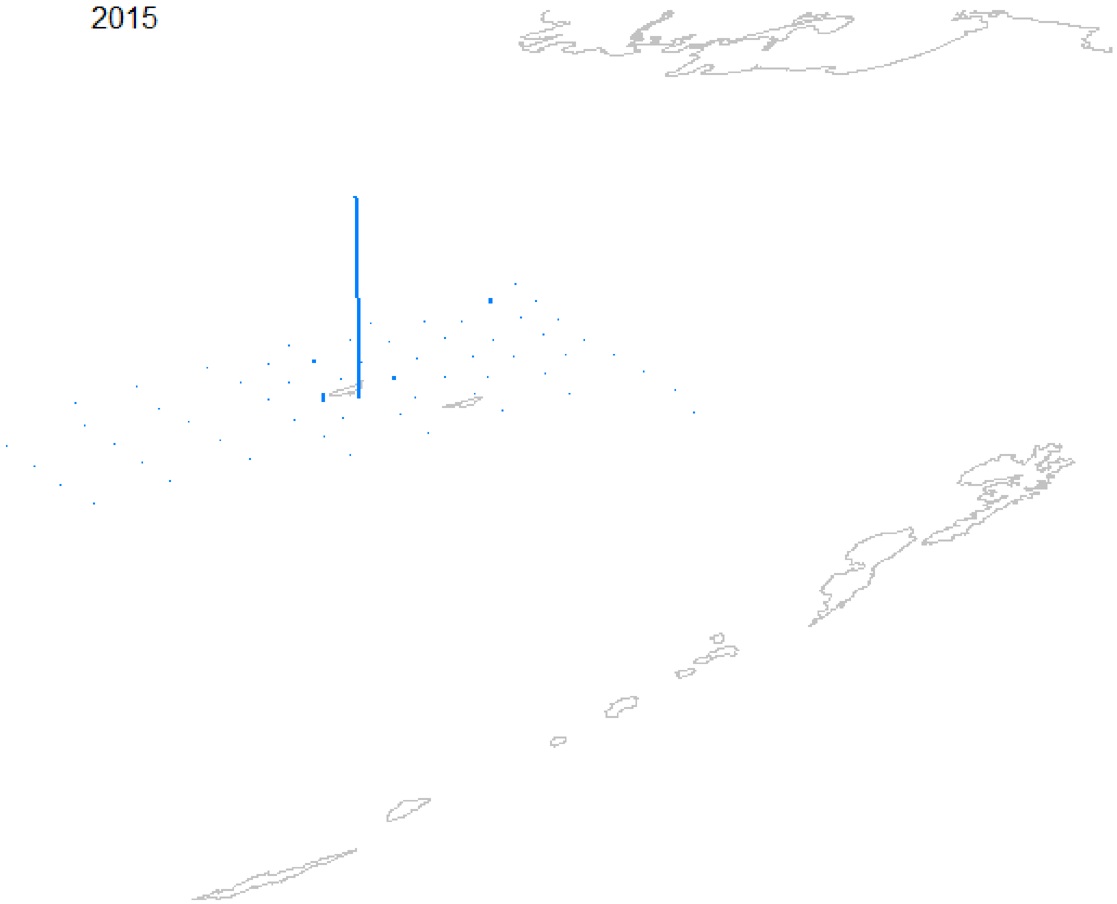

Figure 9. Female red king crab relative density by station in the Pribilof Island district in 2015. Blue bars represent the relative magnitude of the density calculated from the NMFS trawl survey.

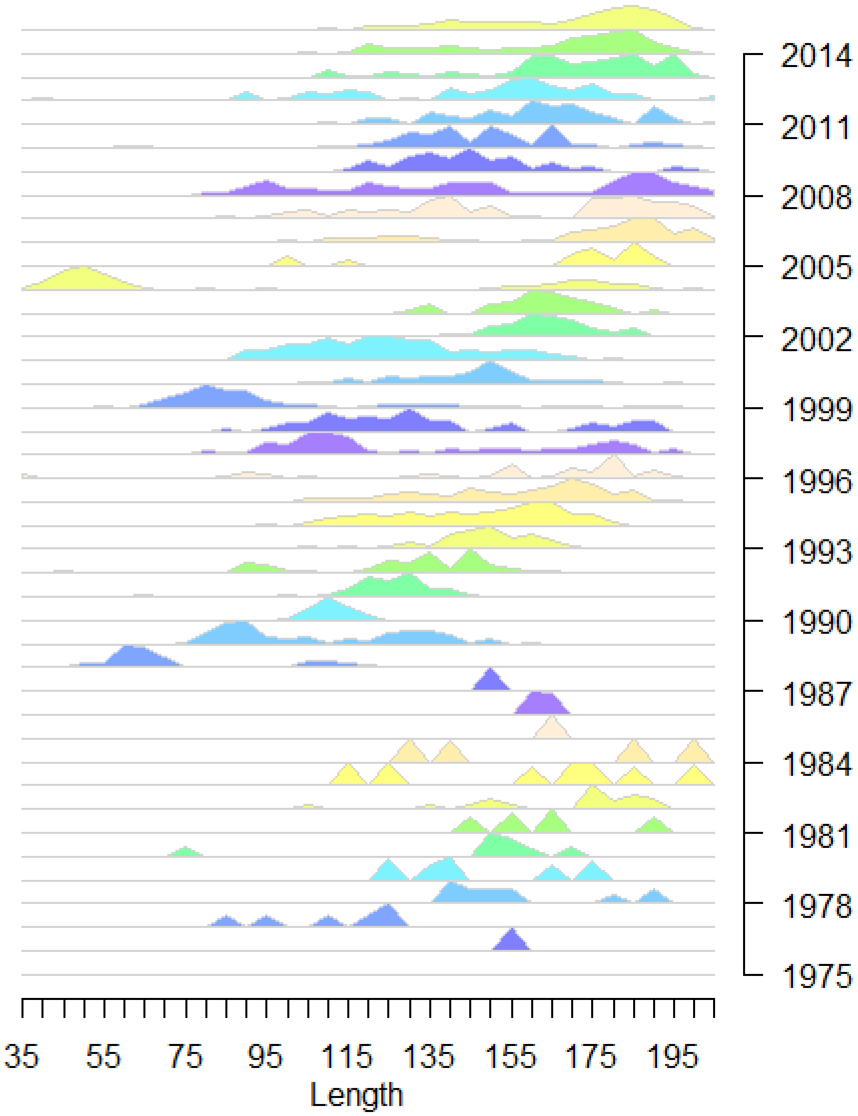

Figure 10. Observed length frequencies by 5 mm length classes of Pribilof Islands male red king crab (Paralithodes camtschaticus) from 1975 to 2015.

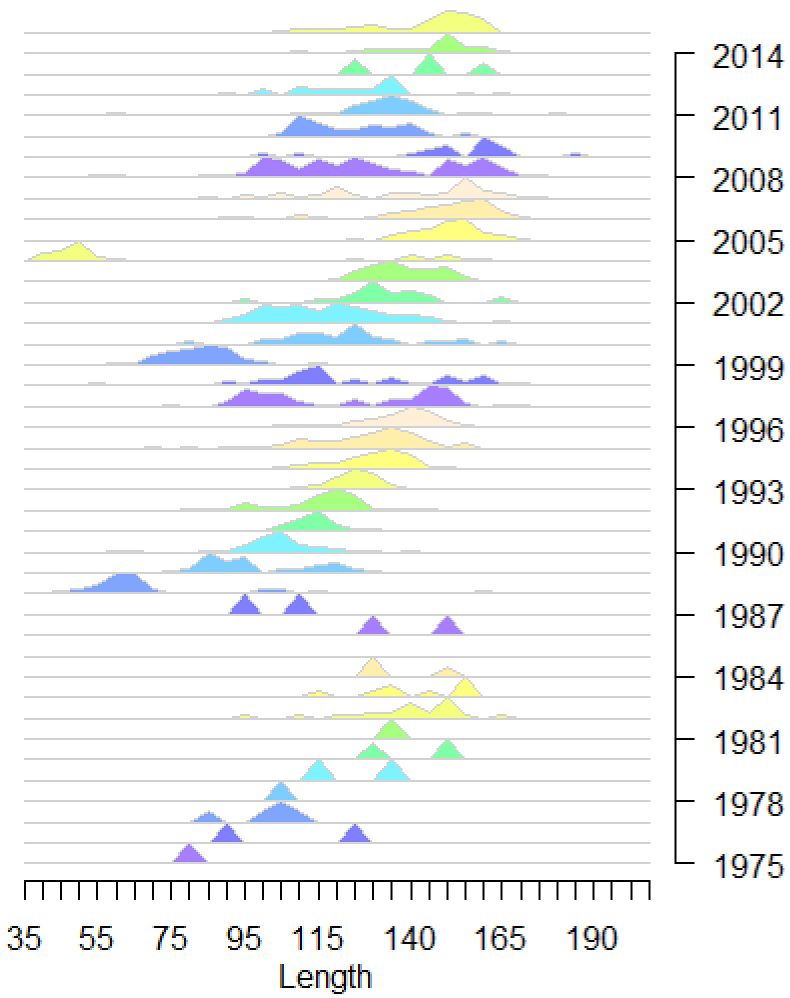

Figure 11. Observed length frequencies by 5 mm length classes of Pribilof Islands female red king crab (Paralithodes camtschaticus) from 1975 to 2015.

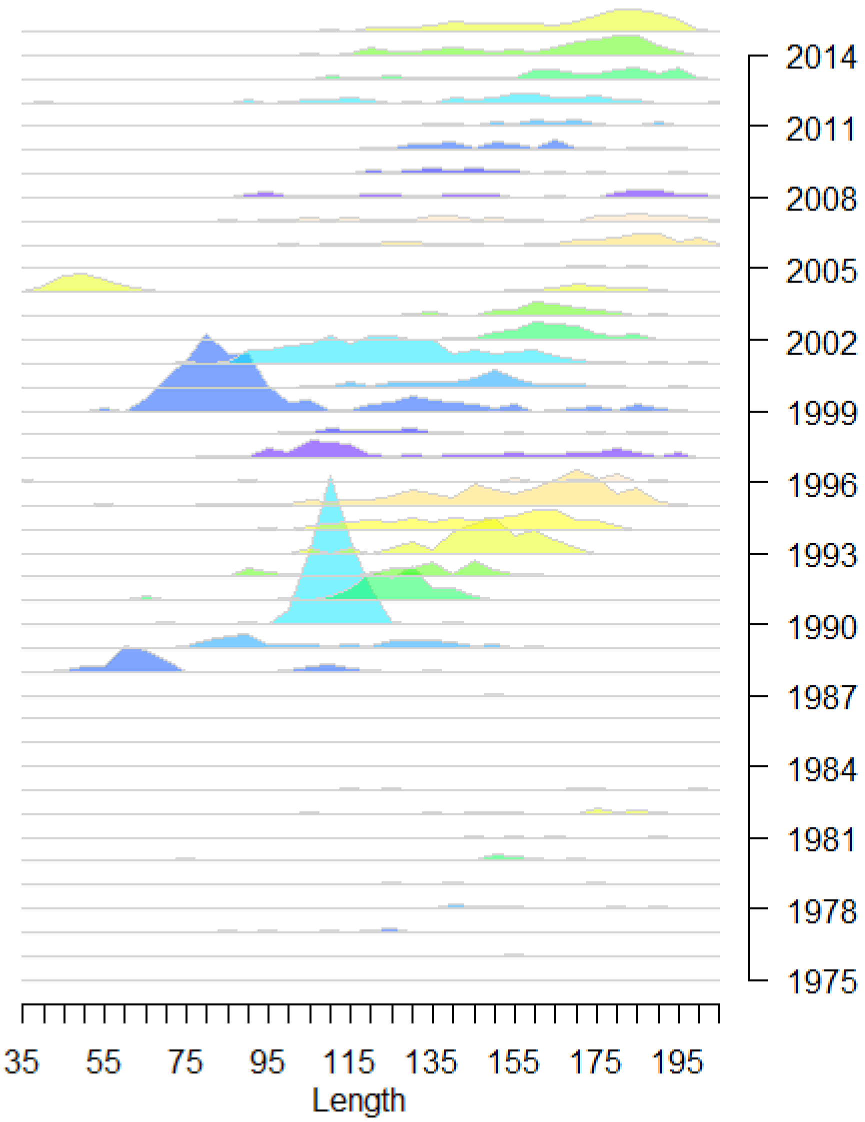

Figure 12. Observed numbers at length by 5 mm length classes of Pribilof Islands male red king crab (Paralithodes camtschaticus) from 1975 to 2015.

