2014 Stock assessment and fishery evaluation report for the Pribilof Island red king crab fishery of the Bering Sea and Aleutian Islands regions

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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 very 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

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

Unita 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. Basis for 2014/2015 OFL projection:

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	1359	5742	8894	1.55	1.0	1991/1992-2013/2014 (MMB)	0.18	0.49	1338
3	Integrated assessment	801	1034	2239	2.16	1.0	1983-present (recruitment)	0.53	0.49	771
4	Integrated assessment	320	2754	2239	0.81	1.0	1991/1992-2013/2014 (MMB)	0.18	0.49	311

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	3.00	12.66	19.60	1.55	1.0	1991/1992-2013/2014 (MMB)	0.18	0.49	2.95
3	Integrated assessment	1.77	2.28	4.94	2.16	1.0	1983-present (recruitment)	0.53	0.49	1.70
4	Integrated assessment	0.71	6.07	4.94	0.81	1.0	1991/1992-2013/2014 (MMB)	0.18	0.49	0.69

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 49^{th} percentile of the distributions of the OFL given a p-star of 0.49.

Summary of Major Changes:

1. Management: None.
2. Input data: The crab fishery retained, bycatch, and discard catch time series were updated with 2013/2014 data. The survey data were updated with 2014/2015 data. A new methodology for estimating discard catch was used for 2009/10-2013/14 replacing the previous estimates.
3. Assessment methodology: Both a 3-year running average and an integrated assessment were used to estimate mature male biomass and Tier 3 and 4 harvest control rules were compared.
4. Assessment results: Results presented in this assessment differ from the May draft due to changes in the integrated assessment (e.g. estimating growth and changing length frequency likelihoods).

CPT May 2014 Comments specific to PIRKC assessment

Add likelihood profile for survey catchability
Done (Figure 18).

Initialize the model before the first year of data to reduce the number of parameters used
The model was initialized in 1970; the first year of data is 1975.

Consider a more generalized growth model.

The primary impetus behind the suggestion of more generalized model was the use of data from a study that showed large, non-linear changes in growth per molt for females after maturity around Kodiak Island (Stevens and Swiney, 2007b). However, a single cohort that established the commercial population in the 1980s provided an opportunity to estimate growth. There appears to be a linear relationship between pre- and post-molt length for females (Figure 13), so a more complicated model was not used.

Do not calculate likelihood contributions for length-bins with very low frequency (~0)
Done (equation A18).

Explore sensitivities to the size of length bin
The assessment was performed with data files prepared using 10mm length bins. The change in bin size did influence the estimates of some quantities important in management, so this question requires further study.

Include 3-year averages on plots
Done.

Include lognormal confidence intervals for the survey estimates of numbers and biomass
Lognormal confidence intervals back-calculated from the CVs provided by the Kodiak lab (and used in the integrated assessment) were included (Figure 6). Bootstrapped CIs were also included as the author thinks they are a more transparent method for representing the uncertainty around estimates of survey numbers.

Consider ADFG pot survey data and retained catch size frequency data
These data area not yet incorporated (or located).

Include more detail on the model
More details on the model were provided in the appendix and associated tables. The code will be made available on Github.

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

The standard survey time series data updated through 2014 and 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 2013/2014 data. The following sources and years of data are available:

Data source	Years available	Used in integrated assessment?
NMFS trawl survey	1975-2014	Yes
Retained catch	1993-2013	Yes

Trawl bycatch	1991-2013	Yes
Fixed gear bycatch	1991-2013	No
Pot discards	1998-2013	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 50% 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 2014 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 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 5). 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.

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

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 6) and uncertainty around area-swept estimates of abundance are large due to relatively low sample sizes (Figure 5). Male crabs were observed at 4 of 35 stations in the Pribilof District during the 2014 NMFS survey (Figure 7); female crabs were observed at 3 (Figure 8). Two (possibly three) cohorts can be seen moving through the length-classes over time (Figure 9 and Figure 10). Numbers at length vary dramatically from year to year, but the cohorts can nonetheless also be discerned in these data (Figure 11 and Figure 12).

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 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.

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 (Fmsy) 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 (2014), 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 was calculated as:

$$MMB_t^{run} = \frac{\frac{1}{\sigma_{t-1}^2} MMB_{t-1} + \frac{1}{\sigma_t^2} MMB_t + \frac{1}{\sigma_{t+1}^2} MMB_{t+1}}{3} \qquad (4)$$

Where,

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

σ_t^2 is calculated from the CVs of the estimates of MMB from the survey provided by the Kodiak lab as:

$$\sigma_t^2 = \ln(\mu_t^{MMB} * CV_t^{MMB})^2 \qquad (5)$$

Where,

μ_t^{MMB}	estimated mature male biomass from the survey at time t
CV_t^{MMB}	Coefficient of variation associated with the estimate of MMB at time t

3.2.2 Integrated assessment

A length-based integrated assessment method was coded in ADMB (Fournier et al. 2012) to estimate trends in recruitment, fishing mortality (directed and bycatch in the non-pelagic trawl fishery) and mature male biomass (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. Sensitivities to the size of bin with were performed by repeating the analysis with 10 mm length bins. A likelihood profile for survey catchability was performed to explore the influence of fixing survey catchability at 1 on the objective function. 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 10,000,000 cycles of the MCMC algorithm, implementing a 20% burn-in period and saving every 3000th draw for the assessments in which growth was estimated (when growth was fixed, fewer cycles were required). 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. MCMC was performed while estimating all parameters in table A1 and while fixing the parameters associated with growth.

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 over this period should be indicative of the growth per molt and, when translated to growth per molt, were well fit by a linear relationship (Figure 13).

4. Model Selection and Evaluation

Three assessment methods are presented for evaluation: a running average with a tier 4 HCR, an integrated assessment with tier 3 HCR, and an integrated assessment with a tier 4 HCR. This is the first comparison of estimates from an integrated assessment to estimates from a running average model for this stock, so alternative weighting schemes, alternate specifications of non-estimated parameters, or alternative functional forms of population processes were not explored.

There are trade-offs between using the running average method and the integrated assessment to estimated 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. 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 natural mortality) 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 like 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 4071 t; estimates of MMB from a 3-year moving average peaked during 1994 at 18203 t (Figure 14; table 7 and 8). Female mature biomass peaked during 2001 at 1541 t; whereas estimates of FMB from the 3-year moving average peaked during 1994 at 5112 t. Estimated trajectories of the two 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 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 both MMB and FMB do not return to the levels estimated during the early 1990s. The integrated assessment estimated mature male biomass for 2014 at 2239 t; the running average method estimated MMB at 9303 (t).

5.2 Integrated assessment model fits

Estimated male survey numbers peaked during 1991 at 1.49 million, corresponding to an estimated mature male biomass at 3954 t (Figure 14). Estimated female survey numbers peaked during 1992 at 1.22 million, corresponding to an estimated mature female biomass of 1525 t (Figure 14). Catch and bycatch in the non-pelagic trawl fishery are well fit by the assessment method (Figure 15). 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 swings in estimates of abundance were attributable to sampling error, given the few data points available to inform these estimates. This is somewhat corroborated by noting the number of observations available to inform the estimates increases over time (Figure 5) and the extreme estimates of biomass are less often observed after the 2000. The differences in interannual variability of estimates of mature biomass 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 (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 16). Estimated recruitment is very poor during recent years (2003-present) and there does not seem to be a relationship between female mature biomass and recruitment at 4, 5, or 6 year lags (Figure 17). Estimated fishing mortality peaks in 1998 (the last year of the directed fishery) at 0.62, which exceeds the calculated F35% of 0.53. Estimated survey selectivity is gradually increases until ~141 mm length at which point 95% of crab are selected in the survey gear (Figure 16) and survey catchability is fixed at 1. The negative log likelihood decreases as survey catchability (*q*) increases, even beyond a value of 1 (Figure 18). However, catchability higher than 1 is difficult to justify, so fixing *q* at 1 is a reasonable practice here. Fishery selectivity is not estimated as there are no catch at length or discard at length data available.

Two (possibly three) cohorts are seen to move 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 19). During 1999 and 2001, two large peaks in small crab appear but do 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. These data conflicts are not resolved by increasing the size bin to 10mm (see below). 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 are fit better than the male frequencies (table A3, Figure 20), but also display 'disappearing' crab (e.g. the year 2000).

The estimated growth relationships are 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 94.2 mm given estimates from the integrated assessment which is less than Weber's estimates (96m m and 97.5 mm), but corroborates the observation that female growth increment decreases compared to males as size increases. A 50 mm male would molt to 66 mm given the estimates from the assessment and an 80 mm male would molt to 100.2 mm. Posteriors for the growth parameters suggest growth is relatively well estimated (but this is also likely influenced by specifying a constant natural mortality; Figure 21). Estimated variability around the growth curve is larger for males than it is for females (.72 vs. .52) and is apparent in the spread of the length frequencies throughout the 1990s (Figure 19 vs. Figure 20).

Estimates of quantities important in management and model fits were not identical when calculating data inputs to the integrated assessment using 10 mm size bins instead of 5 mm (Table A2). Fits to numbers at length and length frequencies were visually similar (Figure 22 and Figure 23), but estimated MMB for 2014 was 16% higher when using the 10mm data (2239 vs. 2588 t). The direction of change in estimated biomass when aggregating length bins depends on the tradeoff between the rate of increase in the probability of maturity, the relationship between weight and length, and natural mortality. For red king crab, the increase in estimated biomass from 'promoting' smaller crab to a higher probability of maturity due to increasing the length bin size outweighed the decrease in estimated biomass from 'demoting' larger crab to a smaller length bin. Differences in estimated growth may also influence the observed discrepancy between estimates of mature male biomass and this issue should be pursued in future assessments.

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 is calculated by applying a fishing mortality determined by equation 4 to the mature male biomass at the time of fishing.

$$F_{OFL} = \begin{cases} Bycatch\ only & if\ \dfrac{B_{cur}}{B_{MSY\ proxy}} \leq \beta \\ \dfrac{\gamma M \left(\dfrac{B_{cur}}{B_{MSY\ proxy}} - \alpha\right)}{1-\alpha} & if\ \beta < \dfrac{B_{cur}}{B_{MSY\ proxy}} < 1 \\ \gamma M & if\ B_{cur} > B_{MSY\ proxy} \end{cases} \quad (4)$$

Where,

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

The F_{OFL} calculated from equation 4 is 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 $B_{35\%}$ are 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).

$$F_{OFL} = \begin{cases} Bycatch\ only & if\ \dfrac{B_{cur}}{B_{35\%}} \leq \beta \\ \dfrac{F_{35\%} \left(\dfrac{B_{cur}}{B_{35\%}} - \alpha\right)}{1-\alpha} & if\ \beta < \dfrac{B_{cur}}{B_{35\%}} < 1 \\ F_{35\%} & if\ B_{cur} > B_{35\%} \end{cases} \quad (5)$$

Where,

B_{cur}	current estimated mature male biomass
$B_{35\%}$	mature male biomass at the time of mating resulting from fishing at $F_{35\%}$
$F_{35\%}$	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
α	Determines the slope of the descending limb of the HCR (0.05)
β	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) is 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

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 1034 t. The corresponding $F_{35\%}$ is 0.53 and, given a ratio of the current biomass to $B_{35\%}$ of 2.16, the calculated F_{OFL} is also 0.54 which results in an OFL of 801 t. $F_{35\%}$ is relatively high compared to natural mortality because a large fraction of MMB is protected by the 138mm size limit.

The traces of the MCMCs performed when growth was estimated were highly autocorrelated, but stationary when thinned sufficiently. Thinning is often used to reduce autocorrelation, but provided the trace is stationary and chains are long, the utility of thinning is debated in the literature (Link and Eaton, 2011). Given this debate, the posteriors derived from the unthinned chains are shown here. Fixing growth at the estimated values and rerunning the MCMC improved mixing and produced more normally distributed and narrow posteriors.

The 90% credibility interval of the posterior distribution of $B_{current}/B_{35\%}$ when growth was estimated ranged from 1.81 to 2.47; the 90% credibility interval for the posterior for $F_{35\%}$ ranged from .522 to .539; and the 90% credibility interval for the OFL ranged from 640 to 1016 t (Figure 24). The 90% credibility interval of the posterior distribution of $B_{current}/B_{35\%}$ when growth was fixed ranged from 2.08 to 2.72; the 90% credibility interval for the posterior for $F_{35\%}$ ranged from .529 to .531; and the 90% credibility interval for the OFL ranged from 636 to 997 t (Figure 25).

Management quantities calculated using 10mm length bins (and estimating growth) differed slightly from the management quantities using 5 mm length bins (Figure 26). $B_{35\%}$ was calculated as 952 t. The corresponding $F_{35\%}$ is 0.56 and, given a ratio of the current biomass to $B_{35\%}$ of 2.72, the calculated F_{OFL} is also 0.56, which resulted in an OFL of 948 t. The 90% credibility interval of the posterior distribution of $B_{current}/B_{35\%}$ ranged from 2.50 to 3.31; the 90% credibility interval for the posterior for $F_{35\%}$ ranged from .547 to .560; and the 90% credibility interval for the OFL ranged from 800 to 1273 t (Figure 26).

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. When estimating growth, B_{MSY} (based on the MMB over the years 1991-present) was calculated as 2754 t. F_{MSY} was set equal to natural mortality (0.18) and the resulting OFL was 320 t. The 90% credibility interval of the posterior distribution of B_{MSY} for the tier 4 control rule ranged from 2268 to 3435 t, and the 90% credibility interval for the OFL ranged from 256 to 404 t (Figure 27). When not estimating growth, B_{MSY} and the OFL were identical, but the posteriors narrowed and appeared more normally distributed. The 90% credibility interval of the posterior distribution of B_{MSY} for the tier 4 control rule ranged from 2344 to 3327 t, and the 90% credibility interval for the OFL ranged from 256 to 398 t (Figure 28). Tier 4 management quantities were not calculated using 10mm length bins.

B_{MSY} and current MMB calculated from the 3-year running averages were substantially higher than the estimates from the integrated assessment (5742 and 8894 t, respectively). Consequently, the calculated OFL was also much higher—1359 t. The 90^{th} quantiles of the bootstrapped distribution for the OFL ranged from 464 to 3978 t (Figure 29).

5.5 Recommended ABCs

Based on the distributions of the OFL calculated using the running-average method and a p-star of 0.49, the ABC for the tier 4 HCR is 1338 t. The ABC for the tier 4 HCR using the posterior of the OFL from the integrated assessment and a p-star of 0.49 is 311 t; the ABC for the tier 3 HCR is 771 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 is relatively high due to small sample sizes. The coefficient of variation for the estimate of male abundance for the most recent year is 0.78 and has ranged between 0.36 and 0.79 since the 1991 peak in numbers. Growth and survey selectivity are 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} is assumed to be equal to natural mortality and B_{MSY} is somewhat arbitrarily set to the average MMB over a predetermined range of years for tier 4 HCRs; both of which are assumptions that have 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.

Retrospective analyses and simulation testing 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 this year 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.

7. Data gaps and research priorities

Catch-at-length data for the fishery would allow fishery selectivity to be estimated and discards to be incorporated into the model. Further research on the impact of different size bins is warranted given the impact of changing the bin size on management quantities. 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).

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).

