2017 Stock assessment and fishery evaluation report for the Pribilof Island red king crab fishery of the Bering Sea and Aleutian Islands regions

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

Executive summary

1. Stock: Pribilof Islands red king crab, *Paralithodes camtschaticus*
2. Catches: Retained catches have not occurred since 1998/1999. Bycatch and discards have been decreasing since 2012/13, and are 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 and 2017. MMB at mating was estimated to be above B_{MSY} (5,502 t) in 2016/17 at 6,445 t.
    b. Observed survey mature male biomass (>=120mm) declined from 15,173 t in 2015 to 4,150 t in 2016 and 3,658 t in 2017. Total female biomass declined from 1898 t in 2016 to 505 t in 2017.

4. Recruitment: No estimates of recruitment are available.
5. Recent management statistics: OFL and ABC in 2011/12 was based on the unweighted 3-year running average. Biomass in 2011/2012 and OFL and ABC from 2012/13 to 2016/17 were based on the weighted 3-year running average using the inverse of the variance. Biomass (MMB) in 2016/17 is based on survey data through 2017 and catches in the crab year 2016/17.

Units in tons

Year	MSST	Biomass (MMB)	TAC	Retained Catch	Total Catch	OFL	ABC
2011/12	2,571	2,775	0	0	5.4	393	307
2012/13	2,609	4,025	0	0	13.1	569	455
2013/14	2,582	4,679	0	0	2.25	903	718
2014/15	2,871	8,894	0	0	1.76	1,359	1,019
2015/16	2,756	9,062	0	0	0.32	2,119	1,467
2016/17	2,751		0	0	0.49	1,492	1,096

Units in millions of pounds

Year	MSST	Biomass (MMB)	TAC	Retained Catch	Total Catch	OFL	ABC
2011/12	5.67	6.12	0	0	0.011	0.87	0.68
2012/13	5.75	8.87	0	0	0.029	1.25	1.00
2013/14	5.66	10.32	0	0	0.005	1.99	1.58
2014/15	6.33	19.61	0	0	0.004	3.00	2.25
2015/16	6.08	19.99	0	0	<0.001	4.67	3.23
2016/17	6.06		0	0	0.001	3.22	2.42

The OFL is the total catch OFL for each year. The stock was above MSST in 2016/2017 according to the 3-year running average at 6,445 t (MSST = 2,751 t). The 3 random effects model runs estimated 2016/17 MMB at mating below B_{MSY} (5,502 t) and above MSST (2,751 t) (see table item 6). The observed survey

MMB at mating in 2016/17 was 3,681 t (67% B_{MSY}). The catch in 2016/17 (0.49 t) was below the OFL (1,492 t) and the ABC (1,096 t).

6. 2017/2018 OFL projections:

All biomass in tons

Tier	Assessment Method	OFL	B_{MSY}	MMB At mating[A]	B/B_{MSY} (MMB)	*MMB at mating Feb 15 2017*	γ	Years to define B_{MSY}	F_{MSY}	ABC (p*=0.49)	ABC = 0.75* OFL
4	Running Average	330	5,502	3,139	0.57	6,445	1.	1991/1992-2016/2017 (MMB)	0.06	319	248
4	Random Effects Model fixed	380	5,502	3,336	0.61	4,683	1	1991/1992-2016/2017 (MMB)	0.10	367	285
4	Random Effects Model prior cv 2.24	404	5,502	3,439	0.63	4,788	1	1991/1992-2016/2017 (MMB)	0.11	390	303
4	Random Effects Model prior cv 4.0	468	5,502	3,669	0.67	4,961	1	1991/1992-2016/2017 (MMB)	0.11	453	351
4	Observed Survey	291	5,502	2,971	0.54	3,681	1	1991/1992-2016/2017 (MMB)	0.09	280	218

A: Feb 15 2018 fishing at OFL

For the following Table units are in millions of pounds.

Tier	Assessment Method	OFL	B_{MSY}	MMB At mating[A]	B/B_{MSY} (MMB)	*MMB at mating Feb 15 2017*	γ	Years to define B_{MSY}	F_{MSY}	ABC (p*=0.49)	ABC = 0.75* OFL
4	Running Average	0.73	12.13	6.92	0.57	14.21	1	1991/1992-2016/2017 (MMB)	0.06	0.70	0.55
4	Random Effects Model fixed	0.84	12.13	7.35	0.61	10.32	1	1991/1992-2016/2017 (MMB)	0.10	0.81	0.63
4	Random Effects Model prior cv 2.24	0.89	12.13	7.58	0.63	10.56	1	1991/1992-2016/2017 (MMB)	0.11	0.86	0.67
4	Random Effects Model prior cv 4.0	1.03	12.13	8.09	0.67	10.94	1	1991/1992-2016/2017 (MMB)	0.11	1.00	0.77
4	Observed Survey	0.64	12.13	6.55	0.54	8.12	1	1991/1992-2016/2017 (MMB)	0.09	0.62	0.48

A. Feb 15 2018 fishing at OFL

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 in 2016/17.

Summary of Major Changes:

1. Management: None.
2. Input data: Survey (2017) and bycatch (2016/17) data were incorporated into the assessment.
3. Assessment methodology: The 3-year running average and random effects models only are presented in this assessment.
4. Assessment results: Male biomass estimates from the 3-year running average and a random effects model were fit to survey male biomass >=120mm with process error fixed at the value estimated from a simple exponential model and with a prior with mean equal to the process error estimated from the simple exponential model and with cv=2.24 and cv=4.0. Tier 4 control rules are used to estimate MMB at mating, OFL and ABC for the four models.

CPT comments May 2017

The CPT recommended that the author continue to develop the random effects model and consider the following for models at the September CPT:

1. Better describe the exponential smoother methods and bring forward one model with the exponential model result as a prior and one model with the process error based on the exponential model fixed.

Included are 3 runs of the random effects model: 1) fixed process error at simple exponential model value, 2) with cv of 2.2 in the prior and 3) cv of 4.0 in the prior.

2. Status quo 3-year running average.

Included.

3. Consider fitting to the female biomass to determine if assessing the effects of single sex high biomass tows are informative for determining the observed error relative to process error.

The random effects model did not converge using female biomass. The simple exponential model was fit to female biomass to compare the estimate of process error to fitting male biomass.

4. Consider fitting spatial models (e.g., Thorson et al. 2015) to the survey data that may better account for zero tows and high biomass tows.

Not done. This will require selection of strata and splitting the data by strata as well as learning how to use the software. It may be necessary to develop a set of alternative strata for estimation.

SSC comments June 2017

There were no comments specific to the Pribilof red king crab assessment by the SSC in June 2017.

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 2016/17) were used in this assessment. The crab fishery retained and discard catch time series were updated with 2016/2017 data. The following sources and years of data are available:

Data source	Years available
NMFS trawl survey	1975-2017
Retained catch	1993-2016/17
Trawl bycatch	1991-2016/17
Fixed gear bycatch	1991-2016/17
Pot discards	1998-2016/17

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).

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

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

Finally, weights, discards, and bycatch were the product of average weight, CPUE, and total pot lifts in the fishery. A 20% handling mortality rate was applied to these estimates (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 2016/2017 there was no catch of Pribilof Islands red king crab from crab fisheries (Table 3).

2.3 Groundfish pot, trawl, and hook and line fisheries

The data through 2016/2017 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 2015/16 was 0.32 t and in 2016/17 0.49 t below the 2016/17 OFL 1,492 t and below the ABC of 1,096 t (Tables 3 and 5, Figures 13 and 14). Catch by weight in 2016/17 was 81% from non-pelagic trawl and 19% 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 2017 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 2017 (in 22 of the 20nm x 20nm grid). The number of stations at which at least one crab was observed in a given year ranges from 0 (in 1975) to 14 (in 1994) 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.

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 and uncertainty around area-swept estimates of abundance are large due to relatively low sample sizes (Table 7). Male crabs were observed at 9 of 35 stations in the Pribilof District during the 2015 NMFS survey (Figure 6); female crabs were observed at 5 (Figure 7). Two (possibly three) cohorts can be seen moving through the length frequencies over time (Figure8 and Figure9). Numbers at length vary dramatically from year to year, but the cohorts can nonetheless also be discerned in these data (Figure 10 and Figure 1).

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 and again in 2017 to 1,158,383 (Table 6). Female biomass (all sizes) declined from 3,859 t in 2015 to 1,898 t in 2016 and declined further in 2017 to 505 t. Survey biomass for males >=120mm declined from 15,173 t in 2015 to 4,150 t in 2016 and declined further in 2017 to 3,658 t (Table 8).

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 2017, biomass and derived management quantities are estimated by a 3-yr running-average method and a random effects method. The Tier 4 harvest control rule (HCR) is applied to the running-average and random effects estimates of mature male biomass (>=120mm). The current year biomass estimate was projected forward to February 15 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 1991/92 to 2016/17 observed survey data projected forward to February 15, removing the observed catch.

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,

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

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 log of survey biomass at the time of the survey. The likelihood equation for the random effects model is,

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

Where,

B_i is the log of observed biomass in year i,

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

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

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

Yrs is the number of years of survey biomass values.

In the case where the random effects model does not converge due to high observation errors, an estimate of the process error is necessary to use as a prior or to fix in the model (P. Spencer pers. comm., Figure 15). A simple exponential model can be used to estimate the ratio of observation error to process error in a time series,

$$\hat{z}_t = \alpha y_t + \alpha(1-\alpha)y_{t-1} + \alpha(1-\alpha)^2 y_{t-2} + \alpha(1-\alpha)^3 y_{t-3} + \cdots,$$

Where,

$\hat{z}_0$ is set equal to y_0, the log of observed biomass in the first year,

y_t is the log of observed biomass in year t and,

α is the parameter estimated in the model which ranges from 0 to 1.