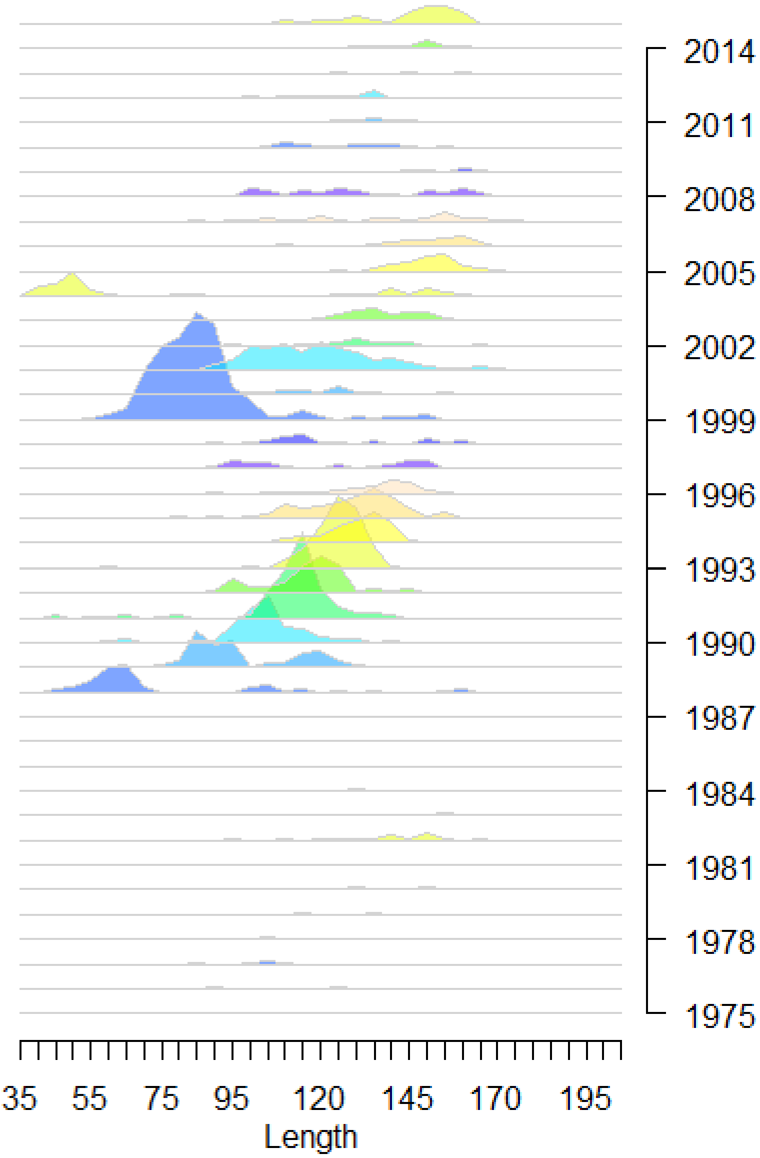

Figure 13. Observed numbers at length by 5 mm length classes of Pribilof Islands female red king crab (Paralithodes camtschaticus) from 1975 to 2015.

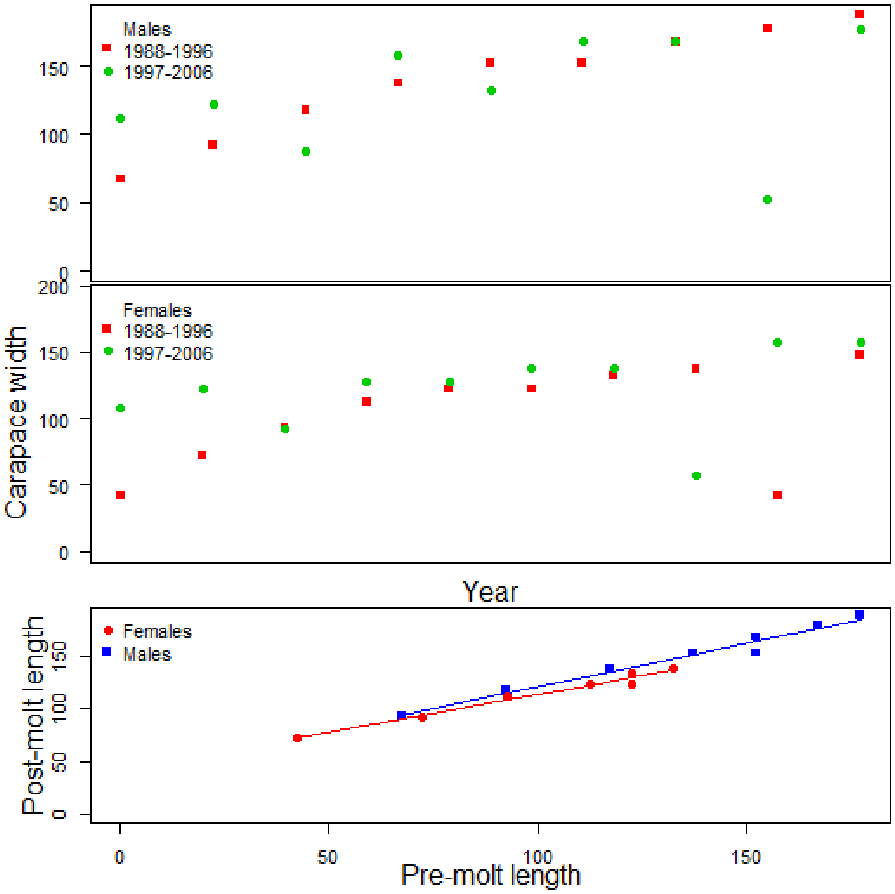

Figure 14. Modes of the length frequency distribution for males and females plotted for two time periods over which two cohorts were observed to move through the population. Growth per molt calculated from the modes from the length frequencies with fitted linear relationship (bottom).

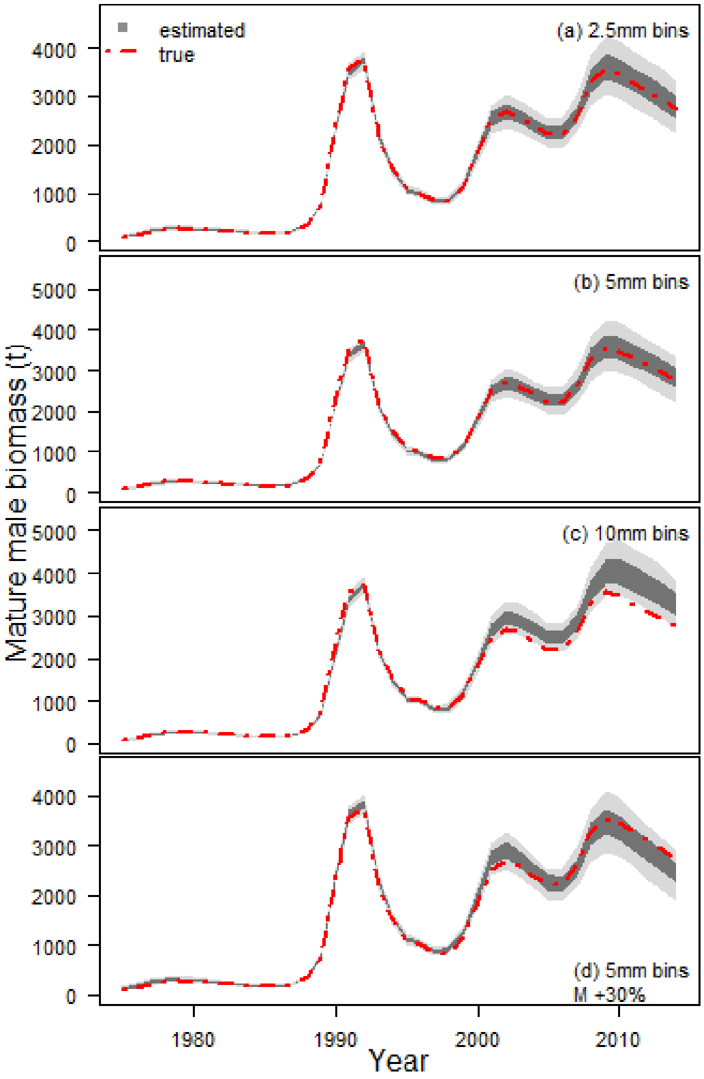

Figure 15. Estimates of MMB in simulation aimed at the testing of the integrated assessment method when binning data into different size bins. Panel (d) shows a case in which M was mis-specified. Red dashed lines are the true quantity; grey shading indicates the intersimulation quantiles for estimated MMB.

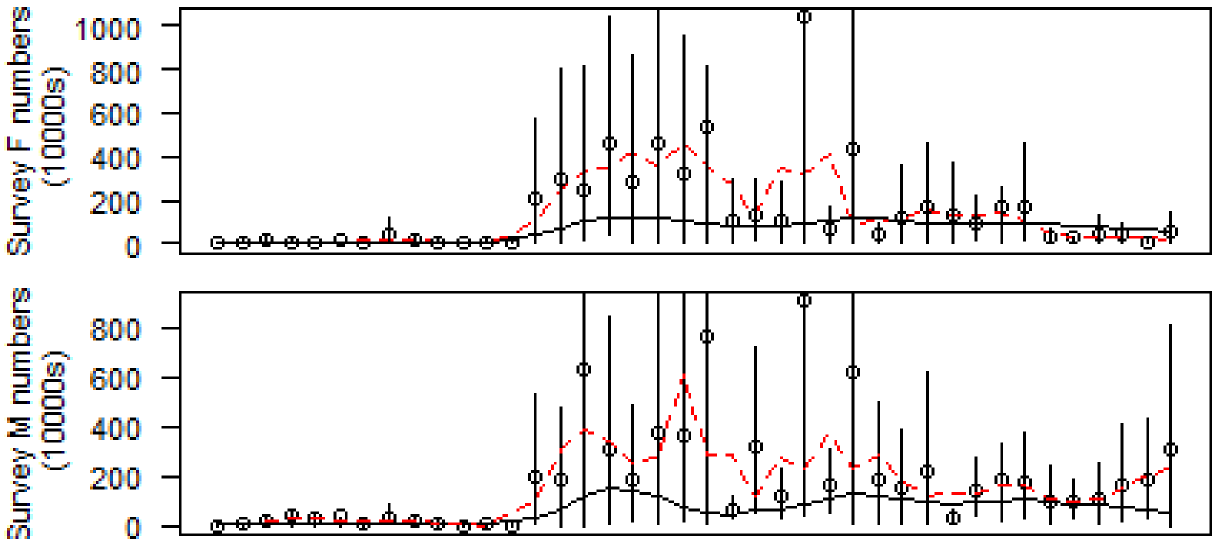

Figure 16. Fits to male and female survey numbers from 2014. Black line is integrated assessment method, dashed red is a 3-year running average.