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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:

$$N_{s,y,l} = N_{s,y,l}e^{-3M/12} \tag{A1}$$

where $N_{s,y,l}$ 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.

$$N_{s,y,l} = N_{s,y,l}e^{-(F_{dir,y,l}+F_{trawl,y,l})} \tag{A2}$$

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

$$N_{s,y,l} = \begin{cases} \Omega_l N_{s,y,l} \mathrm{X}_{l,l'} \\ (1-\Omega_l)N_{s,y,l} + Pr_l R_y \end{cases} \tag{A3}$$

Where Ω_l is the probability of an animal molting at length l, $N_{s,y,l}$, is the number of animals in sex s in length-class l at time step y, $X_{l,l'}$ 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:

$$N_{s,y+1,l} = N_{s,y,l}e^{-4M/12} \tag{A4}$$

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 30). Fishing mortality is calculated by:

$$F_{dir,y,l} = S_{l,dir}e^{\overline{F_{dir}}+n_y} \tag{A5}$$

where $S_{l,dir}$ is the selectivity of the fishery on animals in length-class l, $\overline{F_{dir}}$ is the average (over time) ln-scale fully-selected fishing mortality, and n_y 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:

$$S_{l,dir} = \left(1+\exp\left(-\frac{\log(19)\left(\bar{L}_l - L_{50,dir}\right)}{L_{95,dir} - L_{50,dir}}\right)\right)^{-1} \tag{A6}$$

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

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:

$$F_{trawl,y,l} = S_{l,trawl}e^{\overline{F_{trawl}}+n_y} \tag{A7}$$

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

$$S_{l,trawl} = \left(1+\exp\left(-\frac{\log(19)\left(\bar{L}_l - L_{50,trawl}\right)}{L_{95,trawl} - L_{50,trawl}}\right)\right)^{-1} \tag{A8}$$

where $L_{50,trawl}$ is the length at which 50% of animals are selected, $\bar{L}_l$ is the midpoint of length-class l, and $L_{95,trawl}$ 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 30).

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

$$S_{l,surv} = Surv_q * \left(1+\exp\left(-\frac{\log(19)\left(\bar{L}_l - L_{50,surv}\right)}{L_{95,surv} - L_{50,surv}}\right)\right)^{-1} \tag{A9}$$

where $Surv_q$, is the catchability coefficient for the survey gear, $L_{50,\text{surv}}$ is the length at which 50% of animals are selected, $\bar{L}_l$ is the midpoint of length-class *l*, and $L_{95,\text{surv}}$ is the length at which 95% of animals are selected. Survey selectivity parameters are estimated, except for $Surv_q$, which is fixed to a value of 1.

Survey numbers at length
The model prediction of the number of male crab at length at the time of the survey, $\hat{N}^{surv}_{s,y,l}$, is given by:

$$\hat{N}^{surv}_{s,y,l} = S_{l,surv} N_{s,y,l} \tag{A10}$$

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

$$\hat{C}^{dir}_{y,l} = S_{l,dir} N_{s,y=fishtime,l}(1 - e^{-F_{y,l}}) \tag{A11}$$

where $\hat{C}^{dir}_{y,l}$ 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 Wendel (1969) such that the probability of molting is 1 until approximately the age of maturity at which time it steadily declines (Figure 30):

$$P_l = 1 - \left(1 + \exp\left(-\frac{\log(19)\left(\bar{L}_l - L_{50,molt}\right)}{L_{95,molt} - L_{50,molt}}\right)\right)^{-1} \tag{A12}$$

where $L_{50,\text{molt}}$ is the length at which 50% of animals molt, and $L_{95,\text{molt}}$ 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.:

$$X_{l,l'} = Y_{l,l'} / \sum_{l'} Y_{l,l'} \tag{A13}$$

$$Y_{l,l'} = (\Delta_{l,l'})^{(L_l - (\bar{L}_l - 2.5))/\beta} e^{-\Delta_{l,l'}/\beta} \tag{A14}$$

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

$$L_l = \delta_1 + \delta_2 \bar{L}_l \tag{A15}$$

δ_1, δ_2 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*:

$$\Delta_{l,l'} = \bar{L}_{l'} + 2.5 - \bar{L}_l \tag{A16}$$

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 30.

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

$$Pr_l = (\Delta_{l,l'})^{\mu_1/\mu_2} e^{-\Delta_{l,l'}/\mu_2} / \sum_{l'} (\Delta_{l,l'})^{\mu_1/\mu_2} e^{-\Delta_{l,l'}/\mu_2} \tag{A17}$$

Where μ_1 and μ_2 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 such that all recruitment enters the model in the first size bin (Figure 31).

Likelihood components

The model is fit to survey length frequencies (L1, A18), a survey index of abundance (L2, A19), directed catch (L3, A20) and non-pelagic trawl bycatch (L4, A21).

$$L_1 = \begin{cases} \sum_s \sum_y \sum_l -\gamma_y p^{obs}_{surv,l,y,s} \ln\left(p^{pred}_{surv,l,y,s} + \kappa\right) & if\ \ p^{obs}_{surv,l,y,s} \geq 0.01 \\ 0 & if\ \ p^{obs}_{surv,l,y,s} < 0.01 \end{cases} \quad \text{(A18)}$$

where L_1 is the contribution to the objective function of the fit to survey length frequencies; γ_y is the sample size for year *y*, $p^{pred}_{surv,l,y,s}$ is the model-estimate of the length-frequency for sex *s* for length-class *l* in year *y*; $p^{obs}_{surv,l,y,s}$ 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.

$$L_2 = \sum_s \sum_y \frac{\left(\ln\left(N^{pred}_{y,s} + \kappa\right) - \ln\left(N^{obs}_{y,s} + \kappa\right)\right)^2}{\sqrt{\ln\left(CV_{y,s}\right)^2 + 1}} \quad \text{(A19)}$$

where $N^{pred}_{y,s}$ is the model-estimate of the number of crab of sex *s* caught in the survey in during year *y*, $N^{obs}_{y,s}$ 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 $N^{obs}_{y,s}$. 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

$$L_3 = \sum_y \frac{\left(\ln\left(C^{pred}_y + \kappa\right) - \ln\left(C^{obs}_y + \kappa\right)\right)^2}{\sqrt{\ln\left(CV_y{}^{cat}\right)^2 + 1}} \quad \text{(A20)}$$

where C^{pred}_y is the catch in numbers predicted by the model for year *y*, C^{obs}_y is the observed catch in numbers for year *y*, $CV_y{}^{cat}$ 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).

$$L_3 = \sum_y \frac{\left(\ln\left(\sum_s byC^{pred}_{y,s} + \kappa\right) - \ln\left(byC^{obs}_{y,s} + \kappa\right)\right)^2}{\sqrt{\ln\left(CV_y{}^{bycatch}\right)^2 + 1}} \quad \text{(A21)}$$

where $byC^{pred}_{y,s}$ is the bycatch in tonnes of sex *s* from the non-pelagic trawl fishery predicted by the model for year *y*, byC^{obs}_y is the observed bycatch in tonnes for during year *y*, $CV_y{}^{bycatch}$ 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:

$$P_2 = \gamma_w \sum_l (\ln(\eta_l) - \ln(\eta_{l-1}))\ \hat{}\ 2 \quad \text{(A22)}$$

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 2013/2014	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**

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

Table 5. 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	10
1976/1977	50778	162	80
1977/1978	228477	253	120
1978/1979	367140	1228	42
1979/1980	279707	859	76
1980/1981	400513	1317	195
1981/1982	80928	299	97
1982/1983	352166	1458	673
1983/1984	144735	544	216
1984/1985	64331	261	67
1985/1986	16823	60	0
1986/1987	38419	135	57
1987/1988	18611	53	25
1988/1989	1963775	797	732
1989/1990	1844076	2154	1846
1990/1991	6354076	6815	1775
1991/1992	3100675	4959	3860
1992/1993	1861538	3505	2612
1993/1994	3787997	9962	4837
1994/1995	3669755	9600	3397
1995/1996	7693368	24854	6199
1996/1997	683611	2389	1456
1997/1998	3155556	7528	1442
1998/1999	1192015	2688	1262
1999/2000	9102898	8682	4762
2000/2001	1674067	4393	734
2001/2002	6157584	10714	4333
2002/2003	1910263	6923	571
2003/2004	1506201	5280	1644
2004/2005	2196795	3710	983
2005/2006	302997	1272	2207
2006/2007	1459278	6859	1406
2007/2008	1883489	7378	2534
2008/2009	1721467	5698	2099
2009/2010	923133	2498	546
2010/2011	927825	3137	468
2011/2012	1052228	3878	817
2012/2013	1609444	4813	663
2013/2014	1831377	7854	169
2014/2015	3036807	12129	1093

Table 6. 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 with no running average.

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	0.76
1977/1978	1.00	1.00	1.00
1978/1979	0.83	0.83	1.00
1979/1980	0.37	0.39	0.72
1980/1981	0.47	0.52	0.64
1981/1982	0.57	0.58	0.78
1982/1983	0.70	0.70	0.76
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	0.65
1989/1990	0.69	0.77	0.69
1990/1991	0.87	0.88	0.69
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	0.75	0.74	0.76
1995/1996	0.42	0.43	0.51
1996/1997	0.37	0.37	0.74
1997/1998	0.56	0.54	0.57
1998/1999	0.42	0.37	0.76
1999/2000	0.79	0.58	0.86
2000/2001	0.40	0.38	0.63
2001/2002	0.90	0.83	0.99
2002/2003	0.67	0.69	0.51
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	0.37	0.36	0.61
2007/2008	0.47	0.40	0.52
2008/2009	0.52	0.50	0.70
2009/2010	0.70	0.64	0.55
2010/2011	0.37	0.38	0.41
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

Table 7. Estimated recruitment (numbers), female mature biomass (t), male mature biomass (t), total female abundance and total male abundance (1000s) from the integrated assessment method with 5 mm length bins and estimated growth.

Year	Recruitment	FMB (t)	MMB (t)	Female abundance	Male abundance
1975	7526	67	119	62	64.7
1976	5610	101	210	83.1	93.1
1977	4906	124	304	97	114.1
1978	3989	130	349	101	118.4
1979	3651	127	351	97.1	109.8
1980	5091	121	331	88.8	96.8
1981	12099	112	303	79.1	83.9
1982	62349	103	272	69.4	72.5
1983	262232	93	241	61	62.9
1984	107431	84	213	56.2	56.9
1985	3913786	77	189	58.1	55.4
1986	549495	82	176	96.1	89
1987	160787	120	208	194.4	157.4
1988	165716	236	344	405.8	317.5
1989	116638	780	749	725.9	667.1
1990	56976	1354	2766	1032.4	1195.6
1991	71925	1532	3954	1203.3	1488.3
1992	896675	1525	4071	1221.6	1427.1
1993	478441	1412	2457	1145.2	1239.7
1994	331502	1246	1722	1017.6	725.1
1995	2169231	1000	1192	901.7	523
1996	801165	983	1091	799.4	468.4
1997	49808	807	1103	830.8	588.5
1998	23719	764	1259	806.8	675.4
1999	37128	1085	1704	909.7	833
2000	173801	1432	2872	1081	1129.8
2001	309382	1541	3706	1154.1	1291.1
2002	1028556	1493	3837	1125.3	1229.3
2003	538631	1398	3613	1046.1	1086.2
2004	237795	1312	3293	971.1	962.8
2005	98802	1266	3014	938.5	903.5
2006	90511	1328	2911	950.6	924.4
2007	146090	1420	3211	976.2	1009.1
2008	131534	1426	3448	976.4	1056.6
2009	32195	1361	3440	935.2	1011.6
2010	17845	1263	3241	866.5	917.1
2011	14552	1169	2976	787.5	816.5
2012	13463	1080	2723	708.1	729.7
2013	13053	985	2495	628.5	648.6
2014	12925	881	2239	550.9	566.7

Table 8. Estimates of female and male abundance (1000s individuals) and female and male biomass (t) from a 3-year running average.

Year	Female abundance	Male abundance	Female biomass	Male biomass
1977	106	203	72	420
1978	95	281	71	756
1979	100	325	106	1035
1980	103	249	121	798
1981	192	246	252	879
1982	180	155	251	592
1983	140	143	196	555
1984	94	82	128	305
1985	47	44	59	171
1986	39	26	33	89
1987	408	489	108	101
1988	1112	1009	430	317
1989	2495	3107	1220	651
1990	3374	3859	2355	2192
1991	3460	3412	2769	2863
1992	4231	2551	3847	4682
1993	3639	2704	3714	5992
1994	4622	6080	5112	18203
1995	3549	2906	4053	8991
1996	2694	2867	3102	8503
1997	1205	1211	1394	2752
1998	3518	2779	1592	3439
1999	3224	2298	1253	3413
2000	4071	3730	1677	5018
2001	879	2310	951	5280
2002	1020	2820	1169	6643
2003	1029	1907	803	4990
2004	1520	1205	1277	2946
2005	1354	1285	1267	4489
2006	1320	1329	2055	5579
2007	1420	1667	2032	6598
2008	1061	1615	1522	5557
2009	477	1138	701	3579
2010	315	951	543	3102
2011	351	1112	576	3568
2012	275	1498	454	5236
2013	260	1966	453	7092
2014	152	2267	328	9303

Table A1. List of estimated and fixed parameters.

Fixed parameters (11)	Number
Natural mortality	1
Molting probability	3
Fishery selectivity	2
Weight	4
Survey catchability	1
Estimated parameters (86)	
Growth	6
Proportion recruiting	2
Log recruitment deviations	45
Log average fishing mortality (directed)	1
Log fishing mortality deviations (directed)	6
Log average fishing mortality (trawl)	1
Log fishing mortality deviations (trawl)	23
Survey selectivity	2

Table A2. List of estimated parameter values for models using 5 and 10 mm length bins.

Parameter	5 mm	10 mm
srv_q	1	1
fish_sel50	138	138
fish_sel95	138.05	138.05
srv_sel50	102.15	106.86
srv_sel95	141.06	155.6
log_avg_fmort_dir	-0.98	-0.89
log_avg_fmort_trawl	-4.88	-4.69
mean_log_rec	11.21	11.56
A_f (growth)	25.42	19.95
A_m (growth)	9.77	6.79
B_f (growth)	0.86	0.9
B_m (growth)	1.13	1.14
growth_beta_males	0.72	1.04
alpha_rec	0.86	1.6
beta_rec	0.16	0.37

Table A3. Likelihood component contribution to the likelihood and associated weights.

