2022 preliminary assessment for Pribilof Islands red king crab

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May 16, 2022

Contents

Executive summary

1. **Stock**: Pribilof islands red king crab (PIRKC), *Paralithodes camtschaticus*.
2. **Catches**: Retained catches have not occurred since 1998/1999. Bycatch has been sporadic since the late 2000s. In general, total bycatch is a small fraction of the overfishing level (OFL).
3. **Stock biomass**: In recent years, observed mature male biomass (>120mm carapace length) peaked in 2015, however this peak in biomass does not appear to represent the actual dynamics of the stock. The size composition data suggest that a cohort established in the early 2000s and fluctuations seen over that period in biomass were likely due to observation error. A new cohort appears to have entered the population in 2018. The stock is not overfished based on a tier 4 specification of B_{MSY} revised in 2019.
4. **Recruitment**: Recruitment appears to be episodic and, depending on the model specification, three or four cohorts have passed through the population since the late 1980s.
5. **Recent management statistics**: PIRKC is now on a triennial assessment cycle and was last assessed in 2019. GMACS is now used as the preferred assessment model.

Table 1: Historical status and catch specifications for Pribilof Islands red king crab (t). THIS TABLE IS NOT FINAL AND WILL BE MODIFIED.

Year	MSST	Biomass (MMB)	TAC	Retained catch	Total catch	OFL	ABC
2014/15	2871	8894	0	0	1.06	1359	1019
2015/16	2756	9062	0	0	4.32	2119	1467
2016/17	2751	4788	0	0	0.94	1492	1096
2017/18	2751	3439	0	0	1.41	404	303
2018/19	866	5368	0	0	7.22	404	303
2019/20	866	6431	0	0	3.84	864	648
2020/21	866	6431	0	0	5.09	864	648
2021/22	716	5347				864	648
2022/23						944	708

Table 2: Historical status and catch specifications for Pribilof Islands crab (millions of lbs). THIS TABLE IS NOT FINAL AND WILL BE MODIFIED.

Year	MSST	Biomass (MMB)	TAC	Retained catch	Total catch	OFL	ABC
2014/15	6.33	19.61	0	0	0	3	2.25
2015/16	6.08	19.98	0	0	0.01	4.67	3.23
2016/17	6.06	10.56	0	0	0	3.29	2.42
2017/18	6.06	7.58	0	0	0	0.89	0.67
2018/19	1.91	11.83	0	0	0.02	0.89	0.67
2019/20	1.91	14.18	0	0	0.01	1.9	1.43
2020/21	1.91	14.18	0	0	0.01	1.9	1.43
2021/22	1.58	11.79				1.9	1.43
2022/23						2.08	1.56

6. **2021/2022 OFL projections**:

Table 3: Metrics used in designation of status and OFL (t). 'Years' indicate the year range over which recruitment is averaged for use in calculation of B35. 'Status' is the ratio between MMB and BMSY. 'M' is natural mortality. THIS TABLE IS NOT FINAL AND WILL BE MODIFIED

Year	Tier	BMSY	MMB	Status	FOFL	Years	M
2021/2022	4	1524	4963	3.257	0.21	2000-2020	0.21

7. **Probability distributions of the OFL**: No distribution of the OFL was calculated for this assessment cycle.

8. **Basis for ABC**: ABCs are calculated using a 25% buffer as recommended by the CPT and SSC in 2017.

A. Summary of major changes:

1. **Management**: This is the first assessment since PIRKC shifted to a triennial management cycle in 2019.
2. **Input data**: Survey and bycatch data were updated with the most recent data in this draft. Some small adjustments were made to the recent years of bycatch data after a new download from AKFIN. Data from 2022 will be incorporated into this draft for September.
3. **Assessment methodology**: GMACS was adopted in 2019 as the assessment methodology for this stock. B_{MSY} was redefined in 2019 as 35% of the average MMB observed from 2000-present, which was a period of no fishing.
4. **Assessment results**: Overfishing did not occur from 2019-2021 and the stock was not overfished as of the summer of 2021.

B. CPT and SSC comments/requests from September 2019:

The CPT recommended the following for consideration in the future assessment:

CPT: "Examine the weighting of the length compositions used in the integrated model."

I incorporated two models that modified the weighting of the size composition data (somewhat arbitrarily) for illustrative purposes. Future work could include a more systematic exploration of weighting methodologies (e.g. Francis, McAllister-Ianelli, etc.).

CPT: "A potentially better estimate BMSY would be replay the stock dynamics using the integrated model under the assumption of F=0 (i.e., dynamic B0). BMSY could then be estimated by taking 35% of the average biomass for full period."

Functionality for dynamic B0 does not currently exist in GMACS, but this is on the list of improvements to make.

CPT: "Explore using ADF&G pot survey data for 2003, 2005, 2008, and 2011 in the assessment model."

These data are now in hand and a model incorporating these data will be presented in September.

CPT: "Evaluate the survey or fishery catches adjacent to the defined stock area to see they are indicative of movement into the Pribilof Islands area."

Maps of the survey densities of Bering Sea-wide red king crab and size composition data are now included. The spatio-temporal patterns in distribution provide some clue to the dynamics of interconnection between the crab observed in each of the three main districts in the eastern Bering Sea. I am outlining a proposal to model these dynamics with the goal of understanding how they may change under climate change.

The SSC comments included:

SSC: "The assessment should consider all relevant datasets. Available ADF&G pot survey data should be included."

In addition to the ADF&G pot survey, size composition data for the bycatch from observer data exist. These data will be presented in a model for September. Encouragingly, the cohorts that can be seen in the survey size composition data can be distinguished (though not as well) in the observer data. Incorporating these data should allow for the estimation of the bycatch selectivity rather than specifying it based on Bristol Bay red king crab.

SSC: "The SSC also raises the question whether Pribilof Islands red king crab are a separate stock. Reasons to raise this question include: (1) apparent lack of red king crab in the area in the 1970s and 1980s, (2) increases in stock abundance that do not seem biologically plausible, and (3) distribution of red king crab outside both the Bristol Bay and Pribilof Islands areas. Comparisons of size distributions may shed light on the sudden appearance of cohorts in the survey area."

See response to CPT above.

C. Introduction

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 in the Barents Sea (Jorstad et al. 2002). The distribution and density of red king crab on the Bering Sea shelf has changed somewhat over time (Figure 2). After the collapse in abundance in the mid-1980s, the stock was concentrated in Bristol Bay. Over time, the lower densities of crab were observed farther north (near Nunivak Island) and west (near the Pribilof Islands). The 2021 distribution of red king crab in the Bering Sea is shifted farther north than historically seen.

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 US-Russian boundary (Figure 3). The distribution of red king crab within the Pribilof District is concentrated around the islands (see Figure 4 for a zoomed in version of Figure 2). The numbers of stations at which red king crab were observed around the Pribilof Islands was at an all time high in 2021 (Figure 5).

The connection between the crab in the three different 'districts' in the Bering Sea (Bristol Bay, Pribilof Islands, and Northern) is an open question. Much higher abundances of male crab occur in Bristol Bay (Figure 6), but it is unknown if the crab around the Pribilofs and in the Northern District migrate there from Bristol Bay or if larvae are advected there, settle, and grow. The numbers of males at size plotted by district can provide a clue to the dynamics of red king crab in the Bering Sea. Clear cohorts can be seen developing over time in Bristol Bay and the Pribilof Islands, but these are not seen in the Northern District (Figure 7). Although there appear to be three to four cohorts in the Pribilof District, five or more can be seen Bristol Bay. The larval crab that developed into the first cohort around the Pribilofs in the late 1980s clearly did not originate there, but it is not clear if the subsequent cohorts were supplied from the spawning stock in the Pribilofs or advected from Bristol Bay. Analyses of ocean currents around the time when the Pribilof Island cohorts established could provide some understanding of the origin of the subsequent cohorts.

The lack of cohorts in the Northern District suggests that crab in the north migrated from either Bristol Bay or the Pribilof Islands. The gradual increase in numbers at size in the North paired with the gradual decrease in Bristol Bay is also suggestive of movement to the north. However, it is important to interpret Figure 7 with caution because the figures for each district are plotted relative to the maximum in that district. The decrease in abundance in Bristol Bay is nowhere near compensated for by the increase in the north (Figure 6).

The maximum size of crab in Bristol Bay is smaller than that of the crab around the Pribilof Islands, which is not particularly surprising given there is a commercial fishery in Bristol Bay and not around the Pribilof Islands (Figure 7; compare the numbers to the right of the vertical dashed line at 175 mm carapace length by district). The lack of larger crab in the Northern District may indicate that the crab in the north are migrating back and forth between Bristol Bay and ultimately caught. It is also possible that there are differences in growth and molting frequency between Bristol Bay and the Pribilof Islands stock, but tagging studies and laboratory work would be needed to describe these differences, if they exist.

