2016 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 2015, then declined in 2016. MMB at mating was estimated to be above Bmsy in 2015/16.
    b. According to an integrated length-based assessment, mature male biomass increased from 2007 to 2009 and decreased from 2010 through 2016. MMB at mating was estimated to be above Bmsy in 2015/16
    c. Observed survey biomass declined from 15,173 t in 2015 to 4,150 t in 2016.
4. Recruitment: Recruitment is episodic for PIRKC and has been low recently.
5. Recent management statistics:
   Units in tons

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	8,894 [D**]	0	0	1.76	1,359	1,019
2015/16	2,756	9,062 [**]	0	0	0.32[1]	2,119	1,467

Units in millions of pounds

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	19.61[D**]	0	0	0.004	3.00	2.25
2015/16	6.08	19.99[**]	0	0	<0.001[1]	4.67	3.23

The OFL is the total catch OFL for each year. The stock was above MSST in 2015/2016 according to both a 3-year average. The catch in 2015/16 (0.32 t) was below the OFL (2,119 t) and the ABC (1,467 t).

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 and updated with 2012/2013 catches
* – 2011/12 estimates based on 3 year running average
** –estimates based on weighted 3 year running average using inverse variance
1 – catches in 2015/16 from AKFIN through August 12, 2016

6. 2016/2017 OFL projections:

All biomass in tons

Tier	**Assessment Method**	**OFL**	B_{MSY}	**MMB At mating Feb 15 2017 fishing at OFL**	B/B_{MSY} **(MMB)**	***MMB at mating Feb 15 2016***	γ	**Years to define** B_{MSY}	F_{MSY}	ABC (p*=0.49)	**ABC = 0.75* OFL**
4	Running Average	1,462	5,512	6,980	1.25	9,062	1.	1991/1992-2015/2016 (MMB)	0.18	1,436	1,096
4	Random Effects Model	119	5,512	2,044	0.37	2,154	1	1991/1992-2015/2016 (MMB)	0.05	114	89
4	Observed Survey	370	5,512	3,332	0.60	13,457	1	1991/1992-2015/2016 (MMB)	0.10	357	278
4	Integrated assessment (males only)	822	3,881	5,160	1.33	6127	1	1991/1992-2015/2016 (MMB)	0.18		617
3	Integrated assessment (males only)	1,931	1,598	4,066	2.5	6127	1	1983-present (recruitment)	0.49		1,448

Units are in millions of pounds.

Tier	**Assessment Method**	**OFL**	B_{MSY}	**MMB At mating Feb 15 2017 fishing at OFL**	B/B_{MSY} **(MMB)**	***MMB at mating Feb 15 2016***	γ	**Years to define** B_{MSY}	F_{MSY}	ABC (p*= 0.49)	**ABC = 0.75* OFL**
4	Running Average	3.22	12.16	15.39	1.25	19.99	1	1991/1992-2015/2016 (MMB)	0.18	3.17	2.42
4	Random Effects Model	0.26	12.16	4.51	0.37	4.75	1	1991/1992-2015/2016 (MMB)	0.05	0.25	0.20
4	Observed Survey	0.82	12.16	7.35	0.60	29.68	1		0.10	0.79	0.61
4	Integrated assessment (males only)	1.81	8.56	11.38	1.33	13.51	1	1991/1992-2015/2016 (MMB)	0.18		1.36
3	Integrated assessment (males only)	4.26	3.52	8.97	2.5	13.51	1	1983-present (recruitment)	0.49		3.19

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.
8. Basis for ABC: ABCs were identified as the 49th percentile of the distributions of the OFL given a p-star of 0.49. In addition the ABC was estimated using a 25% buffer from the OFL as recommended by the CPT and SSC for 2015/16.

Summary of Major Changes:

1. Management: None.
2. Input data: Survey (2016) and bycatch (2015) data were incorporated into the assessment.
3. Assessment methodology: Model output for male only fit is presented with the same model configuration as 2015.
4. Assessment results: Male biomass estimates from the 3-year running average and a random effects model fit to survey male biomass >=120mm are used to estimate MMB at mating, OFL and ABC.

CPT comments May 2016

1. *Continue the work on survey biomass and length frequency weighting issues to improve the model fits to abundance data;*

   Addressed in #2 below.

2. *Implement the Francis tuning method to estimate length composition effective sample sizes;*

   The Francis effective N calculation was added to the model. In addition, other multipliers on the survey length frequencies were evaluated.

3. *Provide results for a random effects model and three-year weighted average for the September meeting*

   The random effects model was fit to the survey biomass data and MMB, OFL and ABC estimated. The estimates using the three-year weighted average are also included.

Crab Plan Team September 2015 comments not addressed

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.

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 groundfish discards time series data (updated through 2015) were used in this assessment. The crab fishery retained and discard catch time series were updated with 2015/2016 data. The following sources and years of data are available:

Data source	Years available	Used in integrated assessment?
NMFS trawl survey	1975-2016	Yes
Retained catch	1993-2015	Yes
Trawl bycatch	1991-2015	Yes
Fixed gear bycatch	1991-2015	No
Pot discards	1998-2015	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).

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

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

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 (assumed the same as Bristol Bay red king crab).

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 2015/2016 there was 0.221 t of Pribilof Islands red king crab mortality from crab fisheries (Table 3).

2.3 Groundfish pot, trawl, and hook and line fisheries

The data through 2015/2016 from the 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 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 1991, data 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.

Total catch in 2014/15 was 1.76 t below the 2014/15 OFL 1,359 t (Tables 3 and 5). Total catch in 2015/16 through August 12, 2016 was 0.32 t. Catch in 2014/15 was 47% from non-pelagic trawl and 53% from hook and line fisheries (Table 4).

2.4 Catch-at-length

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

2.5 Survey biomass and length frequencies

The 2016 NOAA Fisheries EBS bottom trawl survey results 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 over the years 1975 to 2016 (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).

Observed survey biomass estimates for males greater than or equal to 120 mm are used in the Tier 4 assessment as an estimate of mature male biomass and to estimate the B_{MSY} proxy, MMB at mating and in fitting the 3-yr running average and the random effects model.

Weight (equation 1) and maturity (equation 3) schedules are applied in the integrated assessment model to calculated abundances and summed to calculate mature male, female, and legal male biomass for the Tier 4 and Tier 3 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 6 and 7), and survey data analyses were standardized in 1980 (Stauffer, 2004). Male and female abundance varies widely over the history of the survey time series' (**Error! Reference source not found.**) and uncertainty around area-swept estimates of abundance are large due to relatively low sample sizes (Figure). Male crabs were observed at 9 of 35 stations in the Pribilof District during the 2015 NMFS survey (Figure); female crabs were observed at 5 (Figure). Two (possibly three) cohorts can be seen moving through the length frequencies over time (Figure and Figure). Numbers at length vary dramatically from year to year, but the cohorts can nonetheless also be discerned in these data (Figure and Figure).

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 abundance for males >=105 mm declined from 3,662,609 in 2015 to 1,807,323 in 2016 (Table 6). Female biomass (all sizes) declined from 3,859 t in 2015 to 1,898 t in 2016. Survey biomass for males >=120mm declined from 15,173 t in 2015 to 4,150 t in 2016 (Table 11).

3. Analytical approaches

3.1 History of modeling

An inverse-variance weighted 3-year running average of male biomass (>=120mm) 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). In 2016, biomass and derived management quantities are estimated by a 3-yr running-average method, a random effects 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 and random effects estimates of male biomass (>=120mm).

3.2 Model descriptions

3.2.1. Running average

A 3 year running average of male biomass (>=120mm) at survey time was calculated using the weighted average with weights being the inverse of the variance,

$$BWRA_t = \frac{\sum_{t-1}^{t+1} \frac{MMB_t}{\sigma_t^2}}{\sum_{t-1}^{t+1} \frac{1}{\sigma_t^2}} \qquad (4)$$

Where,

MMB_t	Estimated male biomass (>=120mm) from the survey data
σ_t^2	The variance associated with the estimate of MMB in year t

3.2.2 Random Effects Model

A random effects model was fit to the survey male biomass (>=120mm) for estimation of current biomass, MMB at mating, OFL and ABC (Model developed for use in NPFMC groundfish assessments). The model uses the CVs as calculated for the 3-yr running average. The random effects model was fit to the survey data at the time of the survey. The biomass estimate in 2016 was projected forward to February 15, 2017 for use in the OFL control rule to estimate the OFL and ABC. The B_{MSY} proxy for both the 3-yr running average and the random effects model was estimated as the average of the 1991 to 2015 observed survey data projected forward to February 15, removing the observed catch. The likelihood equation for the random effects model is,

$$\sum_{i=1}^{yrs}\left\{0.5\left(\log(2\pi\sigma_i^2+\left(\frac{(\widehat{B}_i-B_i)^2}{\sigma_i^2}\right)\right)+0.5\left(\log(2\pi\sigma_p+\left(\frac{(\widehat{B}_i-\hat{B}_{i-1})^2}{\sigma_p}\right)\right)\right\}$$

Where,

B_i is the log of observed biomass in year i

$\widehat{B}_i$ is the model estimated log biomass in year i

σ_i^2 is the variance of observed log biomass in year i

σ_p is the variance of the deviations in log survey biomass between years (i.e. process error variance). σ_p was estimated as $e^{(2\alpha)}$, where α is a parameter estimated in the random effects model.

Yrs is the number of years of survey biomass values

3.2.3 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 with midpoints 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 1991-2016 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.

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 12).

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). 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 2015 integrated assessment in the recent past were poor for both females and males (Szuwalski, et al. 2015). In this assessment a model fit to males only is presented. The estimation of Francis effective sample sizes was added to the model. However, the model did not converge with sample sizes lowered to the Francis estimate (0.05). Several scenarios were run with samples sizes decreased by multiplying by 0.1, 0.2, 0.4 and 0.6.

4. Model Selection and Evaluation

The running average method with a tier 4 HCR was selected in 2015 by the SSC as the model to determine the OFL and ABC based on concerns around different trends over the last decade between the integrated model and the running average and the lack of fit of the integrated model to survey abundance data. In 2016, four assessment methods are presented for comparison: a running average with a tier 4 HCR, a random effects model, an integrated assessment with tier 3 HCR and an integrated assessment with a tier 4 HCR.

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 smooths 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.

5.0 Results

5.1 Tier 4

The 3-yr running average estimates male biomass (>=120mm) at 9,423 t in 2016 at the survey time, while the random effects model estimates 2,431 t (95% CI 2,044 to 2,891 t) (Table 11 and Figure 14). The observed survey male biomass (>=120mm) was 4,150 t in 2016. MMB at mating on February 15, 2016 was estimated at 13,457 t for the observed survey, 9,062 t for the 3-yr weighted average and 2,154 t for the random effects model, projecting forward the respective 2015 biomass (Table 12 and Figure 15). The random effects model estimates no change in biomass over the entire time series. The estimated process error variance of the random effects model that effects smoothness of the fit is estimated at a low value which results in very little change in biomass over time. A prior on the process error variance would be needed to fit the data closer. The use of the 3-yr running average is imposing a prior on smoothness by using 3 biomass values for each estimate. Using more biomass values for the average would result in a smoother fit to the data. The cvs of the survey biomass range from 0.36 to 1.0 with an average of 0.67. The process error variance in the random effects model was fixed at values of 0.005, 0.05, 0.1, 0.2, 0.3 and 0.5 to show the results of fitting with different amounts of smoothness (Figure 26). If a prior ratio of observation error to process error were developed then the process error could be fixed in the random effects model to provide some level of smoothing.

5.2 Assessment Model

The assessment model underestimates abundance in the period 1988 to 2004 (Figure 20). The model fits the abundance better from 2006 to 2016 with some observed values higher and some lower than predicted. Estimated MMB at mating from the integrated assessment peaked during 1992 at 3,901 t then declined to 1095 t in 1997 then increased again to 7,007 t in 2010 then decreased to 6,127 t in 2015 (Table 10 and Figure 21).

Catch biomass was fit well in the model (Figures 16 and 17). Estimates of recruitment showed two main peaks in 1984 and 2002 (Table 10 and Figure 18). The fits to survey length frequency data for males are shown in Figure 22.

Estimated male survey numbers peaked during 2010 at 1.85 million, then declined to 1.54 million in 2016 (Table 10 and Figure 20). Catch and bycatch in the non-pelagic trawl fishery were well fit by the assessment method (Figures 16 and 17). Estimated fishing mortality peaked in 1993 (the first year of the directed fishery) at 0.53 (**Error! Reference source not found.**). Survey selectivity was estimates were sel95% = 160.6 mm and sel50% = 114.8mm (Table A2 and Figure 18). Survey q was fixed at 1.0.

Francis effective sample size multiplier was estimated at 0.05 for the assessment model. However, when sample sizes were reduced using the Francis multiplier (0.05) and for a multiplier of 0.1, the model failed to converge. Model scenarios were run with multipliers of 0.2, 0.4 and 0.6. Lower multipliers resulted in generally higher abundance estimates throughout the time period than the base model (Figure 25). Abundance estimates for 2016 were similar for multipliers of 0.2, 0.4 and 0.6 and lower for the base model. The scenario with multiplier 0.2 had the lowest likelihood for the fit to survey abundance (Table A4). Although the base model seems to fit recent years better than models with lower multipliers (Figure 25).

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 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.

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

Where,

B_{cur}	Estimated mature male biomass projected to time of mating fishing at the OFL
$B_{MSY\ proxy}$	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)

In the integrated assessment for the Tier 4 OFL, the F_{OFL} calculated from equation 4 was applied to the legal male population at the time of the fishery (October 15) and biomass was the model estimated biomass.

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. Clark, 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).

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

Where,

B_{cur}	current estimated mature male biomass at mating fishing at the OFL
$B_{35\%}$	mature male biomass at the time of mating resulting from fishing at $F_{35\%}$
$F_{35\%}$	Fishing mortality that reduced 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) was estimated 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 $\sigma_{total} = \sqrt{\sigma_b^2 + \sigma_w^2}$.

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 1,598 t. The corresponding $F_{35\%}$ was 0.49 and, given a ratio of the MMB at mating to $B_{35\%}$ of 2.5, the calculated F_{OFL} was also 0.49 which resulted in an OFL of 1,931 t. $F_{35\%}$ was relatively high compared to natural mortality because a large fraction of MMB is protected by the 138mm size limit.