Likelihood component	negLogLike	Weighting
Survey numbers (males)	63.5	.36 -1 (CVs)
Survey numbers (females)	46.6	.36-1 (CVs)
Survey length frequencies (male)	7943.0	18-200 (sample size)
Survey length frequencies (female)	5032.2	18-200 (sample size)
Catch	2.2	.005(CV)
Trawl	0.97	.05 (CV)

Smoothness penalties		
Trawl fishing mortality	26.7	1 (CV)
Fishing mortality	4.4	1 (CV)
Recruitment	57.2	1 (CV)

10. Figures

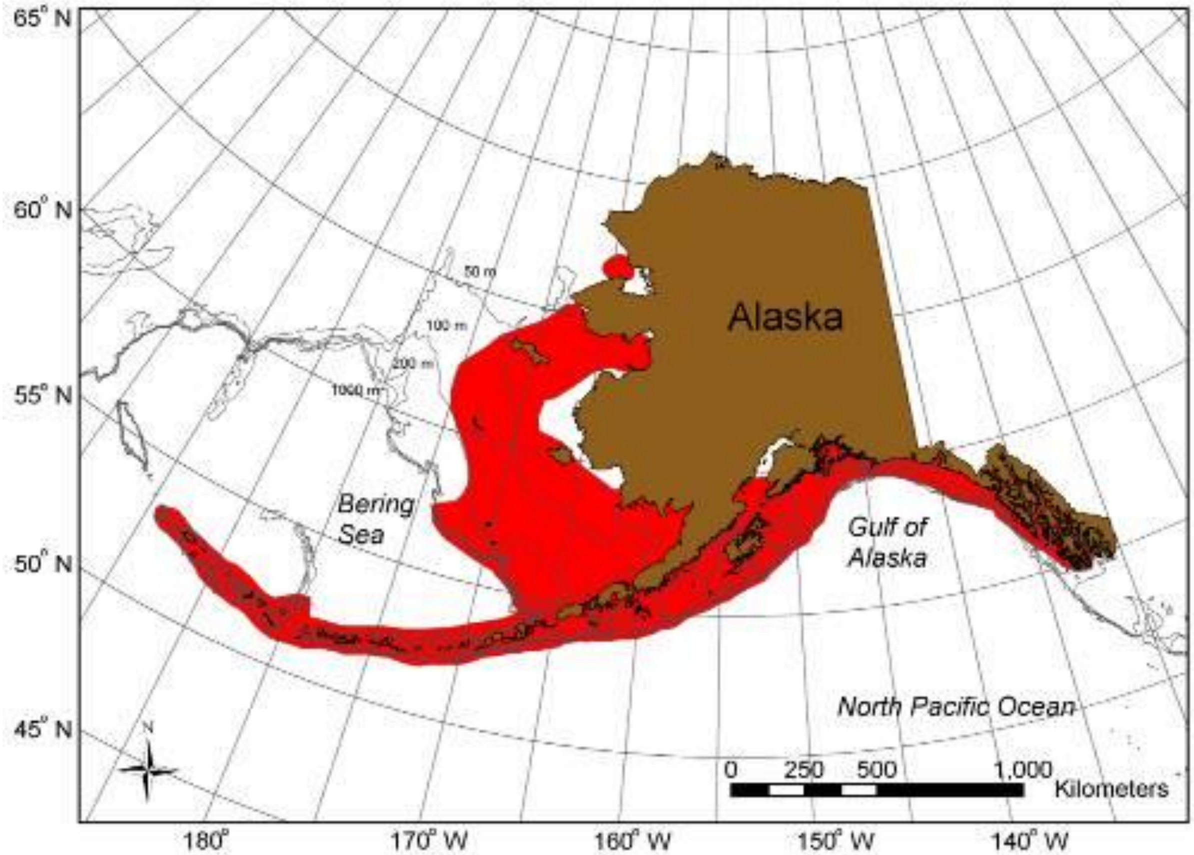

Figure 1. Red king crab distribution.

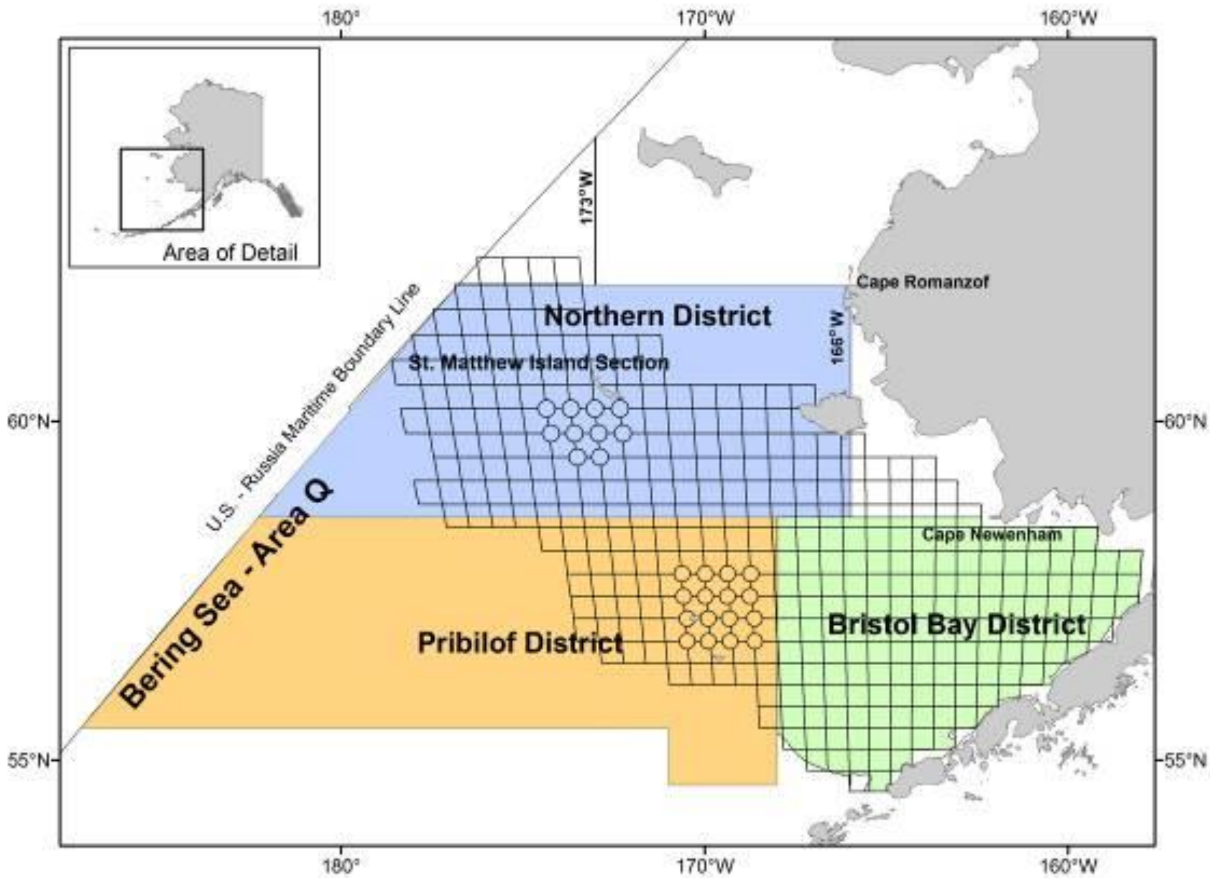

Figure 2. King crab registration area Q (Bering Sea) showing the Pribilof District.

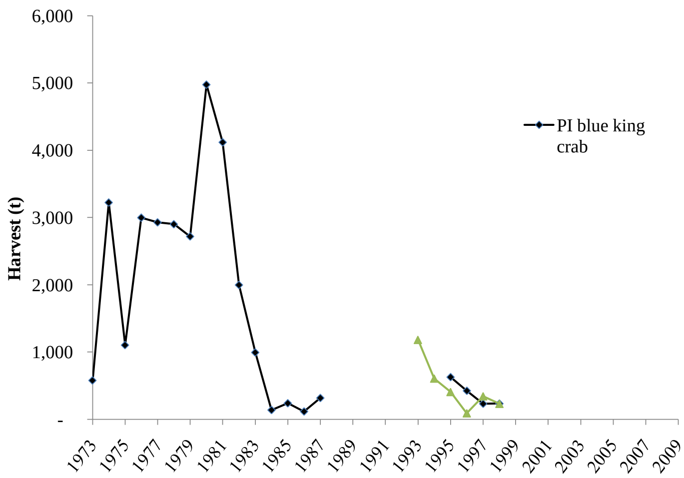

Figure 3. Historical harvests and GHLs for Pribilof Island blue (diamonds) and red king crab (triangles) (Bowers et al. 2011).

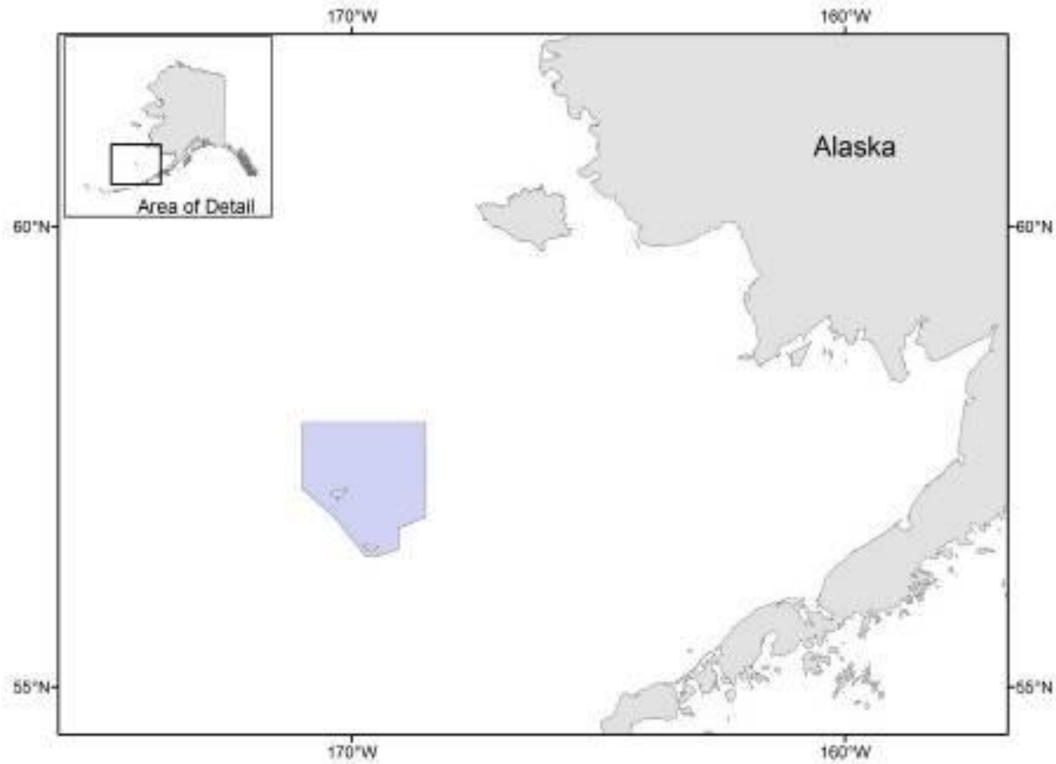

Figure 4. The shaded area shows the Pribilof Islands Habitat Conservation area.

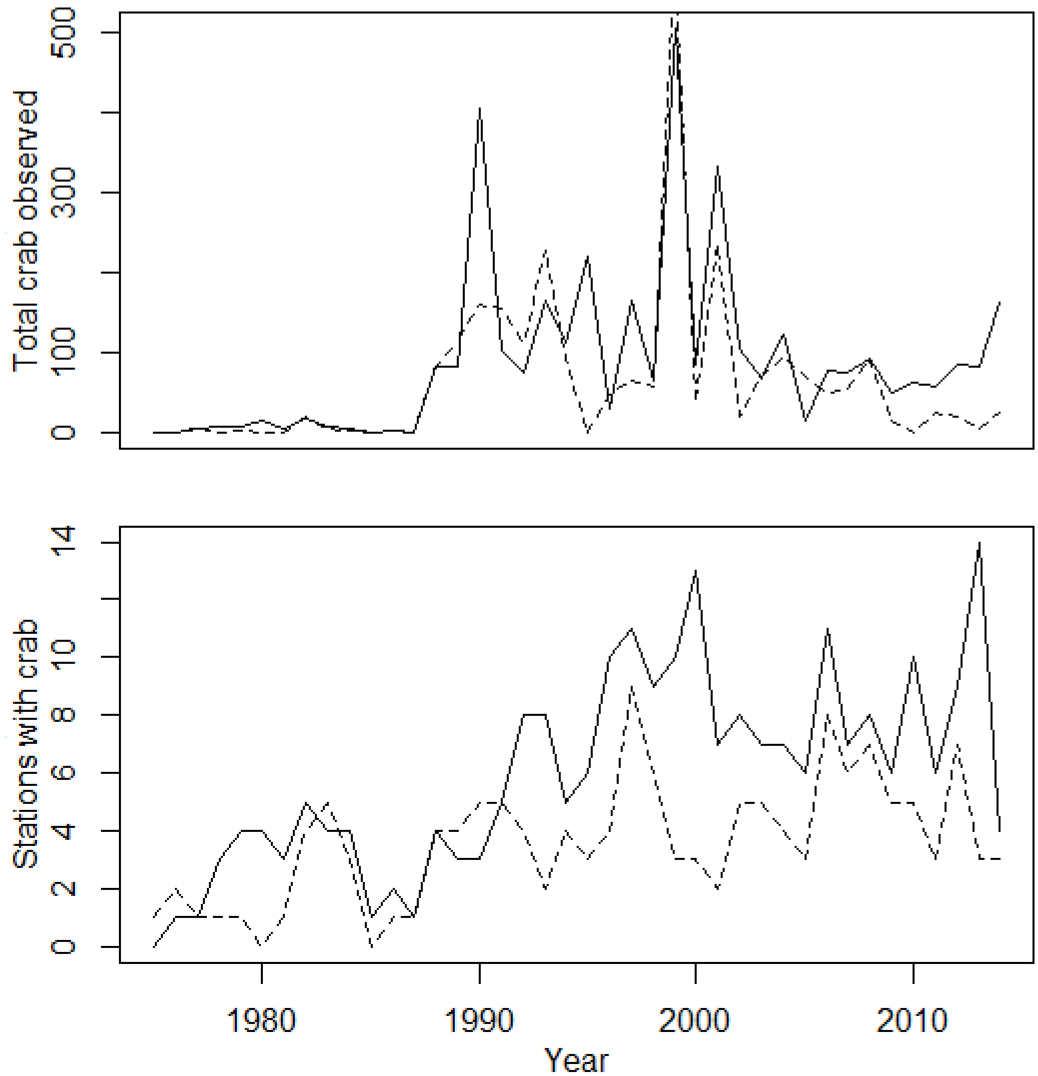

Figure 5. Total number of observed crab (top) and the number of stations that reported observations of crab (female = dashed line, male = solid line) from 1975-2014.