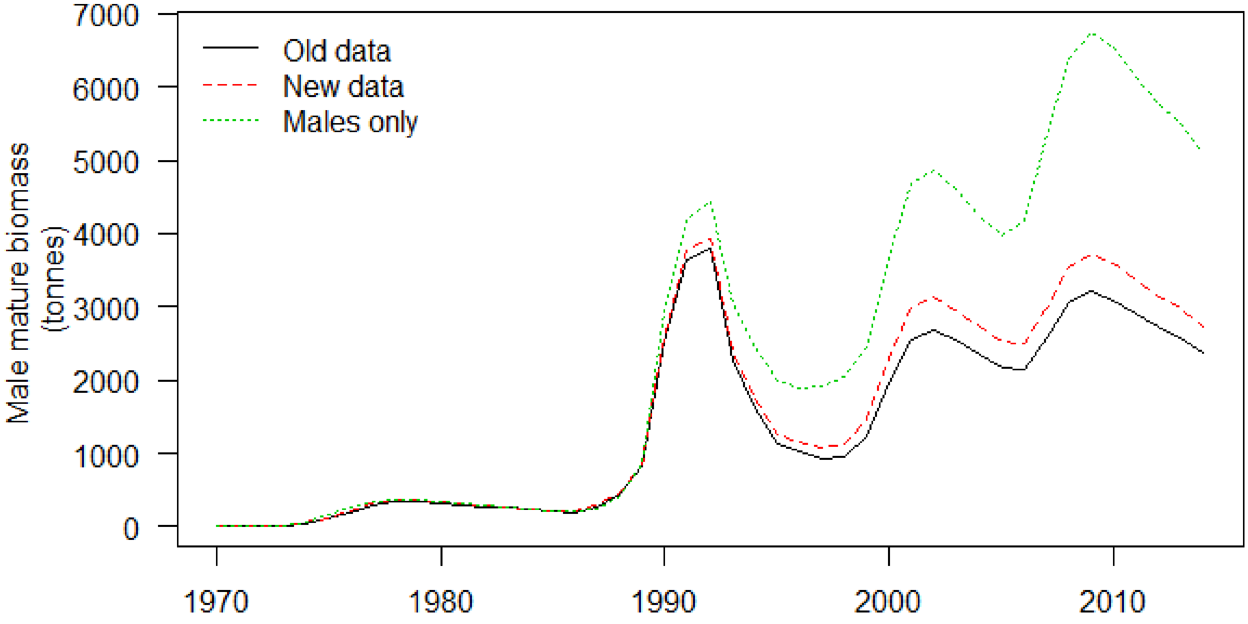

Figure 17. Comparison of estimated MMB using survey data from 1975-2014 using the new and old methodologies for calculating survey numbers and while fitting males only with the new methodology.

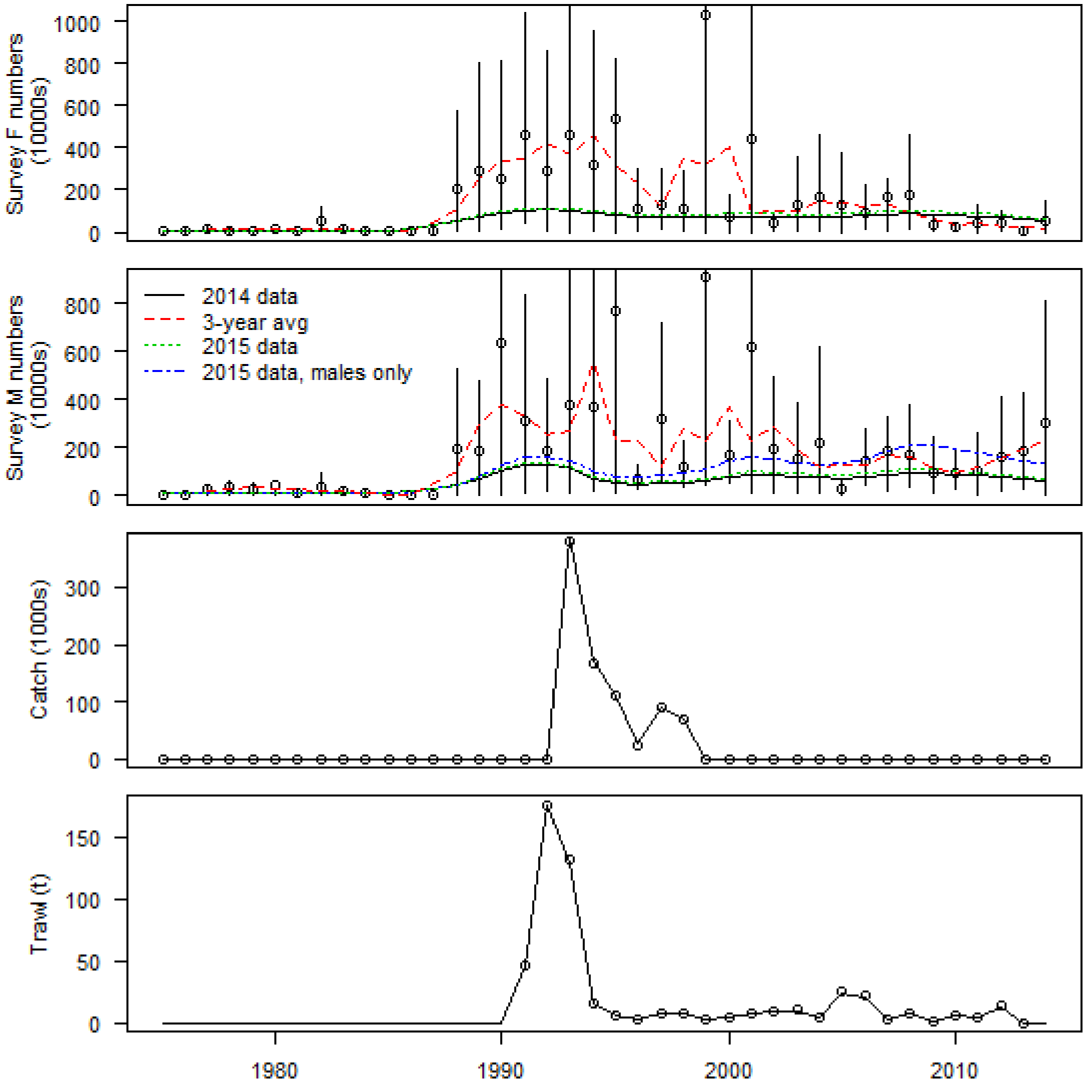

Figure 18. Model fits (black line) to observed survey numbers (black dots) with 95% bootstrapped CIs for females (top) and males (2nd row). Model fits (black line) to observed catches in the directed fishery (dots) in numbers caught (3rd row) and bycatch in the non-pelagic trawl fishery (4th row). Survey data are updated through year 2014, '2015' indicates the new survey methodology here.

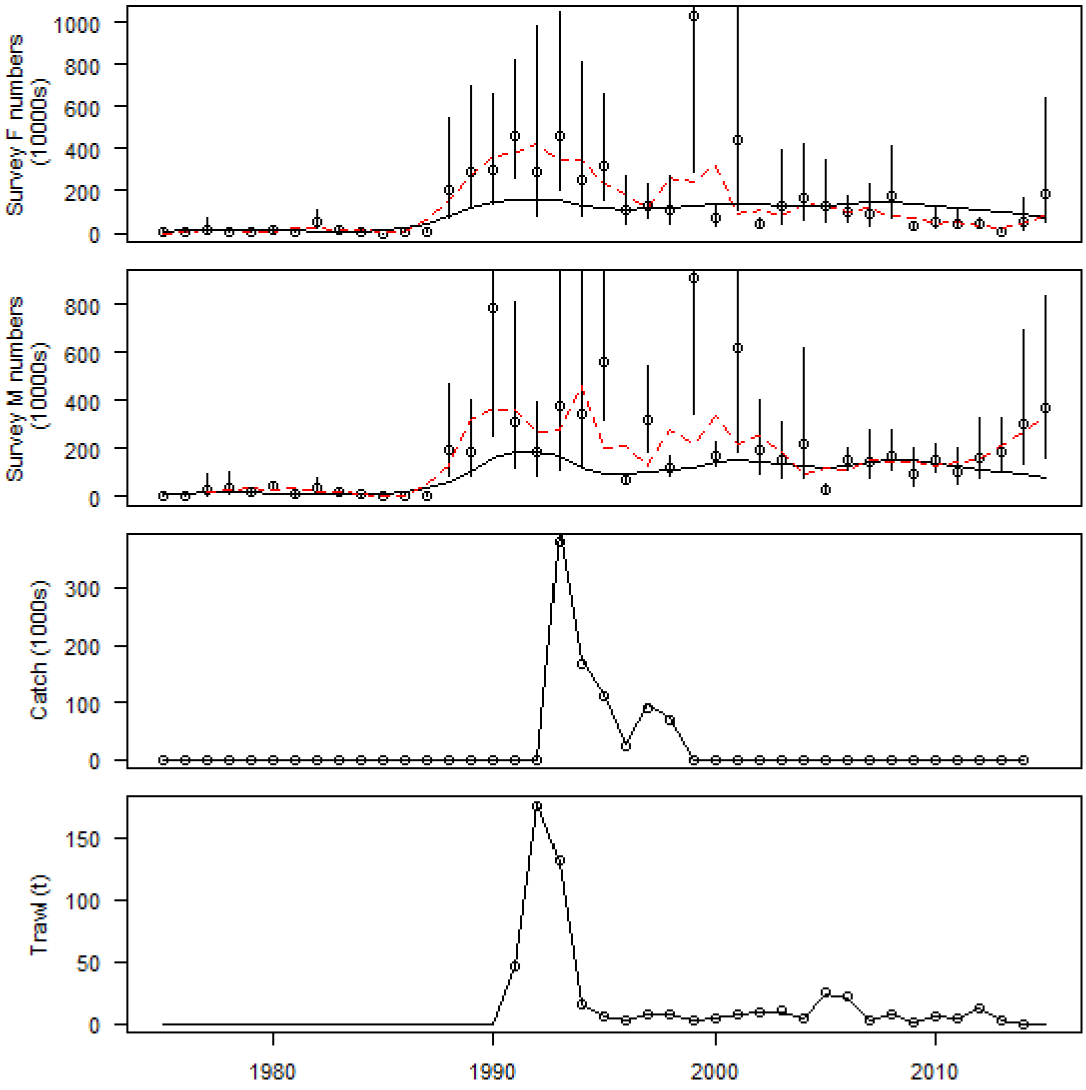

Figure 19. Model fits (black line) to observed survey numbers (black dots) with 95% Poisson CIs (provided by Kodiak lab) for females (top) and males (2nd row). Model fits (black line) to observed catches in the directed fishery (dots) in numbers caught (3rd row) and bycatch in the non-pelagic trawl fishery (4th row).