6.6 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 3,881 t. F_{MSY} was set equal to natural mortality (0.18) and the resulting OFL was 822 t.

B_{MSY} and projected MMB calculated from the 3-year running average were higher than the estimates from the integrated assessment at 5,512 t (B_{MSY}) and 6,980 t (MMB at mating). The B_{MSY} and projected MMB estimated from the random effects model were 5,512 t and 4,945 t. B_{MSY} is the same for both the random effects model and the 3-yr running average because B_{MSY} is the average of the observed survey biomass. OFL for the 3-yr weighted average was 1,462 t and the random effects model 895 t. MMB at mating and the OFL were similar for the random effects model and the integrated assessment Tier 4 calculation.

6.7 Recommended ABCs

The ABC estimated using a p* of 0.49 with an additional sigma of 0.30 was 1,436 t for the 3-yr running average, 114 t for the random effects model and 357 t for the observed survey. The ABC with a 25% buffer (ABC = OFL * 0.75) (recommended by the CPT and SSC in 2015) was 1,096 t for the 3-yr running average, 89 t for the random effects model and 278 t for the observed survey. ABC for the integrated assessment was estimated using the 25% buffer at 617 t for Tier 4 and 1,448 t for Tier 3.

6.8 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 2016 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 catchability, 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 integrated 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).

6.9 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 (often associated with high variance–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 random effects model and the integrated assessment can be useful in these years because it smooths 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 males 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.

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 (Szuwalski, et al. 2015).

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.

8. 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/jturnock/pirkc.

9. Literature cited

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10. 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:

$$N_{s,y,l} = N_{s,y,l} e^{-3M/12} \qquad \text{(A1)}$$

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.

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

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

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

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, $\mathrm{X}_{l,l'}$ 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:

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

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 (**Error! Reference source not found.**). Fishing mortality is calculated by:

$$F_{dir,y,l} = S_{l,dir} e^{\overline{F_{dir}} + n_y} \qquad \text{(A5)}$$

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:

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

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.

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, $S_{l,disc}$ is defined as:

$$S_{l,disc} = \vartheta + \varphi * L_l \qquad if\ L_l \leq 138 \qquad \text{(A7)}$$

$$S_{l,disc} = S_{l-1,disc} + 5 * \delta \qquad if\ L_l > 138 \qquad \text{(A8)}$$

$$S_{l,disc} = 0 \qquad if\ S_{l,disc} < 0 \qquad \text{(A9)}$$

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:

$$F_{trawl,y,l} = S_{l,trawl} e^{\overline{F_{trawl}} + n_y} \qquad \text{(A10)}$$

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:

$$S_{l,trawl} = \left(1 + \exp\left(-\frac{\log(19)\left(\bar{L}_l - L_{50,trawl}\right)}{L_{95,trawl} - L_{50,trawl}}\right)\right)^{-1} \quad \text{(A11)}$$

where $L_{50,\text{trawl}}$ is the length at which 50% of animals are selected, $\bar{L}_l$ is the midpoint of length-class l, and $L_{95,\text{trawl}}$ 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 (**Error! Reference source not found.**).

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

$$S_{l,surv} = Surv_q * \left(1 + \exp\left(-\frac{\log(19)\left(\bar{L}_l - L_{50,surv}\right)}{L_{95,surv} - L_{50,surv}}\right)\right)^{-1} \quad \text{(A12)}$$

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. A switch has been added to the code to allow $Surv_q$ 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, $\hat{N}^{surv}_{s,y,l}$, is given by:

$$\hat{N}^{surv}_{s,y,l} = S_{l,surv} N_{s,y,l} \quad \text{(A13)}$$

Catch

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

$$\hat{C}^{dir}_{y,l} = S_{l,dir} N_{s,y=fishtime,l}(1 - e^{-F_{y,l}}) \quad \text{(A14)}$$

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 Powell (1967) such that the probability of molting is 1 until approximately the age of maturity at which time it steadily declines (**Error! Reference source not found.**):

$$P_l = 1 - \left(1 + \exp\left(-\frac{\log(19)\left(\bar{L}_l - L_{50,molt}\right)}{L_{95,molt} - L_{50,molt}}\right)\right)^{-1} \quad \text{(A15)}$$

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.:

$$X_{l,l'} = Y_{l,l'} / \sum_{l'} Y_{l,l'} \quad \text{(A16)}$$

$$Y_{l,l'} = (\Delta_{l,l'})^{(L_l - (\bar{L}_l - 2.5))/\beta} e^{-\Delta_{l,l'}/\beta} \quad \text{(A17)}$$

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

$$L_l = \delta_1 + \delta_2 \bar{L}_l \quad \text{(A18)}$$

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*:

$$\Delta_{l,l'} = \bar{L}_{l'} + 2.5 - \bar{L}_l \quad \text{(A19)}$$

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 **Error! Reference source not found.**.

Recruitment

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

$$Pr_l = (\Delta_{l,l'})^{\mu_1/\mu_2} e^{-\Delta_{l,l'}/\mu_2} / \sum_{l'} (\Delta_{l,l'})^{\mu_1/\mu_2} e^{-\Delta_{l,l'}/\mu_2} \quad \text{(A20)}$$

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 and changes depending on whether both males and females are fit or if only males are fit (compare **Error! Reference source not found.** and Figure).

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).

$$L_1 = \begin{cases} \sum_s \sum_y \sum_l -\gamma_y p^{obs}_{surv,l,y,s} \ln\left(p^{pred}_{surv,l,y,s} + \kappa\right) & if\ \ p^{obs}_{surv,l,y,s} \geq 0.01 \\ 0 & if\ \ p^{obs}_{surv,l,y,s} < 0.01 \end{cases} \quad \text{(A21)}$$

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.

$$L_2 = \sum_s \sum_y \frac{\left(\ln\left(N^{pred}_{y,s} + \kappa\right) - \ln\left(N^{obs}_{y,s} + \kappa\right)\right)^2}{\ln\left(\left(CV_{y,s}\right)^2 + 1\right)} \quad \text{(A22)}$$

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

$$L_3 = \sum_y \frac{\left(\ln\left(C^{pred}_y + \kappa\right) - \ln\left(C^{obs}_y + \kappa\right)\right)^2}{\ln\left(\left(CV_y{}^{cat}\right)^2 + 1\right)} \quad \text{(A23)}$$

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).

$$L_3 = \sum_y \frac{\left(\ln\left(\sum_s byC_{y,s}^{pred} + \kappa\right) - \ln\left(byC_{y,s}^{obs} + \kappa\right)\right)^2}{\ln\left(\left(CV_y{}^{bycatch}\right)^2 + 1\right)} \tag{A24}$$

where $byC_{y,s}^{pred}$ is the bycatch in tonnes of sex s from the non-pelagic trawl fishery predicted by the model for year y, byC_y^{obs} 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:

$$P_2 = \gamma_w \sum_l (\ln(\eta_l) - \ln(\eta_{l-1}))\ \hat{}2 \tag{A25}$$

where, $\eta_{l,}$ 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).

11. 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 2015/2016	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
1999-2015/16		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. 2015/16 data through August 11, 2016.**

	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	0.73	1.03
2015/2016	0.167	0.00	0.053	0.03	0.07

Table 4. Percent 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	53	47	0	0	1,439
2015/16	40	60	0	0	382

Table 5. Total male bycatch (t), Total bycatch (t) and total catch (t) with mortality applied for Pribilof red king crab from 1991 to August 12, 2015/16.

Year	Total male bycatch (t)	total bycatch (t)	Total catch (t)
1991/1992	46.19	46.19	46.19
1992/1993	192.05	192.05	192.05
1993/1994	132.47	132.47	1315.49
1994/1995	15.56	15.56	622.9
1995/1996	11.13	11.13	418.45
1996/1997	4.05	4.05	94.92
1997/1998	12.1	12.1	355.39
1998/1999	18.13	29.47	265.04
1999/2000	16.89	25.05	16.89
2000/2001	6.79	6.79	6.79
2001/2002	9.52	9.52	9.52
2002/2003	9.61	9.61	9.61
2003/2004	10.6	10.6	10.6
2004/2005	6.69	6.69	6.69
2005/2006	29.43	31.24	29.43
2006/2007	29.84	30.75	29.84
2007/2008	5.64	5.73	5.64
2008/2009	8.67	8.67	8.67
**2009/2010	1.24	1.24	1.24
**2010/2011	6.7	6.7	6.7
**2011/2012	4.82	4.82	4.82
**2012/2013	13.1	13.1	13.1
2013/2014	2.24	2.24	2.24
2014/2015	1.76	1.76	1.76
2015/2016	0.32	0.32	0.32

Table 6. 2016 Pribilof Islands District red king crab male abundance, male biomass (>= 105mm), 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
2016/2017	1807323	4676	1898

Table 7. 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 CV	Total female at survey 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
2016/2017	0.72	0.69	0.61

Table 10. Estimated recruitment (numbers), male mature biomass (t) at time of mating, total male abundance (1000s) from the integrated assessment method when males only are fit (updated).

Year	Recruitment	MMB (t)	Male
1975	9407.1	74	33.5
1976	14102.8	158	51.6
1977	10063.5	224	65.6
1978	7485.4	256	71.2
1979	8530.3	261	69.7
1980	15456.6	249	64.5
1981	53831.7	231	58.3
1982	300177.7	213	52.8
1983	169936.2	195	49.8
1984	3960476.5	177	48.2
1985	972586.8	162	73.9
1986	370107.0	154	105.8
1987	552229.2	185	162.0
1988	257667.6	306	270.0
1989	133827.5	793	456.4
1990	132344.4	2209	725.5
1991	928923.6	3452	1000.7
1992	433556.7	3901	1143.2
1993	310040.0	2464	1117.5
1994	1957708.4	1827	700.5
1995	1570327.9	1345	532.9
1996	170718.6	1243	452.8
1997	74019.3	1095	480.0
1998	113248.9	1115	488.1
1999	454678.2	1521	547.0
2000	691971.3	2338	708.4
2001	1870682.9	3248	875.5
2002	4092438.1	3684	980.2
2003	651297.5	3666	1007.8
2004	263785.9	3475	983.4
2005	305410.3	3335	993.5
2006	788052.4	3469	1083.2
2007	936513.8	4295	1280.7
2008	483788.2	5832	1557.9
2009	983490.3	6845	1787.5
2010	1394605.9	7007	1850.3
2011	233935.4	6755	1784.6
2012	111497.7	6496	1694.1
2013	83897.8	6337	1630.5
2014	75499.6	6169	1593.0
2015	73406.2	6127	1565.4
2016	73406.2		1537.2

Table 11. Estimates of survey male >= 120mm biomass (t) at the time of the survey, 3-year running weighted average and the random effects model with lower and upper confidence intervals for the random effects estimates.

Year	MB GE12 0	3-yr running avg	rando m effect	RE LCI	RE UCI
1976	165	NA	2,283	1,918	2,719
1977	119	585	2,284	1,919	2,718
1978	1,250	648	2,284	1,920	2,717
1979	556	1,042	2,285	1,922	2,717
1980	1,269	850	2,287	1,924	2,718
1981	312	1,060	2,289	1,927	2,719
1982	1,464	691	2,292	1,930	2,722
1983	527	679	2,295	1,933	2,724
1984	317	368	2,298	1,936	2,727
1985	61	211	2,302	1,940	2,732
1986	138	95	2,307	1,945	2,737
1987	54	107	2,313	1,950	2,743
1988	107	609	2,319	1,956	2,749
1989	1,529	961	2,325	1,962	2,756
1990	1,141	2,526	2,332	1,968	2,764
1991	4,430	3,133	2,339	1,974	2,771
1992	3,305	5,172	2,346	1,980	2,779
1993	9,873	6,597	2,353	1,986	2,786
1994	9,139	13,423	2,359	1,992	2,794
1995	18,05	7,350	2,365	1,997	2,800
1996	2,362	6,816	2,371	2,002	2,806
1997	6,159	2,955	2,376	2,007	2,813
1998	2,324	3,783	2,381	2,011	2,819
1999	5,523	3,614	2,386	2,016	2,825
2000	4,320	5,298	2,391	2,020	2,831
2001	8,603	5,614	2,396	2,023	2,837
2002	7,037	6,853	2,400	2,027	2,842
2003	5,373	5,194	2,404	2,030	2,847
2004	3,622	3,283	2,407	2,033	2,852
2005	1,238	4,805	2,411	2,035	2,856
2006	7,003	5,190	2,415	2,038	2,861
2007	5,224	6,086	2,418	2,040	2,865
2008	5,462	4,642	2,420	2,041	2,869
2009	2,500	4,333	2,422	2,043	2,873
2010	4,405	3,779	2,424	2,044	2,876
2011	3,834	4,292	2,426	2,044	2,879
2012	4,477	5,350	2,428	2,045	2,882
2013	7,749	7,455	2,429	2,045	2,885
2014	12,04	11,2	2,430	2,045	2,888
2015	15,17	10,218	2,431	2,045	2,890
2016	4,150	9,423	2,431	2,044	2,891

Table 12. Projected MMB at mating for survey males >= 120mm, the 3-yr running average and the random effects model fit.

	projected GE120mm to feb 15 removing catch		
	Observed survey	3-yr weighted average	Random Effects
1976	146	NA	2,025
1977	105	519	2,025
1978	1,108	575	2,026
1979	493	924	2,027
1980	1,125	754	2,028
1981	277	940	2,030
1982	1,298	613	2,033
1983	467	602	2,035
1984	281	326	2,038
1985	55	187	2,042
1986	122	84	2,046
1987	48	95	2,051
1988	95	540	2,057
1989	1,357	852	2,063
1990	1,012	2,240	2,068
1991	3,929	2,779	2,075
1992	2,739	4,395	2,034
1993	7,441	4,536	1,894
1994	7,482	11,282	777
1995	15,596	6,101	1,475
1996	2,000	5,950	1,684
1997	5,107	2,266	2,012
1998	1,796	3,091	1,756
1999	4,881	3,189	1,851
2000	3,825	4,692	2,104
2001	7,621	4,970	2,118
2002	6,232	6,068	2,119
2003	4,755	4,596	2,122
2004	3,206	2,905	2,125
2005	1,069	4,232	2,132
2006	6,181	4,573	2,112
2007	4,627	5,392	2,114
2008	4,836	4,108	2,141
2009	2,216	3,841	2,140
2010	3,900	3,345	2,149
2011	3,396	3,801	2,145
2012	3,958	4,732	2,148
2013	6,871	6,610	2,141
2014	10,683	9,963	2,153
2015	13,457	9,062	2,154

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	2016
srv_q	1	1	1
fish_sel50	138	138	138
fish_sel95	138.05	138.05	138.05
srv_sel50	102.15	100.3	114.78
srv_sel95	141.06	147.88	160.63
log_avg_fmort_dir	-0.98	-1.72	-1.11
log_avg_fmort_trawl	-4.88	-5.5	-5.39
mean_log_rec	11.21	11.62	12.11
A_f (growth)	25.42	25.3	NA
A_m (growth)	9.77	7.76	5.78
B_f (growth)	0.86	0.86	NA
B_m (growth)	1.13	1.15	1.13
growth_beta_males	0.72	1.12	0.78
alpha_rec	0.86	5.56	0.98
beta_rec	0.16	1.53	0.19

Table A3. Likelihood component contribution to the likelihood and associated weights for the assessment model fit to males only.