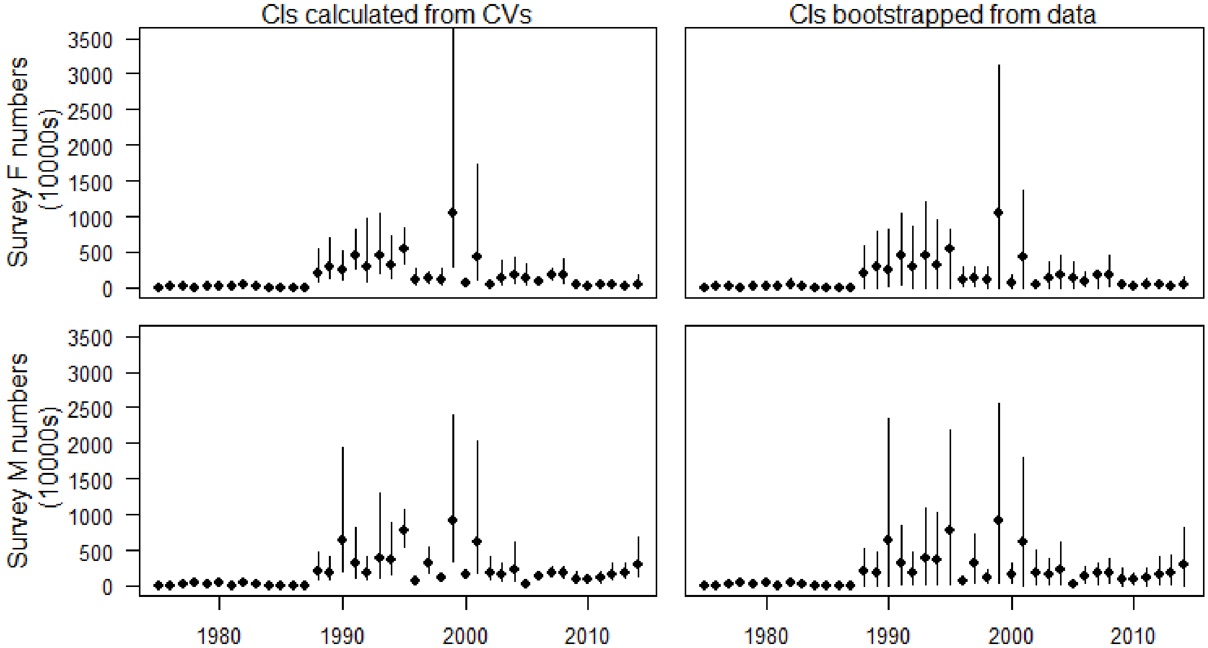

Figure 6. Time series of Pribilof Islands red king crab estimated from the NMFS annual EBS bottom trawl survey. CIs for the left column are based on back calculations from the CVs provided from Kodiak, CIs in the right column are based on bootstraps from the NMFS.

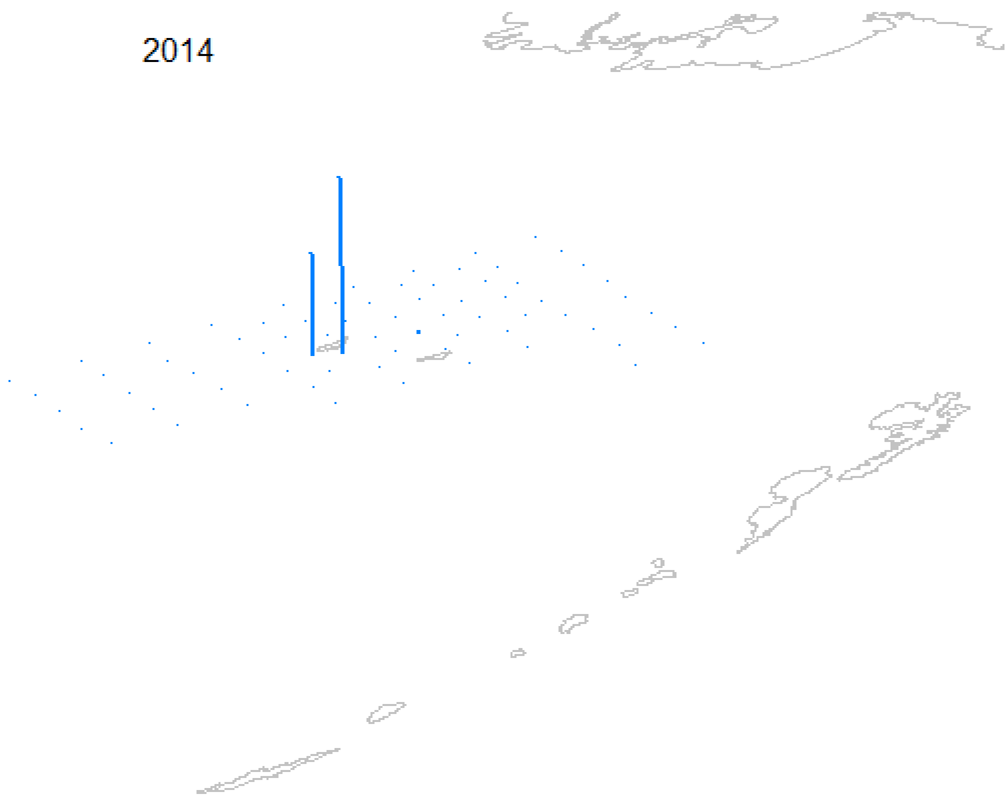

Figure 7. Male red king crab relative density by station in the Pribilof Island district in 2014. Blue bars represent the relative magnitude of the density calculated from the NMFS trawl survey.

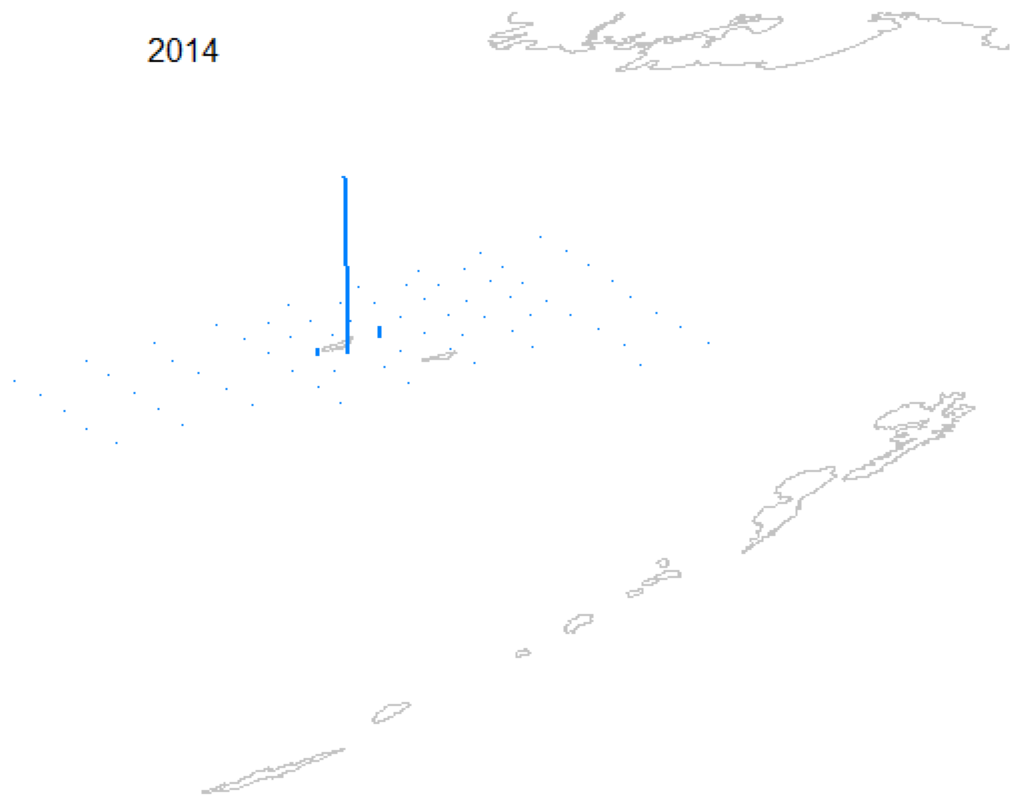

Figure 8. Female red king crab relative density by station in the Pribilof Island district in 2014. Blue bars represent the relative magnitude of the density calculated from the NMFS trawl survey.

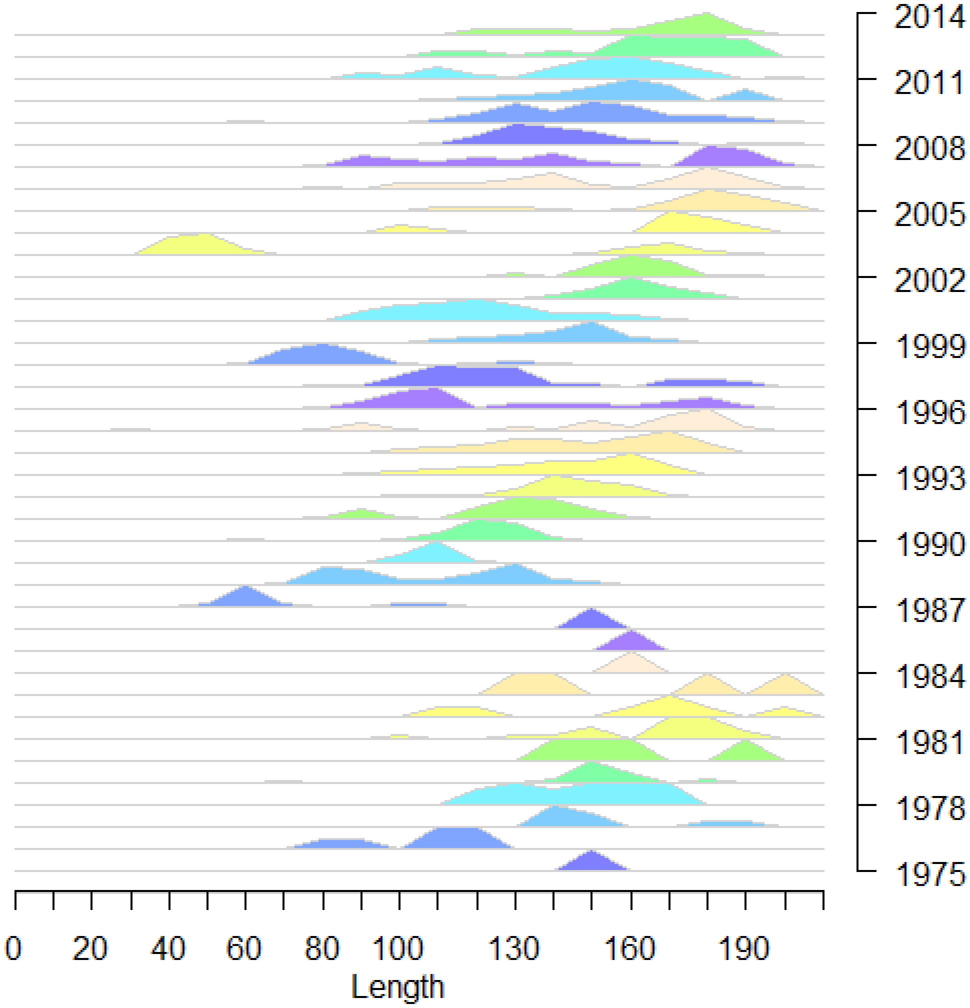

Figure 9. Observed length frequencies by 5 mm length classes of Pribilof Islands male red king crab (Paralithodes camtschaticus) from 1975 to 2014.

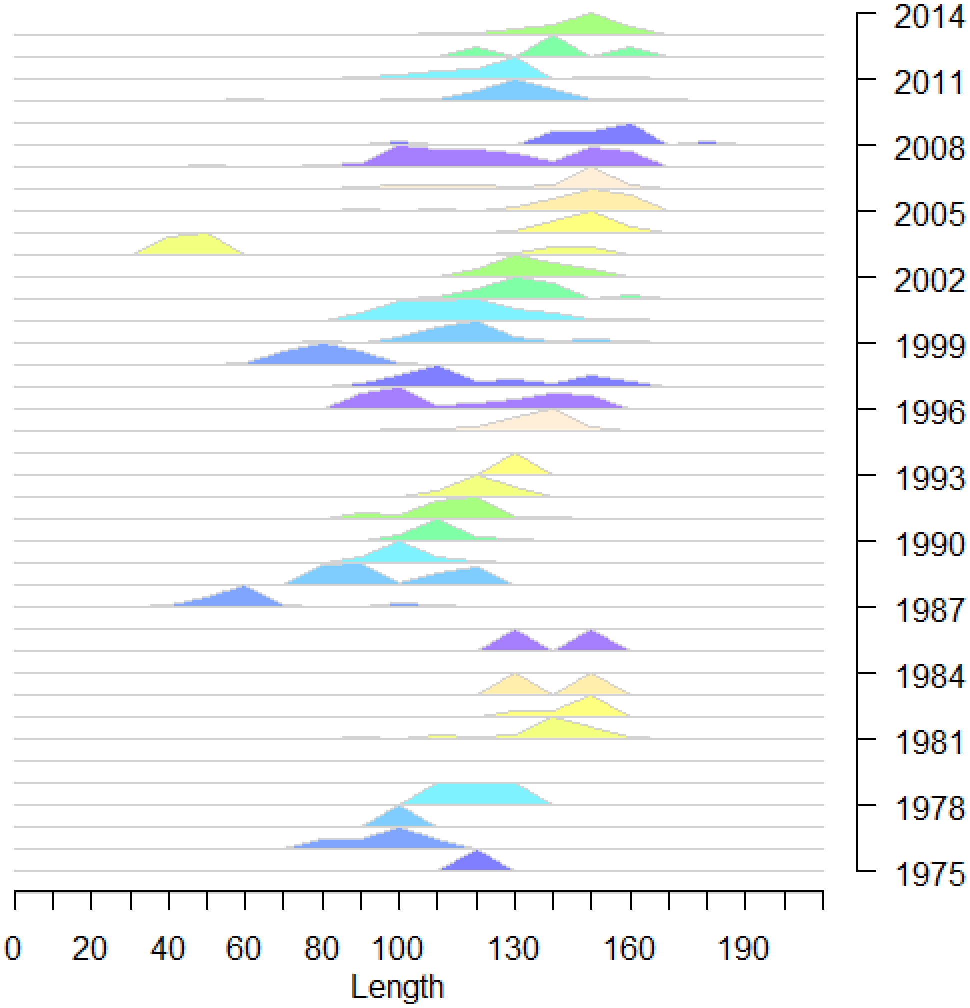

Figure 10. Observed length frequencies by 5 mm length classes of Pribilof Islands female red king crab (Paralithodes camtschaticus) from 1975 to 2014.

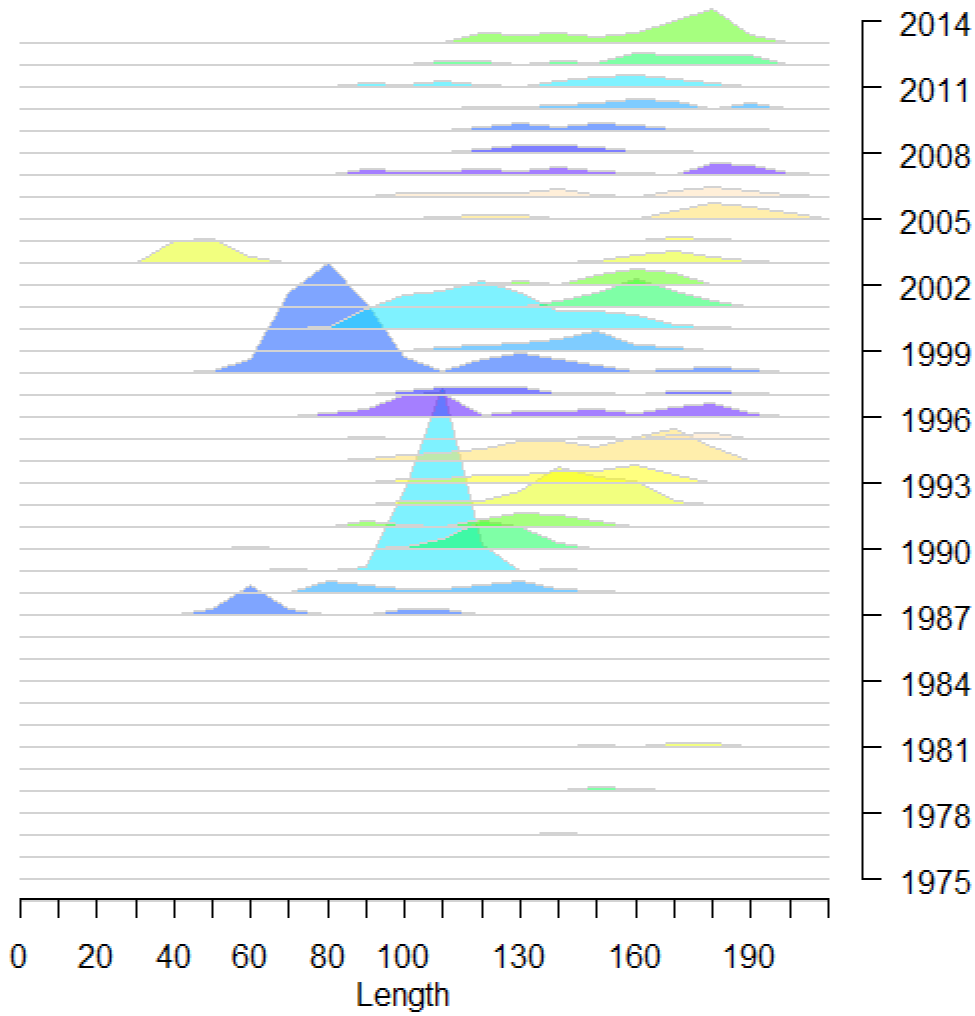

Figure 11. Observed numbers at length by 5 mm length classes of Pribilof Islands male red king crab (Paralithodes camtschaticus) from 1975 to 2014.