An estimate of the ratio of observation error (σ_o^2) to process error (σ_p^2) (log scale) is,

$$\frac{\sigma_o^2}{\sigma_p^2} = \frac{(1-\alpha)}{\alpha^2}$$

.

An estimate of λ to use as a prior in the random effects model is,

$$\lambda = 0.5\log\left(\sigma_p^2\right)$$

The variance of α is an output of the arima function in R which was used to fit the simple exponential model. A bootstrap using the logit distribution on α was used to approximate the variance of λ for use in the prior that is added to the likelihood in the random effects model,

$$0.5\,\frac{(\lambda-\lambda_p)^2}{\sigma_\lambda^2}$$

Where,

λ_p is the prior estimate of λ from the simple exponential model

σ_λ^2 is the variance of λ_p estimated from the parametric bootstrap.

The random effects model was run with λ fixed at the value estimated from the simple exponential model and with λ estimated adding the prior likelihood into the random effects model.

4. Model Selection and Evaluation

The running average method with a tier 4 HCR was selected in 2016 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. Four assessment methods are presented here for comparison: a running average with a tier 4 HCR, a random effects model with fixed λ, and a random effects model with a prior likelihood component added for λ.

5.0 Results

5.1 Tier 4

Survey mature male biomass (>=120mm) declined from 4,150 t in 2016 to 3,658 t in 2017. The 3-yr running average estimate of mature male biomass (>=120mm) was 3,888 t in 2017 at the survey time, while the random effects model with process error fixed estimate was 4,163 t (Table 8 and Figure 16). When process error is estimated with a prior in the random effects model with a cv = 2.24 (estimated from bootstrap) the 2017 biomass estimate was 4,307 t. When process error is estimated with a prior in the random effects model with a cv = 4.0 the 2017 biomass estimate was 4,633 t and results in more smoothing of the estimates (Figure 16). The random effects model was also fit with a CV on the prior of 5.0 which resulted in the model not converging. The random effects model did not converge when trying to fit female biomass due to high observed variances similar to male biomass. The increase in CV in the prior on λ results in lower process error and a smoother fit to biomass. The parameters and process error for the random effects models were,

Random effects Model	λ	σ_p^2	CV
λ fixed	-0.221	0.643	NA
with prior on λ	-0.364	0.483	2.24
with prior on λ	-0.640	0.278	4

MMB at mating on February 15, 2017 (2016/17 crab year) was estimated at 3,681 t for the observed survey, 6,445 t for the 3-yr weighted average, 4,683 t for the random effects model fixed process error, 4,788 t for the random effects model cv=2.24 and 4,961 t for the random effects model cv=4.0 (Table 9 and Figure 17). The estimation of process error in the random effects model with a cv=4.0 results in a smoother fit to biomass than the 3 year running average or the random effects models with lower cv or fixed process error. The 3-yr running average biomass estimate in 2016 is the weighted average of survey biomass in 2015, 2016 and 2017. The high survey biomass in 2015 results in a larger estimated biomass in 2016 (and the projected February 15, 2017 biomass) than for the random effects models which take into account the whole time series. The use of the 3-yr running average can be thought of as 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 as well as using the random effects model with a weaker prior. The CVs of the survey biomass range from 0.36 to 1.0 with an average of 0.67.

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.

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

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)

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.

6.6 Tier 4 Reference points and OFL

B_{MSY} was estimated at 5,502 t using male survey biomass (>=120mm) from 1991/92 to 2016/17. Projected MMB for 2017/18 (on February 15, 2018 removing the OFL) calculated from the 3-year running average was 3,139 t (57% of B_{MSY}), from the random effects model (RE) with fixed process error at 3,336 t (61% of B_{MSY}), the RE with CV=2.24 at 3,439 t (63% of B_{MSY}) and the RE with CV=4.0 at 3,669 t (67% of B_{MSY}). The 2017/18 OFL for the 3-yr weighted average was 330 t, from the random effects model (RE) with fixed process error at 380 t, the RE with CV=2.24 at 404 t and the RE with CV=4.0 at 468 t (see Table in item 6 of the executive summary).

6.7 Recommended ABCs

The ABC estimated using a p* of 0.49 with an additional sigma of 0.30 was 319 t for the 3-yr running average, 367 t for the random effects model (RE) with fixed process error, 390 t for the RE with CV=2.24 and 453 t for the RE with CV=4.0. The ABC with a 25% buffer (ABC = OFL * 0.75) (recommended by the CPT and SSC in 2015) was 248 t for the 3-yr running average, 285 t for the random effects model (RE) with fixed process error, 303 t for the RE with CV=2.24 and 351 t for the RE with CV=4.0 (see Table in item 6 of the executive summary).

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 mature male biomass for 2017 was 0.65 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.

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 (Turnock, et al. 2016If there is a particularly high estimate of MMB from the survey (often associated with high variance–see 2015 for an example), the biomass and OFL can be higher for the 3-yr running average than the random effects models. The random effects model 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 authors recommendation is to use the random effects model with CV=4.0 in the prior on process error as this results in a more smooth fit to biomass and would be less influenced by fluctuations in biomass than the 3-yr running average model, and the random effects models with lower CV in the prior.

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.

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 integrated 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.

9. Literature cited

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Szuwalski, C.S., R. Foy and B.J. Turnock (2015). 2015 Stock assessment and fishery evaluation report for the Pribilof Island red king crab fishery of the Bering Sea and Aleutian Islands regions. In: Bering Sea and Aleutian Islands Crab Stock Assessment and Fishery Evaluation 2015. North Pacific Fishery Management Council, P. O. Box 103136, Anchorage, Ak 99510.

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

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

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

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

Turnock, B.J., C.S. Szuwalski, and R.J. Foy. 2016. 2016 Stock assessment and fishery evaluation report for the Pribilof Island red king crab fishery of the Bering Sea and Aleutian Islands regions. In: Bering Sea and Aleutian Islands Crab Stock Assessment and Fishery Evaluation 2016. North Pacific Fishery Management Council, P. O. Box 103136, Anchorage, Ak 99510.

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

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

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

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

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

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

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 2016/2017	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
1999-2016/17		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). ****From 2009/10 forward the calculation of bycatch uses the 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	0.19	1.05
2010/2011	0.00	0.00	0.00	0.45	6.25
2011/2012	0.00	0.00	0.00	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
2016/2017	0.00	0.00	0.00	0.06	0.43

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
2016/17	19	81	<1	0	857

Table 5. Total male bycatch (t), Total bycatch (t) and total catch (t) with mortality applied for Pribilof red king crab from 1991 to 2016/17.

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
2016/2017	0.49	0.49	0.49

Table 6. 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	Males >=105 mm 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	25645	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	4619	1898
2017/2018	115838	3740	505

Table 7. 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	Males >=105mm 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
2017/2018	0.58	0.64	0.56

Table 8. Estimates of survey male >= 120mm biomass (t) at the time of the survey, 3-year running weighted average, the random effects model with λ fixed at -0.221, the random effects model with a prior on λ with mean = -0.221 and cv = 2.24, the random effects model with a prior on λ with mean = -0.221 and cv = 4.0, and the simple exponential smooth.

Year	MB GE120	CV MB GE120	3-yr running avg	random effects fixed λ	random effects prior λ cv 2.24	random effects prior λ cv 4.0	Simple exponential smooth
1976/1977	165	1.00	NA	206	221	261	165
1977/1978	119	1.00	585	252	271	314	131
1978/1979	1,250	0.83	648	621	593	558	637
1979/1980	556	0.52	1,042	645	647	644	579
1980/1981	1,269	0.38	850	1,005	965	884	1,004
1981/1982	312	0.58	1,060	520	545	581	443
1982/1983	1,464	0.70	691	822	771	688	1,024
1983/1984	527	0.53	679	510	500	480	642
1984/1985	317	0.55	368	292	293	302	392
1985/1986	61	1.00	211	136	149	180	107
1986/1987	138	0.70	95	131	140	166	128
1987/1988	54	1.00	107	117	133	174	69
1988/1989	107	1.00	609	218	240	293	94
1989/1990	1,529	0.91	961	784	759	739	664
1990/1991	1,141	0.93	2,526	1,386	1,370	1,333	971
1991/1992	4,430	0.80	3,133	2,991	2,849	2,579	2,815
1992/1993	3,305	0.60	5,172	3,863	3,839	3,672	3,150
1993/1994	9,873	0.92	6,597	6,935	6,564	5,757	7,019
1994/1995	9,139	0.77	13,423	8,605	8,142	7,070	8,446
1995/1996	18,056	0.60	7,350	9,822	8,954	7,442	14,390
1996/1997	2,362	0.37	6,816	3,151	3,281	3,521	4,051
1997/1998	6,159	0.62	2,955	4,244	4,108	3,935	5,435
1998/1999	2,324	0.36	3,783	2,753	2,831	3,007	2,995
1999/2000	5,523	0.67	3,614	4,365	4,271	4,138	4,600
2000/2001	4,320	0.37	5,298	4,588	4,596	4,578	4,402
2001/2002	8,603	0.79	5,614	6,479	6,217	5,727	7,043
2002/2003	7,037	0.69	6,853	6,268	6,071	5,664	7,039
2003/2004	5,373	0.66	5,194	4,998	4,926	4,789	5,824
2004/2005	3,622	0.59	3,283	3,503	3,556	3,704	4,174
2005/2006	1,238	0.59	4,805	2,285	2,492	2,926	1,780
2006/2007	7,003	0.38	5,190	5,675	5,506	5,208	4,652
2007/2008	5,224	0.49	6,086	5,245	5,198	5,075	5,046
2008/2009	5,462	0.51	4,642	4,907	4,853	4,766	5,334
2009/2010	2,500	0.64	4,333	3,393	3,528	3,789	3,135
2010/2011	4,405	0.44	3,779	4,171	4,175	4,227	3,980
2011/2012	3,834	0.65	4,292	4,190	4,260	4,415	3,877
2012/2013	4,477	0.57	5,350	4,950	5,026	5,156	4,289
2013/2014	7,749	0.62	7,455	7,342	7,217	6,916	6,494
2014/2015	12,047	0.78	11,235	9,786	9,324	8,414	10,017
2015/2016	15,173	0.74	10,218	9,872	9,306	8,314	13,403
2016/2017	4,150	0.70	7,267	5,281	5,399	5,594	5,890
2017/2018	3,658	0.65	3,888	4,163	4,307	4,633	4,205

Table 9. MMB at mating for survey males >= 120mm, the 3-yr running average and the random effects model fit.