Likelihood component	negLogLike (males only)	Weighting
Survey numbers (males)	45.7	.36 -1 (CVs)
Survey length frequencies (male)	10,012.3	18-200 (sample size)
Catch	0.003	.005(CV)
Trawl	0.019	.01 (CV)
Smoothness penalties		
Trawl fishing mortality	38.6	1 (CV)
Fishing mortality	4.3	1 (CV)
Recruitment	48.9	1 (CV)

Table A4. Likelihood component contribution to the likelihood and associated weights for the assessment model scenarios with multipliers on the survey length sample sizes of 0.2, 0.4, 0.6 and the base model (1.0).

Likelihood component	Base Model (1.0)	0.2	0.4	0.6	Weighting
Survey numbers (males)	45.7	29.9	32.7	36.1	.36 -1 (CVs)
Survey length frequencies (male)	10,012.3	2018.9	4024.6	6023.7	18-200 (Base model sample size)
Catch	0.003	0.001	0.001	0.001	.005(CV)
Trawl	0.019	0.019	0.019	0.019	.01 (CV)
Smoothness penalties					
Trawl fishing mortality	38.6	38.4	38.3	38.4	1 (CV)
Fishing mortality	4.3	4.3	4.3	4.3	1 (CV)
Recruitment	48.9	20.4	30.1	37.5	1 (CV)

12. Figures

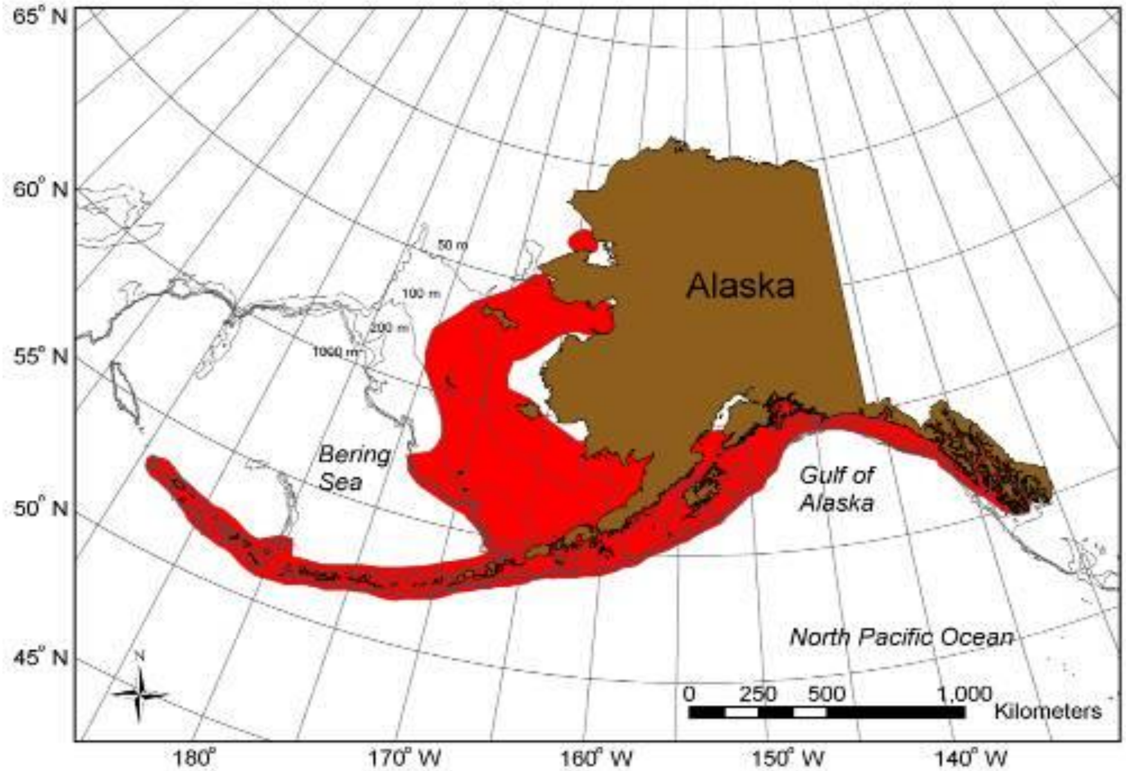

Figure 1. Red king crab distribution.

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

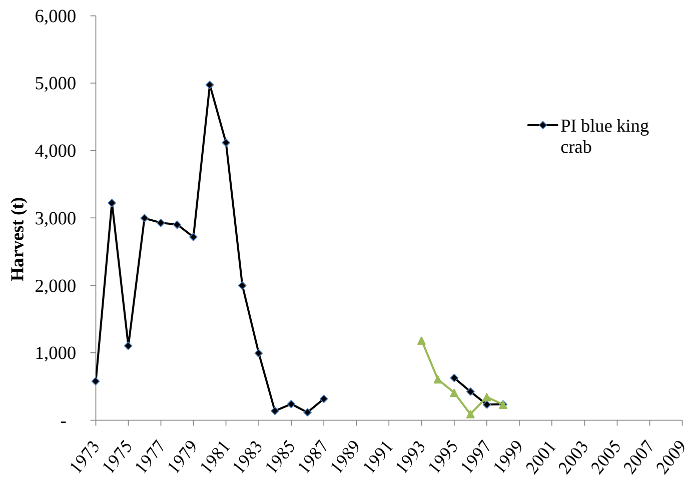

Figure 3. Historical harvests and GHLs for Pribilof Island blue (diamonds) and red king crab (triangles) (Bowers et al. 2011).

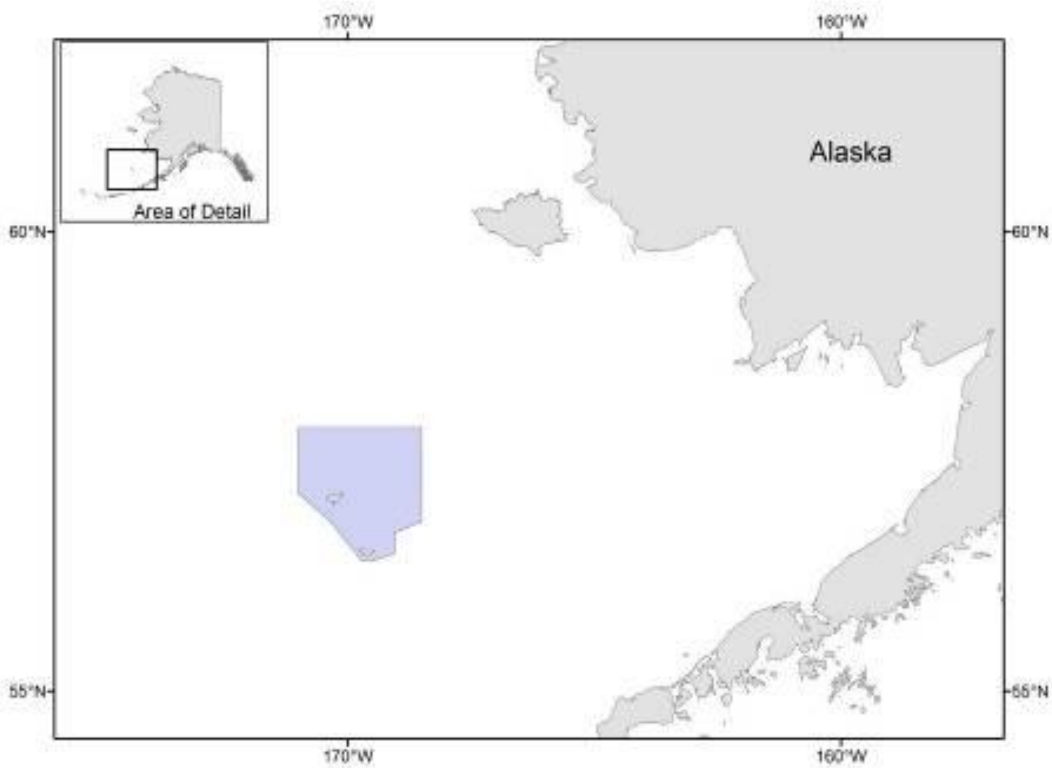

Figure 4. The shaded area shows the Pribilof Islands Habitat Conservation area.

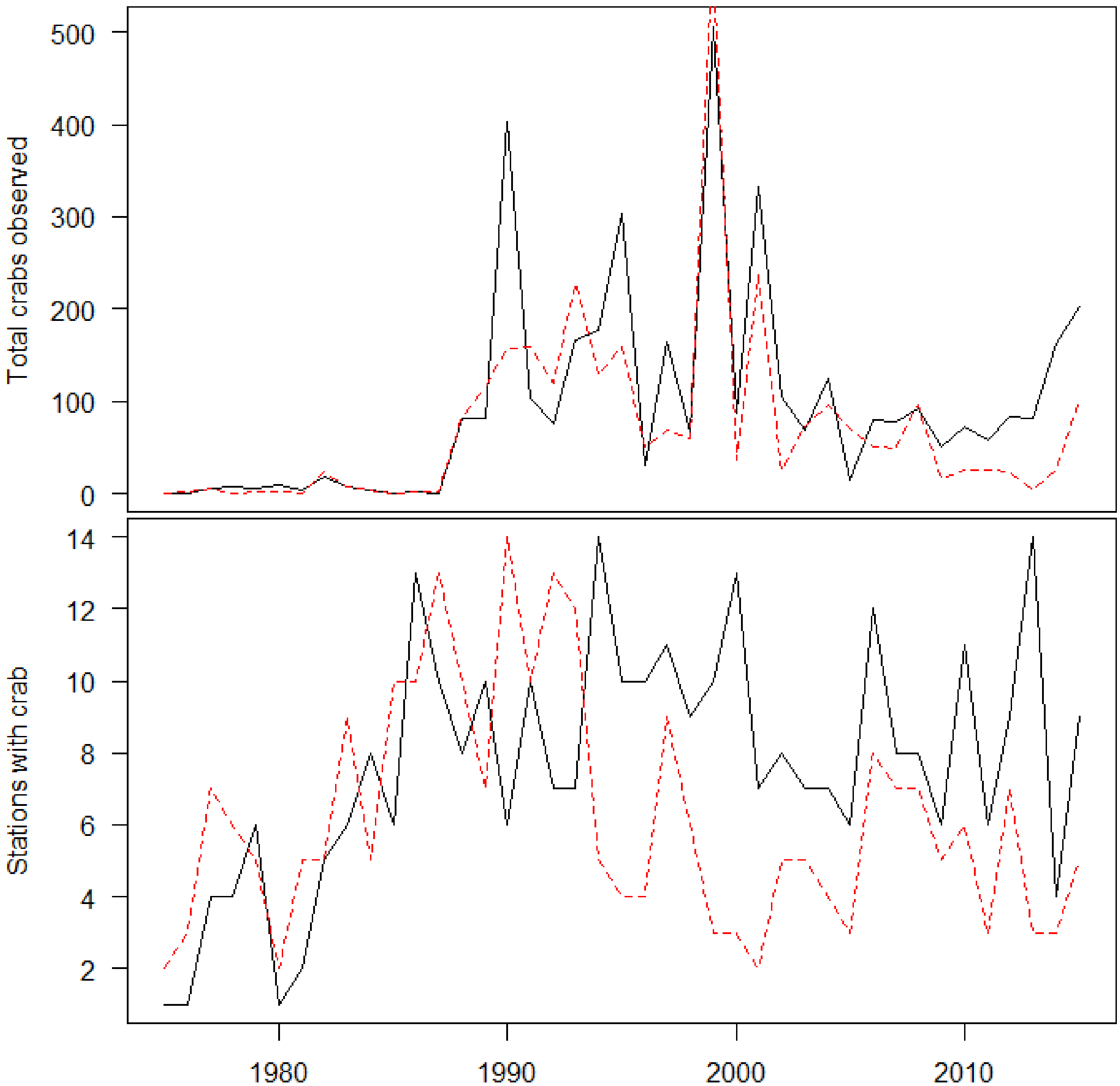

Figure 5. Total number of observed crab (top) and the number of stations that reported observations of crab (female = dashed line, male = solid line) from 1975-2014.