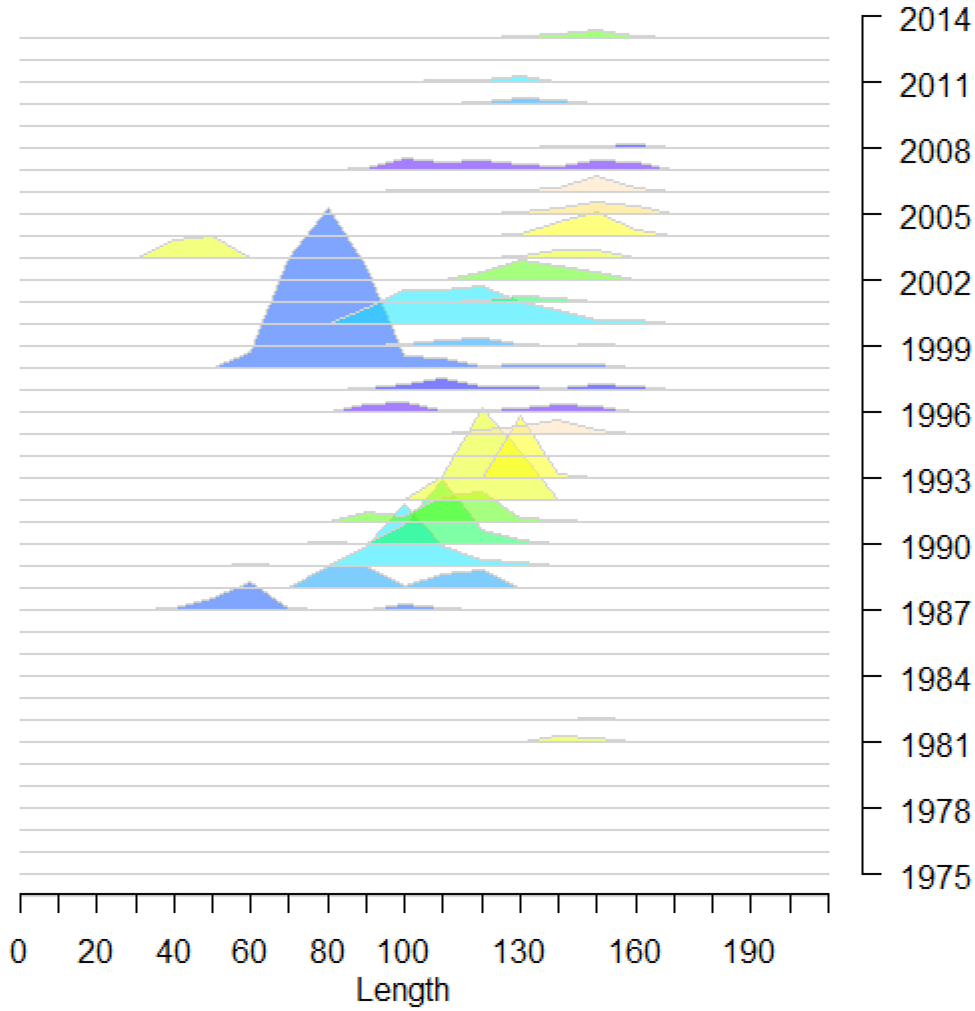

Figure 12. Observed numbers at length by 5 mm length classes of Pribilof Islands female red king crab (Paralithodes camtschaticus) from 1975 to 2014.

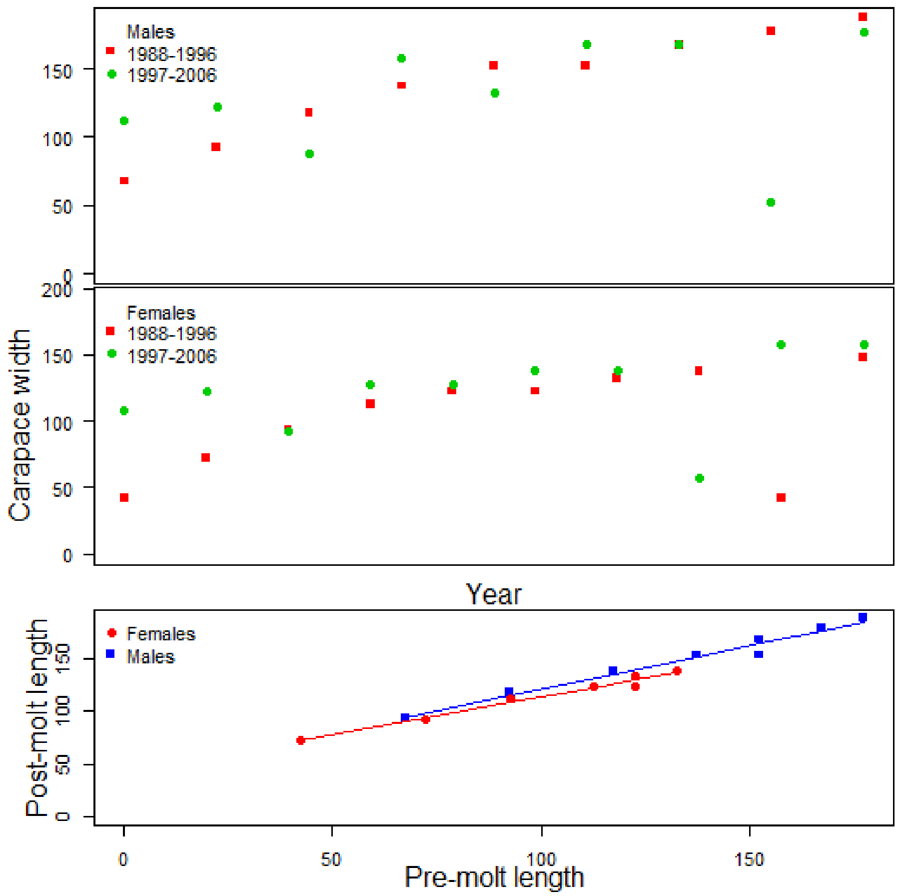

Figure 13. Modes of the length frequency distribution for males and females plotted for two time periods over which two cohorts were observed to move through the population. Growth per molt calculated from the modes from the length frequencies with fitted linear relationship (bottom).

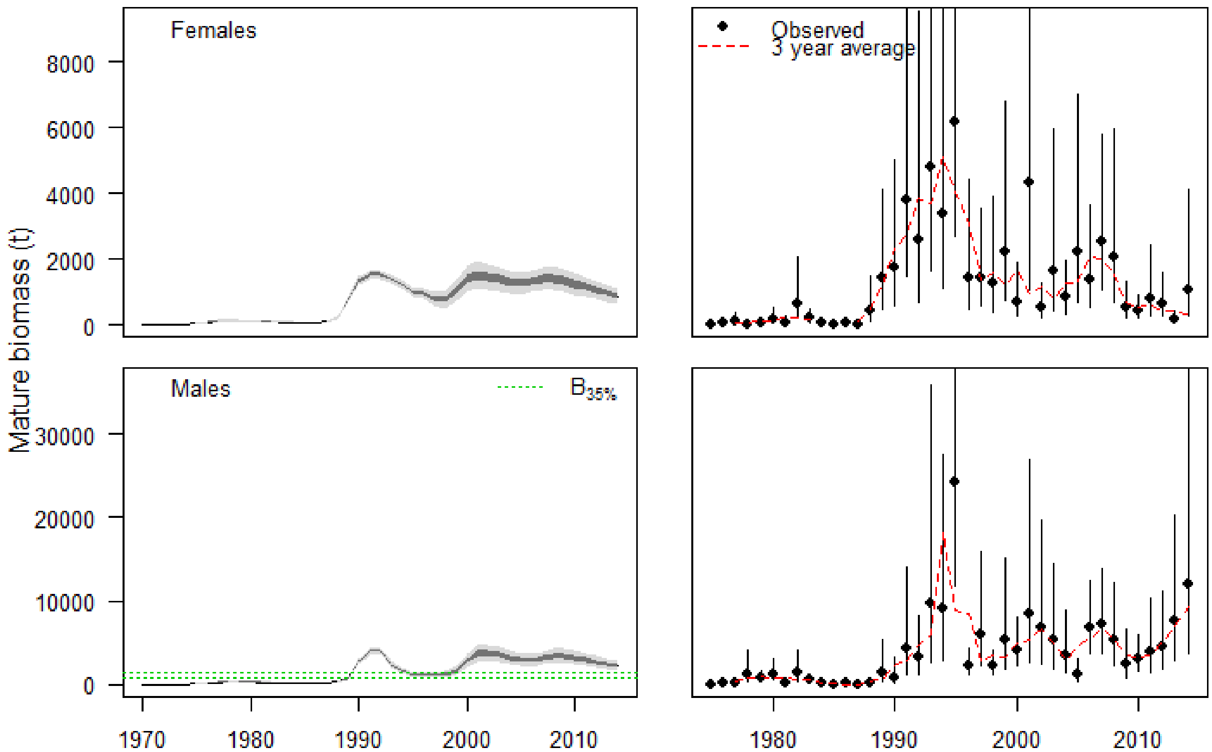

Figure 14. Estimated mature female and male biomass from the integrated assessment (left column) and a 3 year running average from the survey estimates (right column). Scale is different for males and females.

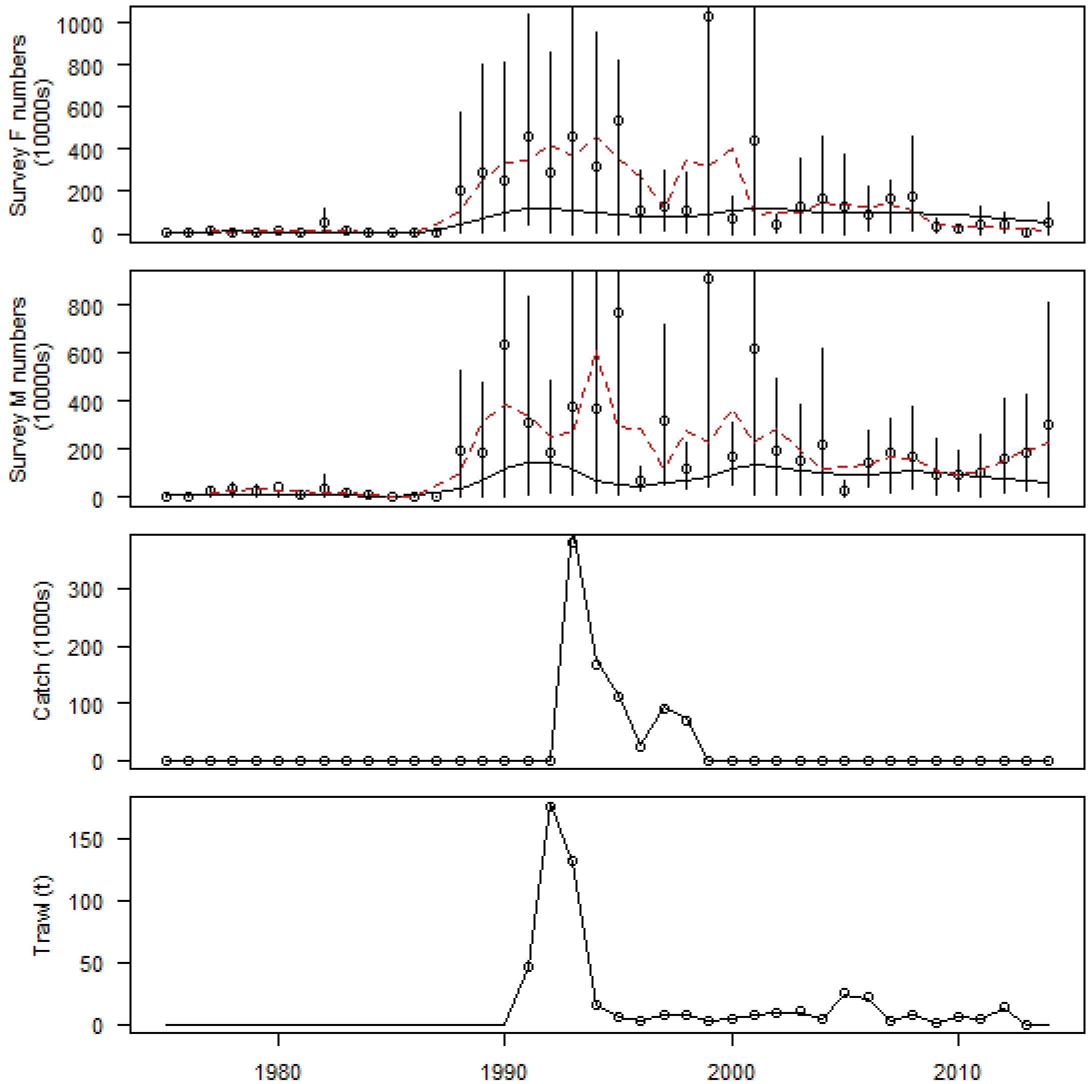

Figure 15. Model fits (black line) to observed survey numbers (black dots) with 95% bootstrapped CIs for females (top) and males (2nd row). Dashed red line is the three year running average. Model fits (black line) to observed catches in the directed fishery (dots) in numbers caught (3rd row) and bycatch in the non-pelagic trawl fishery (4th row).