Finally, if the crab in each district were actually one large population responding to similar environmental pressures, one might expect the mean size between districts to be correlated over time. However, there is no significant correlation between mean size (calculated as the mean size weighted by the abundance) between any of the districts (Figure 8; Prib vs. BB = -0.26, Prib vs. North = -0.05; BB vs. North = - 0.18). This does not exclude the possibility that the Pribilof Islands are supplied with larvae from Bristol Bay, but it does suggest that, if that is the case, the environmental conditions that support good recruitment in Bristol Bay may not be the same conditions that support good recruitment in the Pribilofs.

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 three stocks: Okhotsk Sea-Aleutian Islands-Norton Sound, Southeast Alaska, and the rest of the EBS (Grant and Cheng 2012).

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 eggs per female 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 was reported for eastern Bering Sea male red king crabs (Somerton 1980). In the recent history of the assessment of PIRKC, crab greater than 120 mm carapace length were used as a measure of mature male bioamss. Early studies predicted that red king crab become mature at approximately age 5 (Powell 1967; Weber 1967); however, Stevens (1990) predicted mean age at maturity in Bristol Bay to be 7 to 12 years, and Loher et al. (2001) predicted age at maturity to be approximately 8 to 9 years after settlement.

Natural mortality of Bering Sea red king crab stocks is poorly known (Bell 2006). 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). Siddeek et al. (2002) reviewed natural mortality estimates from various sources. Natural mortality estimates based upon historical tag-recapture data ranged 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 ranged 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. Natural mortality based on empirical estimates for a maximum age of 21 from Hoenig (1983), Hamel (2015), and Then et al. (2015) are 0.21, 0.26, and 0.30, respectively. Assuming a maximum age of 25 (following BBRKC) results in natural mortalities of 0.18, 0.22, 0.26 for Hoenig, Hamel, and Then methodologies, respectively.

The reproductive cycle of Pribilof Islands red king crabs has not been established. However, in Bristol Bay the 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 crab are approximately: 23% at 10 mm CL, 27% at 50 mm CL, 20% at 80 mm CL and 16 mm for immature crab 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 crab 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) reported 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).

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 9). 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 around 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 a more complete management history).

Amendment 21 to the BSAI groundfish FMP established the Pribilof Islands Habitat Conservation Area (Figure 3) 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 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 and the OFL.

D. Data

The following sources and years of data are available: NMFS trawl survey (1976-2019, 2021-present), retained catch (1993-present), trawl bycatch (1991-present), fixed gear bycatch (1991-present), and pot discards (1998 to present).

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 (Table 4), but no retained catch has been allowed since 1999.

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.

$$w_l = \alpha l^{\beta} \tag{1}$$

$$w_{avg} = \frac{\sum_l w_l N_l}{\sum_l N_l} \tag{2}$$

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 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 recent years, catch of PIRKC in other crab fisheries has been almost non-existent.

Bycatch from groundfish fisheries from 1989 to present are available in the AKFIN database and included in the integrated assessment as a single fishery with selectivity equal to the trawl fishery estimated in the BBRKC assessment (Figure 10). See Calahan et al. 2010 for a description of the methodology used to develop these data.

Catch-at-size

Catch-at-size data are not available for the directed fishery, but size compositions for bycatch can be calculated from the observer data (Figure 11). These data are not yet in the model, but appear to mirror the cohort progressions seen in the survey size composition data. These data could be valuable indicators for incoming cohorts that the survey misses. For example, the most recent cohort in the Pribilof district appear in the survey data in 2018 at around 100 mm carapace length. This cohort can be seen as early as 2015 at around 70 mm carapace length in the observer size composition data.

Survey abundance and length composition

The most up-to-date NOAA Fisheries EBS bottom trawl survey results are included in this preliminary SAFE report (1976-2019, 2021; see Lang et al. 2018 for methodology). Data available for estimating the abundance of crab around the Pribilof Islands are relatively sparse. Male abundance varies widely over the history of the survey time series and uncertainty around area-swept estimates of abundance is large due to relatively low sample sizes (Figure 12). Red king crab have been observed at 35 unique stations of the 44 stations in the Pribilof District over the years 1976 to present (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 0-18 over the period from 1976-present (Figure 5). Male crabs were observed at 18 stations in the Pribilof District during the 2021 survey, which was the highest frequency of occurrence of red king crab in the Pribilof district. Although estimated numbers at length are variable from year to year, 3 to 4 cohorts can be discerned in the length composition data (Figure 13).

The centers of distribution for both males and females have moved around St. Paul Island. The center of the red king crab distribution moved to the northeast of St. Paul Island as the population abundance increased in the 1980s and remained in that region until the 1990s. Currently, the largest tows were also observed north and east of St. Paul Island (Figure 4). Mature male biomass (>120 mm) at the time of the survey has declined in recent years to a low in 2018 (Figure 14). However, a pseudocohort was observed in the 2018 survey data and appears to have persisted through the size classes to 2021 (Figure 13). Given the variability in the survey data, more observations will be useful to corroborate this size of this pseudocohort.

E. Analytical approaches

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 was used before 2019 to set the acceptable biological catches. The Tier 4 harvest control rule (HCR) has been used in conjunction with estimates of MMB to calculate the OFL. In the Tier 4 HCR, natural mortality is 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}. The Tier 4 B_{MSY} proxy for PIRKC was calculated in 2017 as the average of the 1991/92 to the present year of observed survey data projected forward to February 15, removing the observed catch. Given the fishing history of PIRKC, accommodating this stock with the current Tier 4 rule is challenging because it has only been fished for 6 year out of the more than 40 years of available survey data. GMACS was adopted as the assessment methodology for PIRKC in 2019 in addition to a change in the definition of $\mathrm{B_{MSY}}$. Both are briefly described below.

GMACS

Results from an integrated assessment framework have been presented since 2014 (Szuwalski, Turnock and Foy, 2015), but an integrated assessment using GMACS was accepted for use in management in 2019. Previous integrated assessments fit to male abundance, but the GMACS model fits male biomass >120 mm carapace length. Retained catches and bycatch were fit using assumed selectivities from the BBRKC assessment (Zheng et al., 2018). Growth was estimated and informed by cohorts moving through the population and assumptions about natural mortality and molting probabilities. Molting probabilities and survey catchability were fixed based on the estimates from the 2018 BBRKC assessment. 127 parameters were estimated (Table 5) and 7 parameters were fixed (Table 6). A bin size of 5 mm was selected to model numbers at length in the integrated assessment based on Szuwalski (2015).

Four models are presented here: the accepted GMACS model from 2019 (19.1), a GMACS model with updated code and data through 2021 (22.1), 22.1 with all weight of size composition data set to 50 (22.1a), and 22.1 with all weights of size composition data divided by 2 (22.1b). Models 22.1a and 22.1b are meant to explore the behavior of the model when different weights are specified for the size composition data and not meant to be candidate models. In September, models with the ADF&G pot survey data and the observer size composition data will be brought forward. Input sample sizes are set to the actual number of crabs observed to calculate the size composition in a given year, but, if that number exceeds 200, it is set to 200. See appendix A and B for .DAT and .CTL files for the author-preferred model.

Fits to data and estimated and assumed population processes

Survey biomass and length composition data

Fits to the survey biomass varied little by models that fit to the updated data (Figure 14). There were slight differences between the model estimates of survey MMB between the 2022 models and the 2019 model. The large increases in survey MMB in 2014 and 2015 are not fit well by any of the models, but this is an important feature of the integrated model. The large survey estimates in 2014 and 2015 were driven by large tows at a single station in years in which the frequency of occurrence (i.e. the number of stations at which crab were observed) was relatively low (Figure 4). The size composition data indicate the presence of a cohort that began to be seen in the survey gear in the mid-2000s and then no further cohorts appeared until the late 2010s. A cohort should get smaller over time as a result of natural mortality, not grow in size, which suggests that the large increased in survey MMB in 2014 and 2015 are due to measurement error.

All models estimate three pulses of survey biomass and differences between fits to size composition data were relatively small in spite of changes in the weightings of the size composition data (Figure 15). One of the largest differences comes in the first two years of size composition data in which the model predictions for the largest size classes are much higher than the observations for 22.1 and 22.1b. The first two years have sample sizes of 82, which influences how well they are fit relative to other years of size composition data. Smaller differences in fits to the size composition data are likely related to differences in estimated survey selectivity (Figure 16). Both the midpoint and slope parameter (‘log_slx_pars[5] & ’log_slx_pars[6]’ in GMACS; Table 5) for the logistic function varied among models. Trajectories of predicted mature male biomass at the time of mating were similar across models and showed an uptick since 2017, which was the lowest MMB since the late 1990s (Figure 17).