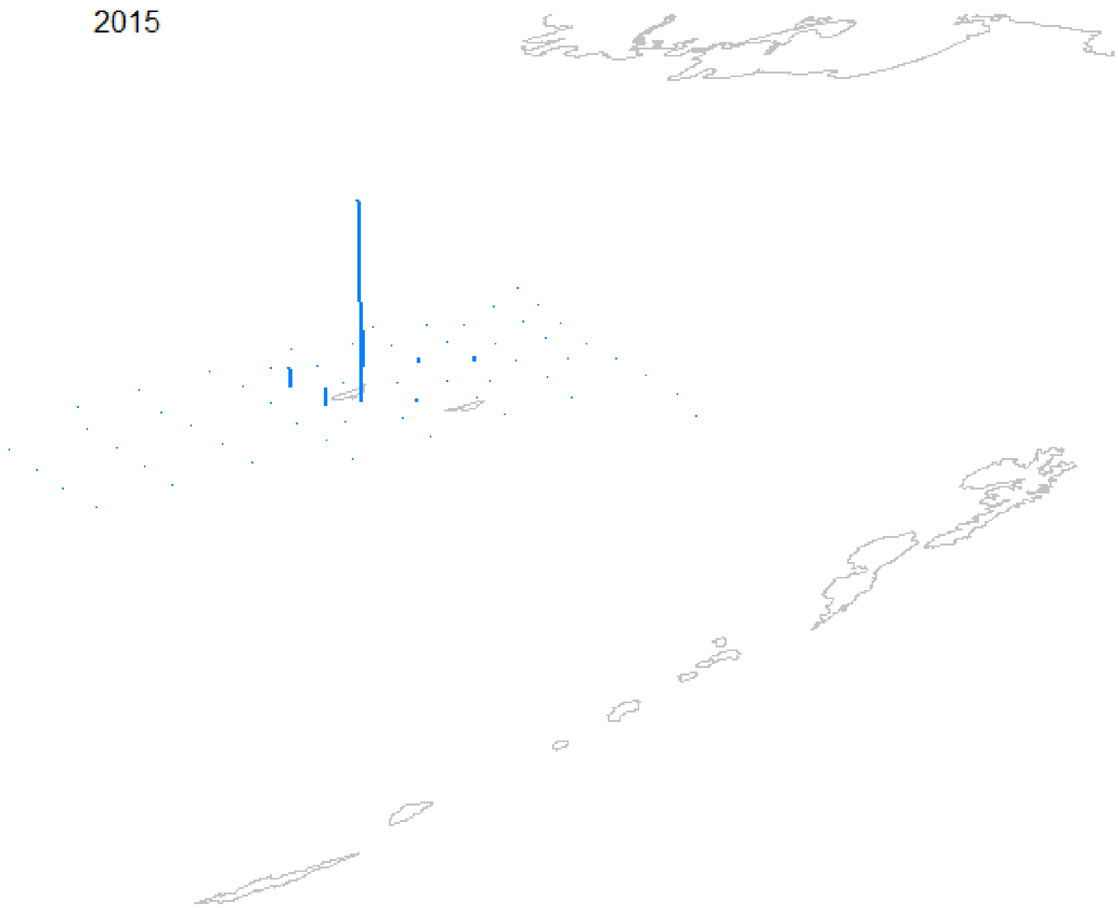

Figure 6. Male red king crab relative density by station in the Pribilof Island district in 2015. Blue bars represent the relative magnitude of the density calculated from the NMFS trawl survey.

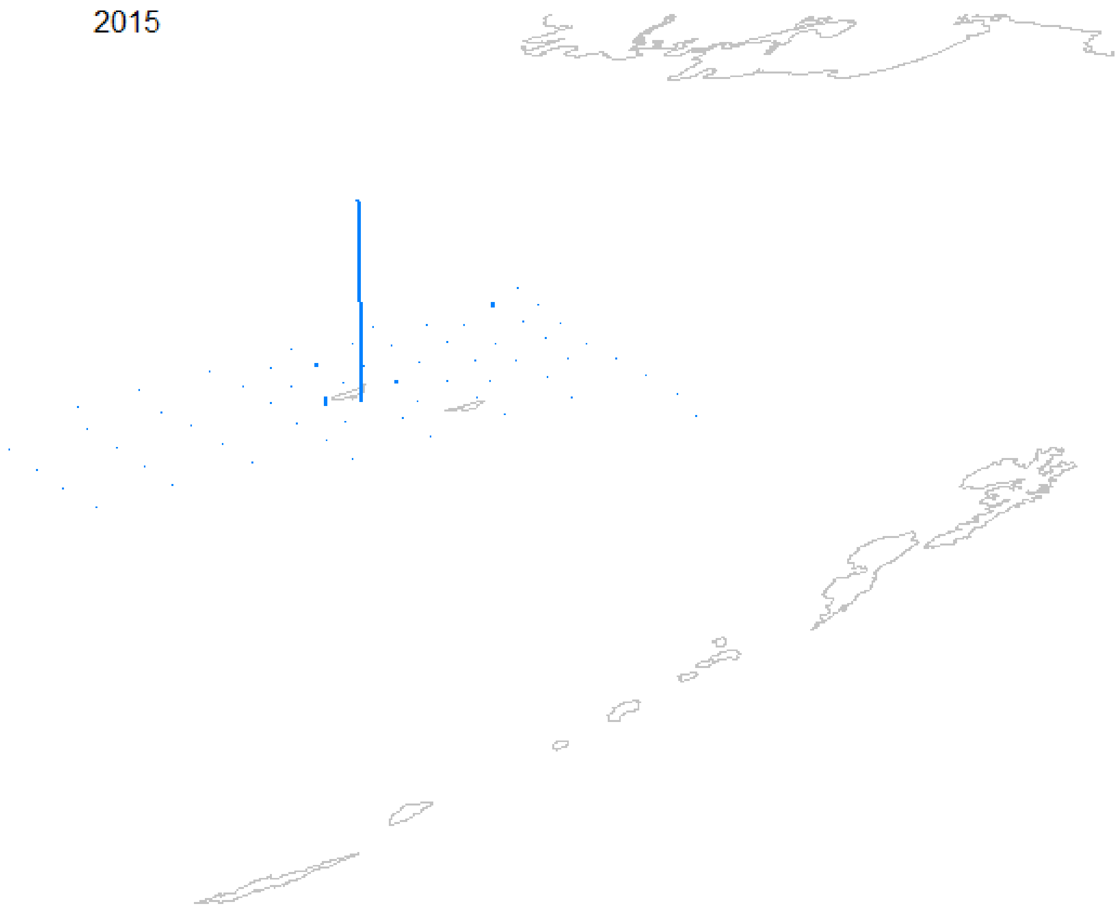

Figure 7. Female red king crab relative density by station in the Pribilof Island district in 2015. Blue bars represent the relative magnitude of the density calculated from the NMFS trawl survey.

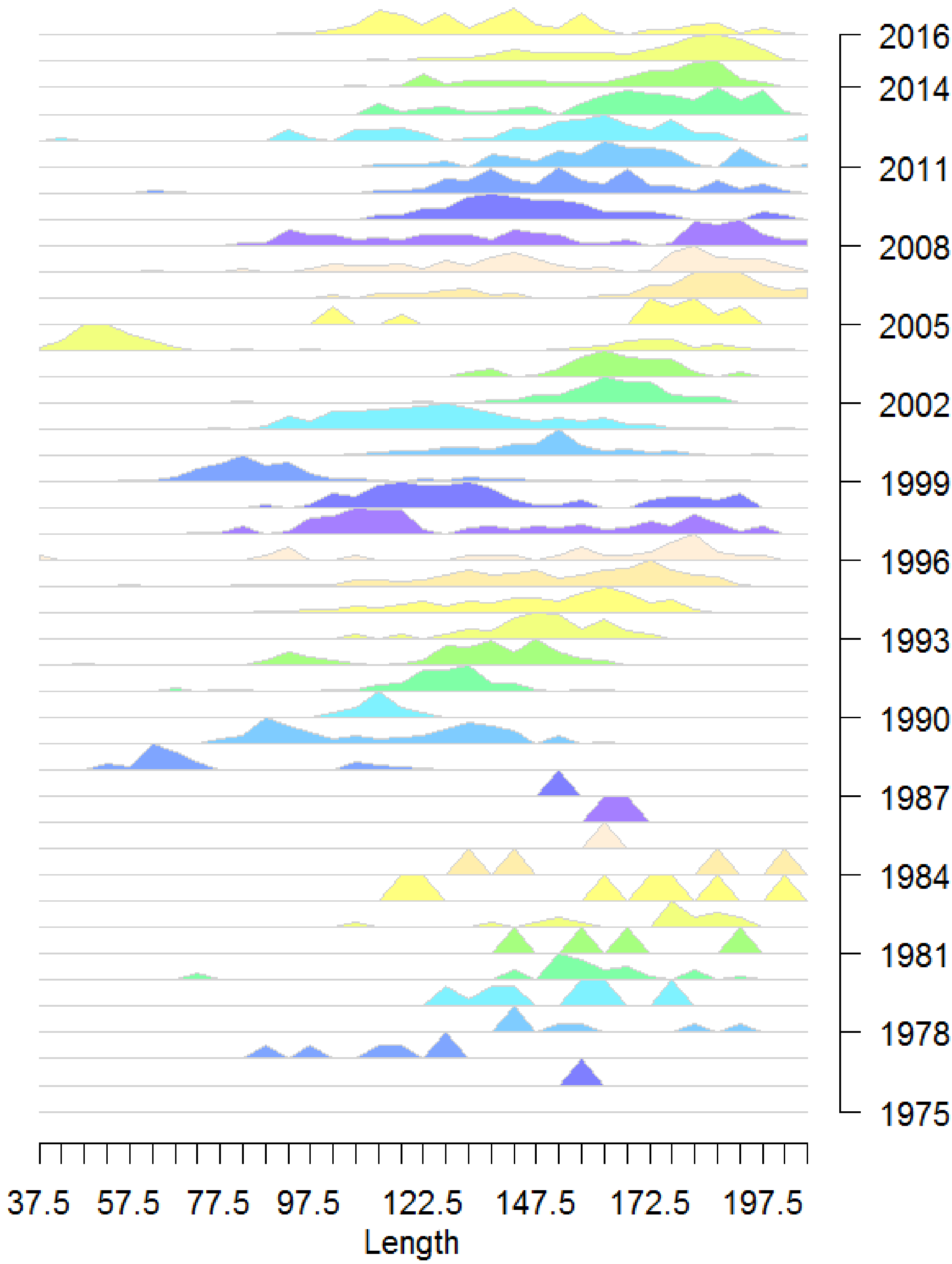

Figure 8. Observed length frequencies (proportions sum to 1.0) by 5 mm length classes of Pribilof Islands male red king crab (Paralithodes camtschaticus) from 1975 to 2016.

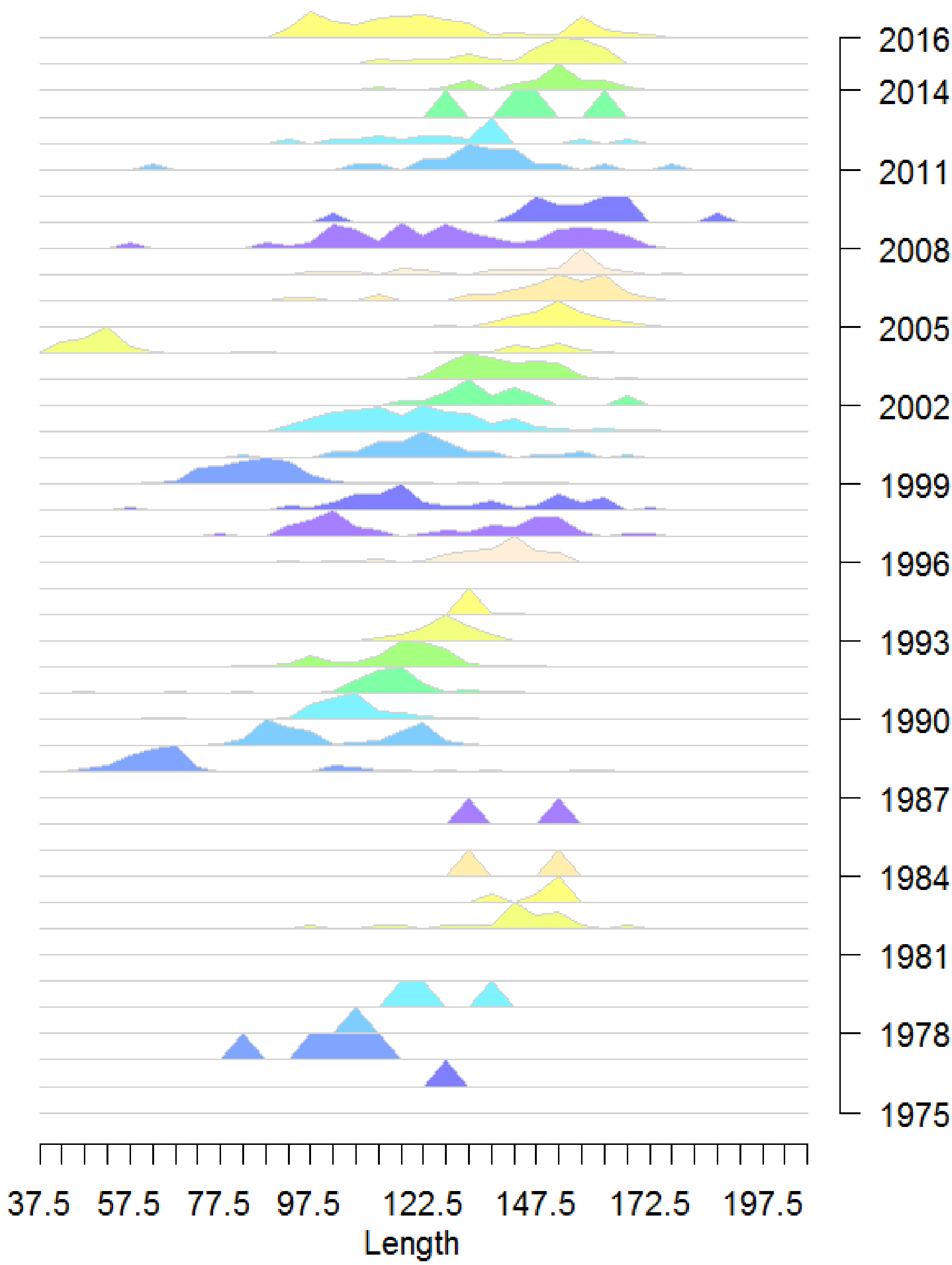

Figure 9. Observed length frequencies (proportions sum to 1.0) by 5 mm length classes of Pribilof Islands female red king crab (Paralithodes camtschaticus) from 1975 to 2016.