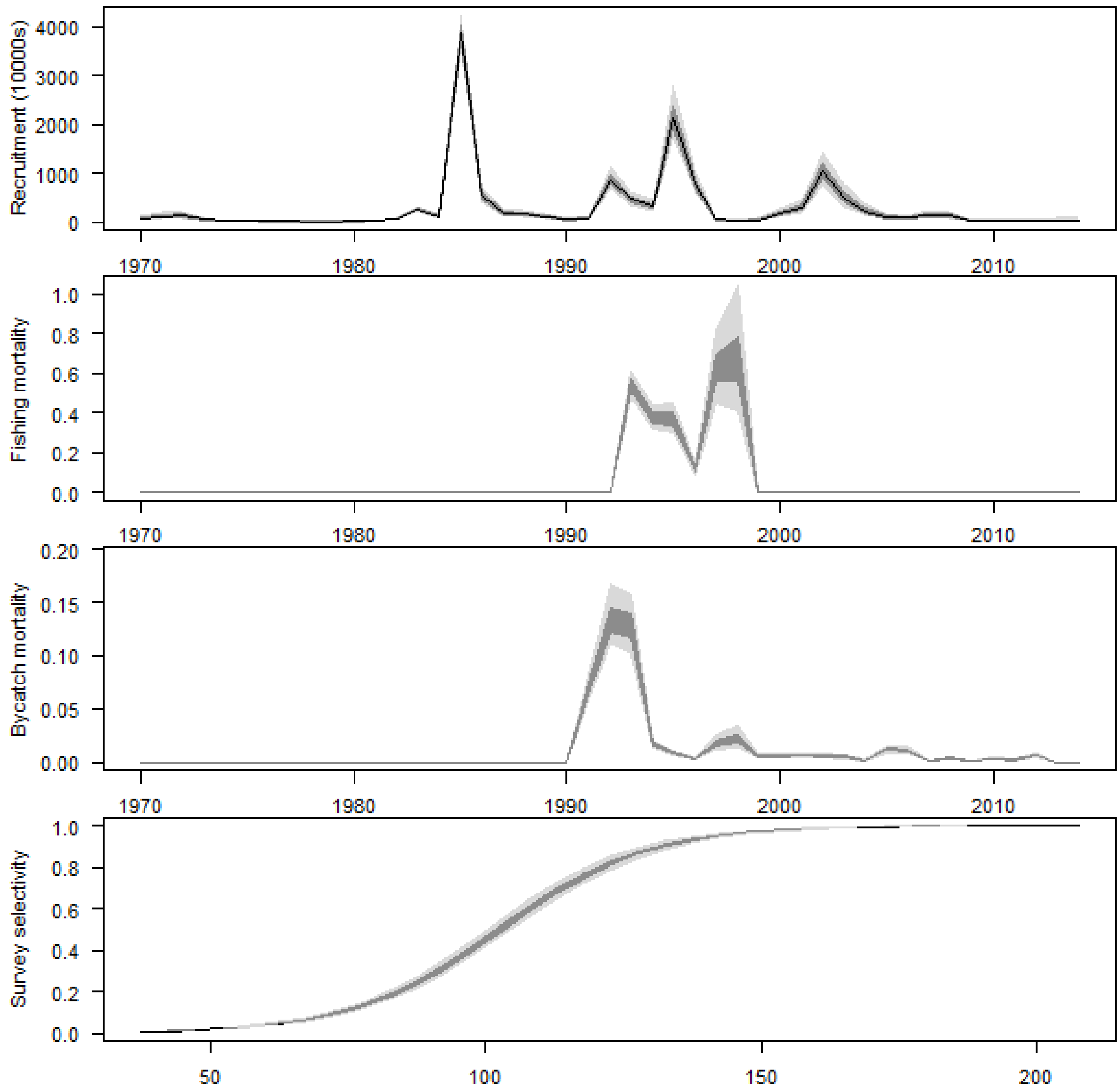

Figure 16. Estimated recruitment (top), fishing mortality in the directed fishery (2nd row), fishing mortality in the non-pelagic trawl (3rd row) and survey selectivity (bottom). Light grey areas indicate the 90% credibility interval and darker grey are the 50% credibility interval.

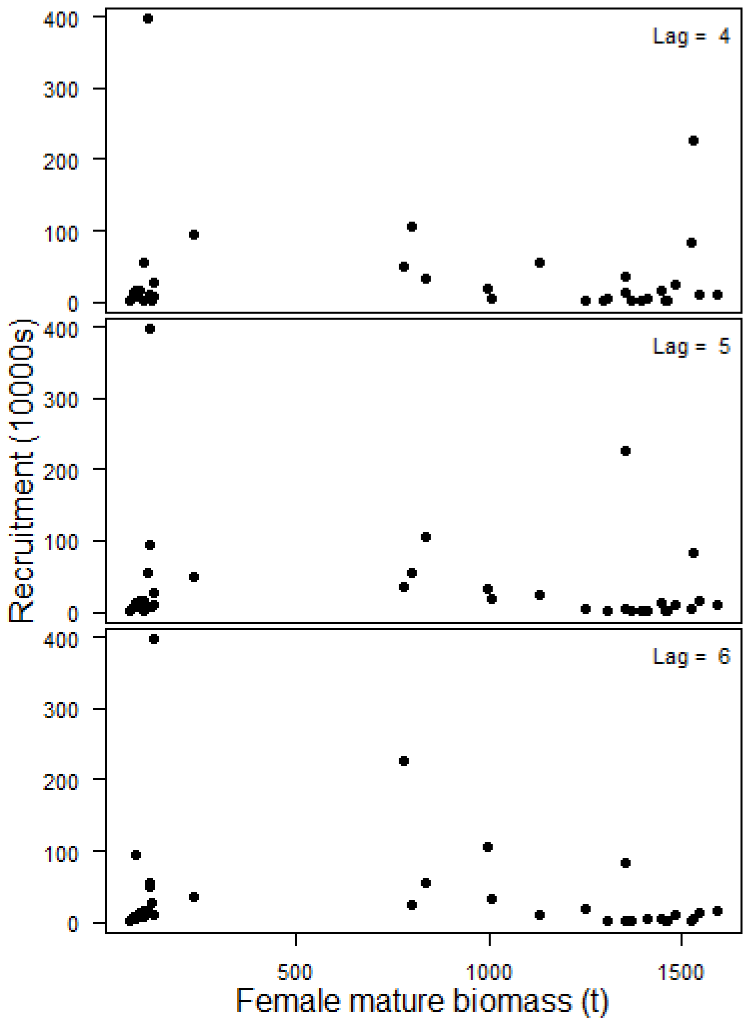

Figure 17. Recruitment vs. estimated female mature biomass at lags of 4, 5, and 6 years.

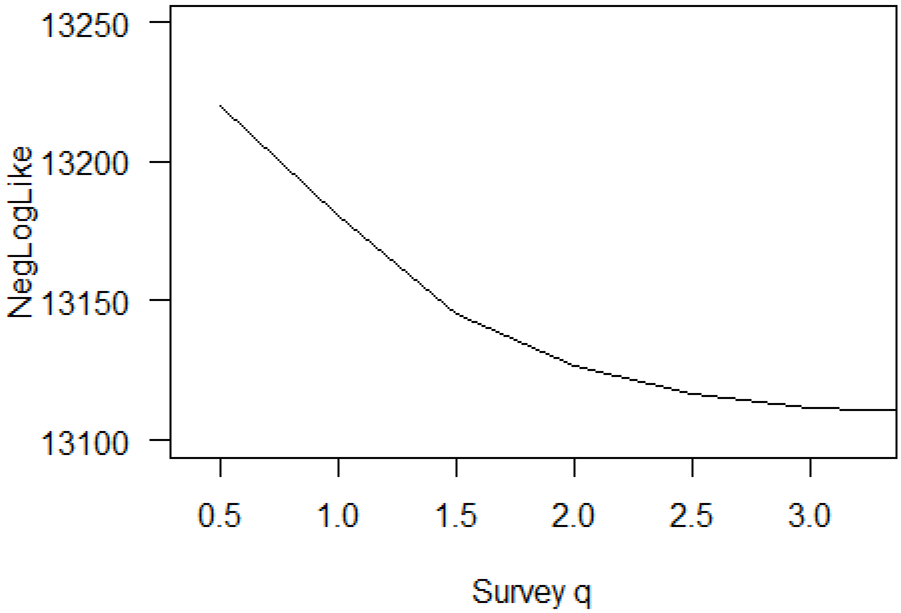

Figure 18. Likelihood profile for survey catchabillity (q).

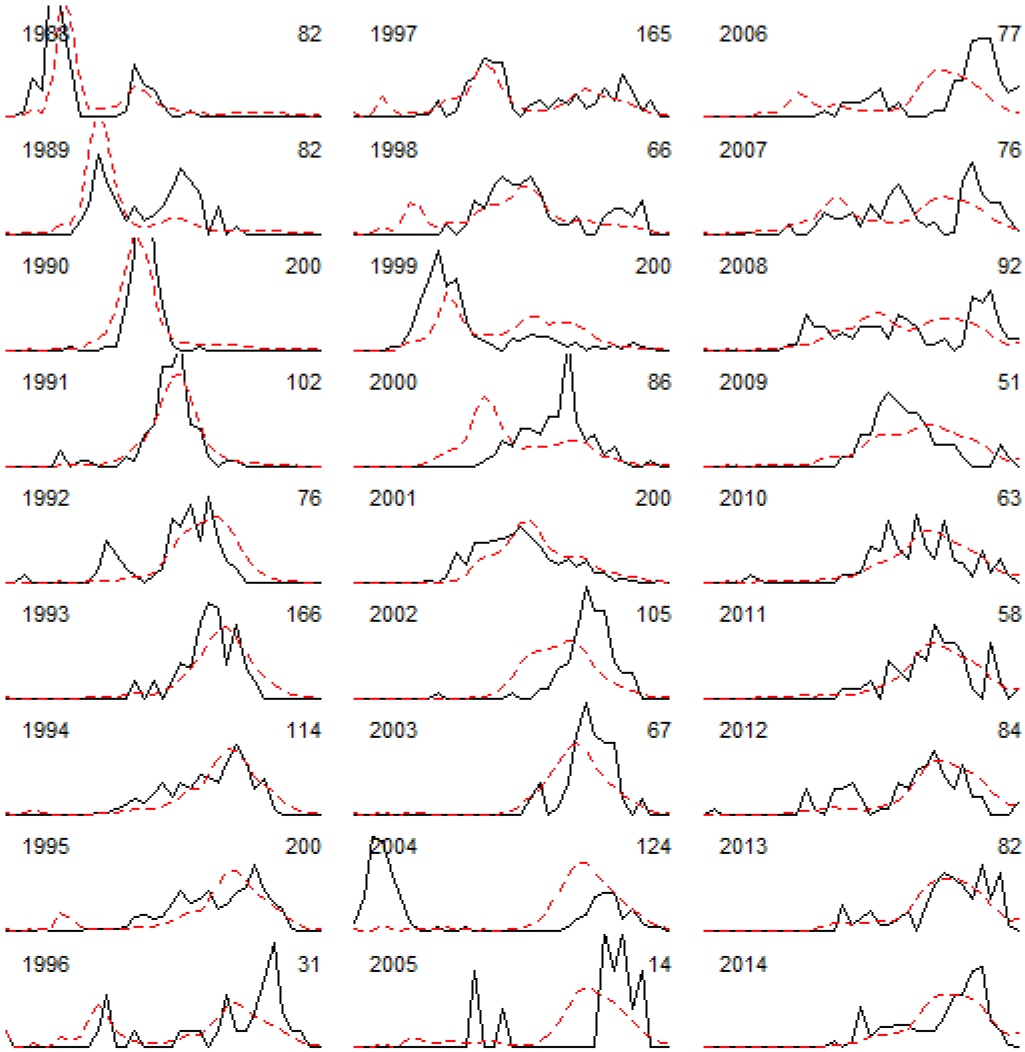

Figure 19. Model fits (red dashed line) to observed male length frequencies in the survey (solid line) by year using 5 mm length bins. Sample size is noted in the top right hand corner of each plot. Length frequencies for the years 1975-1987 are not shown because the associated sample sizes were <=18 and therefore held very little information.

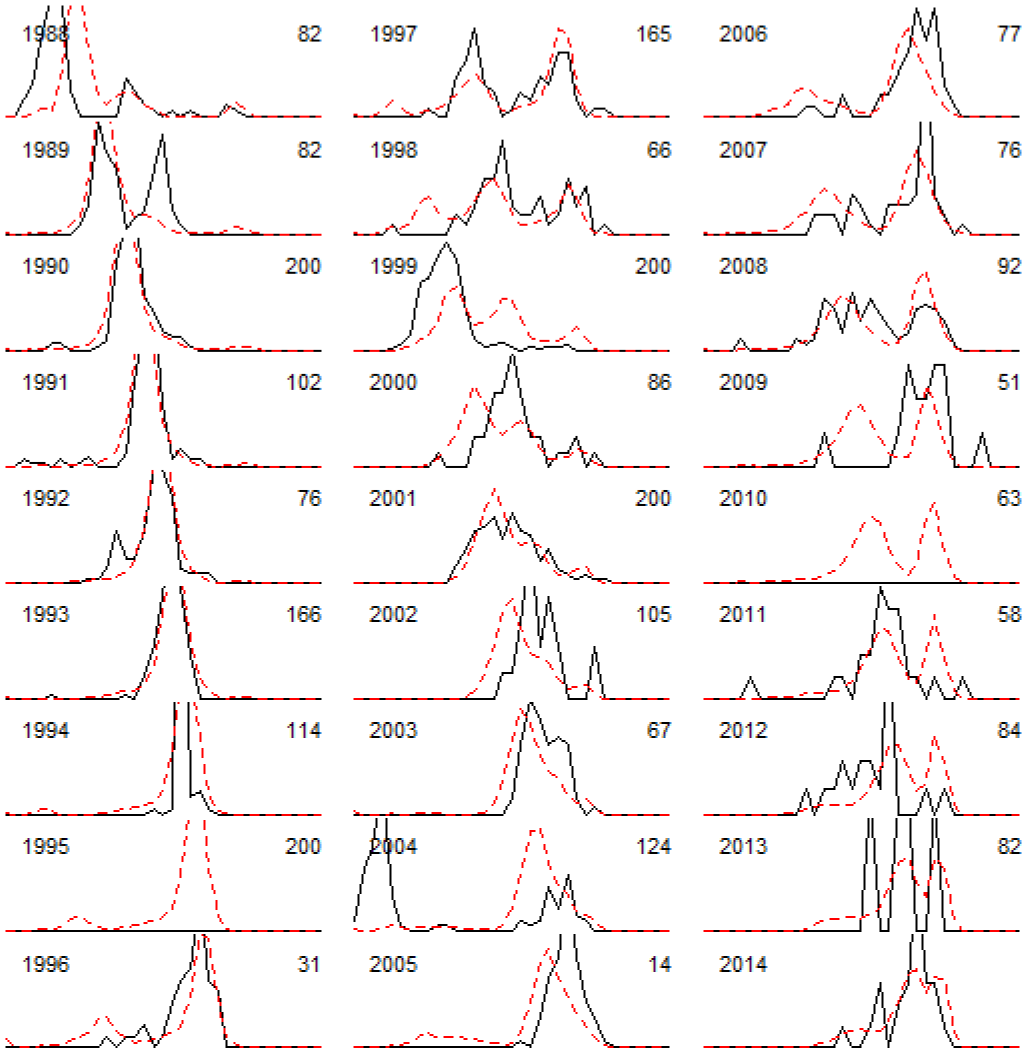

Figure 20. Model fits (red dashed line) to observed female length frequencies in the survey (solid line) by year using 5 mm length bins. Sample size is noted in the top right hand corner of each plot. Length frequencies for the years 1975-1987 are not shown because the associated sample sizes were <=18 and therefore held very little information.