Retained catches, bycatches, and estimated fishing mortality

Retained catches and bycatches were fit essentially identically by all models with the same input data (Figure 18), but the inferred influence of the directed fishery on the population as seen through the estimated fishing mortality varied by model (Figure 19). The model with the lightest weight on size composition data returned the highest estimates of fishing mortality (22.1b). Fits from models with updated data through 2021 reflect changes in the calculation of bycatch (compare the pink line in Figure 18 in the trawl panel to the other lines).

Molting probability and growth

Growth was estimated within each model and varied somewhat among models, with a difference of approximately 1.5 mm carapace length per molt for crab over 200 mm carapace length (Figure 20). Molting probability was fixed according to the estimates from the 2018 BBRKC assessment (Figure 21). No growth data exist to fit to, so the information to estimate growth comes from the modes of the survey size composition data, input natural mortality, and probability of molting by size.

Estimated recruitment

Three large pseudocohorts were estimated by all models (Figure 22). Estimates of the second recruitment pulse (around the early 1990s) were the most variable in size and timing across models. This seems to be primarily a result of different fits to somewhat noisy length compositions in 1996-99.

F. Calculation of reference points

Tier 4 OFL and B_{MSY}

Historically, Tier 4 control rules used natural mortality as a proxy for F_{MSY} and calculated a proxy for B_{MSY} by averaging the biomass over a period of time when the stock was thought to have been at B_{MSY}. However, given that PIRKC has only been fished for six years in its history, identifying a period of time during which it was fished at $\mathrm{F_{MSY}}$ is difficult. In 2019, the CPT chose a different strategy and defined the proxy for $\mathrm{B_{MSY}}$ as 35% of the average MMB over the years 2000-2018. This strategy retains the intention of the original definition and incorporates the concept of $\mathrm{B_{35\%}}$ used for tier 3 stocks. Using this redefined proxy for $\mathrm{B_{MSY}}$ and natural mortality as a proxy for $\mathrm{F_{MSY}}$, the OFL is calculated for PIRKC by applying a fishing mortality determined by the harvest control rule below to the mature male biomass at the time of fishing.

$$F_{OFL} = \begin{cases} Bycatchonly & if \frac{MMB}{MMB_{MSY}} \leq 0.25 \\ \frac{\lambda M(\frac{MMB}{MMB_{MSY}} - \alpha)}{1-\alpha} & if 0.25 < \frac{MMB}{MMB_{MSY}} < 1 \\ \lambda M & if MMB > MMB_{MSY} \end{cases} \tag{3}$$

Where MMB is the mature male biomass projected to the time of mating, MMB_{MSY} is 35% of the average mature male biomass over the years 2000-present, M is natural mortality, and α determines the slope of the descending limb of the HCR (here set to 0.1).

A range of terminal year MMBs were estimated by the presented scenarios (4894-5347 t). Similarly, the resulting B_{MSY} varied somewhat (1433-1594 t) along with the calculated OFLs (864-944 t).

Acceptable biological catches

ABCs are calculated for other crab stocks in the Bering Sea by multiplying the OFL by a buffer determined by the CPT and SSC. Stocks with similar levels of uncertainty use a buffer of 25% and this was the percentage recommended by the CPT And SSC in 2017. Consequently, the ABC for the author's preferred model 22.1 is 657.75 t.

Variables related to scientific uncertainty in the OFL probability distribution

Uncertainty in the time series of survey estimated of biomass for Pribilof Islands red king crab is relatively high due to small sample sizes. However, the coefficient of variation for the estimate of male abundance for 2021 was 0.296, which is the lowest on record due in part to the highest frequency of occurence on record. The c.v. has ranged between 0.297 and 0.92 since the 1991 peak in biomass (Figure 14). Recruitment, growth, and survey selectivity were estimated within the integrated assessment, but maturity, survey catchability, fishery selectivity, and natural mortality were fixed to values from the BBRKC assessment. Fitting to data to inform these processes might increase both the accuracy and uncertainty in estimates of management quantities. F_{MSY} was assumed to be equal to natural mortality, which is poorly known.

G. Author Recommendation

The author's preferred model is 22.1 because it is the only model that uses both the updated code and data, but is not meant as a sensitivity to explore the impact of different weights for the size composition data. In September, the ADF&G pot survey data will be added in addition to the size composition data for the bycatch, both individually and in a single model to explore the impacts of each new data set on estimation.

H. Data gaps and research priorities

The largest data gap is the number of observations from which the population size and biomass is extrapolated and this will not likely change appreciably in the future. The small sample sizes (and no expected increases in sample size) support the use of as much of the available data as possible in assessment efforts. 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 in the NMFS survey may also shed some light on divergent changes in abundance in recent years. The Bering Sea Fisheries Research Foundation (BSFRF) selectivity studies sampled crab around the Pribilof Islands in 2017 and 2018, so it is possible some analysis could be performed with those data. Retrospective analyses will be performed in September. Finally, Bayesian methods with relatively uninformative priors for population processes is a potential methodology to better account for the uncertainties.

I. 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 and/or Arctic Oscillation with snow crab recruitment in the EBS (Szuwalski and Punt, 2013b; overland et al., 2008; Szuwalski et al., 2020). Ocean acidification also appears to have a detrimental effect on red king crab (Long et al., 2013), which may impact the productivity of this stock in the future. Finally, an understanding of meta-population dynamics would help in understanding potential futures for this stock.

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Appendix A. Data file for the reference model