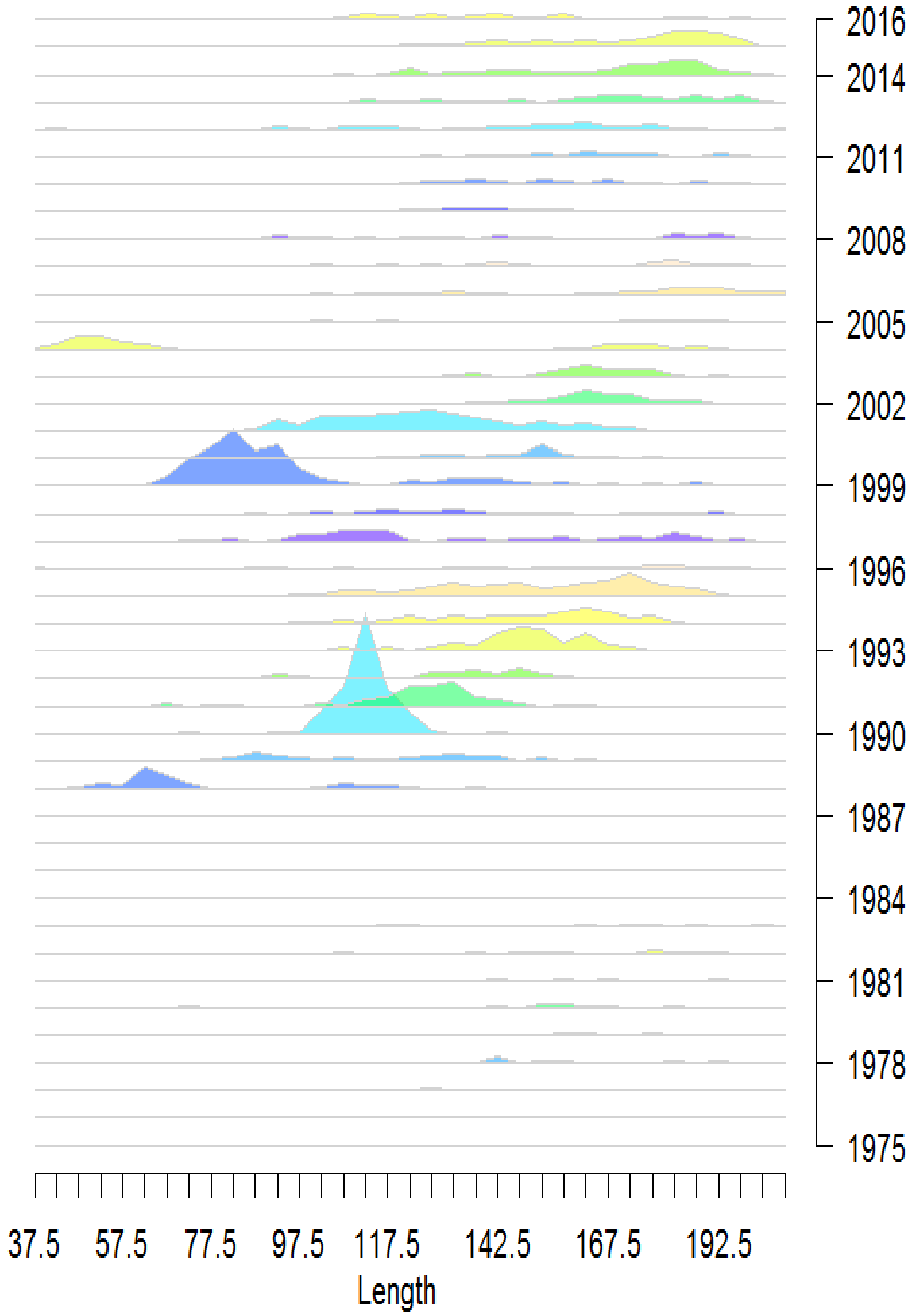

Figure 10. Observed numbers at length by 5 mm length classes of Pribilof Islands male red king crab (Paralithodes camtschaticus) from 1975 to 2016.

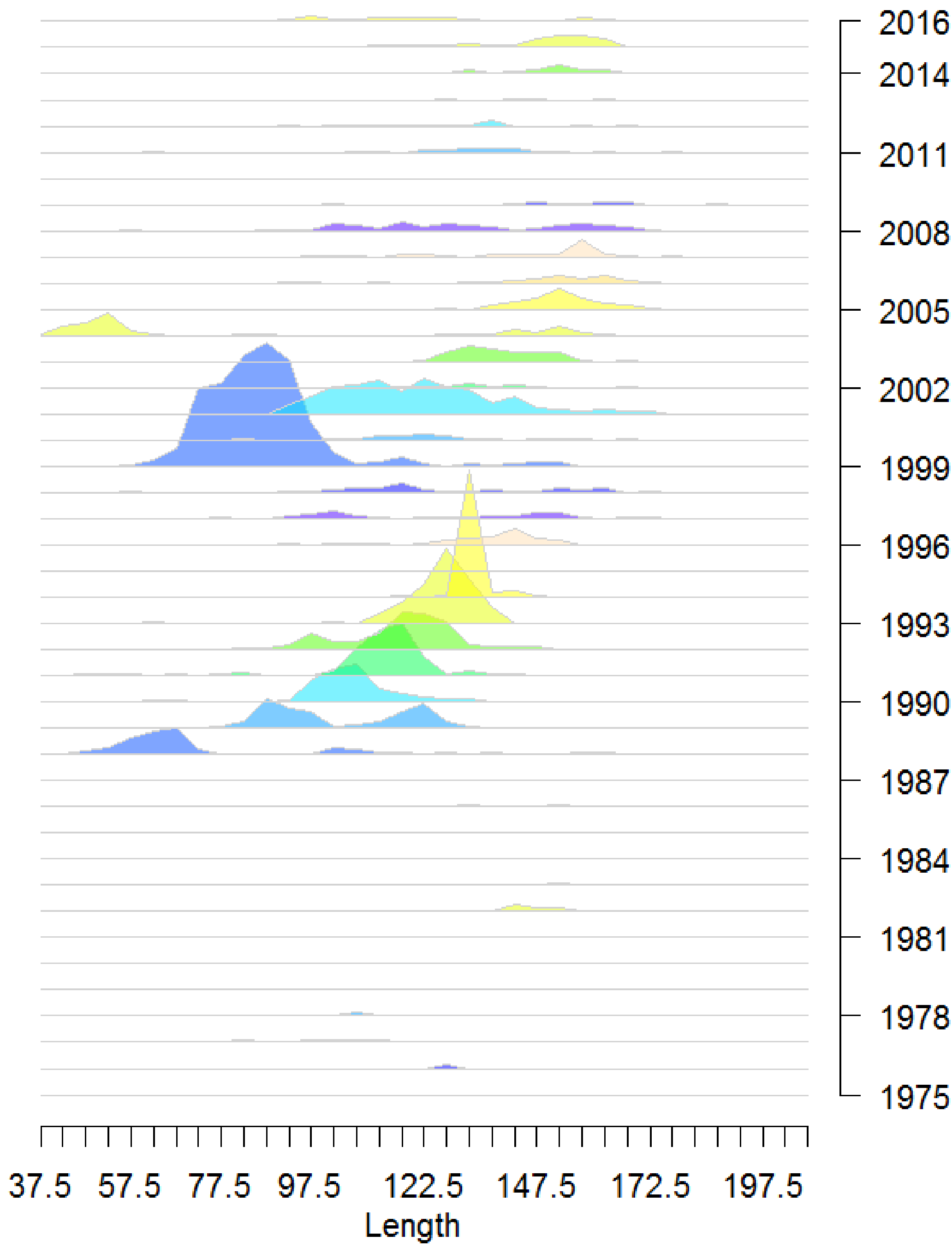

Figure 11. Observed numbers at length by 5 mm length classes of Pribilof Islands female red king crab (Paralithodes camtschaticus) from 1975 to 2016.

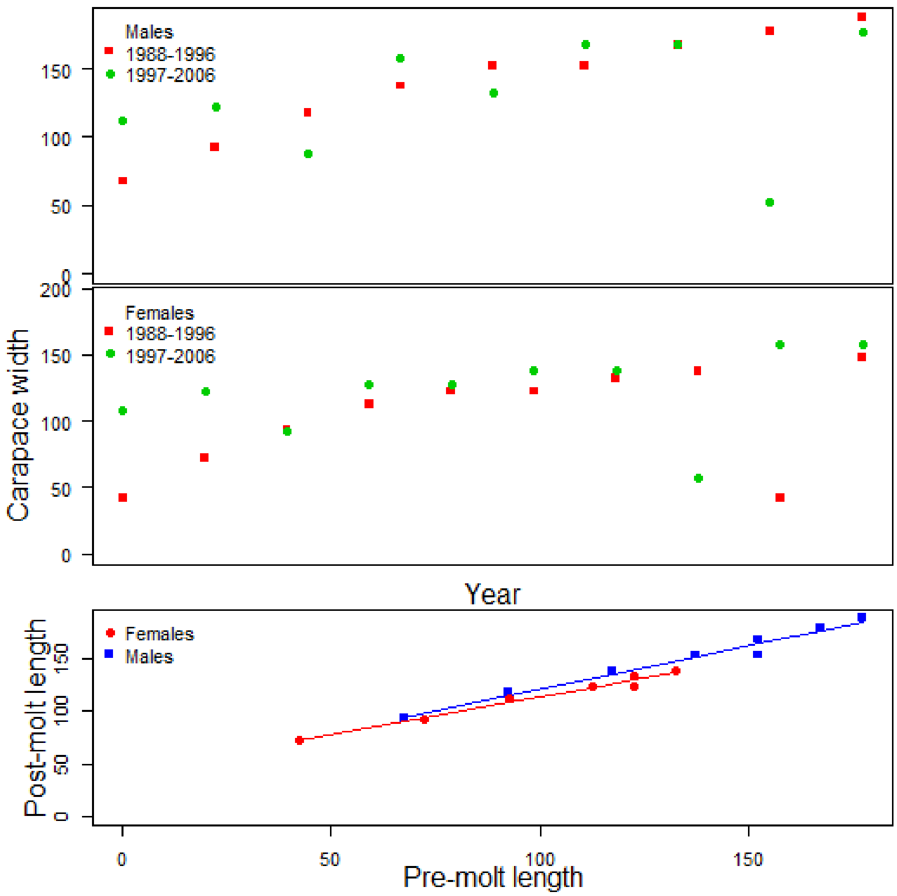

Figure 12. Modes of the length frequency distribution for males and females plotted for two time periods over which two cohorts were observed to move through the population. Growth per molt calculated from the modes from the length frequencies with fitted linear relationship (bottom).

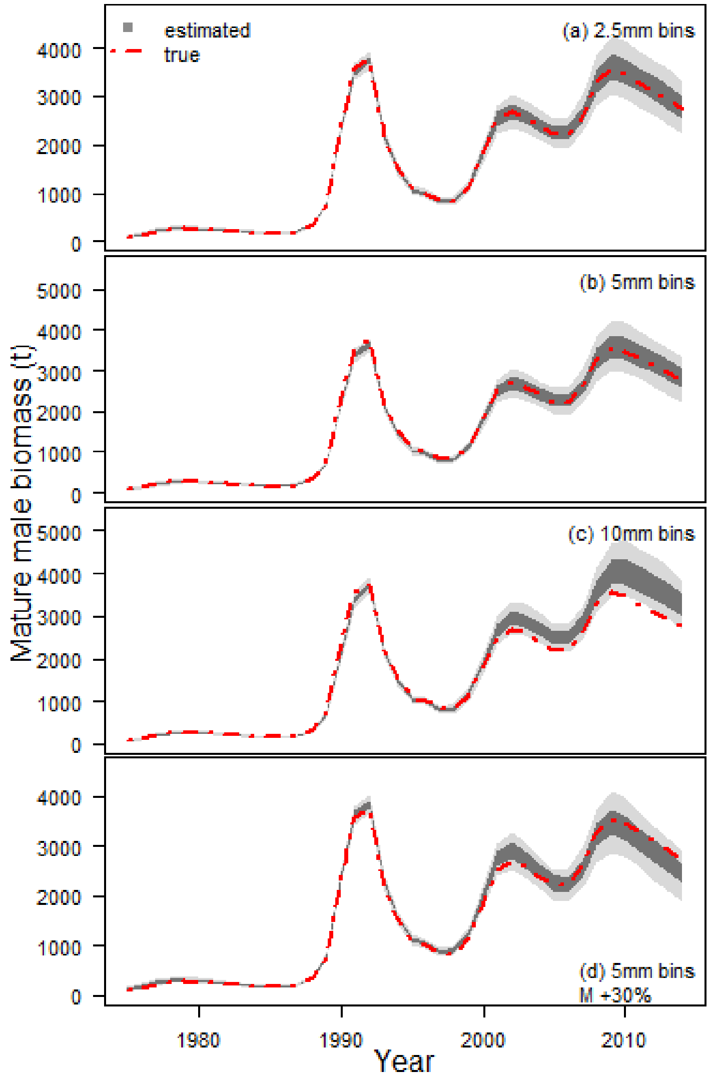

Figure 13. Estimates of MMB in simulation aimed at the testing of the integrated assessment method when binning data into different size bins. Panel (d) shows a case in which M was mis-specified. Red dashed lines are the true quantity; grey shading indicates the intersimulation quantiles for estimated MMB.