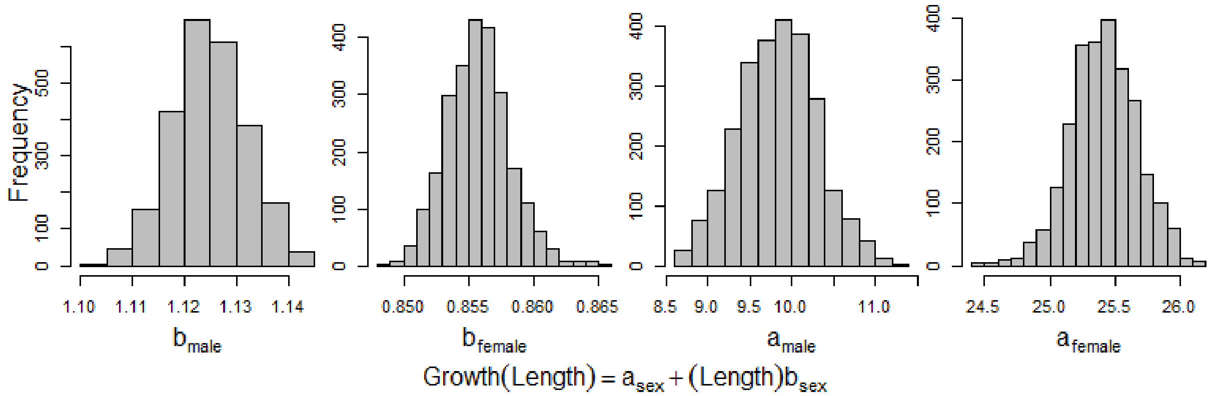

Figure 21. Posterior distributions of estimated growth parameters.

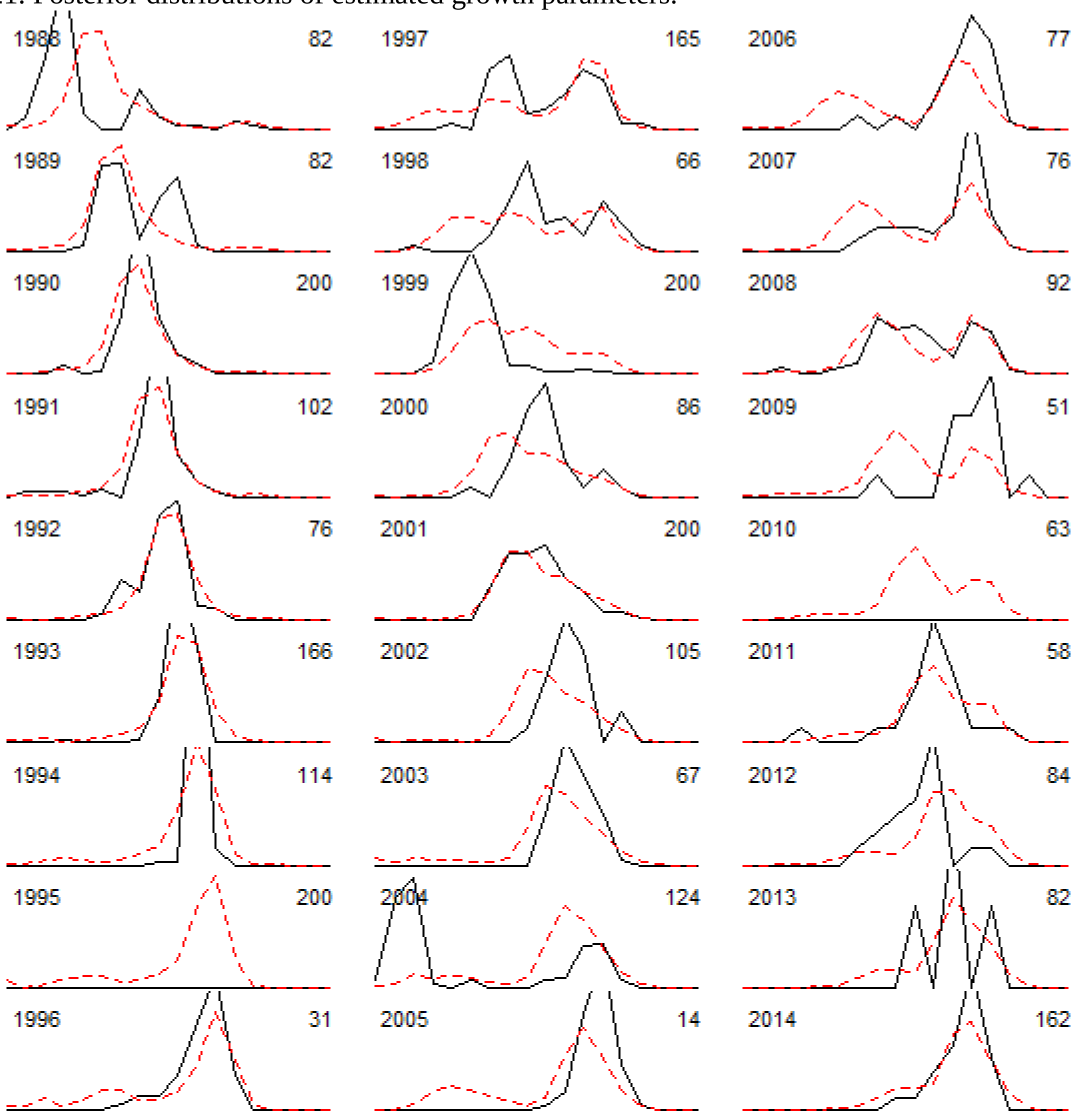

Figure 22. Model fits (red dashed line) to observed female length frequencies in the survey (solid line) by year using 10 mm length bins. Sample size is noted in the top right hand corner of each plot. Length frequencies for the years 1975-1987 are not shown because the associated sample sizes were <=18 and

therefore held very little information.

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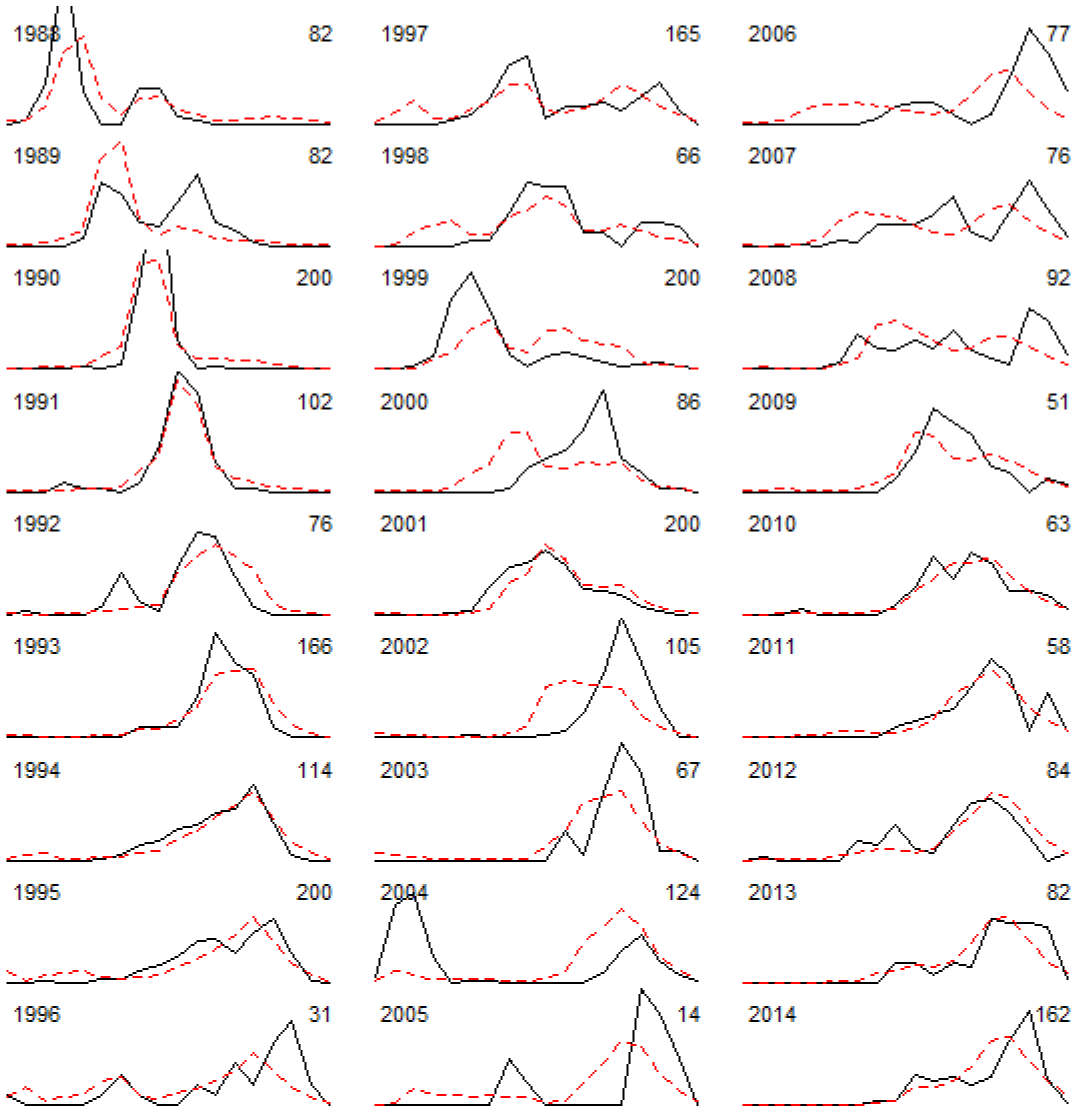

Figure 23. Model fits (red dashed line) to observed male length frequencies in the survey (solid line) by year using 10 mm length bins. Sample size is noted in the top right hand corner of each plot. Length frequencies for the years 1975-1987 are not shown because the associated sample sizes were <=18 and therefore held very little information.

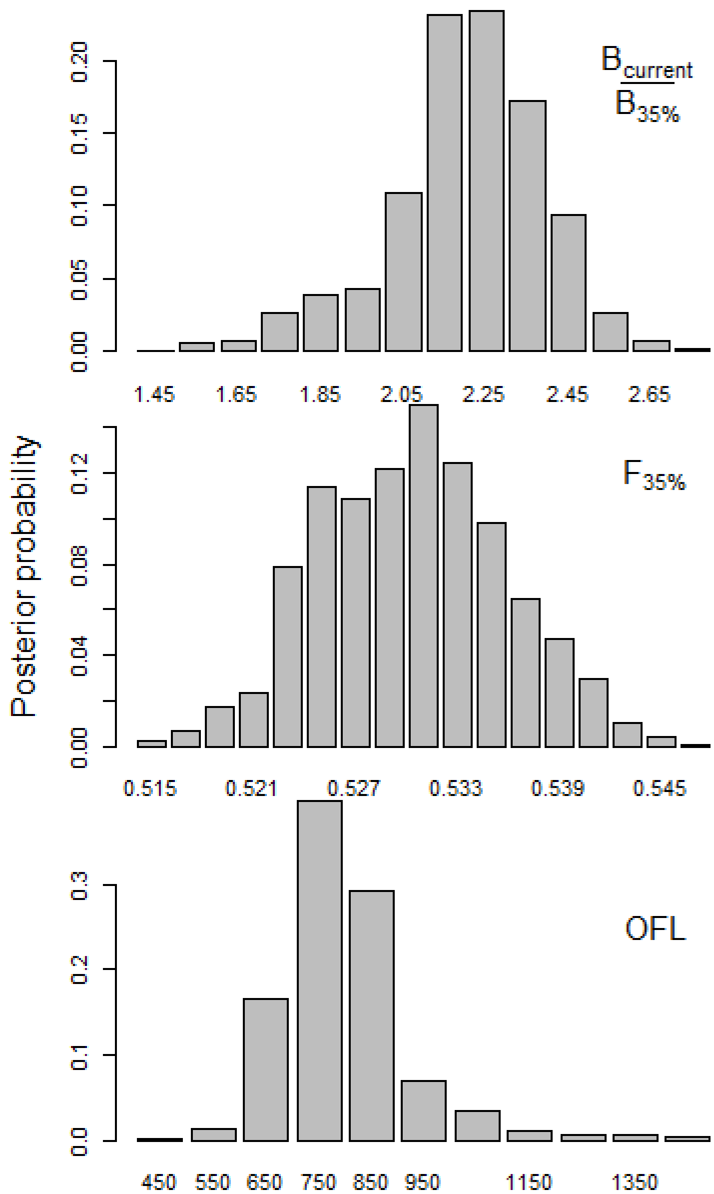

Figure 24. Posterior distributions for the ratio of the current biomass to the target biomass (top), F35% (middle) and the overfishing level (bottom) for an MCMC in which growth and associated parameters were estimated.

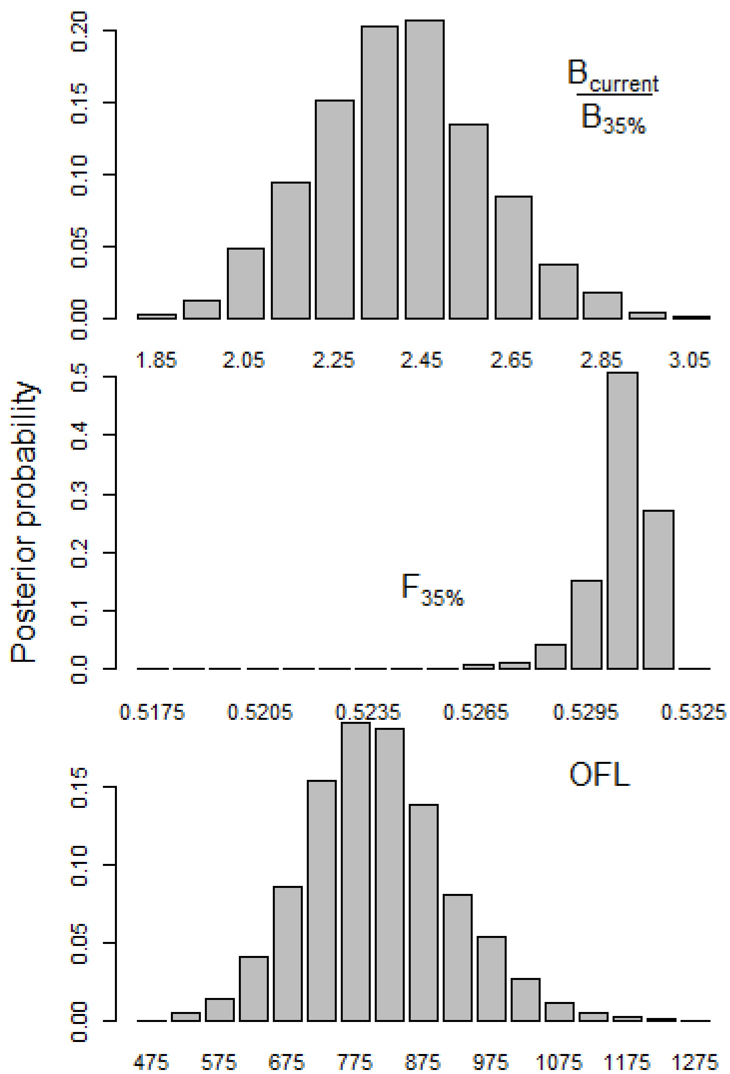

Figure 25. Posterior distributions for the ratio of the current biomass to the target biomass (top), $F_{35\%}$ (middle) and the overfishing level (bottom) for an MCMC in which growth and associated parameters were not estimated.