	Projected Biomass from survey time (y) to February 15 (y+1) removing catch				
	Observed survey	3-yr weighted average	Random Effects fixed = -0.221	Random Effects CV = 2.24	Random Effects CV = 4.0
1976/1977	146	NA	182	196	232
1977/1978	105	519	223	241	279
1978/1979	1,108	575	551	526	495
1979/1980	493	924	572	574	571
1980/1981	1,125	754	891	856	784
1981/1982	277	940	461	484	516
1982/1983	1,298	613	729	684	610
1983/1984	467	602	452	443	426
1984/1985	281	326	259	260	268
1985/1986	55	187	120	132	160
1986/1987	122	84	116	124	147
1987/1988	48	95	104	118	154
1988/1989	95	540	193	213	260
1989/1990	1,357	852	696	673	655
1990/1991	1,012	2,240	1,229	1,215	1,182
1991/1992	3,929	2,779	2,653	2,527	2,287
1992/1993	2,739	4,395	3,234	3,213	3,065
1993/1994	7,441	4,536	4,835	4,506	3,790
1994/1995	7,482	11,282	7,009	6,599	5,648
1995/1996	15,596	6,101	8,293	7,523	6,182
1996/1997	2,000	5,950	2,700	2,815	3,028
1997/1998	5,107	2,266	3,409	3,288	3,135
1998/1999	1,796	3,091	2,176	2,246	2,402
1999/2000	4,881	3,189	3,854	3,771	3,653
2000/2001	3,825	4,692	4,062	4,070	4,053
2001/2002	7,621	4,970	5,737	5,505	5,070
2002/2003	6,232	6,068	5,549	5,375	5,014
2003/2004	4,755	4,596	4,423	4,358	4,237
2004/2005	3,206	2,905	3,100	3,147	3,279
2005/2006	1,069	4,232	1,997	2,181	2,565
2006/2007	6,181	4,573	5,004	4,854	4,590
2007/2008	4,627	5,392	4,646	4,605	4,496
2008/2009	4,836	4,108	4,343	4,296	4,218
2009/2010	2,216	3,841	3,008	3,128	3,359
2010/2011	3,900	3,345	3,692	3,697	3,742
2011/2012	3,396	3,801	3,711	3,774	3,911
2012/2013	3,958	4,732	4,378	4,445	4,560
2013/2014	6,871	6,610	6,510	6,399	6,132
2014/2015	10,683	9,963	8,677	8,268	7,461
2015/2016	13,457	9,062	8,755	8,253	7,373
2016/2017	3,681	6,445	4,683	4,788	4,961

12. Figures

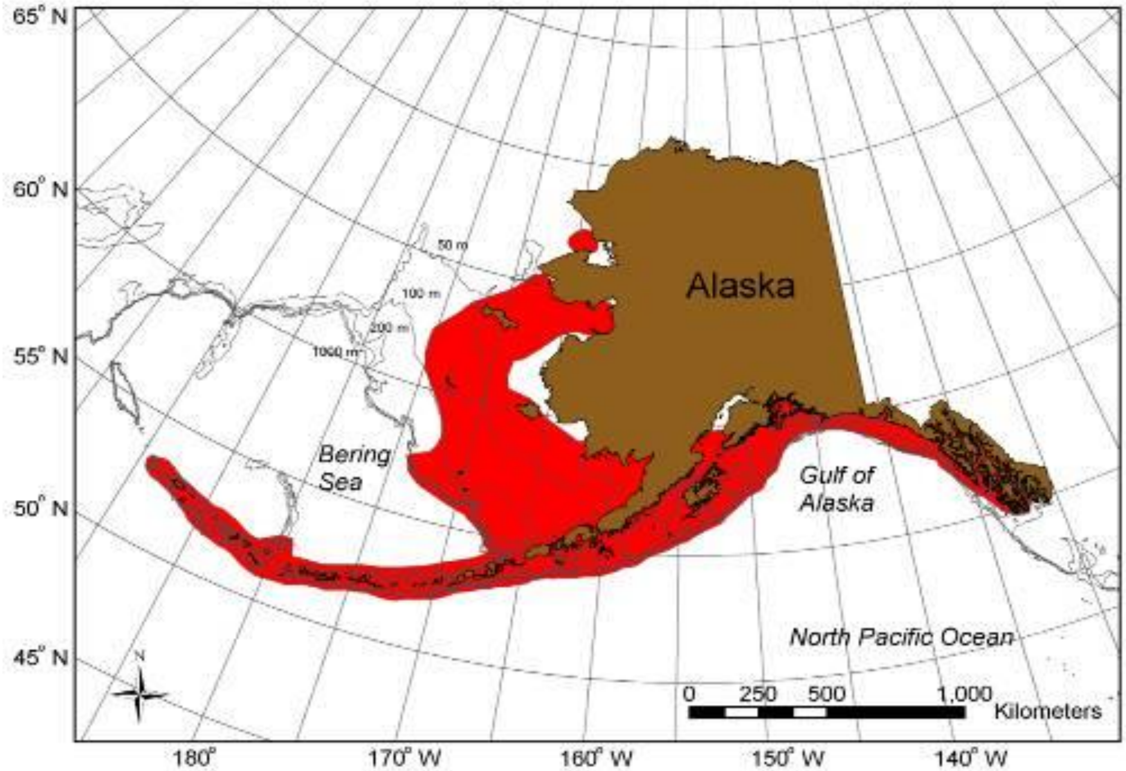

Figure 1. Red king crab distribution.

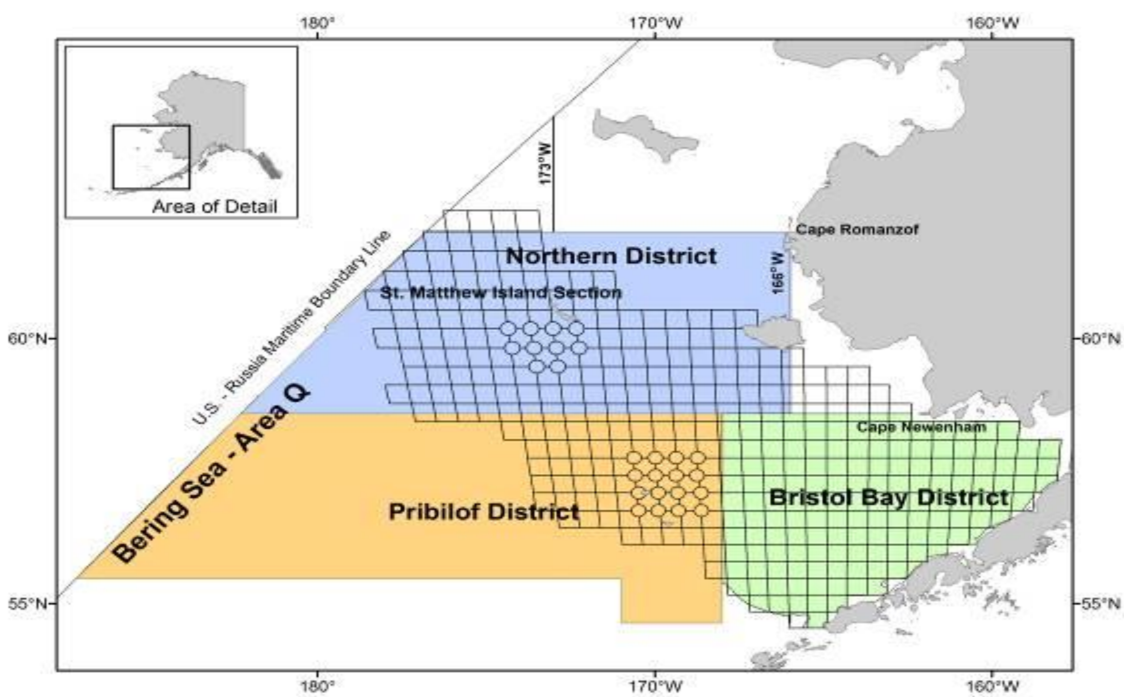

Figure 2. King crab registration area Q (Bering Sea) showing the Pribilof District.

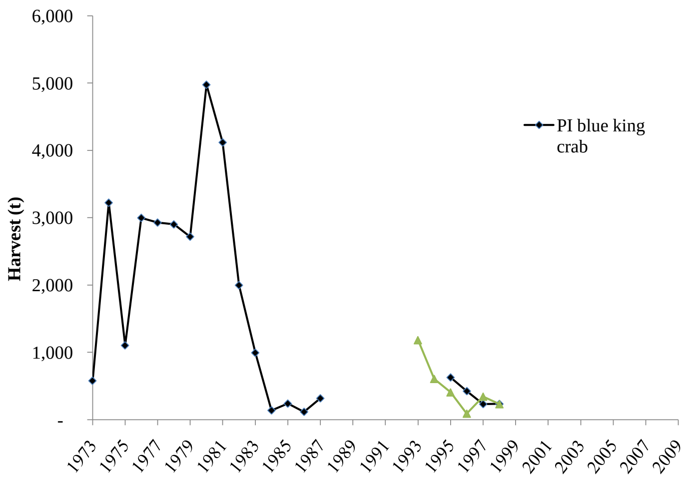

Figure 3. Historical harvests and GHLs for Pribilof Island blue (diamonds) and red king crab (triangles) (Bowers et al. 2011).