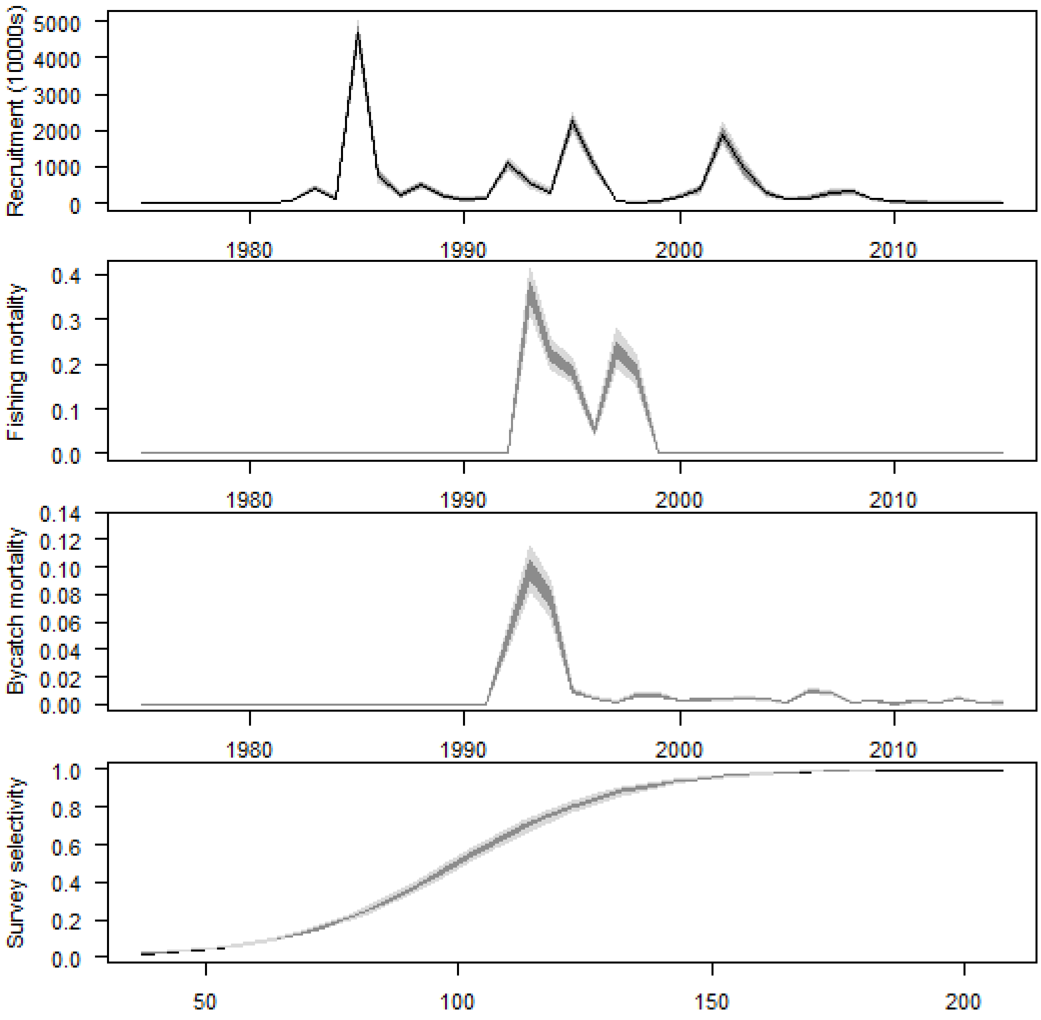

Figure 20. Estimated recruitment (top), fishing mortality in the directed fishery (2nd row), fishing mortality in the non-pelagic trawl (3rd row) and survey selectivity (bottom). Light grey areas indicate the 90% credibility interval and darker grey are the 50% credibility interval. Assessment method uses the 2015 data and fits both females and males.

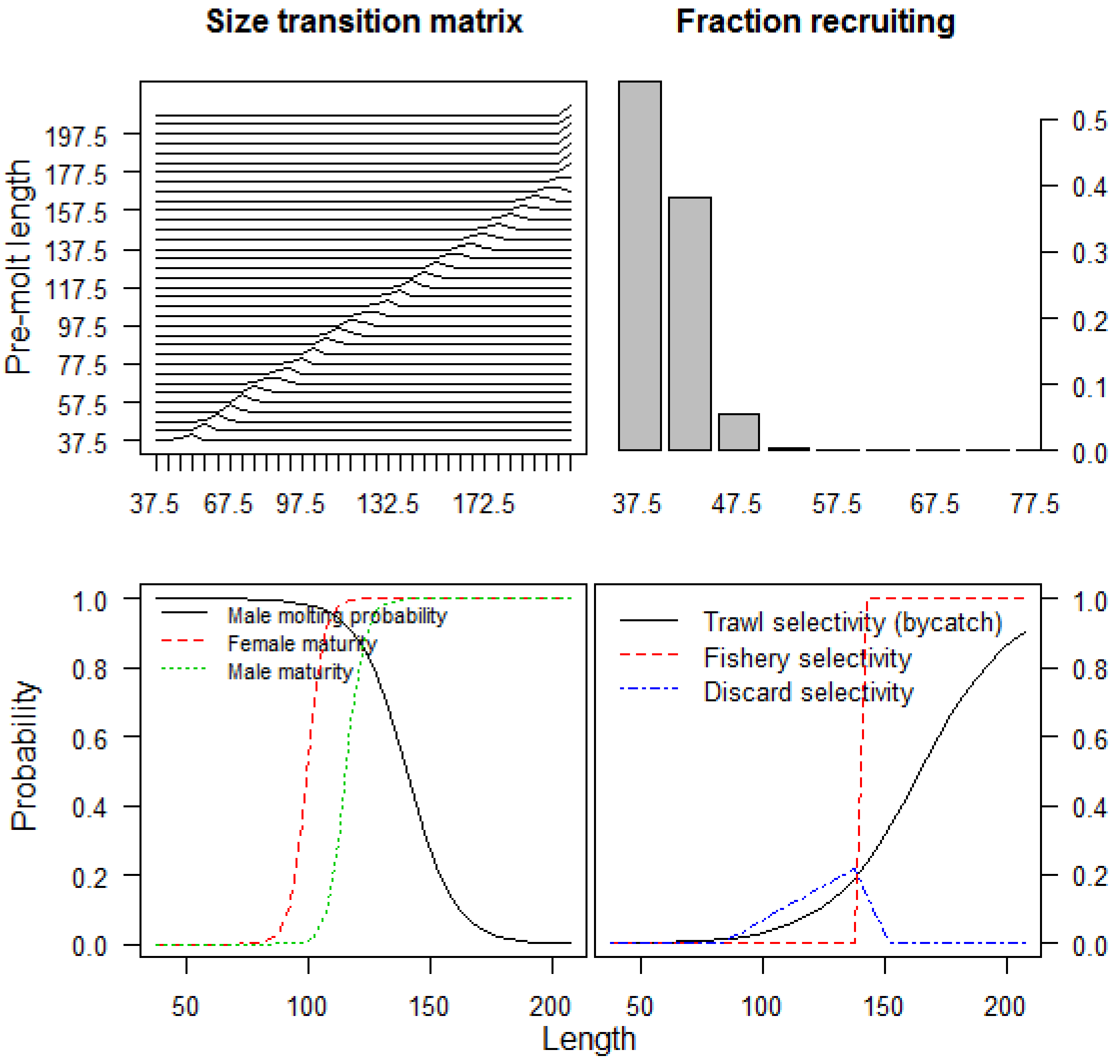

Figure 21. Size transition matrix (topleft), fraction recruiting to a given size class (top right), probability of molting (males only) and maturing (females and males; bottom left), probability of being selected in the directed and trawl fisheries (bottom right). Blue line indicates the discard selectivity from the directed fishery. All from the assessment method fit to both males and females.

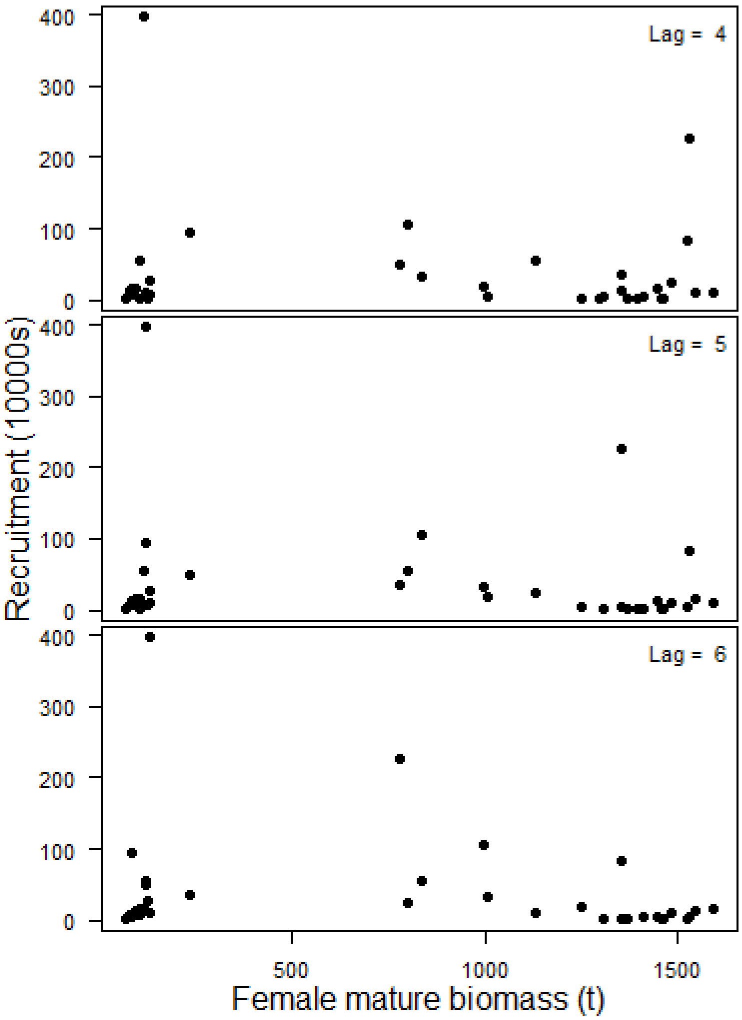

Figure 22. Recruitment vs. estimated female mature biomass at lags of 4, 5, and 6 years.

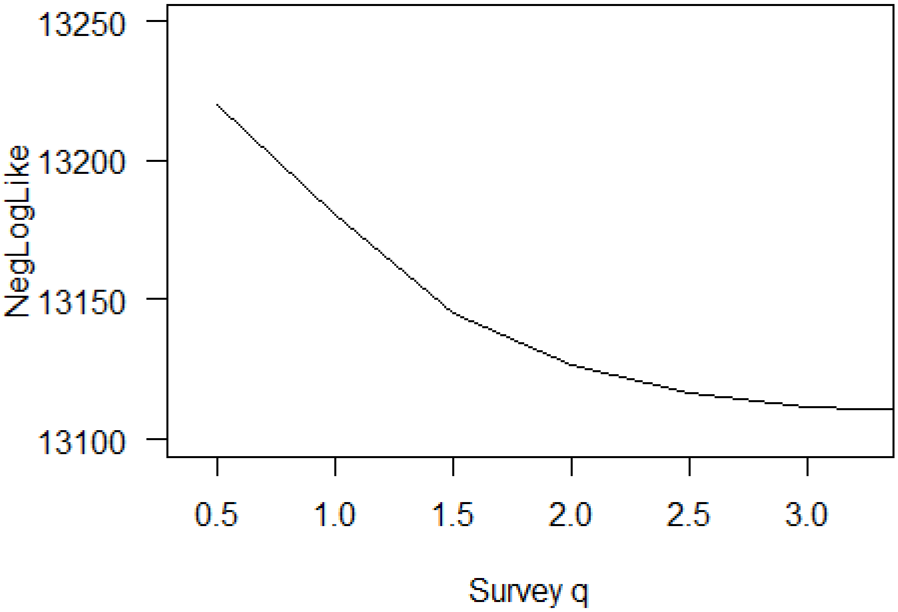

Figure 23. Likelihood profile for the catchability coefficient (q) in the survey.