Some portions of the .DAT and .CTL files do not fit on the page. For complete .DAT files or .CTL files, contact the author.

```
#==========================================================================================
# Gmacs Main  Data  File  Version 1.1:  SM20 Sept 2020 version.
#   GEAR_INDEX  DESCRIPTION
#   1   :   Pot fishery retained    catch.
#   1   :   Pot fishery with    discarded   catch.
#   2   :   Trawl   bycatch
#   3   :   Trawl   survey
#   Fisheries:  1   Pot "Fishery,"  2   Trawl   "by-catch,"
#   Surveys:    3   NMFS    Trawl   "Survey,"
#==========================================================================================
# Fisheries:  1 Pot Fishery,  2 Pot Discard,  3 Trawl by-catch, 3 Fixed by-catch
# Surveys:   4 NMFS Trawl Survey, 5 Pot Survey
#==========================================================================================
1976  # Start year
2021  # End year (updated) last year of fishery does NOT include current survey year
3    # Number of seasons
3   # Number of fleets (fisheries and surveys)
1    # Number of sexes
1    # Number of shell condition types
1    # Number of maturity types
35    # Number of size-classes in the model
3    # Season recruitment occurs
3   # Season molting and growth occurs
3   # Season to calculate SSB
1    # Season for N output
# maximum size-class (males then females)
35
# size_breaks (a vector giving the break points between size intervals with dimension nclass+1)
35  40  45  50  55  60  65  70  75  80  85  90  95  100 105 110 115 120 125 130 135 140 145 150 155 160
# Natural mortality per season input type (1 = vector by season, 2 = matrix by season/year)
1
# Proportion of the total natural mortality to be applied each season (each row must add to 1)
0.33 0.33 0.34
# Fishing fleet names (delimited with spaces no spaces in names)
Pot_Fishery trawl_bycatch
# Survey names (delimited with spaces no spaces in names)
NMFS_Trawl
# Are the fleets instantaneous (0) or continuous (1)
1 1 1
# Number  of  catch data  frames
2
# Number  of  rows  in  each  data  frame
6 31
##  Type of catch: 1 = retained, 2 = discard
##  Units of catch: 1 = biomass, 2 = numbers
##  Male Retained
##  Male    retained    pot fishery (tonnes)
#year   seas    fleet   sex obs cv  type    units   mult    effort  discard_mortality
1993    2   1   1   1183    0.05    1   1   1   0   0
```

```
1994    2   1   1   607.34  0.05    1   1   1   0   0
1995    2   1   1   407.32  0.05    1   1   1   0   0
1996    2   1   1   90.87   0.05    1   1   1   0   0
1997    2   1   1   343.29  0.05    1   1   1   0   0
1998    2   1   1   246.91  0.05    1   1   1   0   0
##  trawl bycatch
#year   seas    fleet   sex obs cv  type    units   mult    effort  discard_mortality
1991    2   2   1   1.70974 0.05    2   1   1   0   0.2
1992    2   2   1   45.6118 0.05    2   1   1   0   0.2
1993    2   2   1   39.2184 0.05    2   1   1   0   0.2
1994    2   2   1   5.3439  0.05    2   1   1   0   0.2
1995    2   2   1   0.39271 0.05    2   1   1   0   0.2
1996    2   2   1   0.82968 0.05    2   1   1   0   0.2
1997    2   2   1   0.42638 0.05    2   1   1   0   0.2
1998    2   2   1   2.13652 0.05    2   1   1   0   0.2
1999    2   2   1   5.38023 0.05    2   1   1   0   0.2
2000    2   2   1   1.67492 0.05    2   1   1   0   0.2
2001    2   2   1   0.38506 0.05    2   1   1   0   0.2
2002    2   2   1   0.30775 0.05    2   1   1   0   0.2
2003    2   2   1   1.78570 0.05    2   1   1   0   0.2
2004    2   2   1   4.23464 0.05    2   1   1   0   0.2
2005    2   2   1   6.43697 0.05    2   1   1   0   0.2
2006    2   2   1   16.3143 0.05    2   1   1   0   0.2
2007    2   2   1   1.81987 0.05    2   1   1   0   0.2
2008    2   2   1   8.26152 0.05    2   1   1   0   0.2
2009    2   2   1   1.37112 0.05    2   1   1   0   0.2
2010    2   2   1   8.21497 0.05    2   1   1   0   0.2
2011    2   2   1   5.87314 0.05    2   1   1   0   0.2
2012    2   2   1   15.7143 0.05    2   1   1   0   0.2
2013    2   2   1   2.67646 0.05    2   1   1   0   0.2
2014    2   2   1   1.1826  0.05    2   1   1   0   0.2
2015    2   2   1   3.34955 0.05    2   1   1   0   0.2
2016    2   2   1   1.01445 0.05    2   1   1   0   0.2
2017    2   2   1   0.64834 0.05    2   1   1   0   0.2
2018    2   2   1   6.55489 0.05    2   1   1   0   0.2
2019    2   2   1   4.4921  0.05    2   1   1   0   0.2
2020    2   2   1   6.53815 0.05    2   1   1   0   0.2
2021    2   2   1   1.33561 0.05    2   1   1   0   0.2
##  RELATIVE  ABUNDANCE DATA
##  Units of abundance: 1 = biomass, 2 = numbers
##  Number  of  relative  abundance indicies
1
##  Type of Survey (1=Selectivity; 2=Selectivity+Retention)
1
##  Number  of  rows  in  each  index
45
# Survey data (abundance indices, units are mt for trawl survey and crab/potlift for pot survey)
#   Year,   Seas,   Fleet,  Sex,    Maturity,   Abundance,  CV  units, timing
1 1976  1   3   1   1 165.0820617   1           1       0
1 1977  1   3   1   1 118.6098455   1           1       0
1 1978  1   3   1   1 1249.504275   0.825444585 1       0
1 1979  1   3   1   1 555.786924    0.515229785 1       0
1 1980  1   3   1   1 1268.984093   0.382081279 1       0
1 1981  1   3   1   1 312.2868886   0.584325303 1       0
```

```
1 1982  1   3   1   1 1463.679065   0.698000353 1       0
1 1983  1   3   1   1 526.744361    0.533724327 1       0
1 1984  1   3   1   1 317.2336136   0.548811503 1       0
1 1985  1   3   1   1 61.48435668   1           1       0
1 1986  1   3   1   1 137.6189026   0.69839786  1       0
1 1987  1   3   1   1 53.57634662   1           1       0
1 1988  1   3   1   1 106.6465639   1           1       0
1 1989  1   3   1   1 1529.464076   0.90992879  1       0
1 1990  1   3   1   1 1141.083317   0.928450918 1       0
1 1991  1   3   1   1 4429.984707   0.796181771 1       0
1 1992  1   3   1   1 3304.807041   0.596461097 1       0
1 1993  1   3   1   1 9873.34095    0.921566362 1       0
1 1994  1   3   1   1 9138.77513    0.767521538 1       0
1 1995  1   3   1   1 18055.69546   0.60095161  1       0
1 1996  1   3   1   1 2361.497955   0.371521839 1       0
1 1997  1   3   1   1 6158.829812   0.622539865 1       0
1 1998  1   3   1   1 2323.52199    0.35996772  1       0
1 1999  1   3   1   1 5522.918743   0.666747632 1       0
1 2000  1   3   1   1 4320.463935   0.37363563  1       0
1 2001  1   3   1   1 8603.167987   0.786467508 1       0
1 2002  1   3   1   1 7037.318355   0.685911274 1       0
1 2003  1   3   1   1 5372.970101   0.657890334 1       0
1 2004  1   3   1   1 3621.908657   0.589178579 1       0
1 2005  1   3   1   1 1238.268912   0.585062881 1       0
1 2006  1   3   1   1 7002.930989   0.382674833 1       0
1 2007  1   3   1   1 5223.698293   0.492451158 1       0
1 2008  1   3   1   1 5462.268463   0.506106314 1       0
1 2009  1   3   1   1 2500.339048   0.63776799  1       0
1 2010  1   3   1   1 4404.990634   0.436292304 1       0
1 2011  1   3   1   1 3834.344372   0.648228535 1       0
1 2012  1   3   1   1 4477.112792   0.573312819 1       0
1 2013  1   3   1   1 7749.452256   0.619447168 1       0
1 2014  1   3   1   1 12046.84171   0.784574994 1       0
1 2015  1   3   1   1 15172.86095   0.738783782 1       0
1 2016  1   3   1   1 4150.360114   0.700657951 1       0
1 2017  1   3   1   1 3658.466372   0.645985498 1       0
1 2018  1   3   1   1 928.7018441   0.42596546  1       0
1 2019  1   3   1   1 2086.406334   0.343726969 1       0
1 2021  1   3   1   1 3743.943686   0.296597935 1       0
##  Number  of  length  frequency matrices
1
##  Number  of  rows  in  each  matrix
33
##  Number  of  bins  in  each  matrix  (columns  of  size  data)
35
##  SIZE  COMPOSITION DATA  FOR ALL FLEETS
##  SIZE  COMP  LEGEND
##  Sex:  1 = male, 2 = female, 0 = both  sexes combined
##  Type  of  composition:  1 = retained, 2 = discard,  0 = total composition
##  Maturity  state:  1 = immature, 2 = mature, 0 = both  states  combined
##  Shell condition:  1 = new shell,  2 = old shell,  0 = both  shell types combined
##length  proportions of  pot discarded males
##Year, Seas, Fleet,  Sex,  Type, Shell,  Maturity, Nsamp,  DataVec
1988    1   3   1   1   0   0   82  0   0   0   0.012195122 0.073170732 0.048780488 0.30487805  0.20731
```

```
1989 1 3 1 1 0 0 82 0 0 0 0 0 0 0 0 0 0.024390244 0.048780488 0.14634
1990 1 3 1 1 0 0 200 0 0 0 0 0 0 0 0 0.007508939 0 0 0 0.004962619
1991 1 3 1 1 0 0 102 0 0 0 0 0 0 0 0.029126214 0 0.009708738 0.009708738
1992 1 3 1 1 0 0 76 0 0 0 0.013157895 0 0 0 0 0 0 0 0.026315789 0.07
1993 1 3 1 1 0 0 166 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0.03330
1994 1 3 1 1 0 0 113 0 0 0 0 0 0 0 0 0 0 0 0 0 0.005649717 0.00
1995 1 3 1 1 0 0 200 0 0 0 0 0 0.00330033 0 0 0 0 0.00330033 0.00330
1996 1 3 1 1 0 0 31 0 0.032258065 0 0 0 0 0 0 0 0 0 0.032258065 0.09
1997 1 3 1 1 0 0 165 0 0 0 0 0 0 0 0 0.006060606 0.006060606 0.030303031
1998 1 3 1 1 0 0 66 0 0 0 0 0 0 0 0 0 0 0 0.015151515 0 0.01515
1999 1 3 1 1 0 0 200 0 0 0 0 0 0.005086686 0.005086686 0.0356068 0.091560343
2000 1 3 1 1 0 0 86 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0.01162
2001 1 3 1 1 0 0 200 0 0 0 0 0 0 0 0 0 0.003012048 0 0.012048193 0.05
2002 1 3 1 1 0 0 105 0 0 0 0 0 0 0 0 0 0 0.00952381 0 0 0 0
2003 1 3 1 1 0 0 67 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
2004 1 3 1 1 0 0 124 0 0.016129032 0.064516128 0.177419353 0.169354837 0.104838709 0.00
2005 1 3 1 1 0 0 14 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0.142857143
2006 1 3 1 1 0 0 76 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0.013157895
2007 1 3 1 1 0 0 76 0 0 0 0 0 0 0 0 0 0 0.012987013 0 0 0.01298
2008 1 3 1 1 0 0 92 0 0 0 0 0 0 0 0 0 0 0.011111111 0.011111111 0.00
2009 1 3 1 1 0 0 51 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0.01
2010 1 3 1 1 0 0 62 0 0 0 0 0 0 0.01369863 0.01369863 0 0 0 0 0
2011 1 3 1 1 0 0 58 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0.01
2012 1 3 1 1 0 0 84 0 0 0.012048193 0 0 0 0 0 0 0 0 0 0.048192772
2013 1 3 1 1 0 0 82 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0.04
2014 1 3 1 1 0 0 162 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0.01234
2015 1 3 1 1 0 0 200 0 0 0 0 0 0 0 0 0 0 0 0.004950495 0.004950495
2016 1 3 1 1 0 0 62 0 0 0 0 0 0 0 0 0 0 0 0 0.010526316 0.01052
2017 1 3 1 1 0 0 200 0 0 0 0 0 0 0 0 0 0.016129032 0 0 0 0 0
2018 1 3 1 1 0 0 91 0 0 0 0 0 0 0 0 0 0 0 0 0.065934066 0.12087
2019 1 3 1 1 0 0 59 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0.03389
2021 1 3 1 1 0 0 68 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0.04
##  Growth data (increment)
# Type of growth increment (0=ignore;1=growth increment with a CV;2=size-at-release; size-at)
0
# nobs_growth
0
#3
# MidPoint Sex Increment CV
# 97.5  1  14.1  0.2197
#112.5  1  14.1  0.2197
#127.5  1  14.1  0.2197
#  97.5  1 13.8 0.2197
#  112.5  1 14.1 0.2197
#  127.5  1 14.4 0.2197
## eof
9999
```