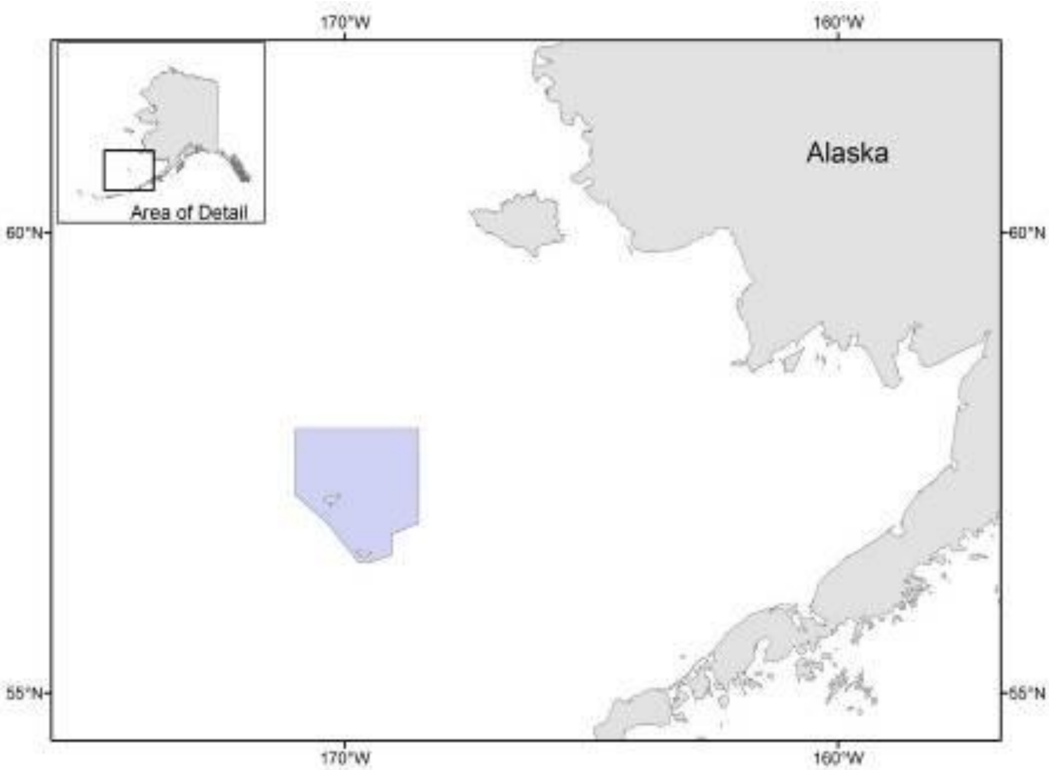

Figure 4. The shaded area shows the Pribilof Islands Habitat Conservation area.

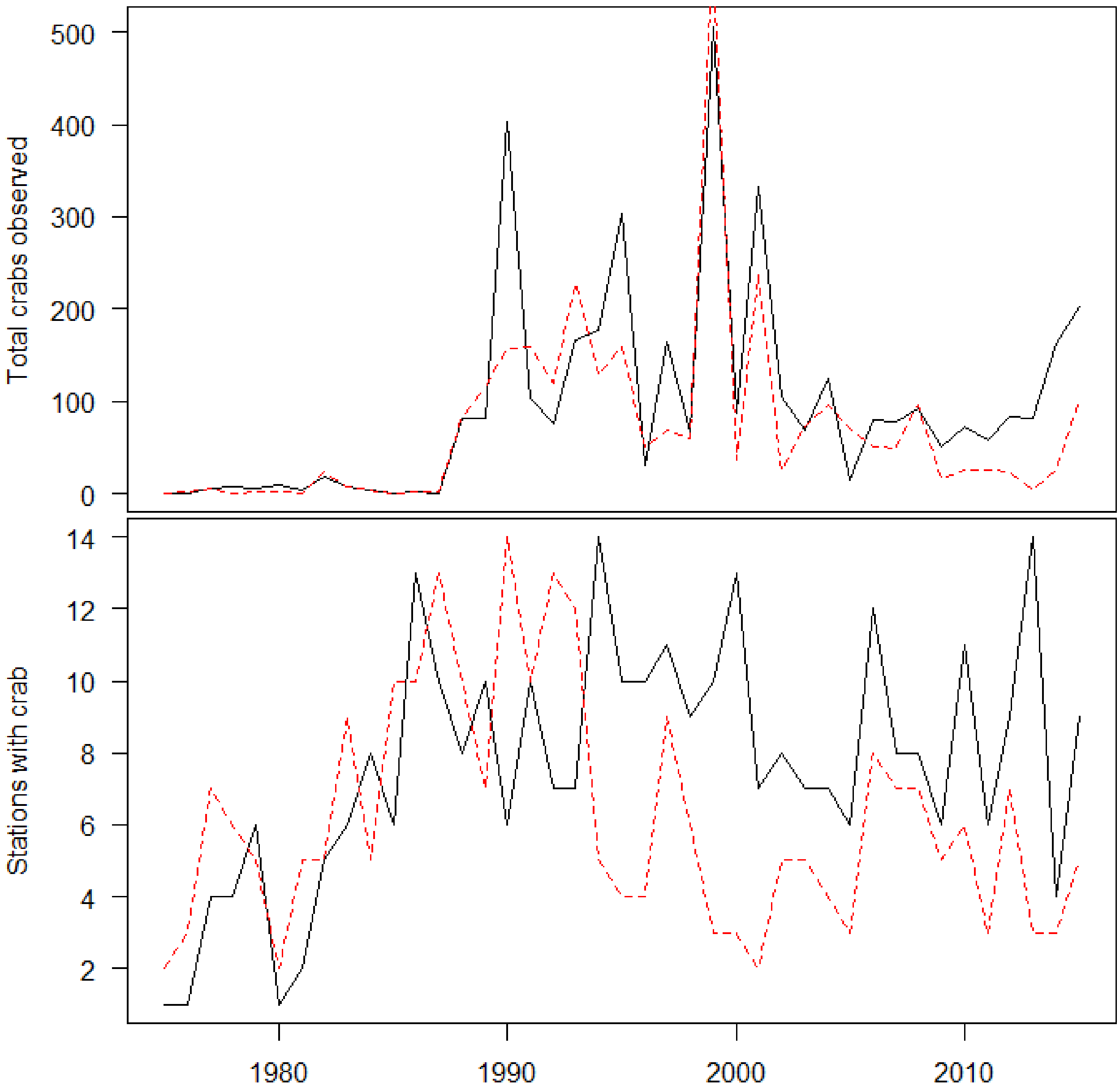

Figure 5. Total number of observed crab (top) and the number of stations that reported observations of crab (female = dashed line, male = solid line) from 1975-2014.

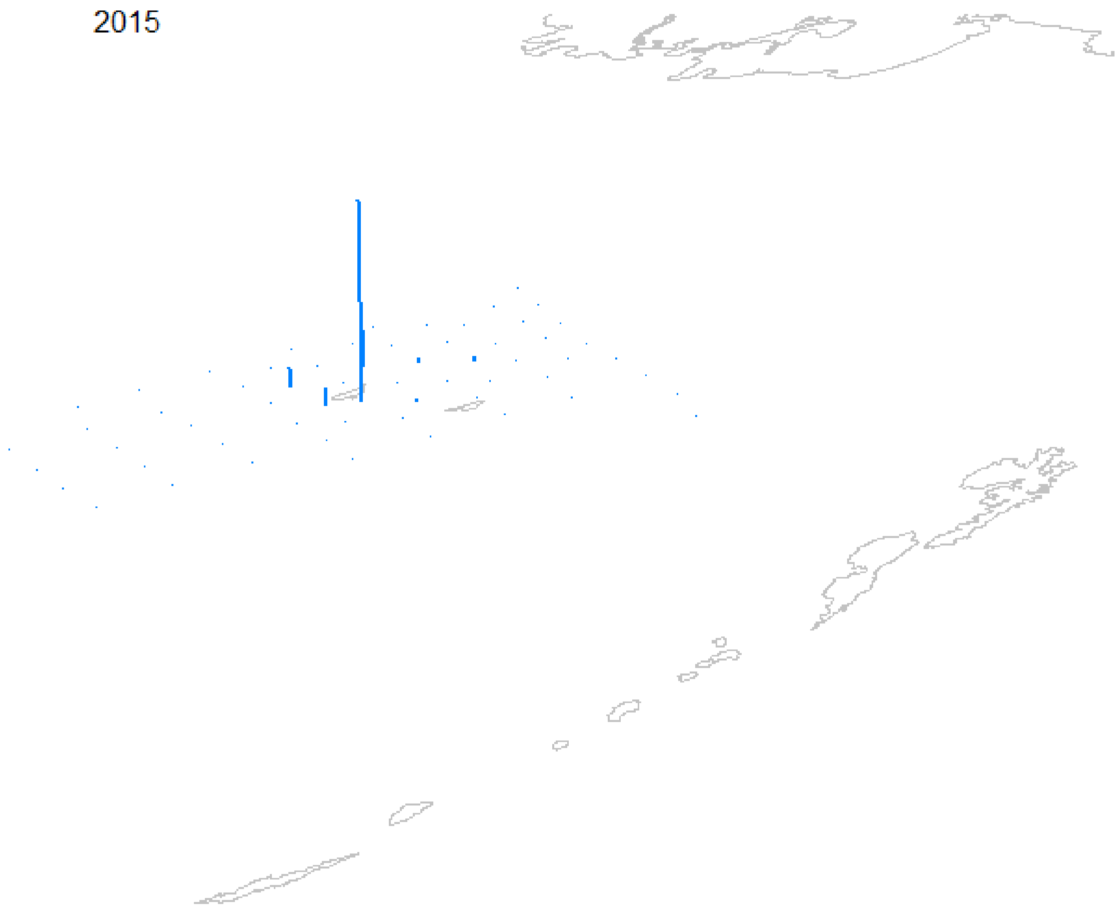

Figure 6. Male red king crab relative density by station in the Pribilof Island district in 2015. Blue bars represent the relative magnitude of the density calculated from the NMFS trawl survey.