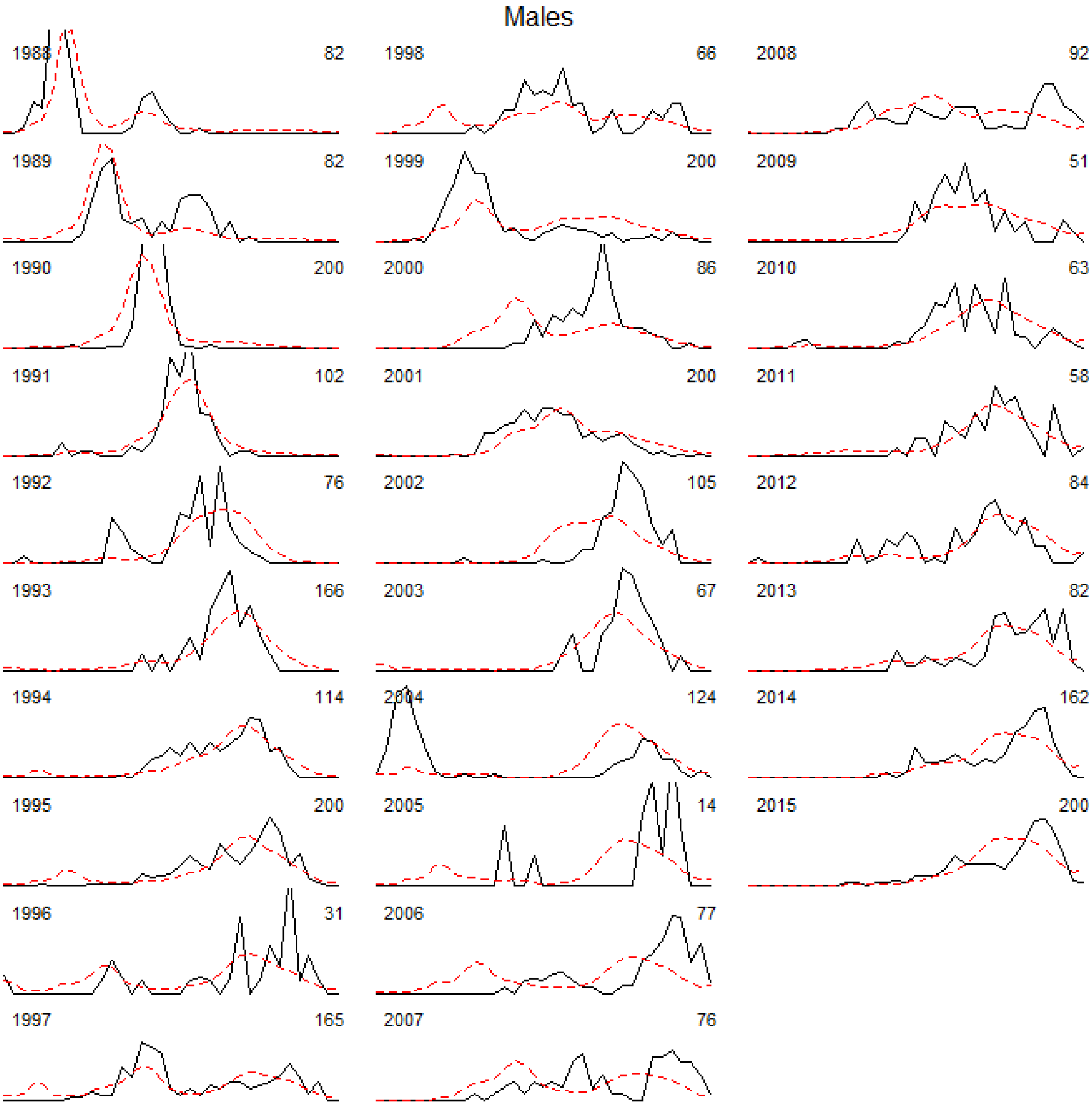

Figure 24. Model fits (red dashed line) to observed male length frequencies in the survey (solid line) by year using 5 mm length bins and fitting males and females. Sample size is noted in the top right hand corner of each plot. Length frequencies for the years 1975-1987 are not shown because the associated sample sizes were <=18 and therefore held very little information.

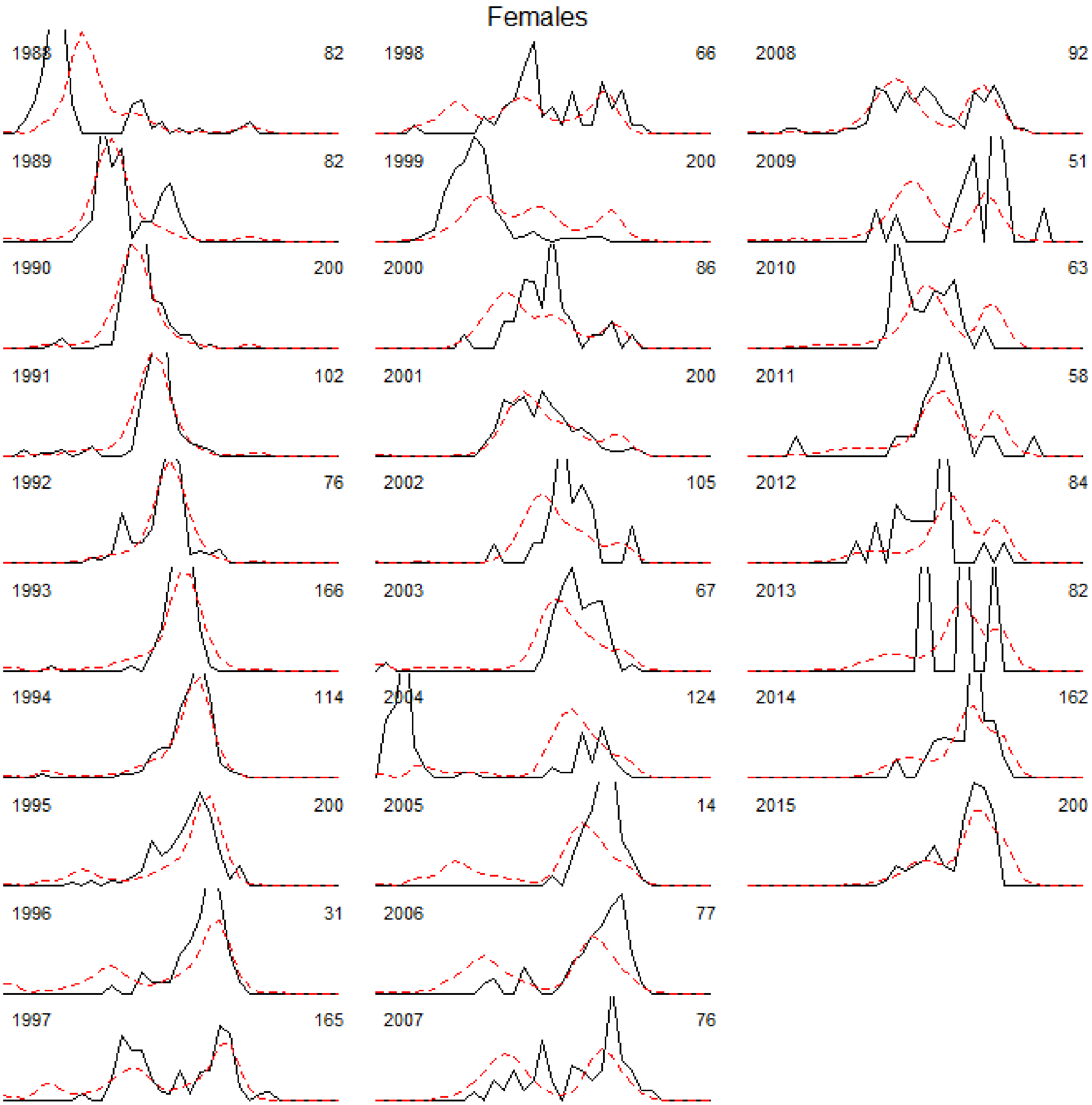

Figure 25. Model fits (red dashed line) to observed female length frequencies in the survey (solid line) by year using 5 mm length bins. Sample size is noted in the top right hand corner of each plot. Length frequencies for the years 1975-1987 are not shown because the associated sample sizes were <=18 and therefore held very little information.

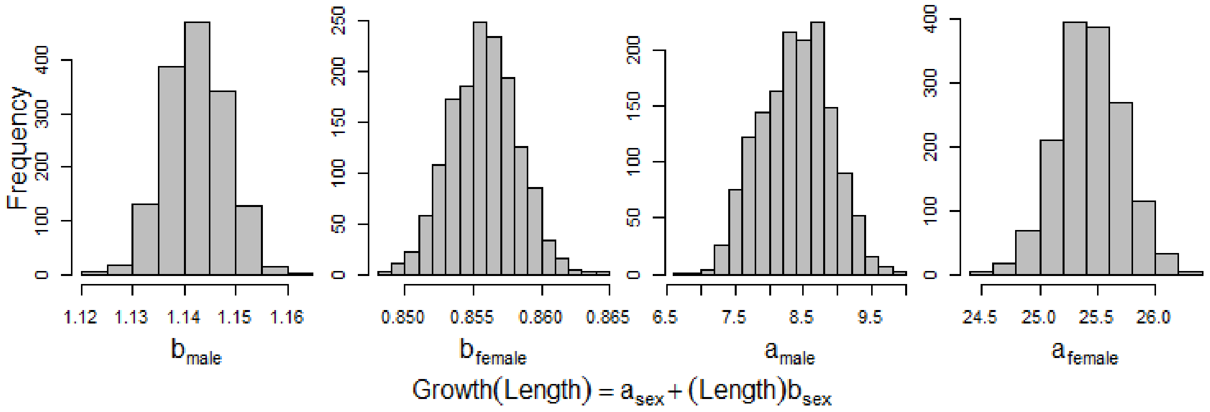

Figure 26. Posterior distributions of estimated growth parameters.

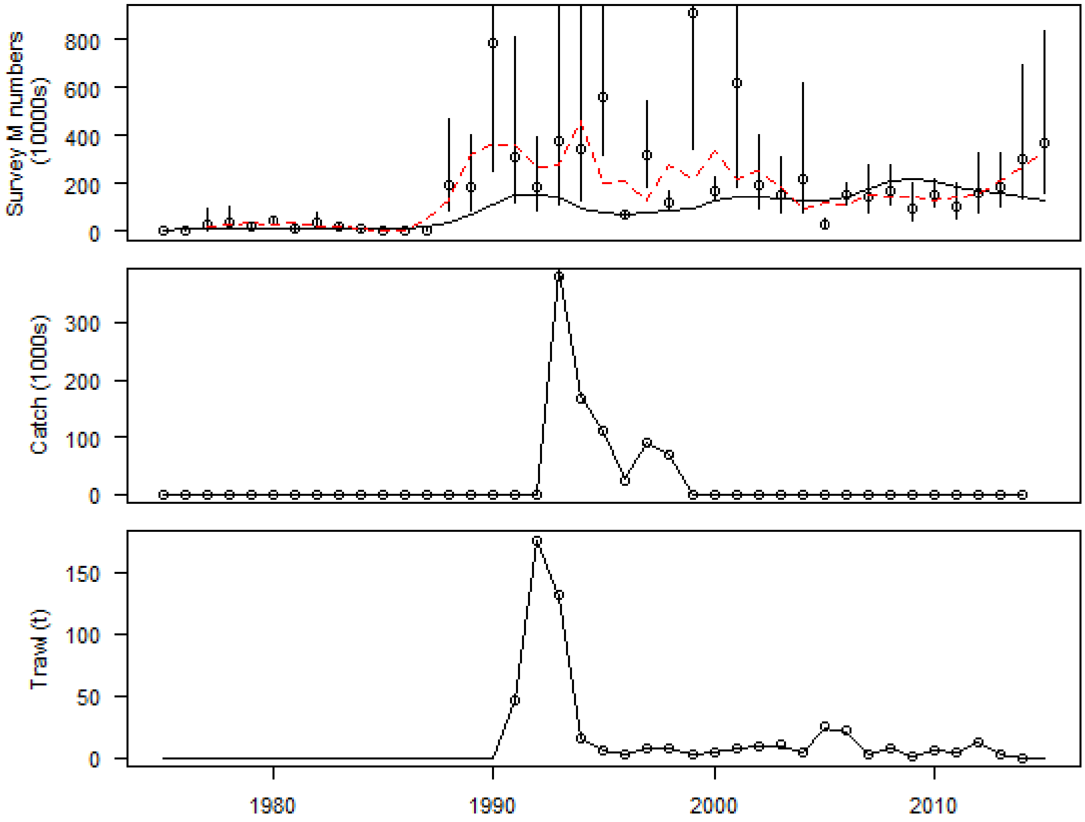

Figure 27. Male only model fits (black line) to observed survey numbers (black dots) with Poisson CIs for males (top row). Model fits (black line) to observed catches in the directed fishery (dots) in numbers caught (2^{rd} row) and bycatch in the non-pelagic trawl fishery (3^{th} row).