Appendix B. Control file for the reference model

```
## ================================================= updated for sept 2020 base model     ##
## LEADING PARAMETER CONTROLS                                                            ##
# Controls for leading parameter vector theta
# LEGEND FOR PRIOR:
#                  0 -> uniform #                 1 -> normal #                 2 -> lognormal
#                  3 -> beta
#                  4 -> gamma
# ntheta
  44
## ==================================================================================== ##
# ival       lb       ub       phz   prior     p1      p2         # parameter         #
    0.21      0.15    0.25       -4      2    0.18    0.04      # M
   16.5      -10       18        -1      0  -10.0    20.0       # logR0
   12.0      -10       25        -1       0   10.0    20.0        # logRini, to estimate if NOT initi
   12.5      -10       25        1       0   10.0    20.0        # logRbar, to estimate if NOT initia
   32.5       25       75        -4      1   72.5     7.25      # recruitment expected value (males o
    0.8      0.32     1.64       -3      0    0.1     5.0       # recruitment scale (variance compone
    0.9      -10        11       -4      0  -10.0     0.75      # ln(sigma_R)
    0.75      0.20     1.00      -2      3    3.0     2.00      #  steepness
    0.01      0.00     1.00      -3      3    1.01    1.01      # recruitment autocorrelation
   -0.63      -10       30         1       0   10.0    20.00        # Deviation for size-class 1 (nor
   0      -10       30         1       0   10.0    20.00        # Deviation for size-class 2
   0      -10       30         1       0   10.0    20.00        # Deviation for size-class 3
   0     -10       30        1       0   10.0    20.00        # Deviation for size-class 4
   0     -10       30        1       0   10.0    20.00        # Deviation for size-class 5
   0     -10       30        1       0   10.0    20.00        # Deviation for size-class 6
   0     -10       30        1       0   10.0    20.00        # Deviation for size-class 7
   0    -10       30        1       0   10.0    20.00        # Deviation for size-class 8
   0     -10       30        1       0   10.0    20.00        # Deviation for size-class 9
   0     -10       30        1       0   10.0    20.00        # Deviation for size-class 10
   0     -10       30        1       0   10.0    20.00        # Deviation for size-class 11
   0     -10       30        1       0   10.0    20.00        # Deviation for size-class 12
   0     -10       30        1       0   10.0    20.00        # Deviation for size-class 13
   0     -10       30        1       0   10.0    20.00        # Deviation for size-class 14
   0     -10       30        1       0   10.0    20.00        # Deviation for size-class 15
   0     -10       30        1       0   10.0    20.00        # Deviation for size-class 16
   0     -10       30        1       0   10.0    20.00        # Deviation for size-class 17
   0     -10       30        1       0   10.0    20.00        # Deviation for size-class 18
   0     -10       30        1       0   10.0    20.00        # Deviation for size-class 19
   0     -10       30        1       0   10.0    20.00        # Deviation for size-class 20
   0     -10       30        1       0   10.0    20.00        # Deviation for size-class 21
   0     -10       30        1       0   10.0    20.00        # Deviation for size-class 22
   0     -10       30        1       0   10.0    20.00        # Deviation for size-class 23
   0     -10       30        1       0   10.0    20.00        # Deviation for size-class 24
   0     -10       30        1       0   10.0    20.00        # Deviation for size-class 25
   0     -10       30        1       0   10.0    20.00        # Deviation for size-class 26
   0     -10       30        1       0   10.0    20.00        # Deviation for size-class 27
   0     -10       30        1       0   10.0    20.00        # Deviation for size-class 28
   0     -10       30        1       0   10.0    20.00        # Deviation for size-class 29
   0     -10       30        1       0   10.0    20.00        # Deviation for size-class 30
   0     -10       30        1       0   10.0    20.00        # Deviation for size-class 31
   0     -10       30        1       0   10.0    20.00        # Deviation for size-class 32
```

```
   0      -10         30          1       0   10.0    20.00        # Deviation for size-class 33
   0      -10         30          1       0   10.0    20.00        # Deviation for size-class 34
   0     -10          30          1       0   10.0    20.00        # Deviation for size-class 35
# weight-at-length input method (1 = allometry i.e. w_l = a*l^b, 2 = vector by sex, 3 = matrix by sex)
1
# Male weight-at-length
# weight parameters (male) A
0.000361
# weight parameter (male) B
3.16
# Proportion mature by sex
0.00E+00    0.00E+00    0.00E+00    0.00E+00    0.00E+00    0.00E+00    0.00E+00    0.00E+00    0.00E+0
# Proportion legal by sex
0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
## ==================================================== ##
## GROWTH PARAM CONTROLS                                                                     ##
## ==================================================== ##
# Use custom transition matrix (0=no, 1=growth matrix, 2=transition matrix, i.e. growth and molting)
8
# growth increment model (0=prespecified;1=alpha/beta; 2=estimated by size-class;3=pre-specified/emprica
1
# molt probability function (0=pre-specified; 1=flat;2=declining logistic)
2
# Maximum size-class for recruitment(males then females)
7
## number of size-increment periods
1
## Two lines for each parameter if split sex, one line if not                                ##
## number of molt periods
1
## Year(s) molt period changes (blank if no changes)
## Beta parameters are relative (1=Yes;0=no)
1
## ==================================================== ##
## ival       lb        ub        phz   prior     p1      p2          # parameter       ##
## ==================================================== ##
5.8     -100    100     2   0   0   999 # males alpha growth (linear)
-0.13   -2      2       2   0   0   999 # males beta growth (linear)
1       0.5     3.7     -3  0   0   999     # Males (beta)
## ==================================================== ##
## MOLTING PROBABILITY CONTROLS                                                              ##
##     Two lines for each parameter if split sex, one line if not                            ##"
## ==================================================== ##
## ival       lb        ub        phz   prior     p1      p2          # parameter       ##
## ==================================================== ##
## males and combined
   139.77     100.     500.0       -3       0    0.0    999.0         # molt_mu males
   0.093      0.02     2.0         -3       0    0.0    999.0         # molt_cv males
  # 145.0386     100.     500.0       3       0    0.0    999.0       # molt_mu males
  # 0.053036     0.02     2.0       3       0    0.0    999.0         # molt_cv males
## ==================================================== ##

## ======================================================================== ##
## SELECTIVITY CONTROLS                                                                      ##
```

```
##     Each gear must have a selectivity and a retention selectivity. If a uniform      ##
##     prior is selected for a parameter then the lb and ub are used (p1 and p2 are     ##
##     ignored)                                                                         ##
## LEGEND                                                                               ##
##     sel type: 0 = parametric, 1 = coefficients, 2 = logistic, 3 = logistic95,        ##
##               4 = double normal (NIY)                                                ##
##     gear index: use +ve for selectivity, -ve for retention                           ##
##     sex dep: 0 for sex-independent, 1 for sex-dependent                              ##
## ==================================================================================== ##
## ivector for number of year periods or nodes                                          ##
## POT       TBycatch NMFS
## Gear-1    Gear-2   Gear-3
   1         1        1         # Selectivity periods
   0         0        0         # sex specific selectivity
   2         2        2         # male selectivity type
   0         0        0         # within another gear
   0         0        0         # extra parameters
## Gear-1    Gear-2   Gear-3
   1         1        1         # Retention periods
   0         0        0         # sex specific retention
   2         6        6         # male retention type
   1         0        0         # male retention flag (0 -> no, 1 -> yes)
   0         0        0         # extra parameters
   1         0        0         # survey maximum always at 1?