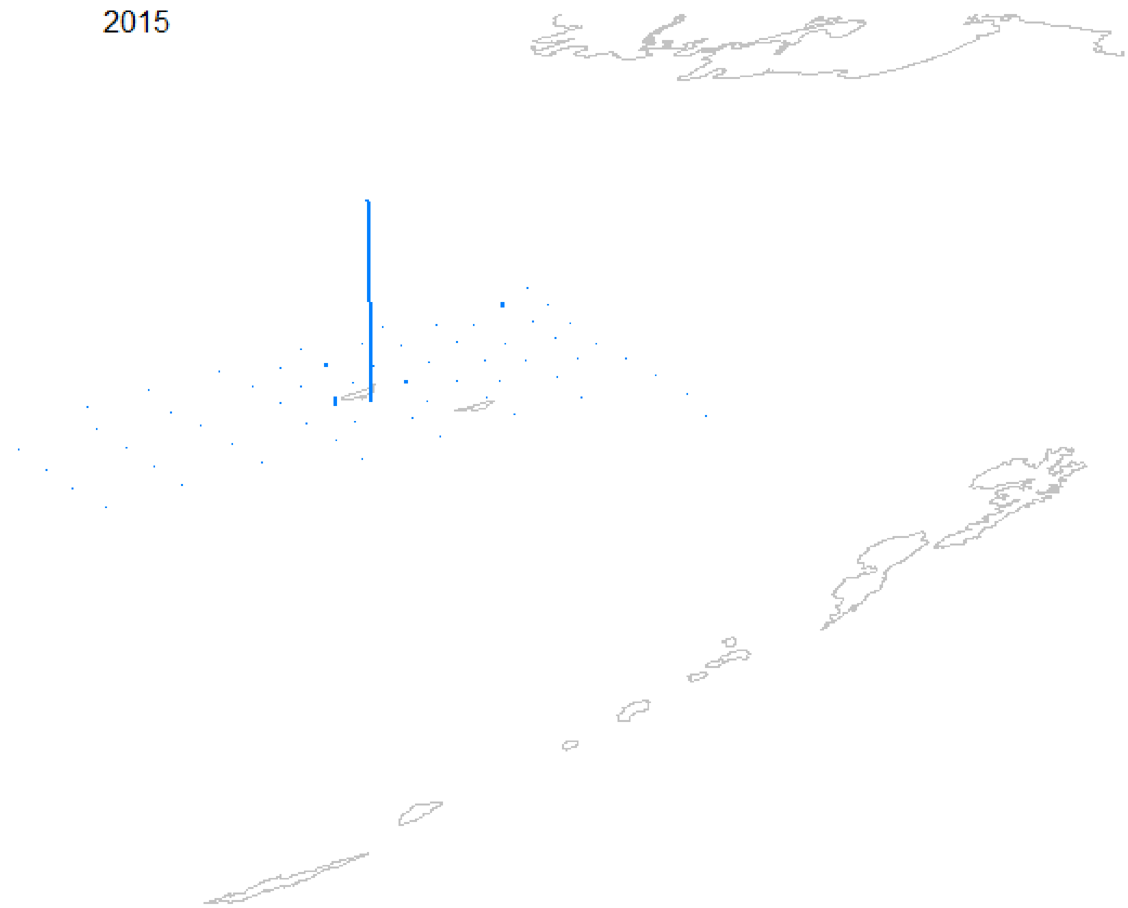

Figure 7. Female red king crab relative density by station in the Pribilof Island district in 2015. Blue bars represent the relative magnitude of the density calculated from the NMFS trawl survey.

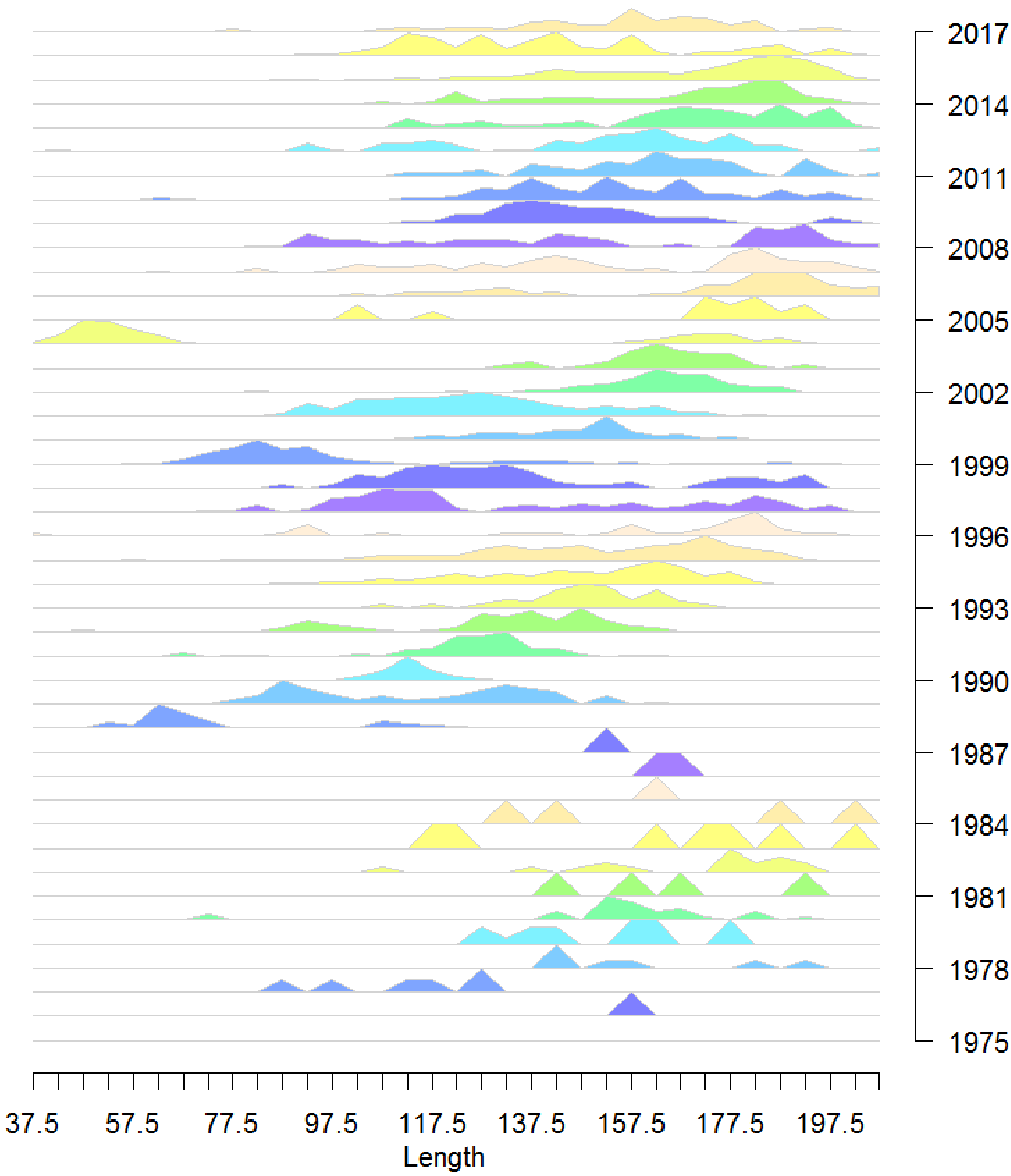

Figure 8. Observed length frequencies (proportions sum to 1.0) by 5 mm length classes of Pribilof Islands male red king crab (Paralithodes camtschaticus) from 1975 to 2017.