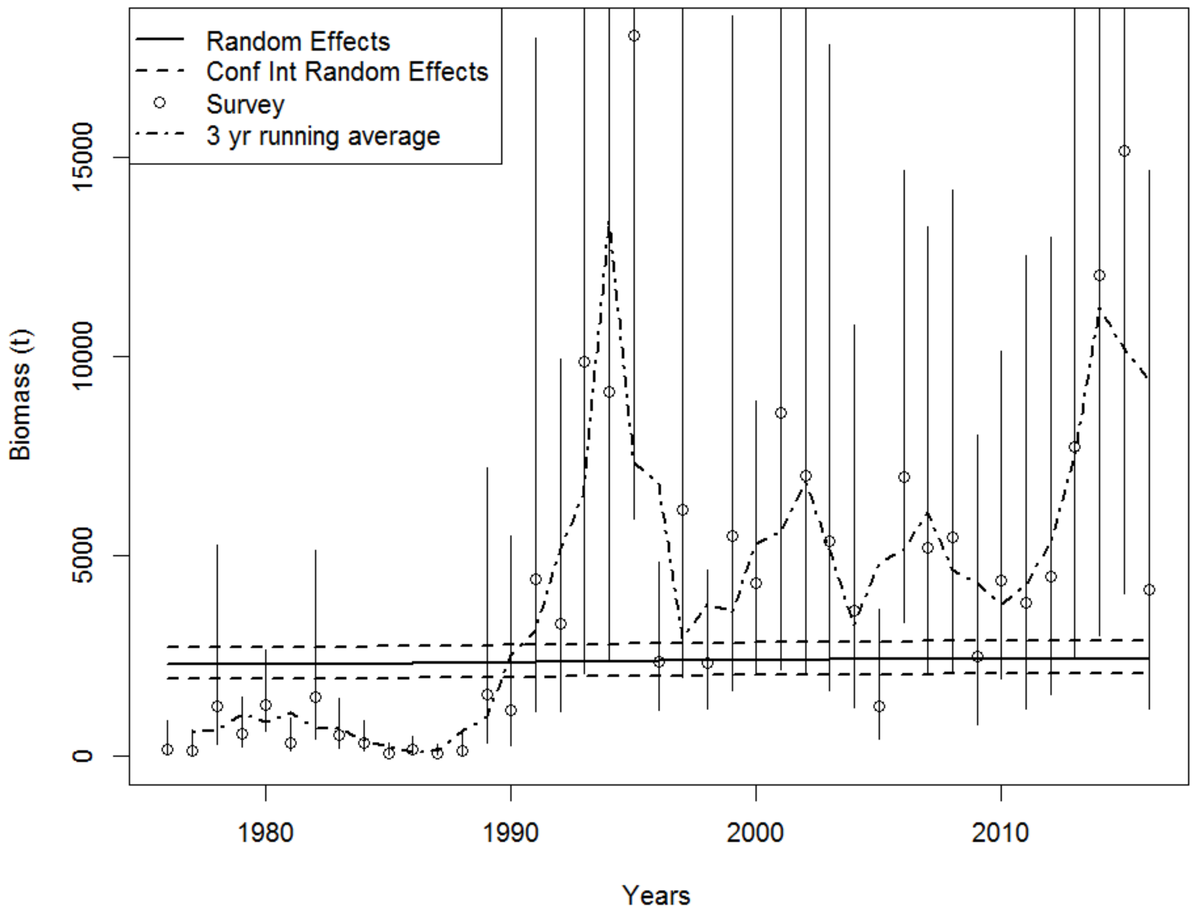

Figure 14. Three-year running average and random effects model fit to male biomass > 120mm at survey time.

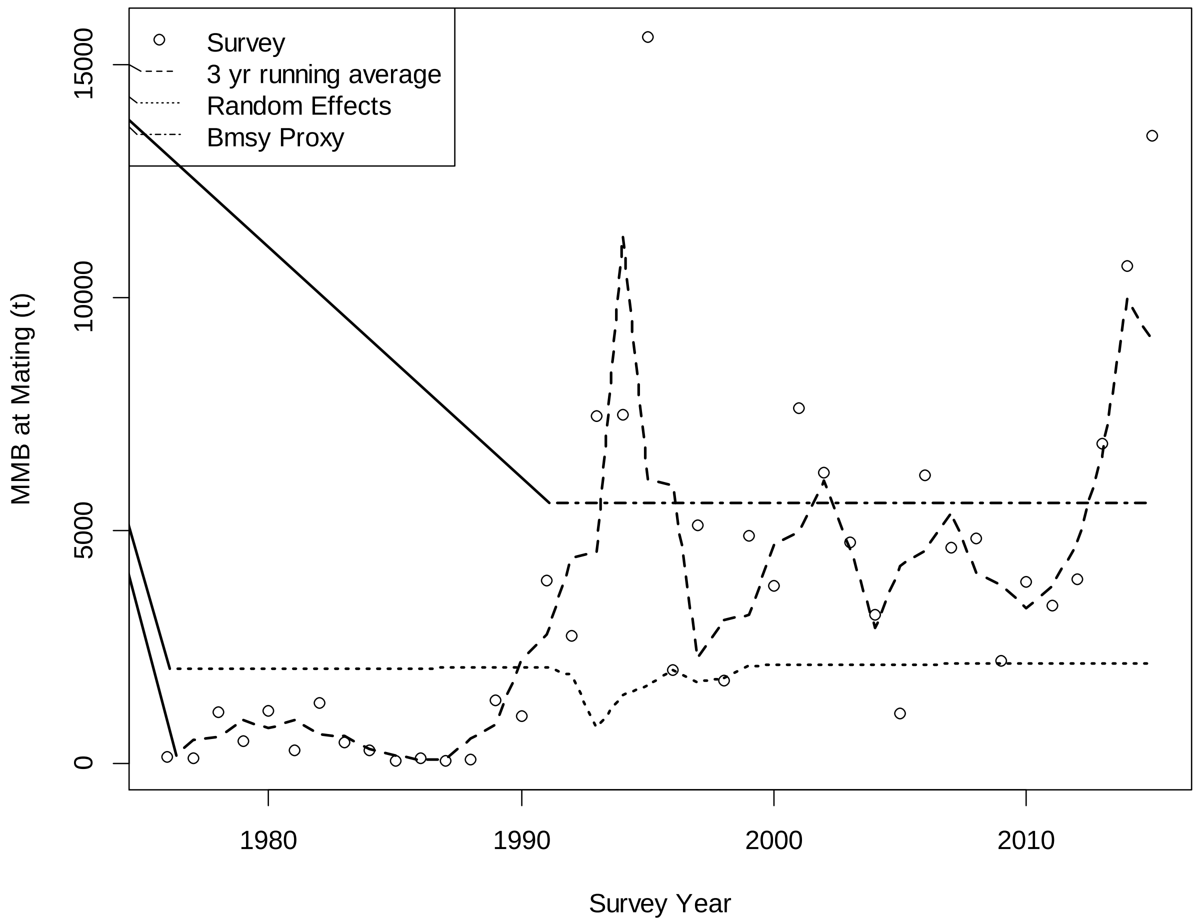

Figure 15. MMB at mating (February 15 of survey year +1) estimated from the survey data, 3 yr running average and the Random effects model. Bmsy proxy is the average of the 1991 to 2015 MMB at mating survey data (February 15 1992 to February 15 2016).

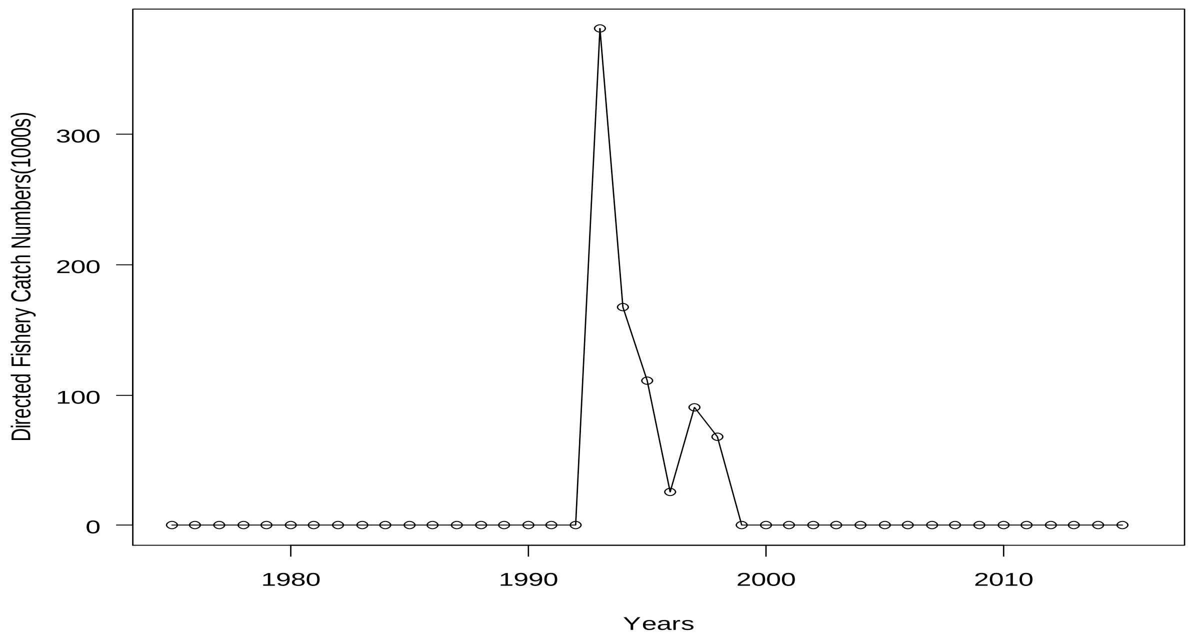

Figure 16. Model fit to directed fishery catch.

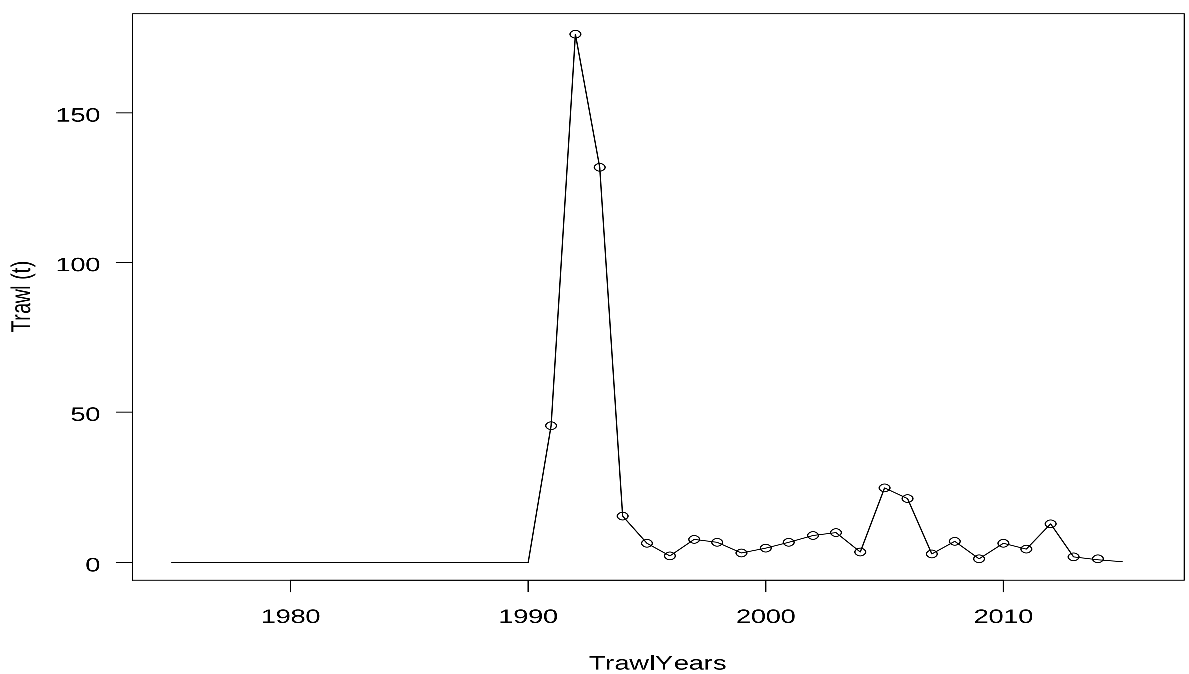

Figure 17. Model fit to Trawl bycatch.

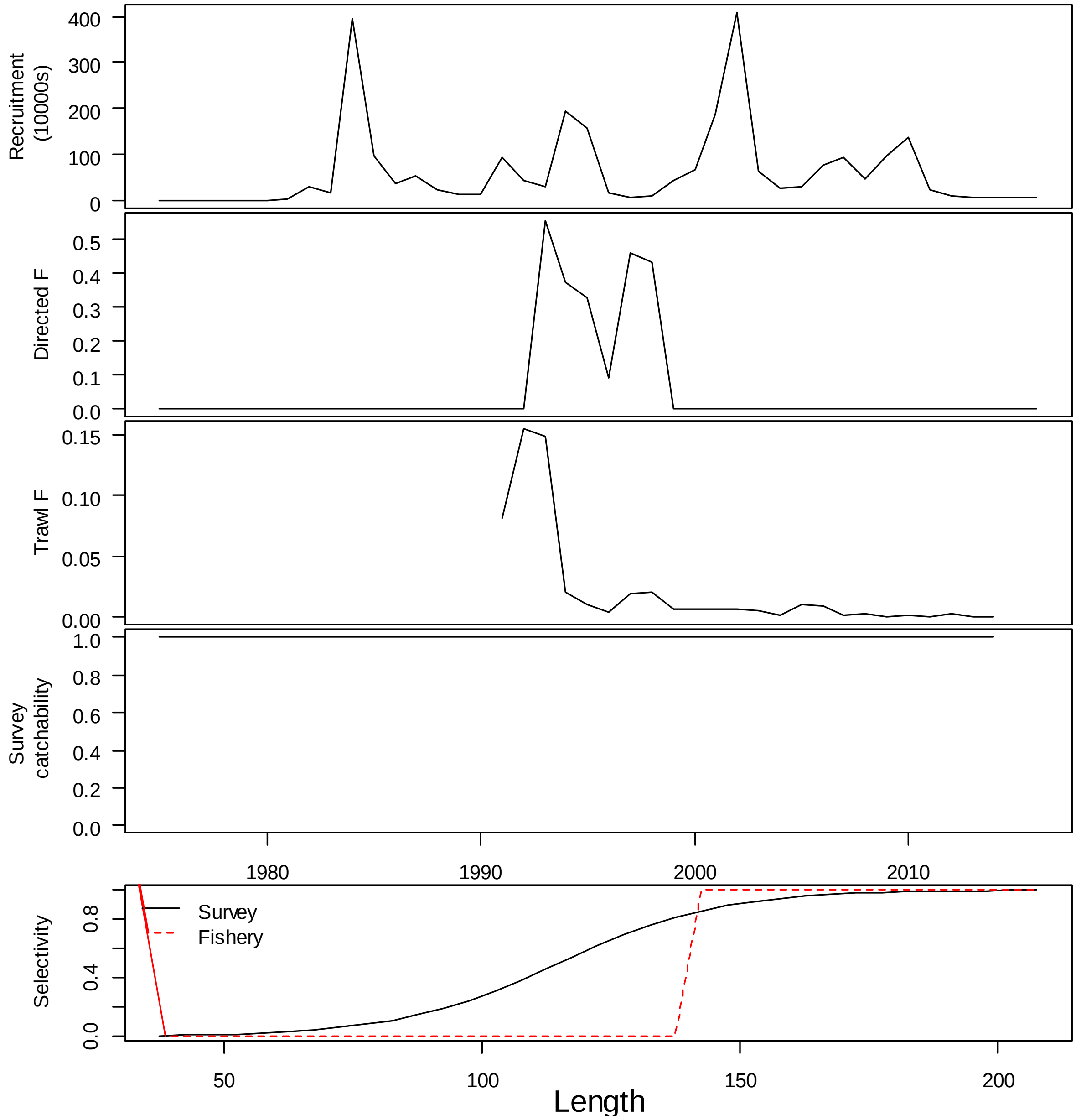

Figure 18. Model estimates of recruitment, directed F, trawl bycatch F, survey catchability, fishery selectivity and survey selectivity.