## gear  par   sel                                             phz    start  end        ##
## index index par sex  ival  lb    ub     prior p1     p2     mirror period period     ##
# Gear-1
   1      1    1   1    138.00    5    186    0       1    999   -4     1976   2021  #4
   1      2    2   1      0.1    0.1   20    0       1    999   -4     1976   2021  #4
# Gear-2
   2      3    1   1    150.0000    5    185    0       1    999   -4     1976   2021
   2      4    2   1     10.0000    0.1   20    0       1    999   -4     1976   2021
# Gear-3-
   3      5    1   1    106.3990    5    300    0       1    999    4     1976   2021
   3      6    2   1      14.053    0.1   20    0       1    999    4     1976   2021
## ============================================== ##
## Retained                                                                             ##
## gear  par   sel                                                   start  end         ##
## index index par sex  ival  lb    ub     prior   p1   p2     phz   period period      ##
## ============================================== ##
# Gear-1
  -1     7    1   1    138    1    999    0       1    999    -4     1976   2021
  -1     8    2   1    .1    0.1   20    0       1    999    -4     1976   2021
  # Gear-2
  -2     9    1   1    595    1    999    0       1    999   -3     1976   2021
    # Gear-3
  -3     10    1   1    595    1    999    0       1    999   -3     1976   2021
# Number of asymptotic parameters
0
# Fleet   Sex     Year       ival  lb   ub    phz
#      1     1     1978   0.000001   0    1     -3

## ==================================================================================== ##
## PRIORS FOR CATCHABILITY
```

```
##     If a uniform prior is selected for a parameter then the lb and ub are used (p1   ##
##     and p2 are ignored). ival must be > 0                                            ##
## LEGEND                                                                               ##
##     prior: 0 = uniform, 1 = normal, 2 = lognormal, 3 = beta, 4 = gamma               ##
## ==================================================================================== ##
##  LAMBDA: Arbitrary relative weights for each series, 0 = do not fit.
## SURVEYS/INDICES ONLY
## ival    lb      ub    phz   prior   p1       p2    Analytic?   LAMBDA Emphasis
   0.925     0       2    -6    1      0.925   0.03   0           1            1   # NMFS, 0.896 is tl
 ## ==================================================================================== ##

## ==================================================================================== ##
## ADDITIONAL CV FOR SURVEYS/INDICES                                                    ##
##     If a uniform prior is selected for a parameter then the lb and ub are used (p1   ##
##     and p2 are ignored). ival must be > 0                                            ##
## LEGEND                                                                               ##
##     prior: 0 = uniform, 1 = normal, 2 = lognormal, 3 = beta, 4 = gamma               ##
## ==================================================================================== ##
## ival        lb        ub        phz   prior     p1      p2
   0.0001      0.00001   10.0      -4    4         1.0     100   # NMFS
## ==================================================================================== ##
0
## ==================================================================================== ##
## PENALTIES FOR AVERAGE FISHING MORTALITY RATE FOR EACH GEAR
## ==================================================================================== ##
## Mean_F   Female Offset STD_PHZ1   STD_PHZ2   PHZ_M   PHZ_F Fbar_l Fbar_h Fdev_L Fdev_h Foff_l Foff_h
   0.2             0.0     3.0      50.0        1       -1     -12     4     -10     10    -10     10
   0.01            0.0     4.0      50.0        1       -1     -12     4     -10     10    -10     10
   0.0001          0.0     4.0      50.0        1       -1     -12     4     -10     10    -10     10
 ## ==================================================================================== ##

## ==================================================================================== ##
## OPTIONS FOR SIZE COMPOSTION DATA (COLUMN FOR EACH MATRIX)
## ==================================================================================== ##
## LIKELIHOOD OPTIONS
##   -1) Multinomial with estimated/fixed sample size
##   -2) Robust approximation to multinomial
##   -3) logistic normal (NIY)
##   -4) multivariate-t (NIY)
##   -5) Dirichlet
## AUTOTAIL COMPRESSION
##   pmin is the cumulative proportion used in tail compression.
## ==================================================================================== ##
  2    # Type of likelihood
  0    # Auto tail compression (pmin)
  1    # Initial value for effective sample size multiplier
 -4    # Phz for estimating effective sample size (if appl.)
  1    # Composition aggregator
  1    # LAMBDA
  1    # Emphasis
  1
## ==================================================================================== ##

## ==================================================================================== ##
```

```
## TIME VARYING NATURAL MORTALIIY RATES                                              ##
## ================================================================================ ##
## TYPE:
##     0 = constant natural mortality
##     1 = Random walk (deviates constrained by variance in M)
##     2 = Cubic Spline (deviates constrained by nodes & node-placement)
##     3 = Blocked changes (deviates constrained by variance at specific knots)
##     4 = Time blocks
## ================================================================================ ##
## Type
0
## Phase of estimation (only use if parameters are default)
3
## STDEV in m_dev for Random walk
10.0
## Number of nodes for cubic spline or number of step-changes for option 3
2
## Year position of the knots (vector must be equal to the number of nodes)
1998 1999
## Number of Breakpoints in M by size
0
## Size-class of breakpoint
#3
## Specific initial values for the natural mortality devs (0-no, 1=yes)
1
## ========================================================================================= ##
## ival       lb        ub        phz   extra    prior    p1      p2        # parameter     ##
## ========================================================================================= ##
 #1.600000      0         2         3      0                        # Males
 #0.000000     -2         2       -99      0                        # Dummy to retun to base value
# 2.000000      0         4        -1      0                        # Size-specific M
## ================================================================================ ##
# tag emphasis
0
## â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â
## Maturity specific natural mortality
## â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â
# maturity specific natural mortality? (yes = 1; no = 0; only for use if nmature > 1)
0

## â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â
## ival        lb        ub        phz      prior     p1      p2        # parameter     ##
## â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â
 0     -4         4       4       1       0       0.05    # offset for immature male natural mortality
## ================================================================================ ##
## OTHER CONTROLS
## ================================================================================ ##
1977       # First rec_dev
2021       # last rec_dev (updated annually)
   1       # Estimated rec_dev phase
  -3       # Estimated sex_ratio
 0.5       # initial sex-ratio
  -3       # Estimated rec_ini phase
   1       # VERBOSE FLAG (0 = off, 1 = on, 2 = objective func)
```

```
   2       # Initial conditions (0 = Unfished, 1 = Steady-state fished, 2 = Free parameters)
   1       # Lambda (proportion of mature male biomass for SPR reference points)
   0       # Stock-Recruit-Relationship (0 = None, 1 = Beverton-Holt)
   10      # Maximum phase (stop the estimation after this phase).
   -1      # Maximum number of function calls, if 1, stop at fn1 call; if -1 run as long as it takes
   1       # Calculate reference points (0=no)
  200      # Years to compute equilibria
## â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â
## EMPHASIS FACTORS (CATCH)
## â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â
#Dir_ret Trawl
      1        1
## â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â
## EMPHASIS FACTORS (Priors) by fleet:fdev_total, Fdov_total, Fdev_year, Fdov_year
## â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â
#
1 1 0 0 # Pot_Fishery
1 1 0 0 # Trawl_Bycatch
1 1 0 0 # Trawl_Bycatch
## â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â
## EMPHASIS FACTORS (Priors)
## â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â€"â
# Log_fdevs   meanF       Mdevs  Rec_devs Initial_devs Fst_dif_dev Mean_sex-Ratio  Molt_prob    Free sel
#    10000       0           1         1            15          1              3           60
    10000       0           1         1            15          1              3           60
## EOF
9999
```