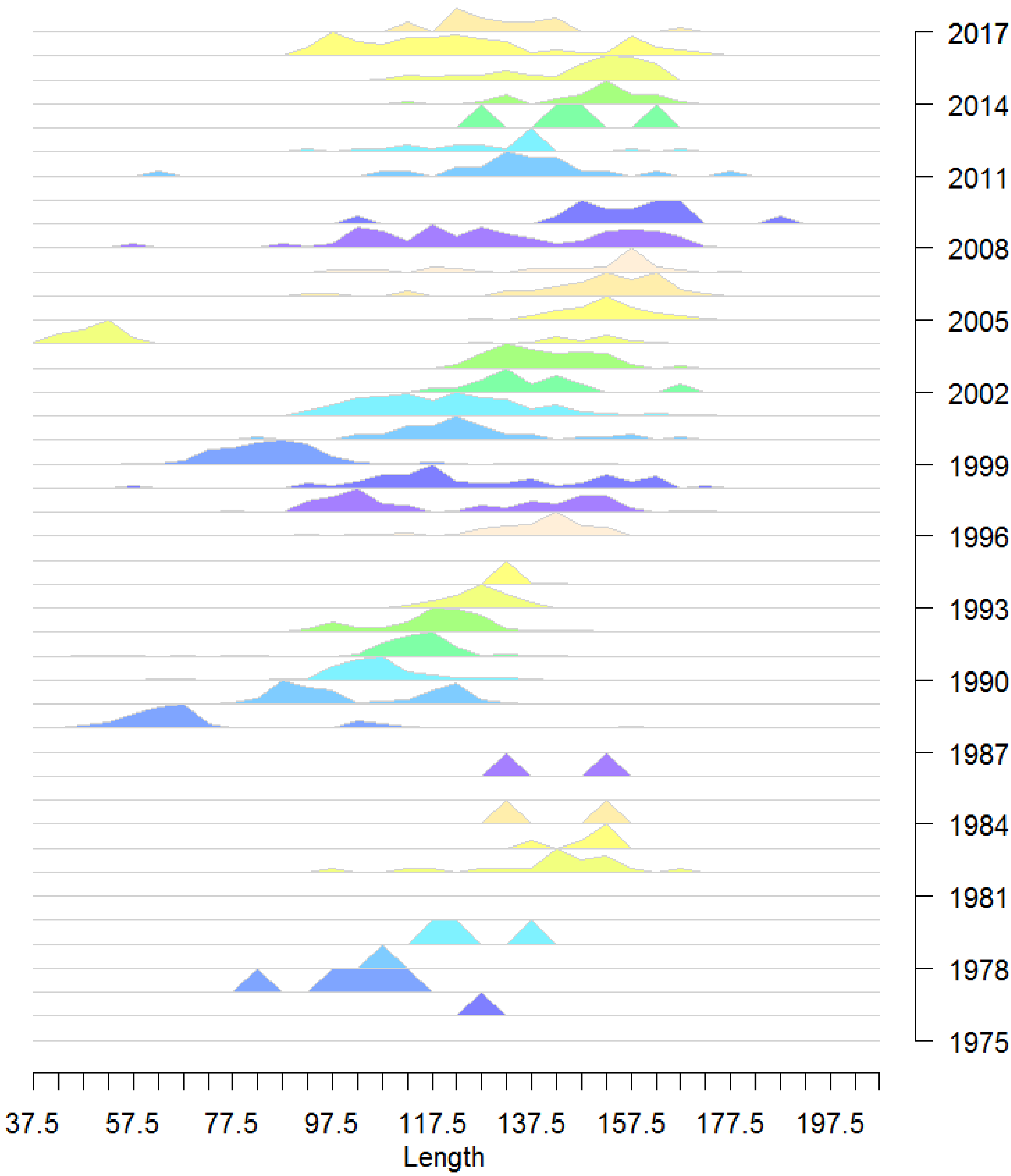

Figure 9. Observed length frequencies (proportions sum to 1.0) by 5 mm length classes of Pribilof Islands female red king crab (Paralithodes camtschaticus) from 1975 to 2017.

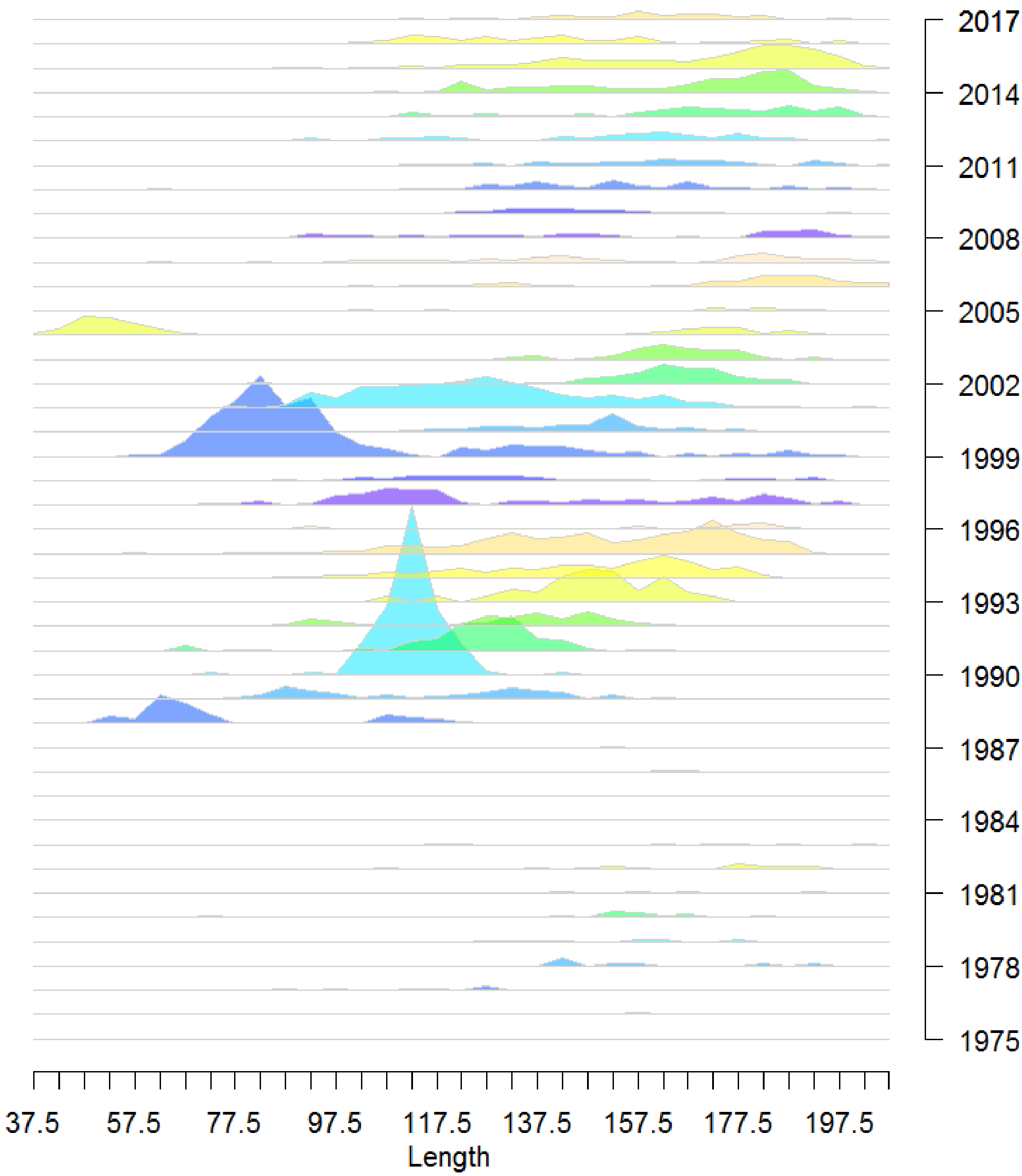

Figure 10. Observed numbers at length by 5 mm length classes of Pribilof Islands male red king crab (Paralithodes camtschaticus) from 1975 to 2017.

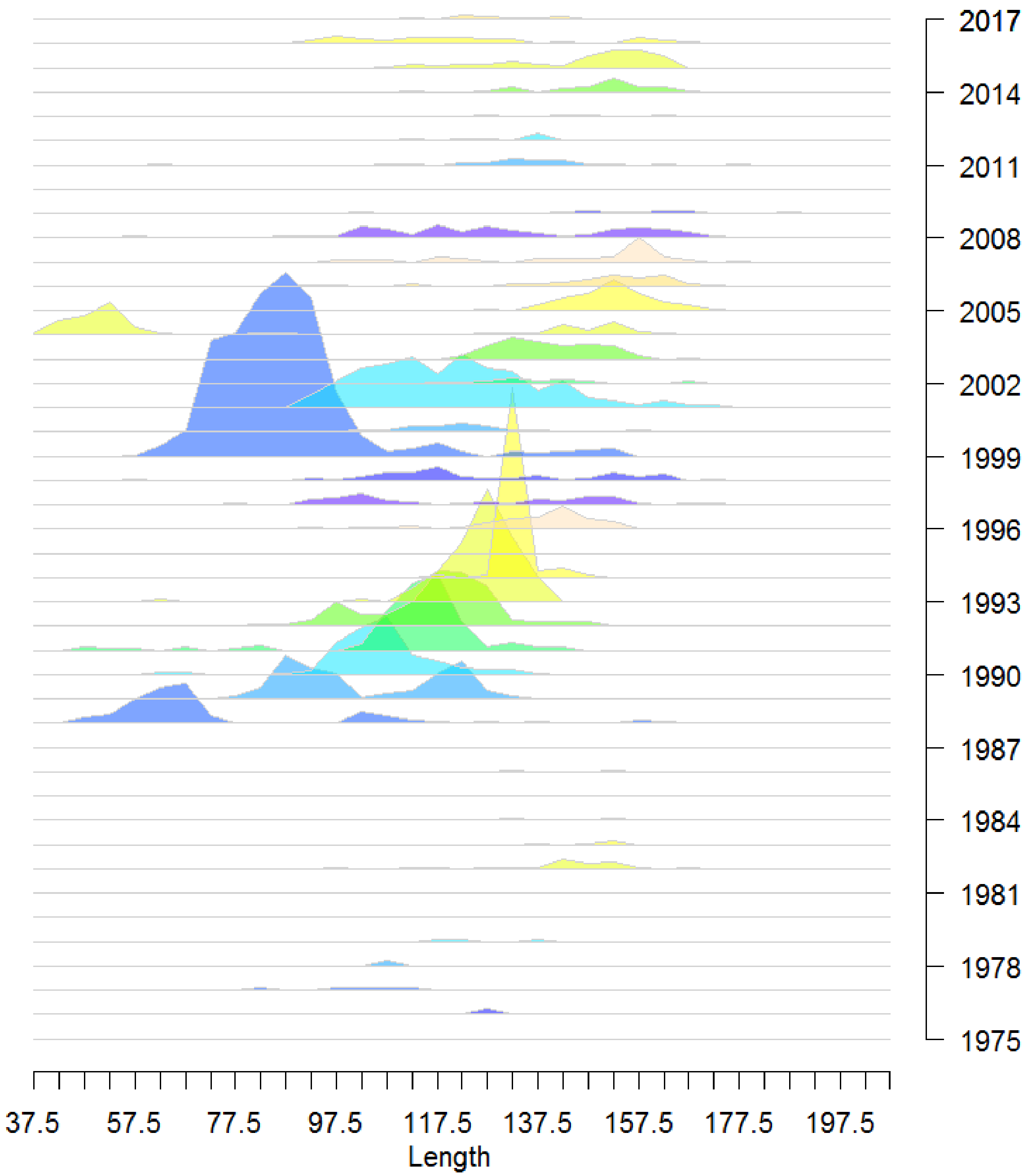

Figure 11. Observed numbers at length by 5 mm length classes of Pribilof Islands female red king crab (Paralithodes camtschaticus) from 1975 to 2017.