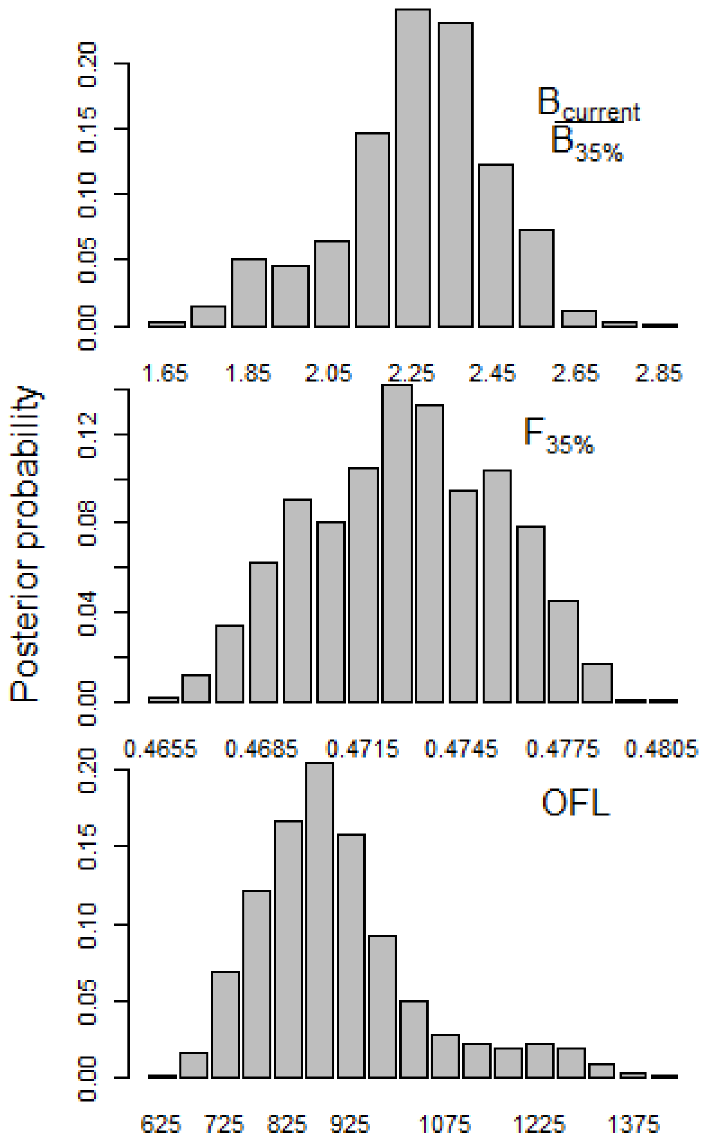

Figure 26. Posterior distributions for the ratio of the current biomass to the target biomass (top), F35% (middle) and the overfishing level (bottom) for an MCMC in which growth and associated parameters were estimated and length bins were in 10 mm intervals.

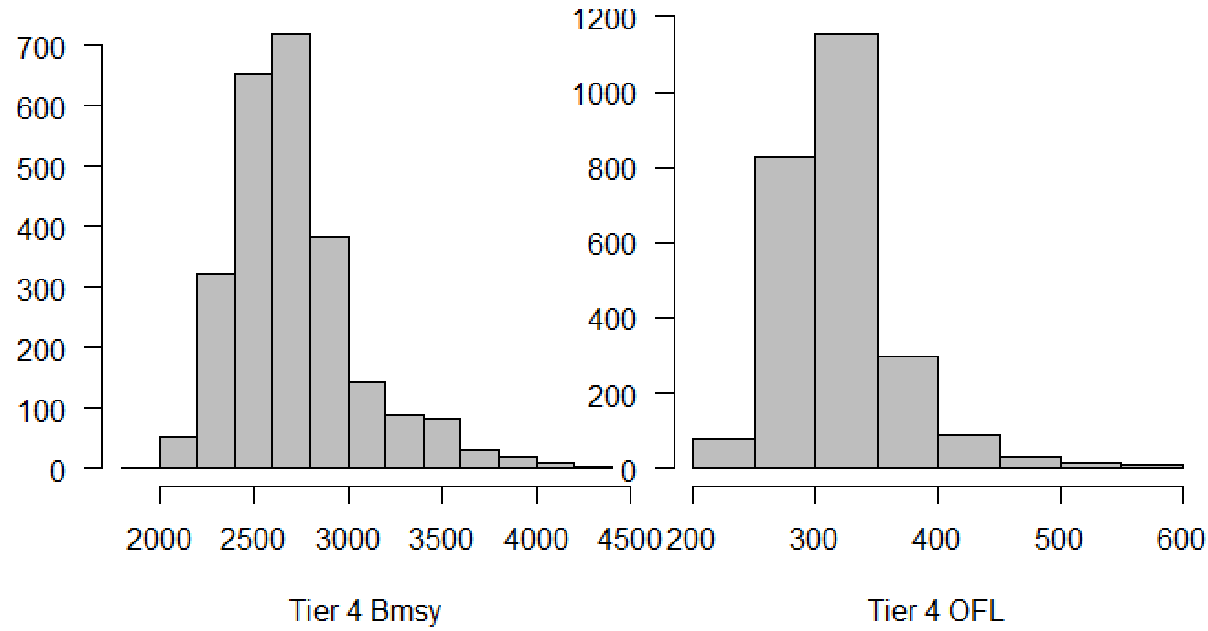

Figure 27. Posterior distribution for Tier 4 BMSY and OFL (in tonnes) from the integrated assessment when growth and associated parameters were estimated.

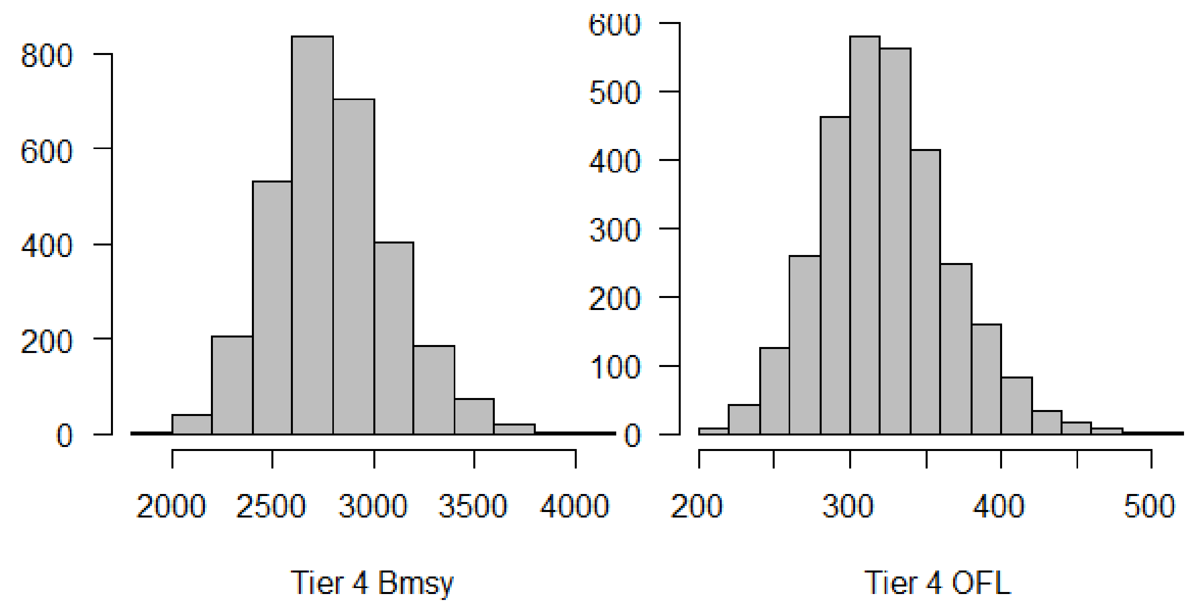

Figure 28. Posterior distribution for Tier 4 BMSY and OFL (in tonnes) from the integrated assessment when growth and associated parameters were fixed.

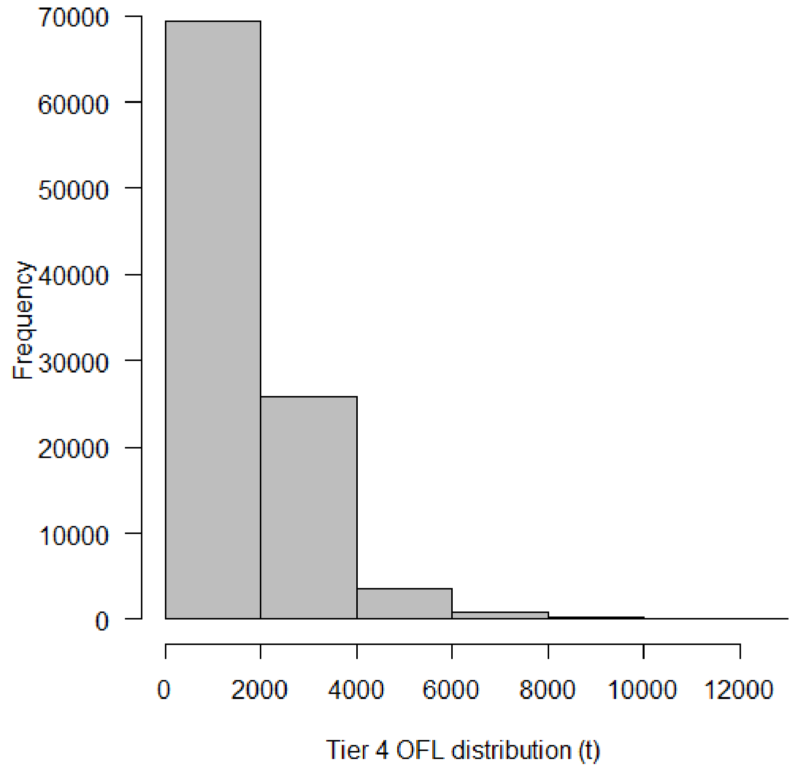

Figure 29. Distribution of tier 4 OFL generated by bootstrapping values of MMB with an additional sigma of 0.3.

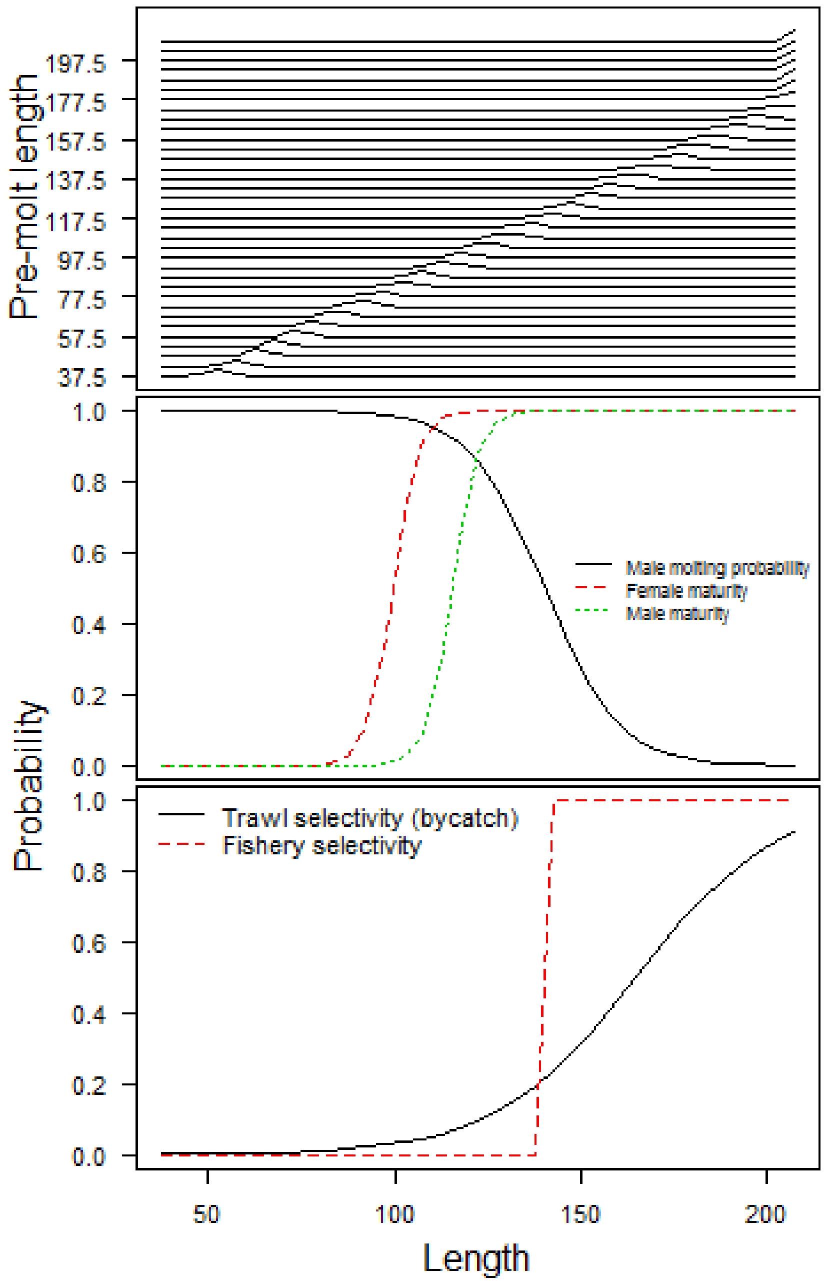

Figure 30. Size transition matrix (top), probability of molting (males only) and maturing (females and males; middle), probability of being selected in the directed and trawl fisheries (bottom).

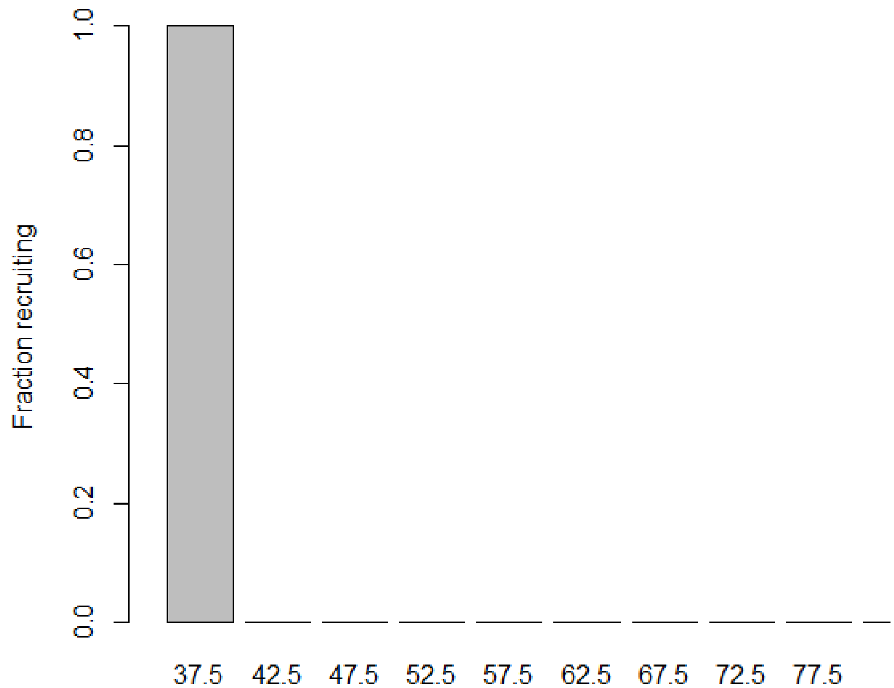

Figure 31. Estimated fraction of incoming recruitment allocated to a given length bin.