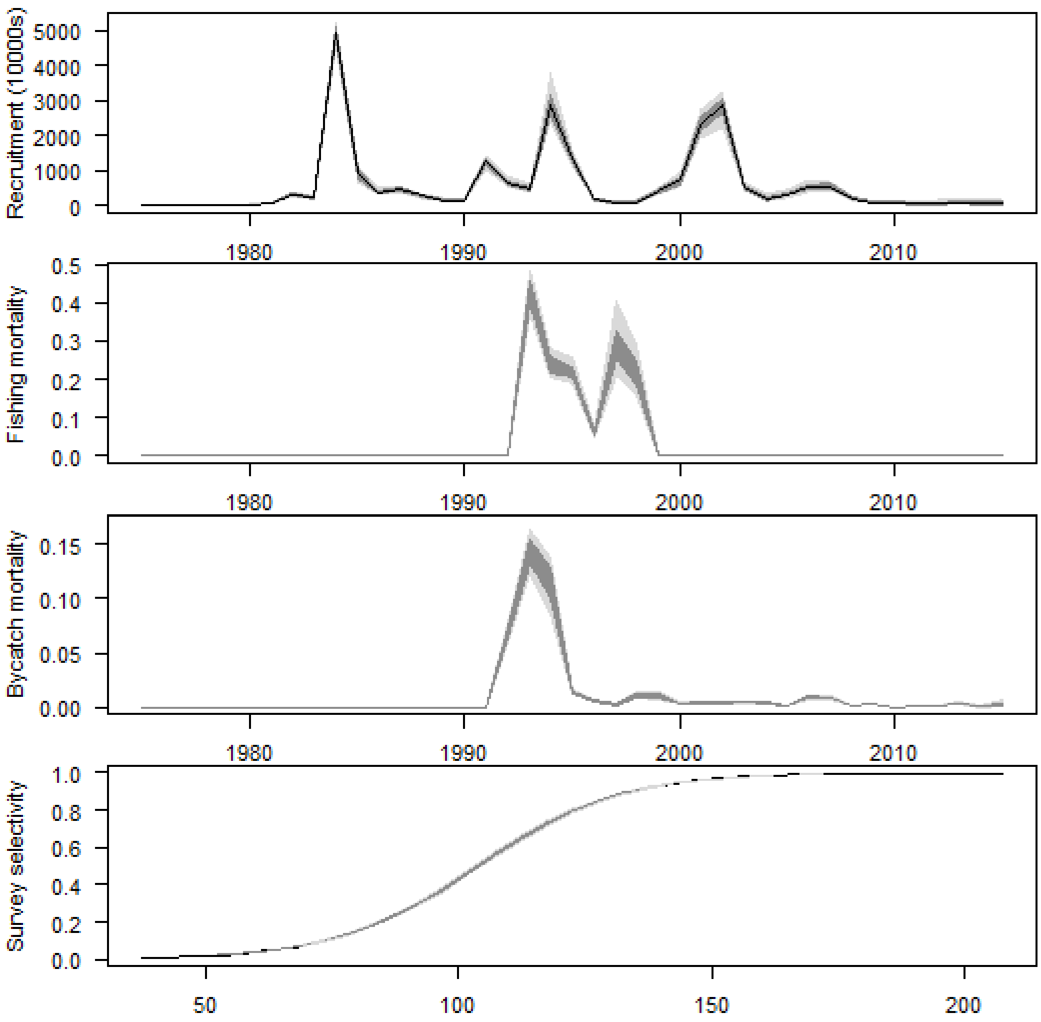

Figure 28. Estimated recruitment (top), fishing mortality in the directed fishery (2nd row), fishing mortality in the non-pelagic trawl (3rd row) and survey selectivity (bottom). Light grey areas indicate the 90% credibility interval and darker grey are the 50% credibility interval. Assessment method uses the 2015 data and fits males.

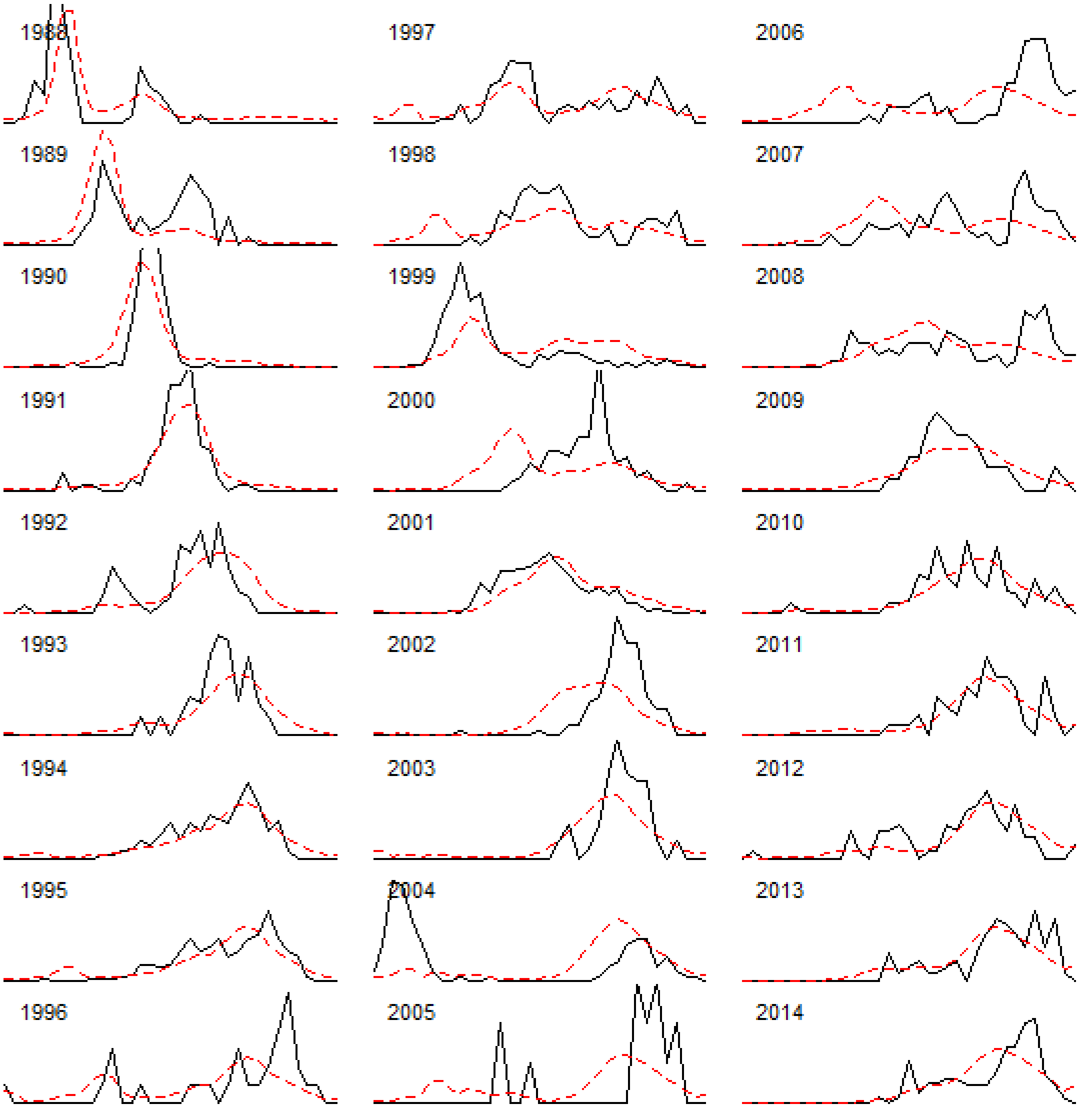

Figure 29. Model fits (red dashed line) to observed male length frequencies in the survey (solid line) by year using 5 mm length bins and fitting only males. Sample size is noted in the top right hand corner of each plot. Length frequencies for the years 1975-1987 are not shown because the associated sample sizes were <=18 and therefore held very little information.

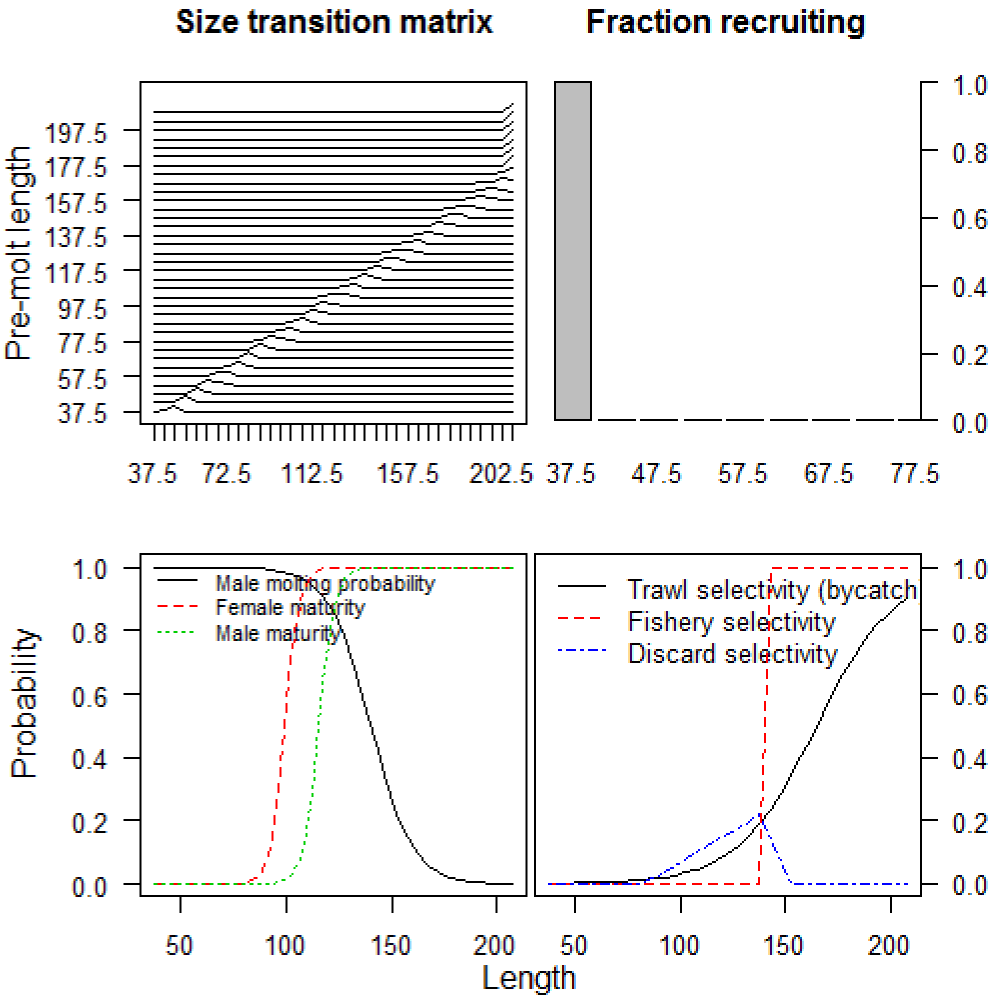

Figure 30. Size transition matrix (topleft), fraction recruiting to a given size class (top right), probability of molting (males only) and maturing (females and males; bottom left), probability of being selected in the directed and trawl fisheries (bottom right). Blue line indicates the discard selectivity from the directed fishery. All from the assessment method fit to both males and females.