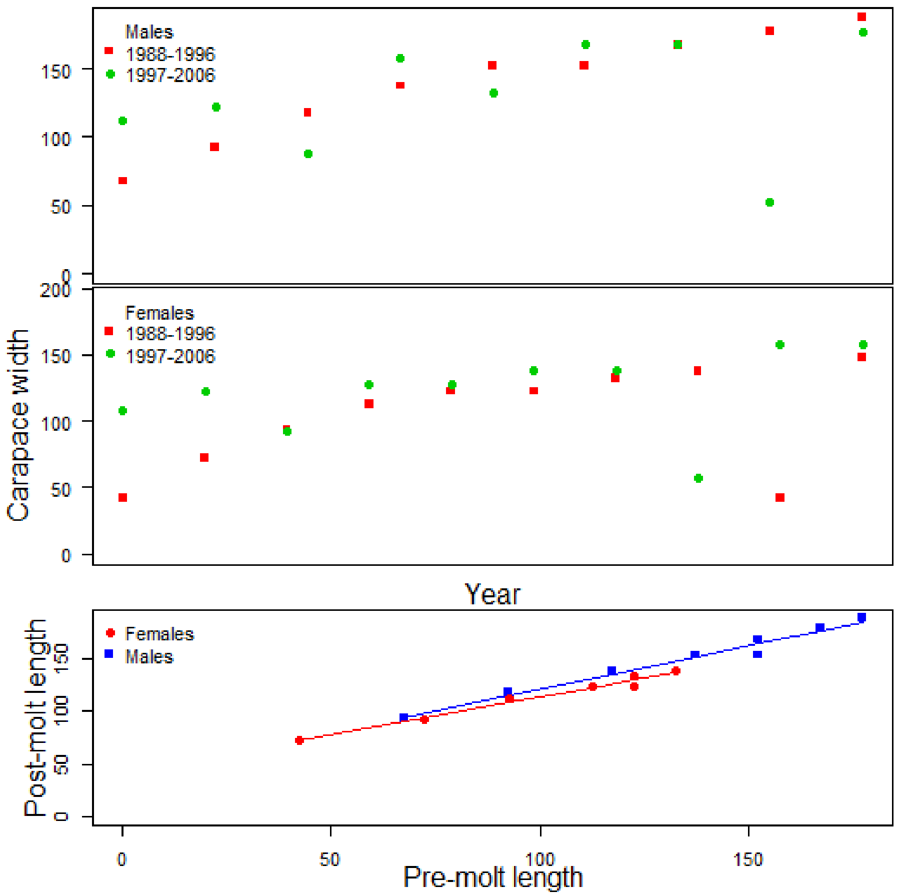

Figure 12. Modes of the length frequency distribution for males and females plotted for two time periods over which two cohorts were observed to move through the population. Growth per molt calculated from the modes from the length frequencies with fitted linear relationship (bottom).

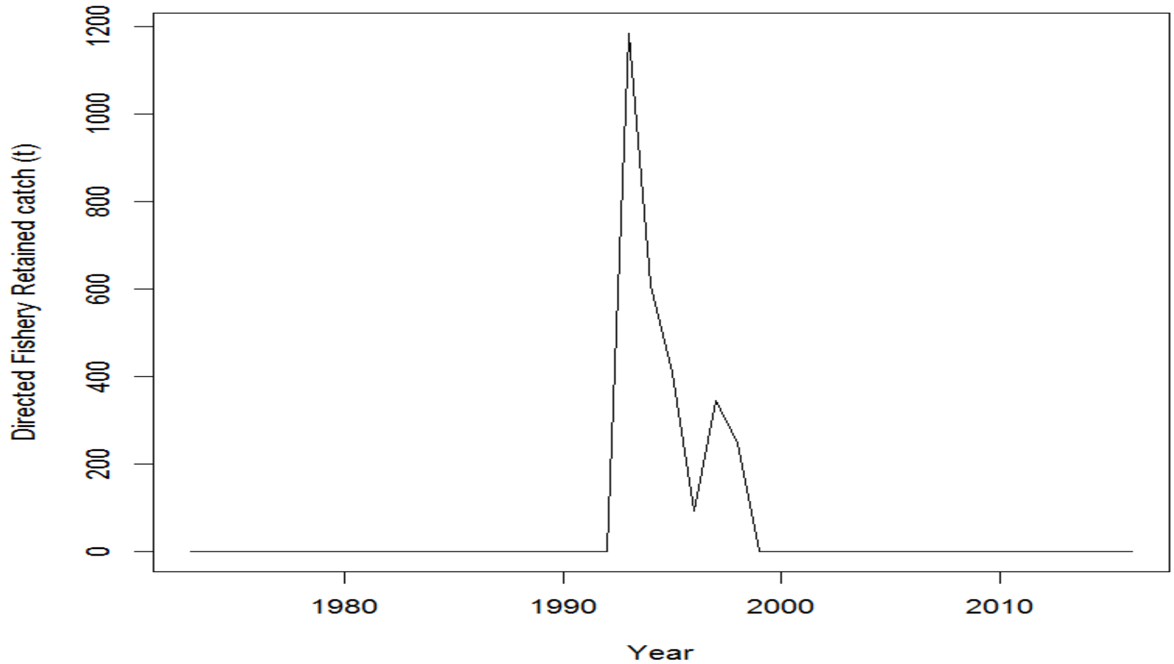

Figure 13. Directed fishery retained catch.

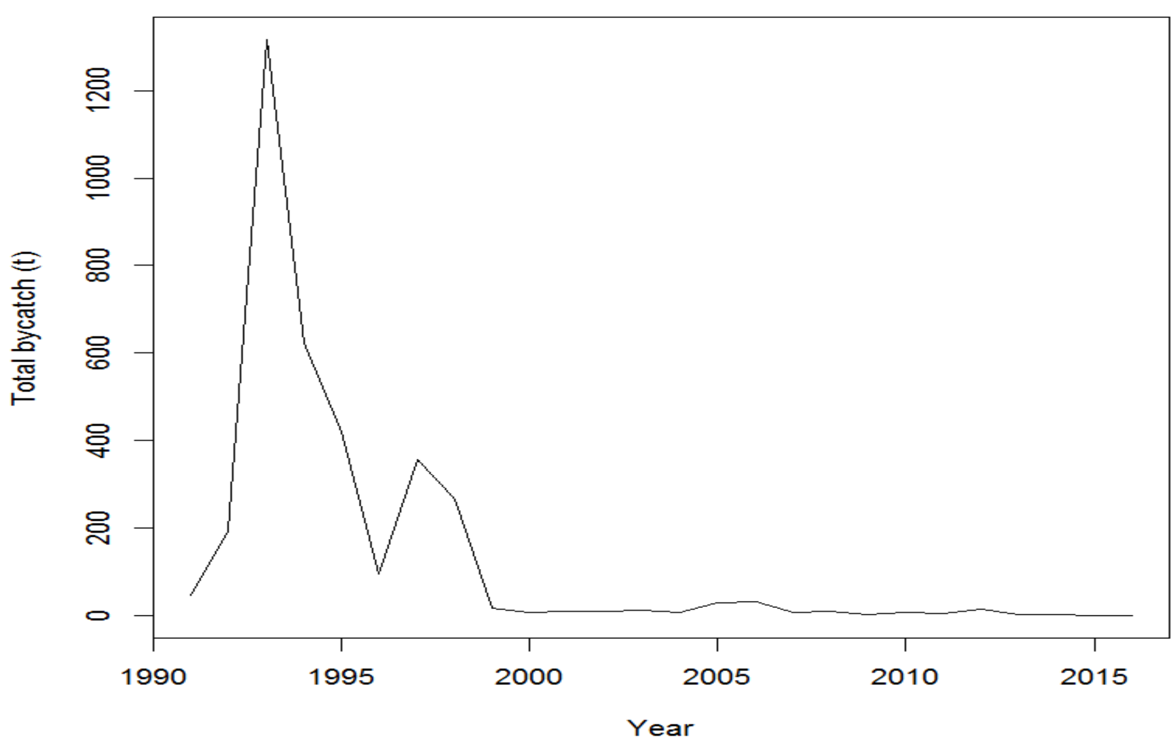

Figure 14. Total bycatch for Pribilof red king crab.