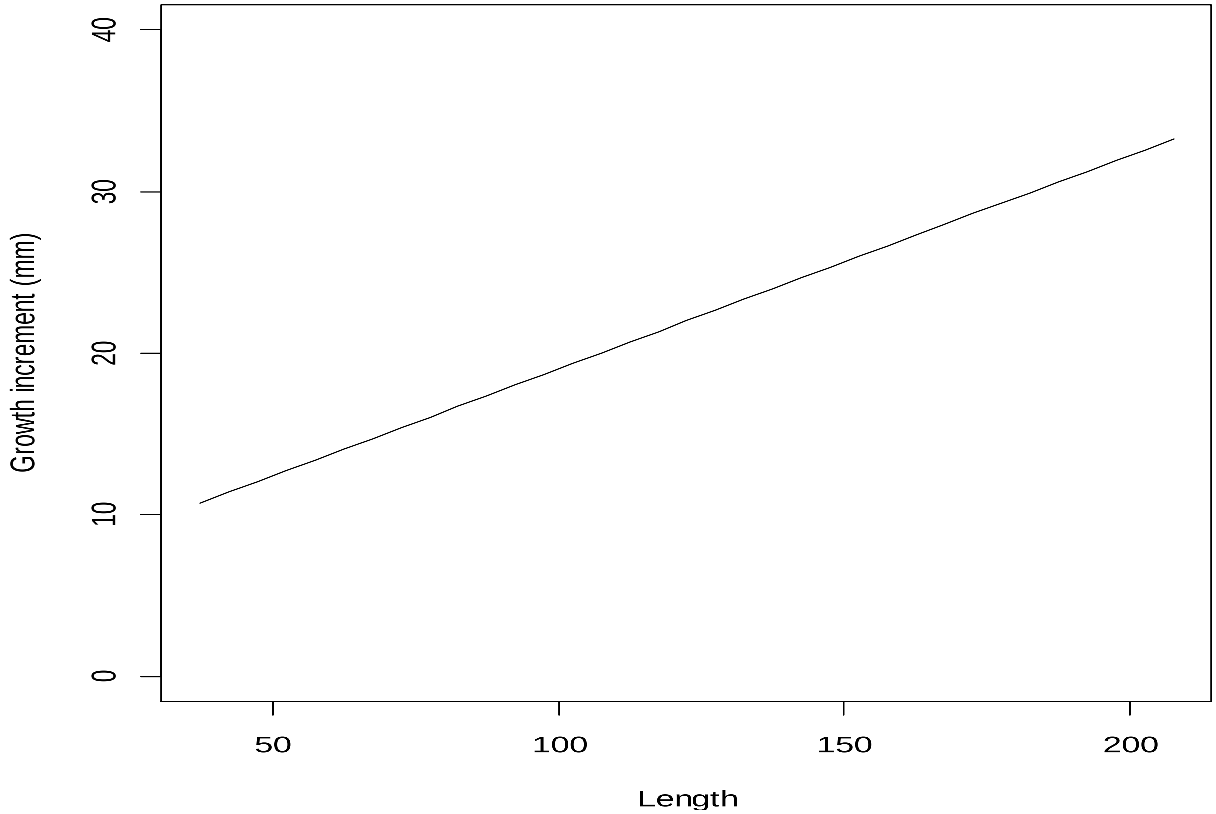

Figure 19. Model estimated growth increment for male crab.

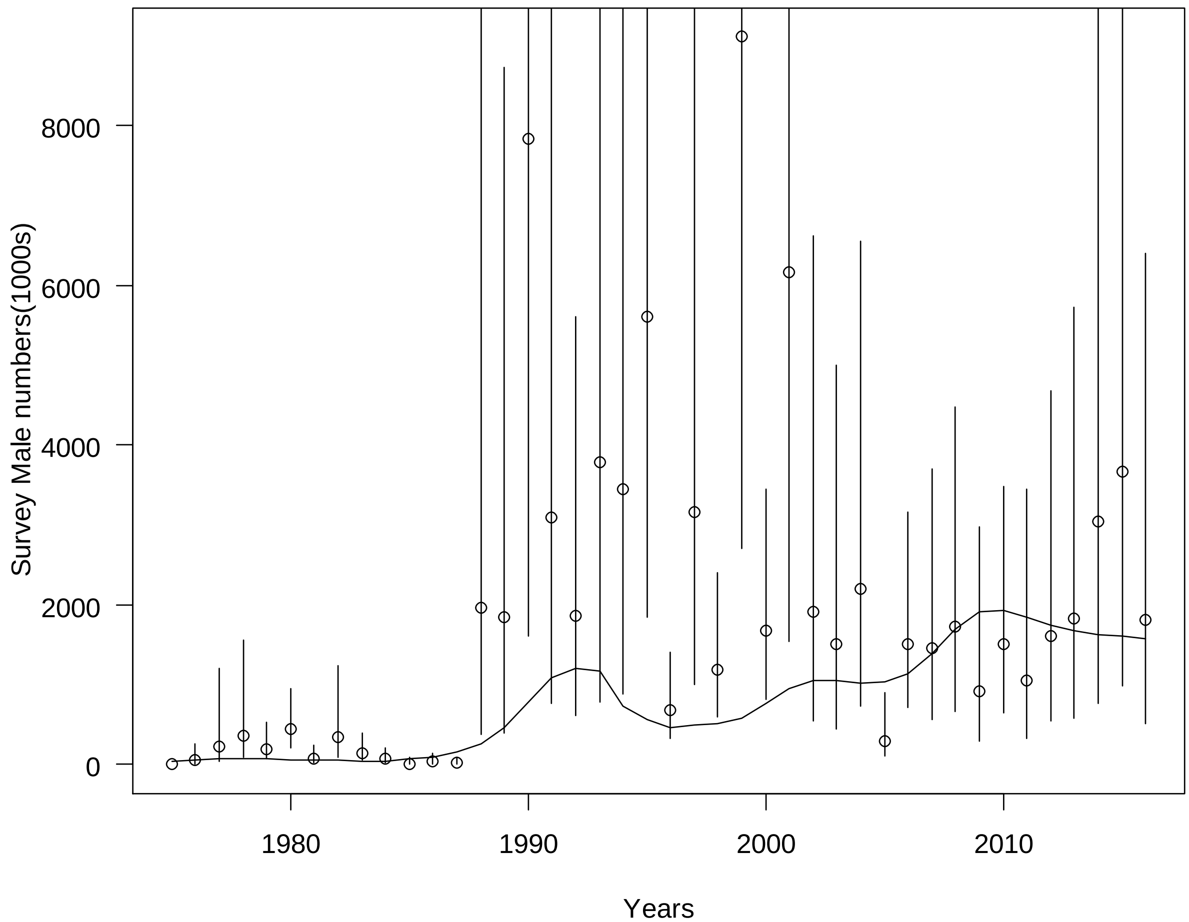

Figure 20. Model fit to survey male numbers.

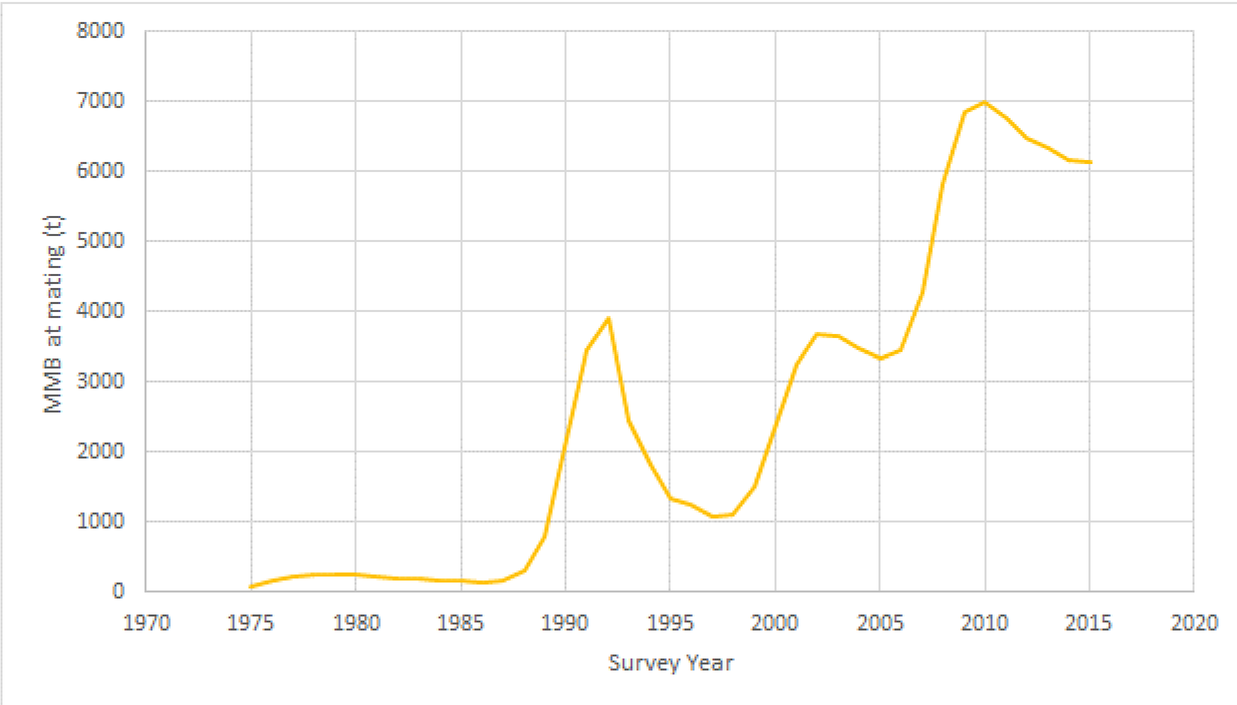

Figure 21. Assessment Model estimate of Mature male biomass at mating.

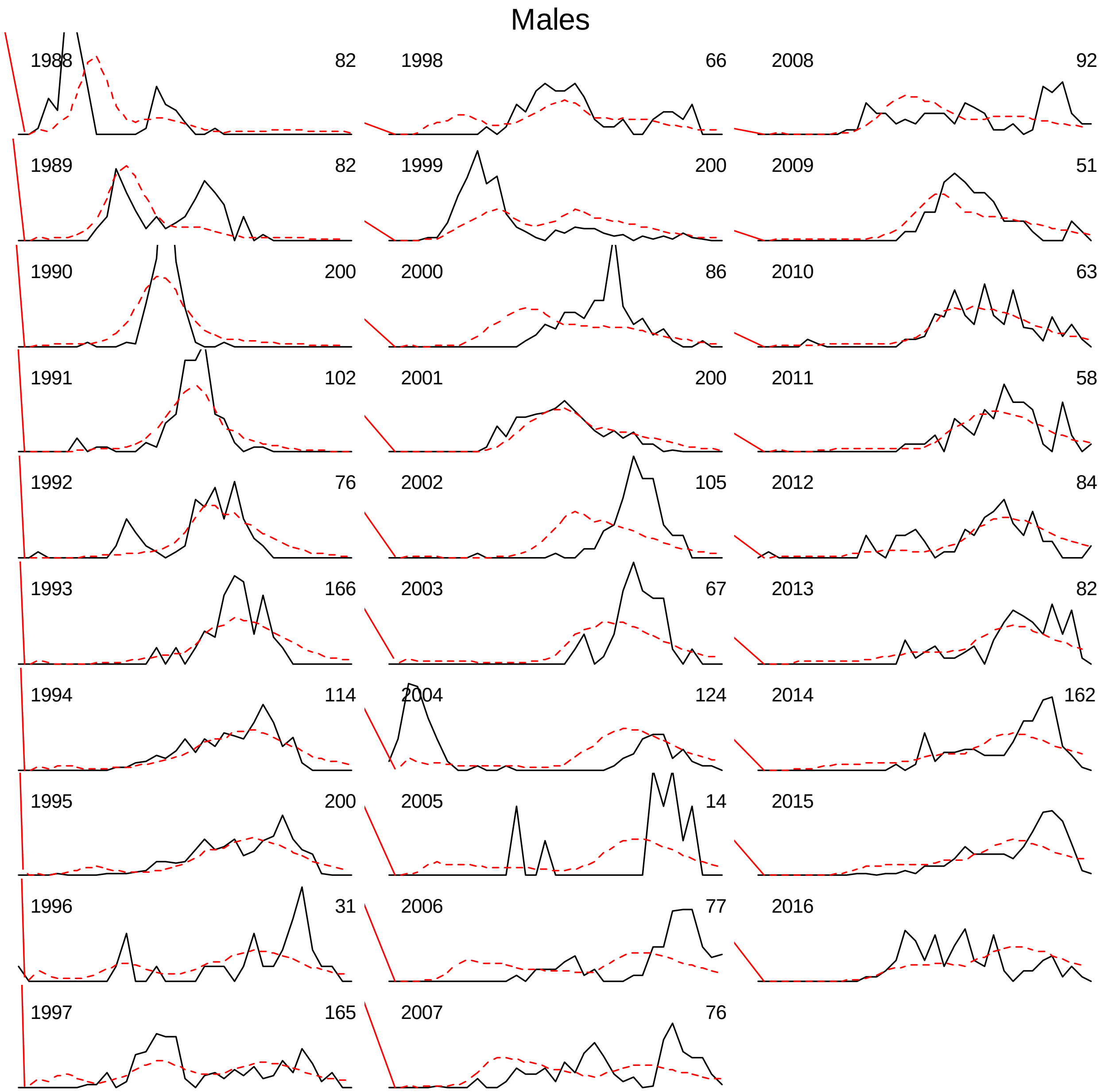

Figure 22. Model fits (red dashed line) to observed male length frequencies in the survey (solid line) by year using 5 mm length bins and fitting only males. Sample size is noted in the top right hand corner of each plot. Length frequencies for the years 1975-1987 are not shown because the associated sample sizes were <=18 and therefore held very little information.