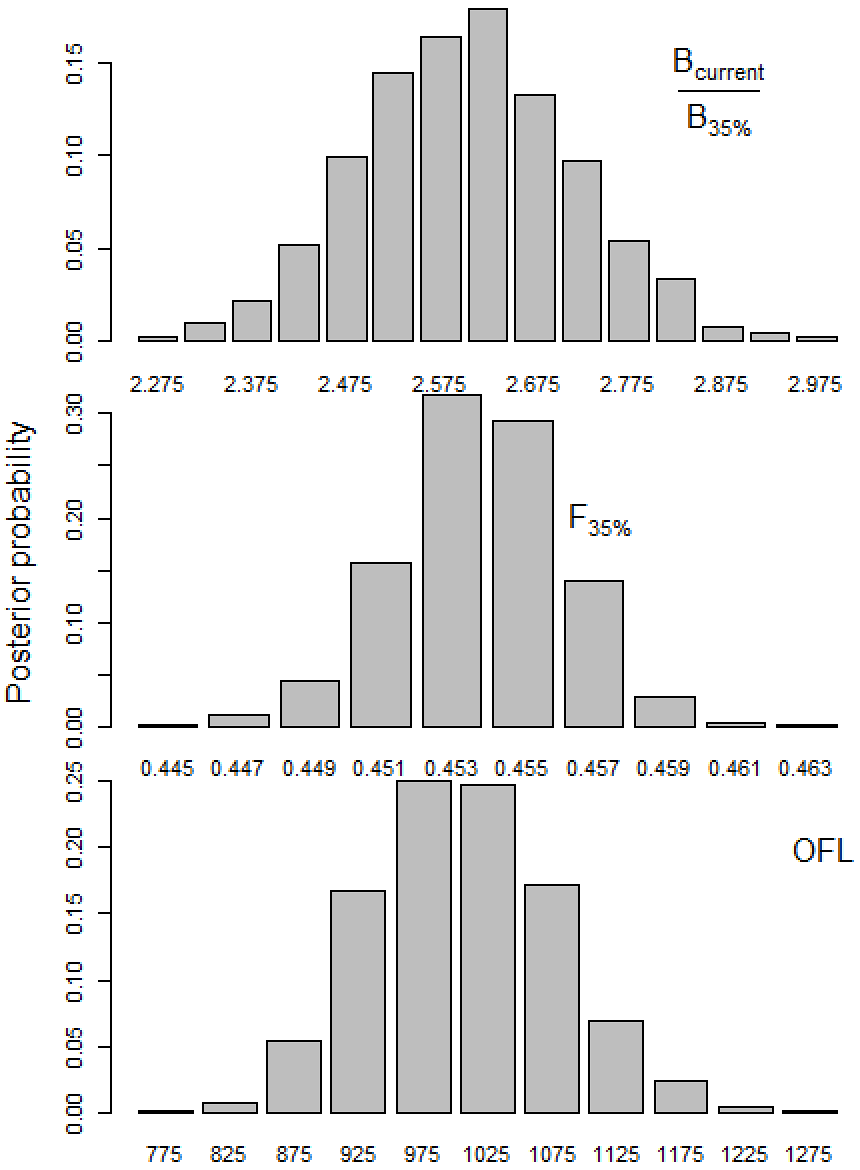

Figure 31. Posterior distributions for the ratio of the current biomass to the target biomass (top), F35% (middle) and the overfishing level (bottom) for an MCMC in which both the male and female 2015 data were fit to.

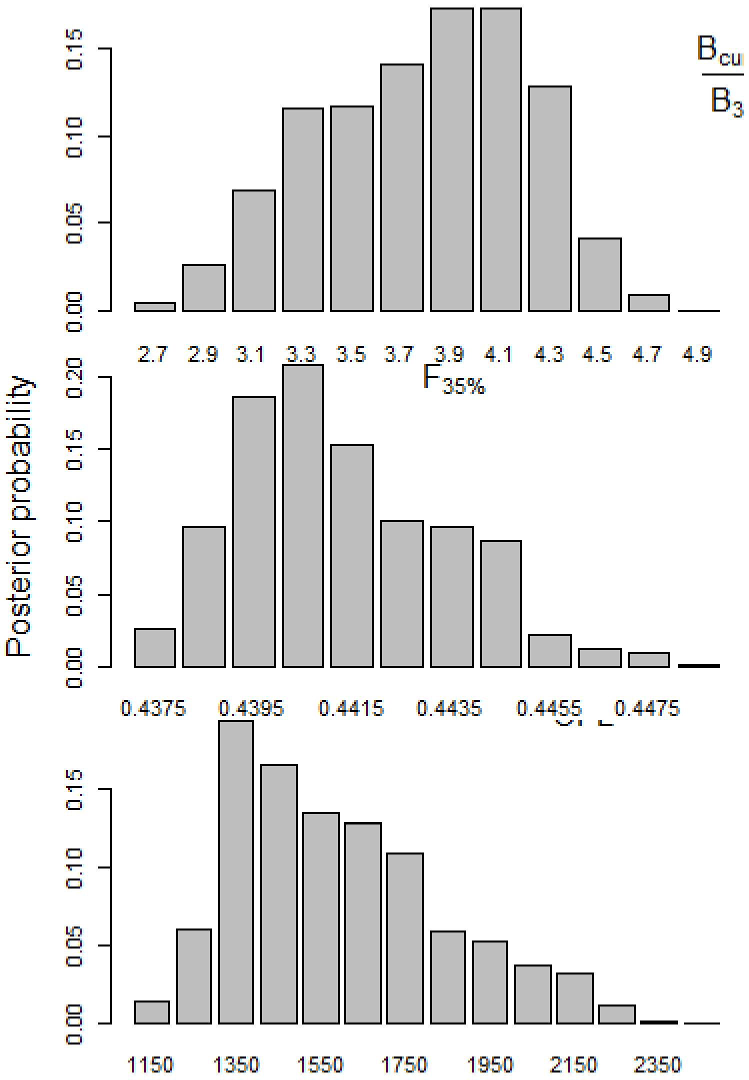

Figure 32. Posterior distributions for the ratio of the current biomass to the target biomass (top), F35% (middle) and the overfishing level (bottom) for an MCMC in which the 2015 data were fit to and only males were fit.

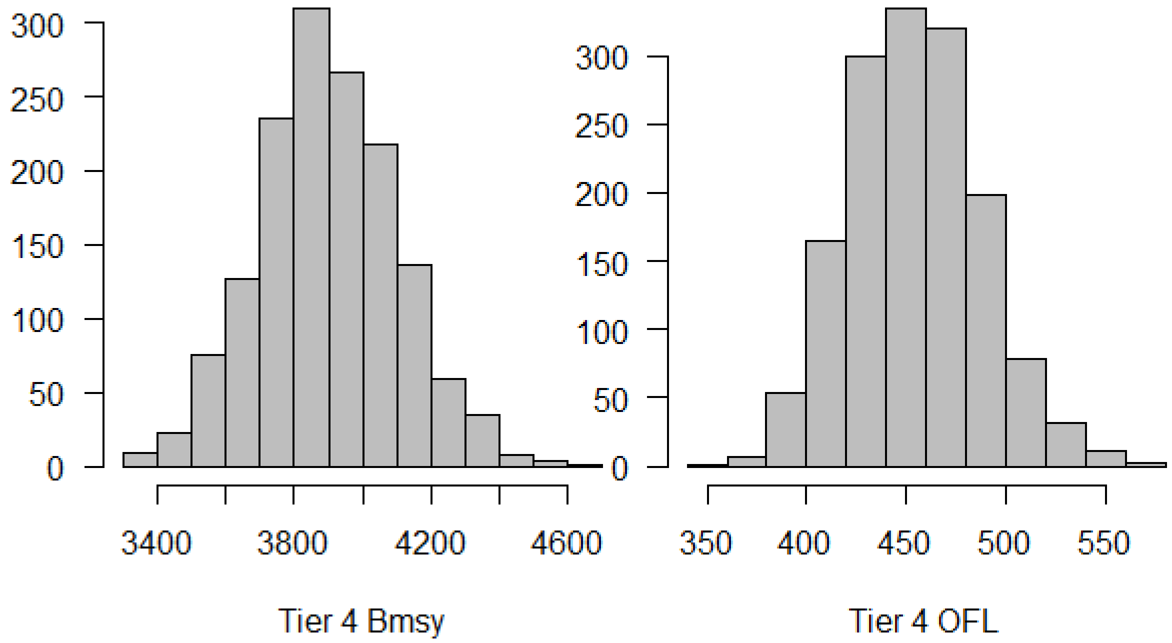

Figure 33. Posterior distribution for Tier 4 BMSY and OFL (in tonnes) from the integrated assessment when both males and females were fit using the 2015 data..

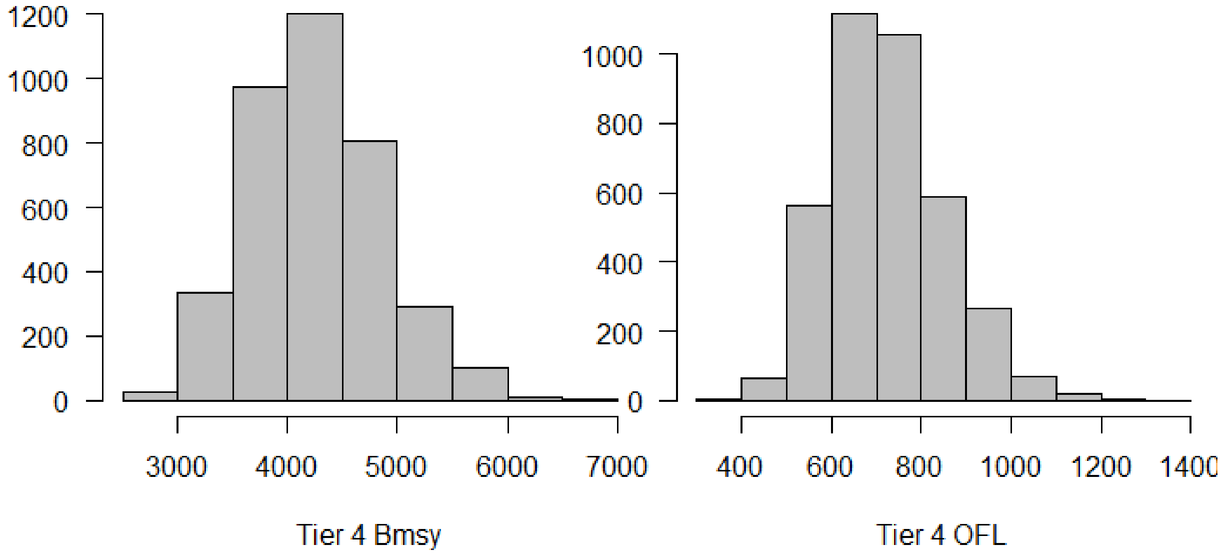

Figure 34. Posterior distribution for Tier 4 BMSY and OFL (in tonnes) from the integrated assessment when only males were fit from the 2015 data..