From Spencer presentation at Wakefield 2015

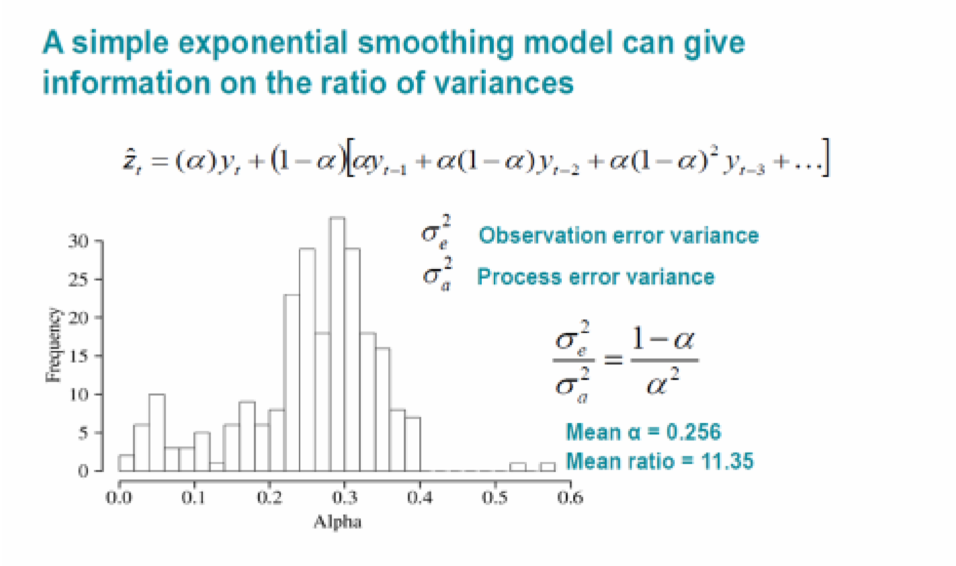

Figure 15. Using a simple exponential smoothing model to estimate the variance ratio of observation error and process error.

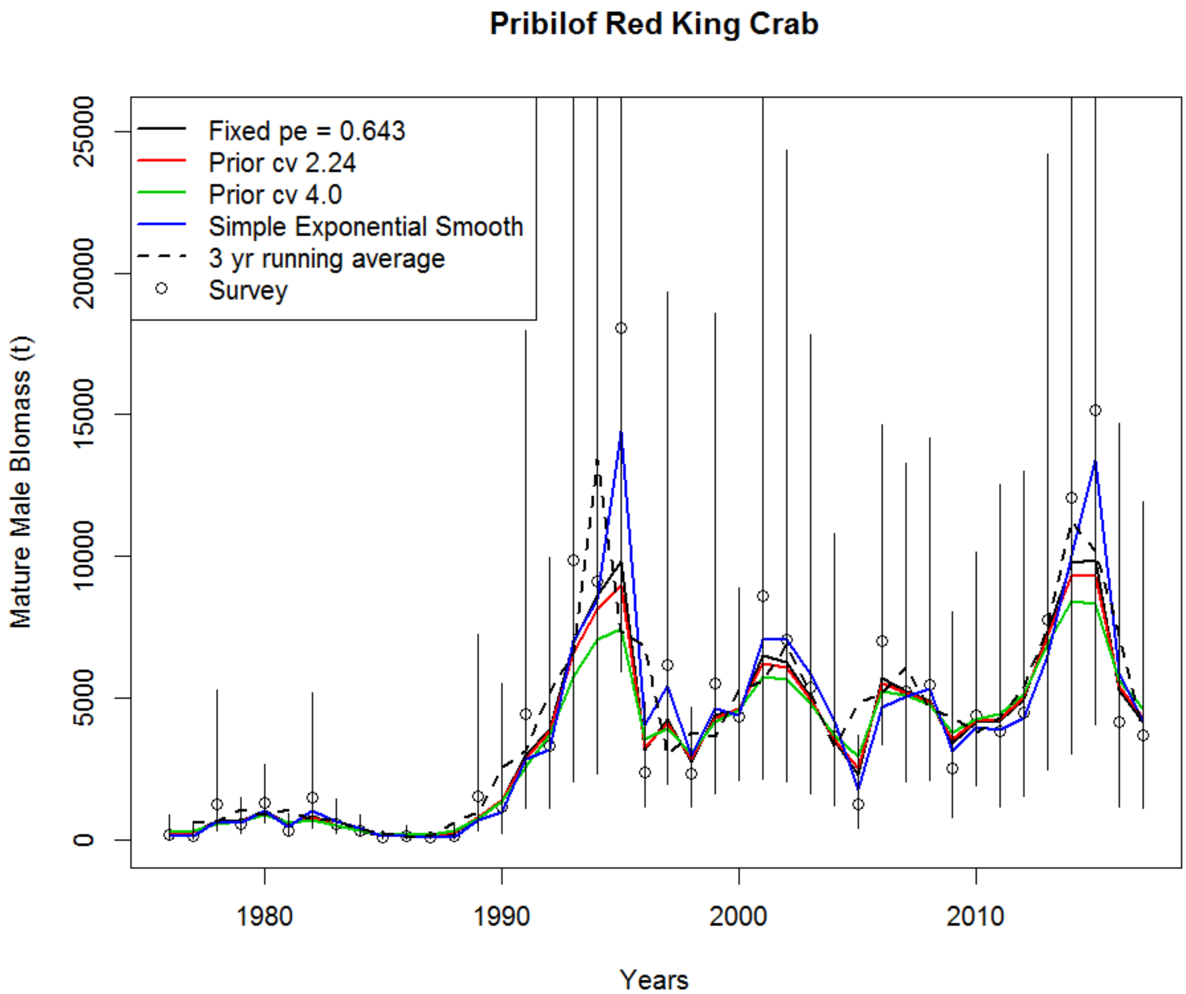

Figure 16. Mature male biomass (t) (>=120mm) at the time of the survey. Lines are the fit for the 3 year weighted average, the random effects model with process error fixed (0.643), the random effects model with cv on prior of 2.24, the random effects model with cv on prior of 4.0 and the simple exponential model.

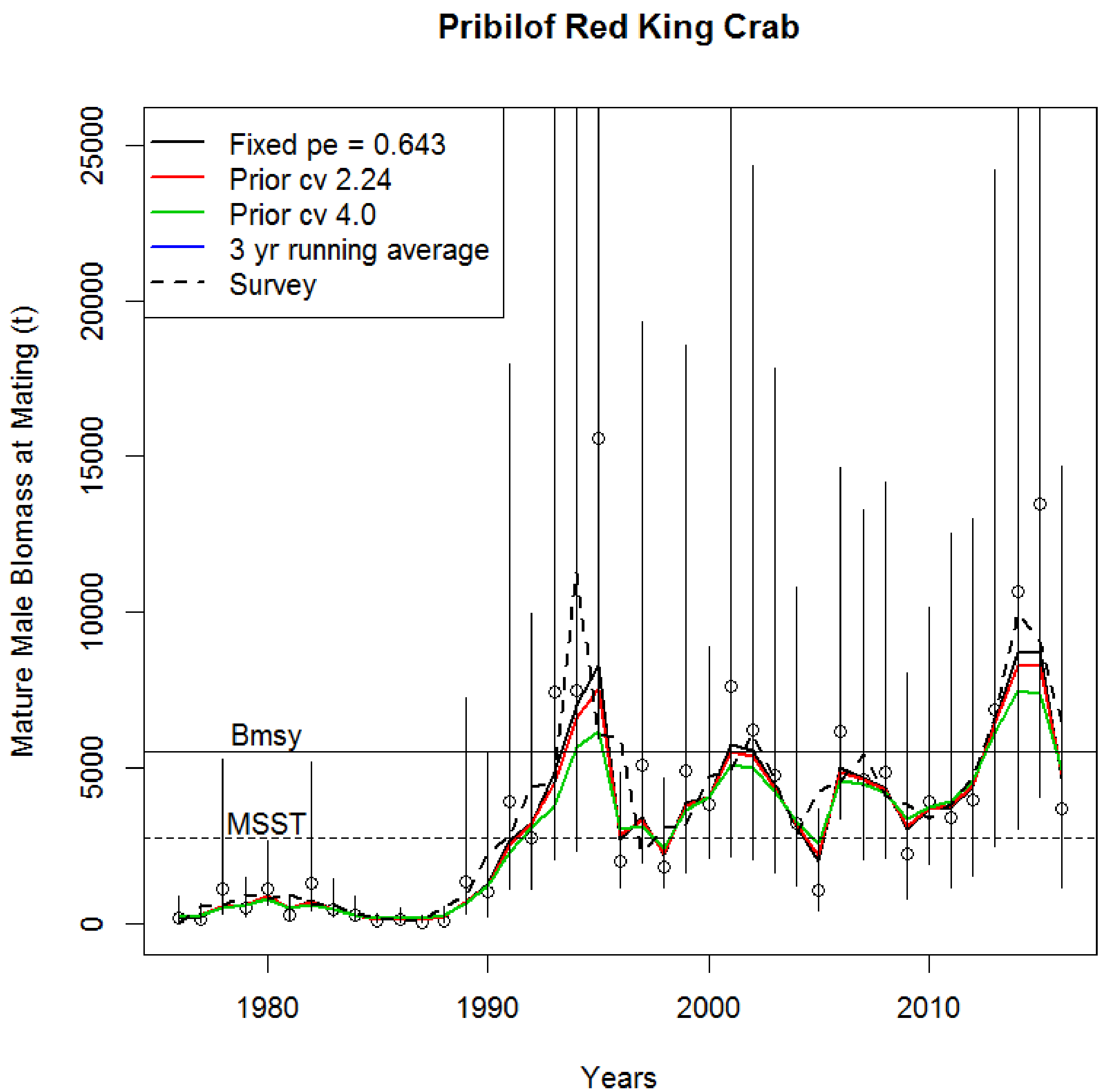

Figure 17. MMB at mating (t) for the 3 year weighted average, the random effects model with process error fixed, the random effects model with cv on prior of 2.24 and the random effects model with cv on prior of 4.0. Bmsy is the average of the survey biomass from 1991/92 to 2016/17. MSST is 50% of Bmsy.