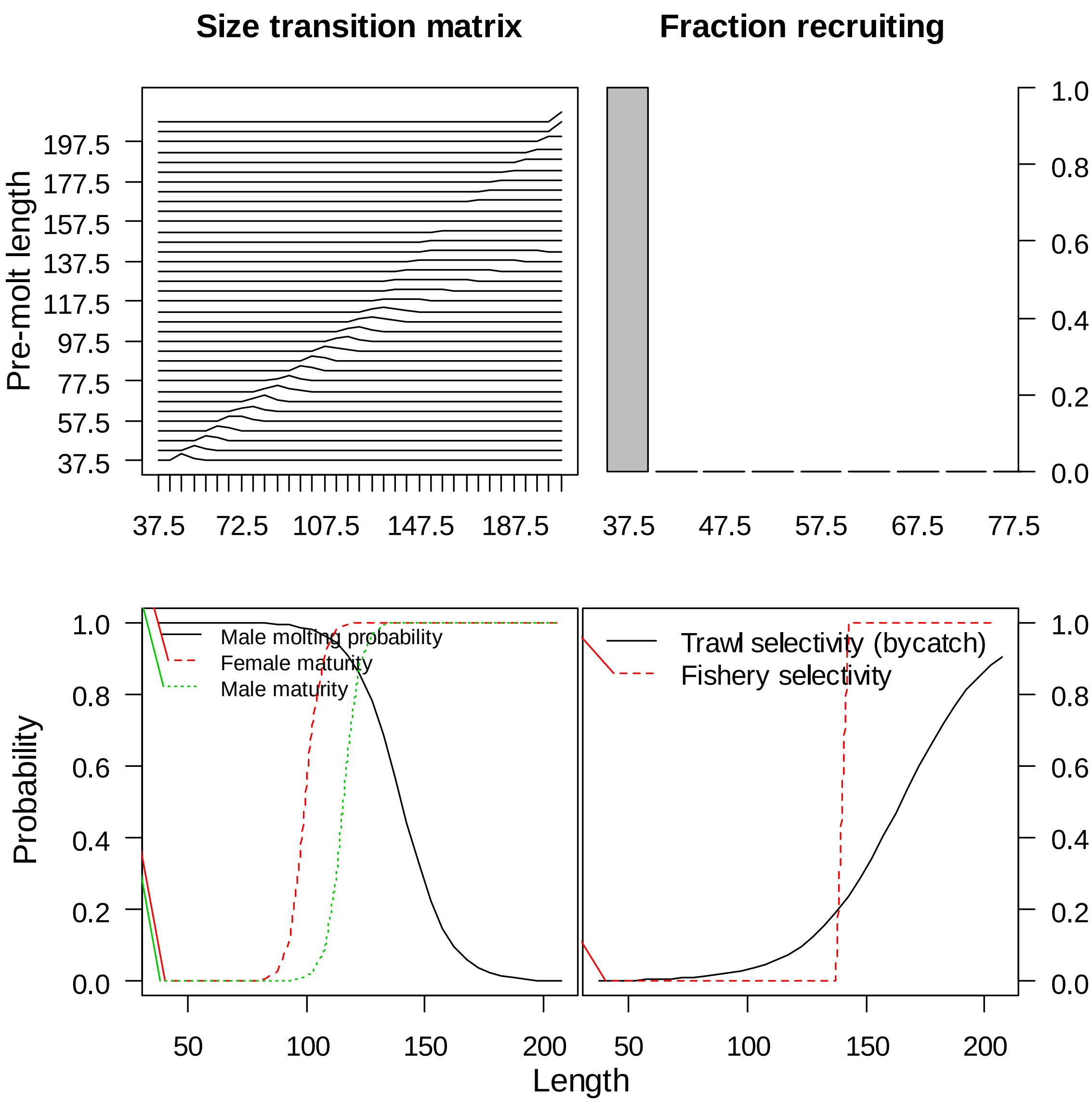

Figure 23. Size transition matrix (top left), fraction recruiting to a given size class (top right), probability of molting (males only) and maturing (females and males; bottom left), probability of being selected in the directed and trawl fisheries (bottom right).

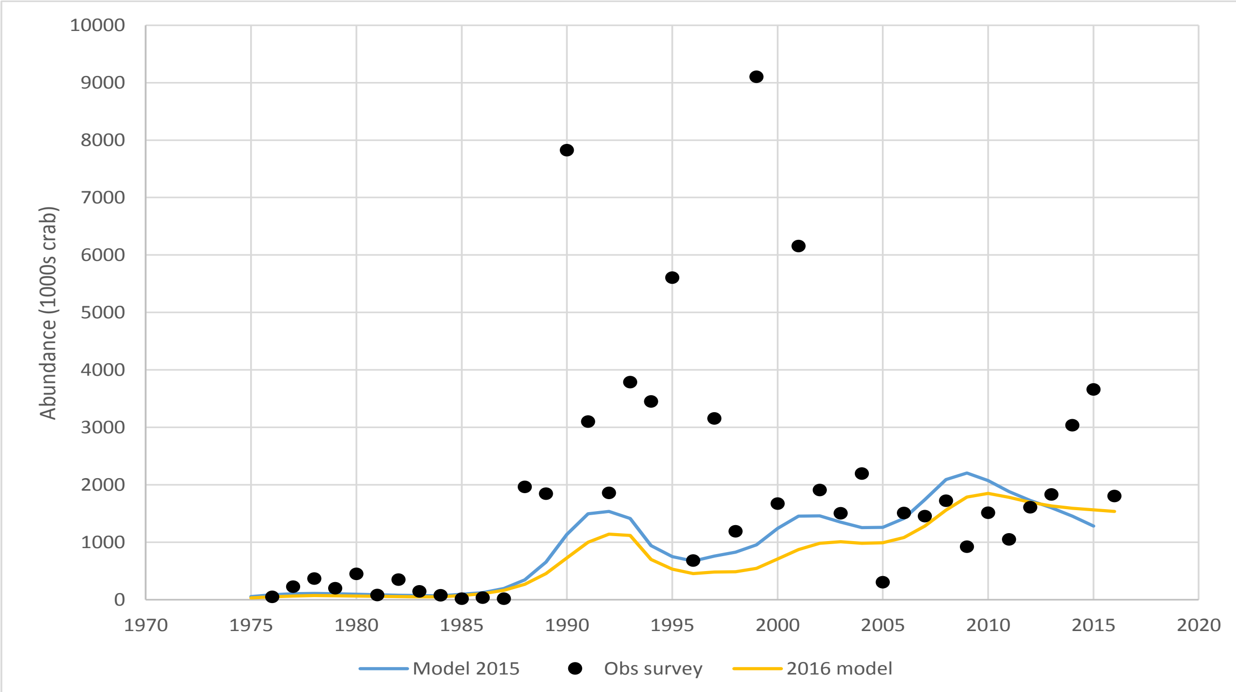

Figure 24. Fit to male abundance for the 2015 assessment model and the 2016 assessment model.

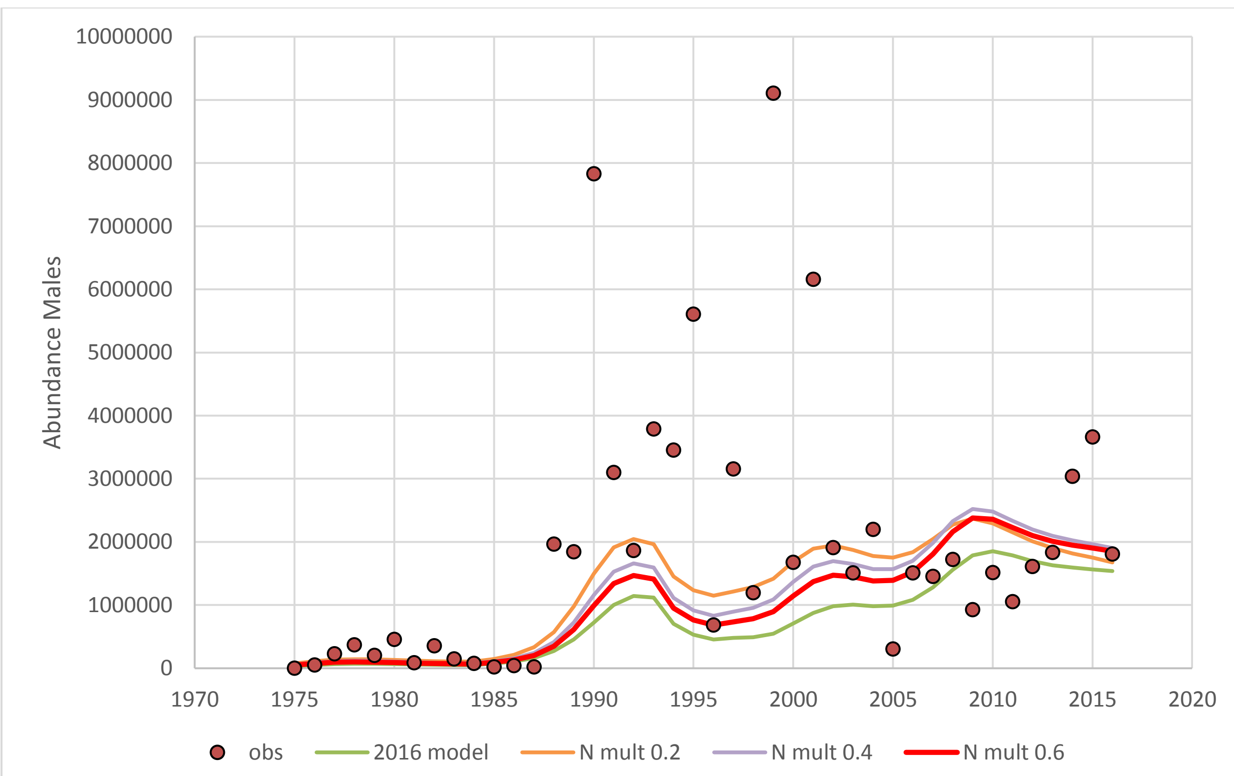

Figure 25. Fit to male abundance for the 2016 base model and model scenarios with multipliers on the survey length sample size of 0.2, 0.4 and 0.6.

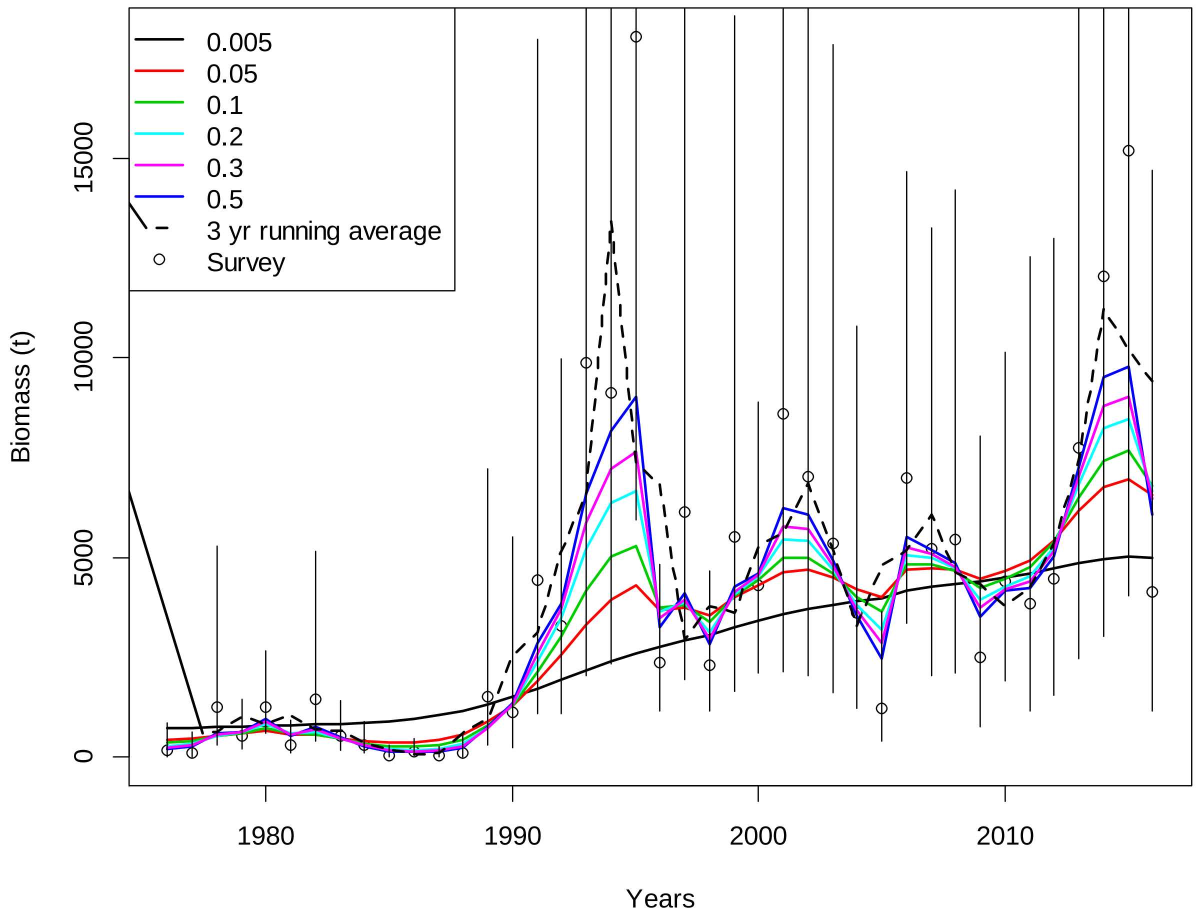

Figure 26. Random effects model estimates of biomass with process error fixed at 0.005, 0.05, 0.1,0.2,0.3 and 0.5.