Table 4: Observed retained catches and bycatch in tonnes

year	Pot	Trawl bycatch
1976	0	0
1977	0	0
1978	0	0
1979	0	0
1980	0	0
1981	0	0
1982	0	0
1983	0	0
1984	0	0
1985	0	0
1986	0	0
1987	0	0
1988	0	0
1989	0	0
1990	0	0
1991	0	2
1992	0	50
1993	1305	43
1994	670	6
1995	449	0
1996	100	1
1997	379	0
1998	272	2
1999	0	6
2000	0	2
2001	0	0
2002	0	0
2003	0	2
2004	0	5
2005	0	7
2006	0	18
2007	0	2
2008	0	9
2009	0	2
2010	0	9
2011	0	6
2012	0	17
2013	0	3
2014	0	1
2015	0	4
2016	0	1
2017	0	1
2018	0	7
2019	0	5
2020	0	7
2021	0	1

Table 5: Estimated parameters and selected derived quantities by scenario. 'Theta' parameters are scaling parameters and initial numbers at sizes. Vectors of deviations for fishing mortality and recruitment are not displayed–see their respective figures.

Parameter	22.1	22.1a	22.1b
theta[4]	-7.424	-6.218	-7.507
theta[10]	-8.720	-6.434	-8.950
theta[11]	-8.717	-6.423	-8.946
theta[12]	-8.710	-6.401	-8.940
theta[13]	-8.699	-6.369	-8.931
theta[14]	-8.684	-6.327	-8.918
theta[15]	-8.666	-6.277	-8.901
theta[16]	-8.643	-6.220	-8.880
theta[17]	-8.617	-6.156	-8.856
theta[18]	-8.586	-6.087	-8.828
theta[19]	-8.551	-6.015	-8.795
theta[20]	-8.512	-5.938	-8.759
theta[21]	-8.468	-5.861	-8.717
theta[22]	-8.419	-5.786	-8.670
theta[23]	-8.366	-5.708	-8.619
theta[24]	-8.307	-5.631	-8.562
theta[25]	-8.240	-5.559	-8.496
theta[26]	-8.169	-5.489	-8.426
theta[27]	-8.092	-5.415	-8.350
theta[28]	-8.007	-5.343	-8.266
theta[29]	-7.910	-5.277	-8.168
theta[30]	-7.806	-5.211	-8.065
theta[31]	-7.695	-5.137	-7.953
theta[32]	-7.571	-5.063	-7.828
theta[33]	-7.425	-4.996	-7.680
theta[34]	-7.268	-4.934	-7.521
theta[35]	-7.101	-4.859	-7.351
theta[36]	-6.913	-4.776	-7.160
theta[37]	-6.690	-4.698	-6.930
theta[38]	-6.399	-4.632	-6.631
theta[39]	-6.091	-4.579	-6.312
theta[40]	-5.756	-4.505	-5.959
theta[41]	-5.346	-4.419	-5.522
theta[42]	-4.737	-4.336	-4.856
theta[43]	-3.452	-4.284	-3.390
theta[44]	-2.215	-4.301	-1.796
log__fbar[1]	-1.835	-2.159	-1.713
log__fbar[2]	-6.815	-6.856	-6.725
log__fbar[3]	-4.522	-5.051	-4.417
log__slx__pars[5]	4.792	4.727	4.718
log__slx__pars[6]	1.968	1.821	1.014
Grwth[1]	8.551	8.468	8.300
Grwth[2]	-0.097	-0.097	-0.100

Table 6: Parameters fixed in the assessment

Fixed.parameter	Value
Survey catchability	0.925
Size at 50% capture in fishery	138.000
SD of above	0.100
Size at 50% capture in trawl fishery	150.000
SD of above	10.000
Size at 50% molting probability	139.770
SD of above	0.093
Natural mortality	0.180

Table 7: Observed male biomass >120 mm carapace length in the NMFS summer trawl survey in tonnes.

Year	Survey.MMB	Survey.CV
1976	165.08	1.00
1977	118.61	1.00
1978	1249.50	0.83
1979	555.79	0.52
1980	1268.98	0.38
1981	312.29	0.58
1982	1463.68	0.70
1983	526.74	0.53
1984	317.23	0.55
1985	61.48	1.00
1986	137.62	0.70
1987	53.58	1.00
1988	106.65	1.00
1989	1529.46	0.91
1990	1141.08	0.93
1991	4429.98	0.80
1992	3304.81	0.60
1993	9873.34	0.92
1994	9138.78	0.77
1995	18055.70	0.60
1996	2361.50	0.37
1997	6158.83	0.62
1998	2323.52	0.36
1999	5522.92	0.67
2000	4320.46	0.37
2001	8603.17	0.79
2002	7037.32	0.69
2003	5372.97	0.66
2004	3621.91	0.59
2005	1238.27	0.59
2006	7002.93	0.38
2007	5223.70	0.49
2008	5462.27	0.51
2009	2500.34	0.64
2010	4404.99	0.44
2011	3834.34	0.65
2012	4477.11	0.57
2013	7749.45	0.62
2014	12046.84	0.78
2015	15172.86	0.74
2016	4150.36	0.70
2017	3658.47	0.65
2018	928.70	0.43
2019	2086.41	0.34
2021	3743.94	0.30

Table 8: Estimated mature male biomass by model in tonnes.

year	19.1	22.1	22.1a	22.1b
1976	514	1038	628	1404
1977	475	845	549	1141
1978	435	688	476	927
1979	394	559	409	753
1980	354	455	349	612
1981	315	370	296	497
1982	284	301	249	404
1983	263	245	209	328
1984	233	199	174	267
1985	202	162	146	217
1986	174	133	123	177
1987	151	109	107	144
1988	285	105	147	124
1989	591	156	331	142
1990	2111	1272	1694	1131
1991	5013	3854	4871	3635
1992	5679	4623	5812	4388
1993	4416	3537	4735	3320
1994	3571	2830	3945	2621
1995	2934	2287	3246	2080
1996	2541	2046	2840	1830
1997	2169	2176	2750	1551
1998	4251	4113	4365	2731
1999	8294	6708	6597	5557
2000	9276	7810	7611	6698
2001	9277	7924	7670	6987
2002	8596	7423	7165	6642
2003	7669	6668	6427	6016
2004	6690	5854	5631	5308
2005	5823	5128	4884	4655
2006	5124	4582	4269	4204
2007	4549	4212	3892	4041
2008	4246	4098	3819	4040
2009	3954	4023	3740	3925
2010	3508	3714	3443	3597
2011	3042	3314	3070	3198
2012	2636	2930	2713	2831
2013	2346	2644	2429	2554
2014	2084	2400	2162	2277
2015	1808	2163	1921	2007
2016	1595	1982	1751	1783
2017	1449	1873	1687	1632
2018	2532	2605	2464	2401
2019	4894	4466	4512	4623
2020	NA	5010	5081	5332
2021	NA	4964	5026	5348

Table 9: Negative log likelihood for integrated assessments.