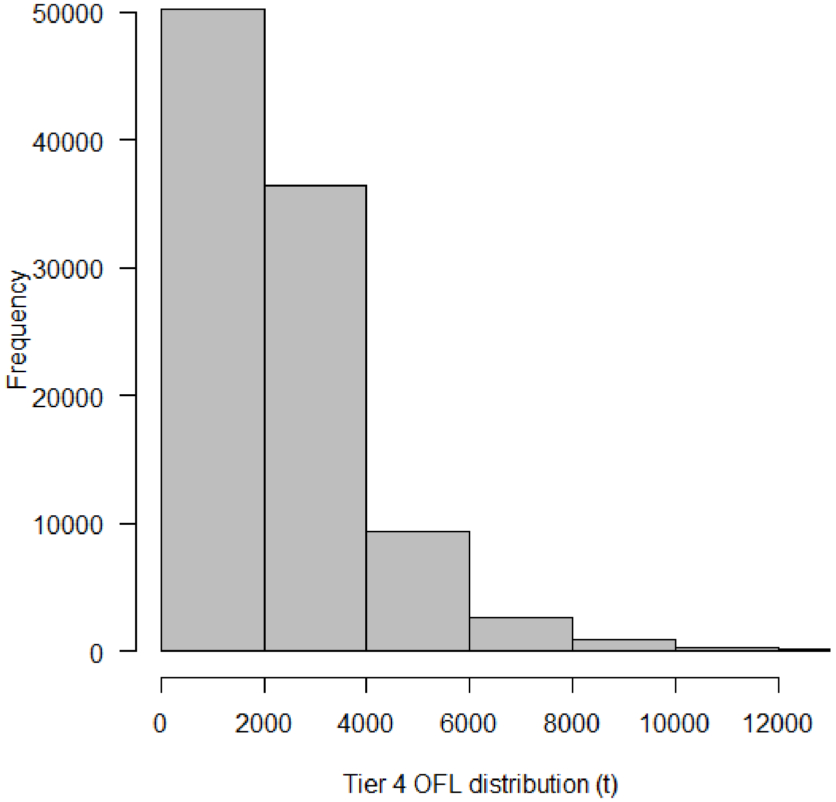

Figure 35. Distribution of tier 4 OFL generated by bootstrapping values of MMB from a 3-year, inverse-variance weighted, running average with an additional sigma of 0.3.

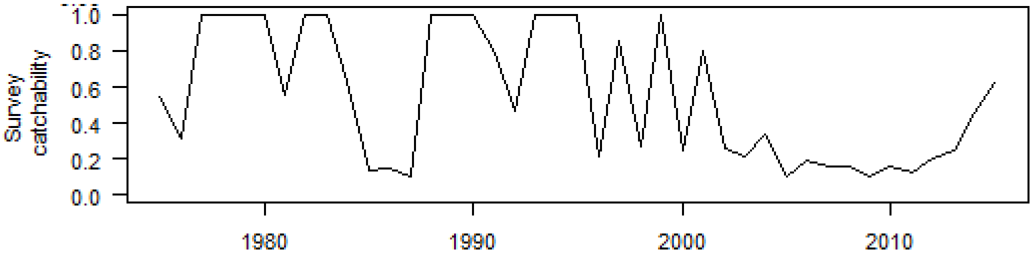

Figure 36. Estimated survey catchability when only males were fit by the integrated assessment method.

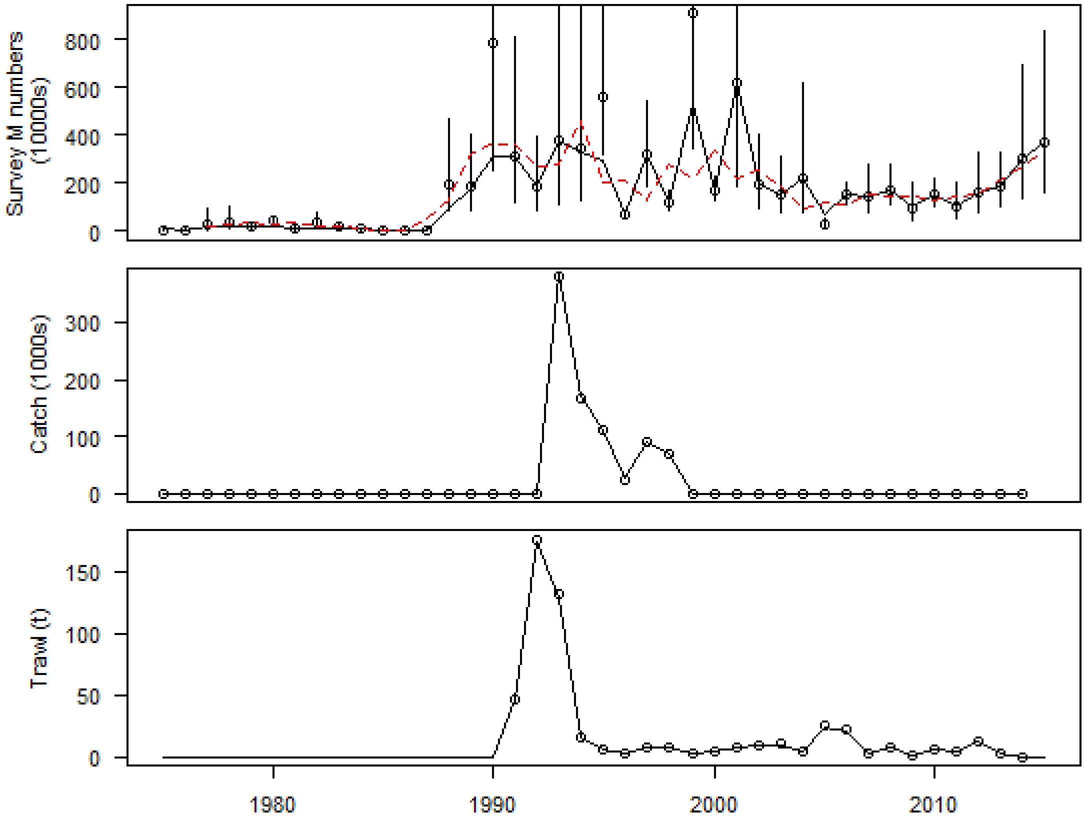

Figure 37. Fits to male numbers with time-varying survey catchabilty.

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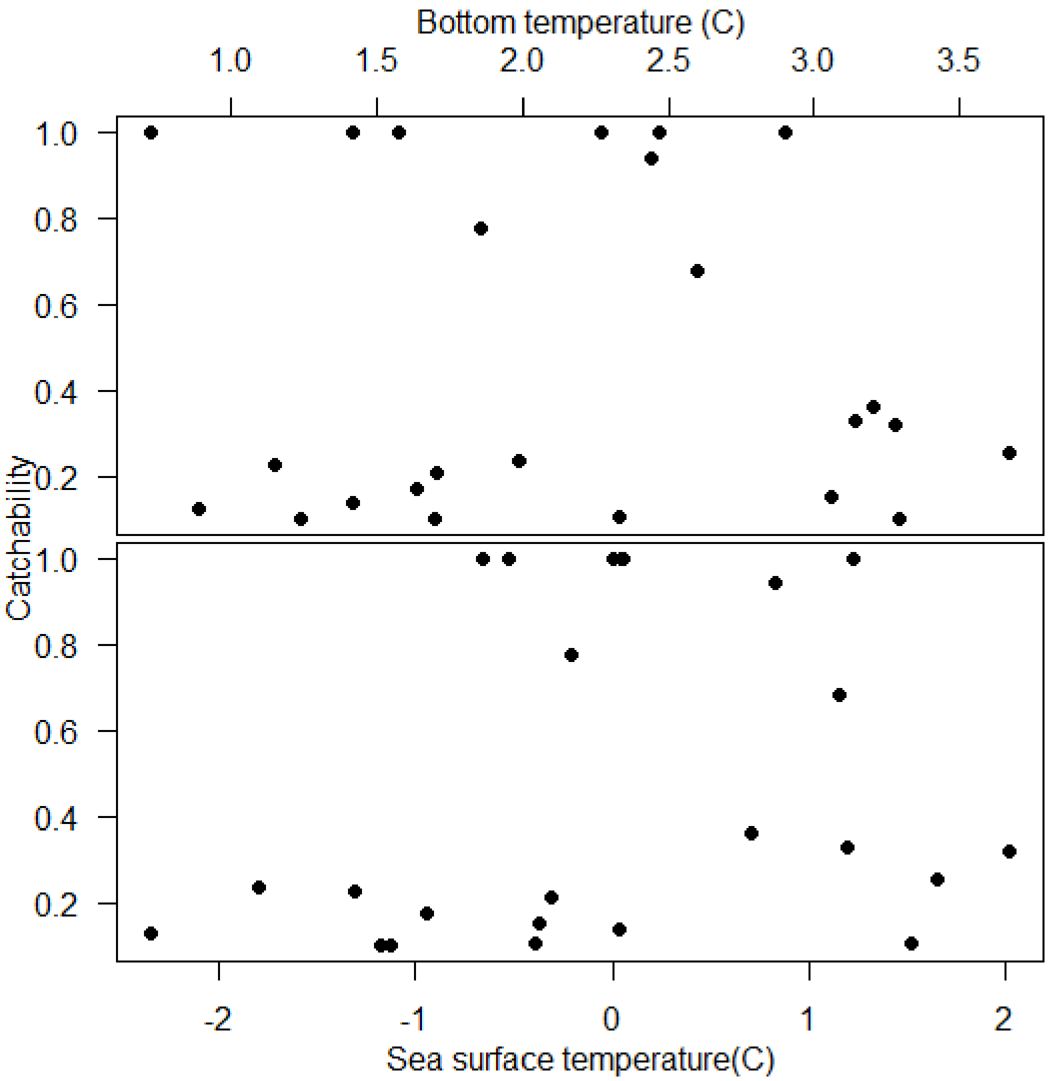

Figure 38. Relationship between estimated yearly catchability for males during the years 1992-2015 and sea surface temperature and bottom temperature around the Pribilof Islands.

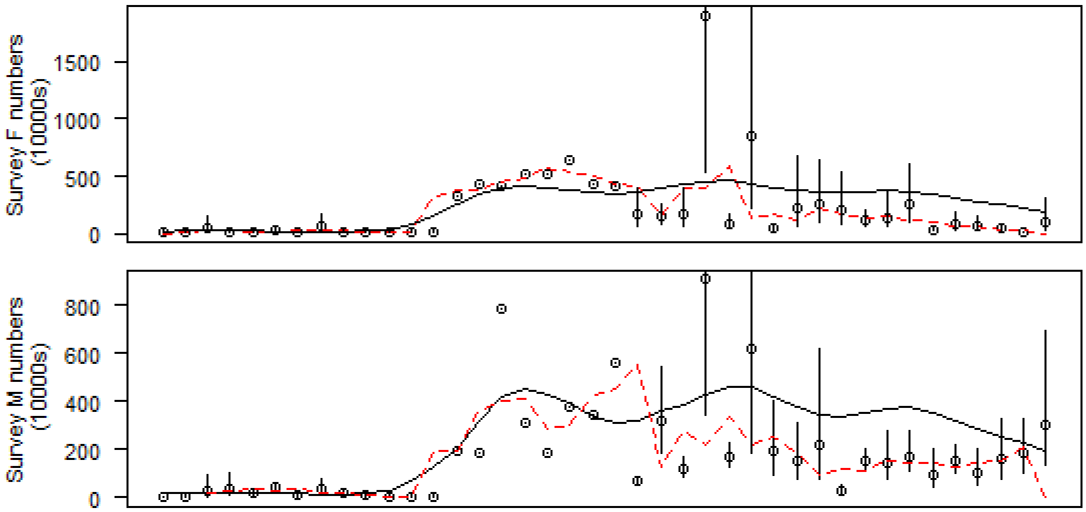

Figure 39. Estimated survey numbers when the CVs for the large numbers estimates in the 1990s are decreased to 0.001.