Model	X.log.like.
19.1	-3889
22.1	-3793
22.1a	-3736
22.1b	-3716

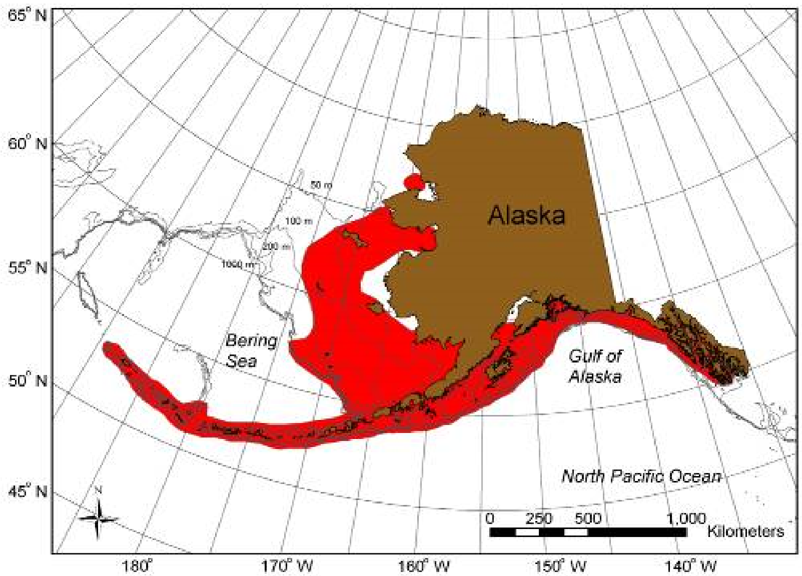

Figure 1: Red king crab distribution in the North Pacific

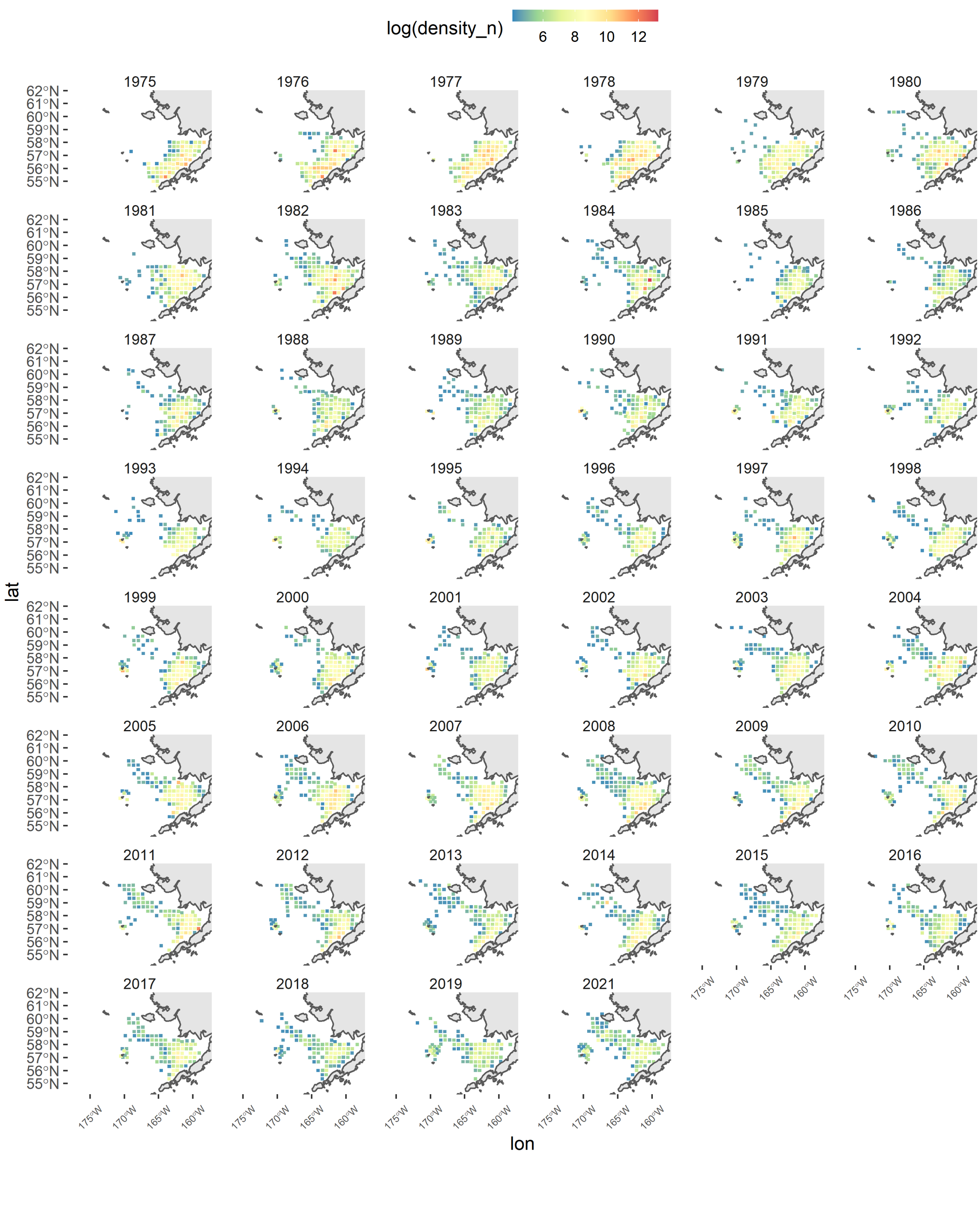

Figure 2: Distribution and density of red king crab observed in the NMFS summer survey.

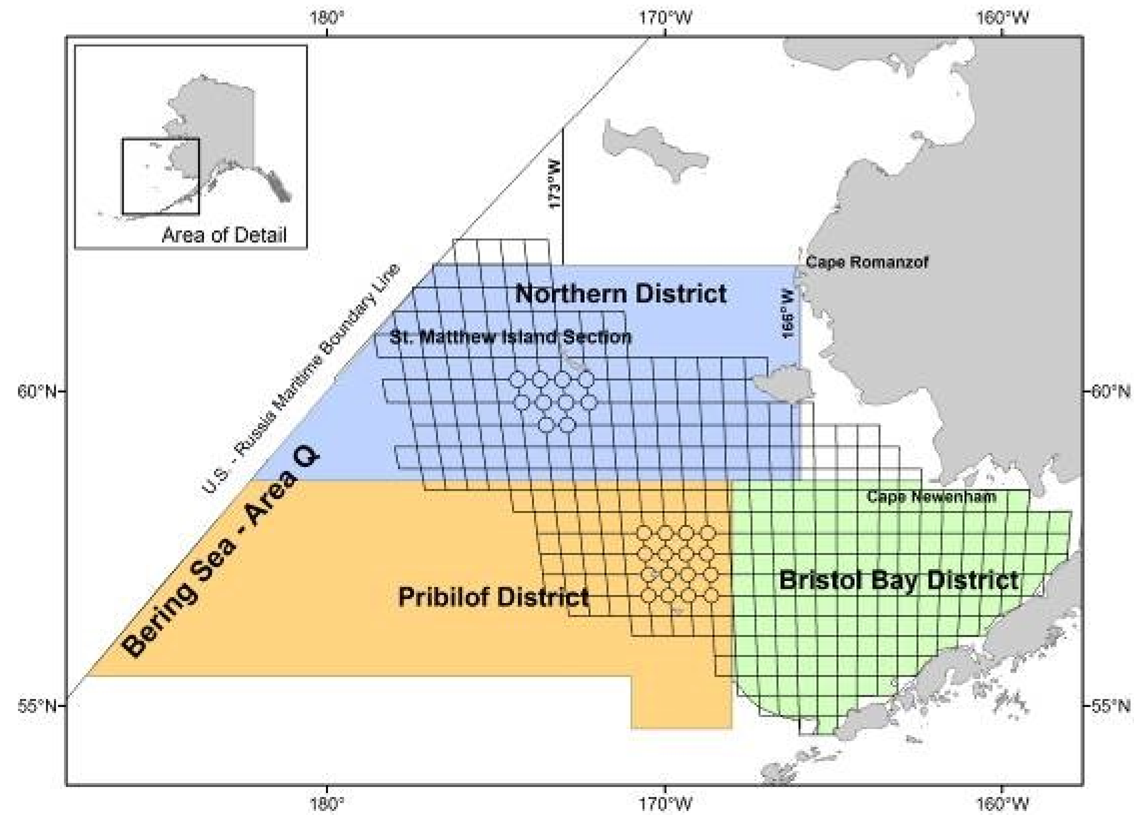

Figure 3: Management areas in the Bering Sea.

Figure 4: Distribution and density of red king crab observed in the NMFS summer survey around the Pribilof Islands.

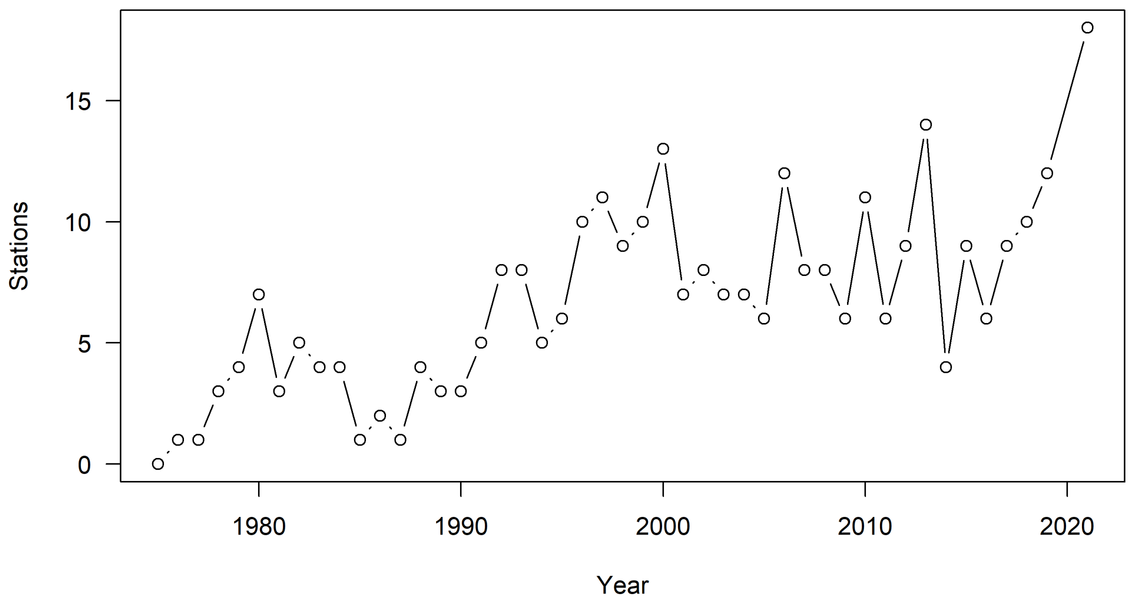

Figure 5: The number of stations at which crab were observed in the Pribilof District in the NMFS summer survey over time.

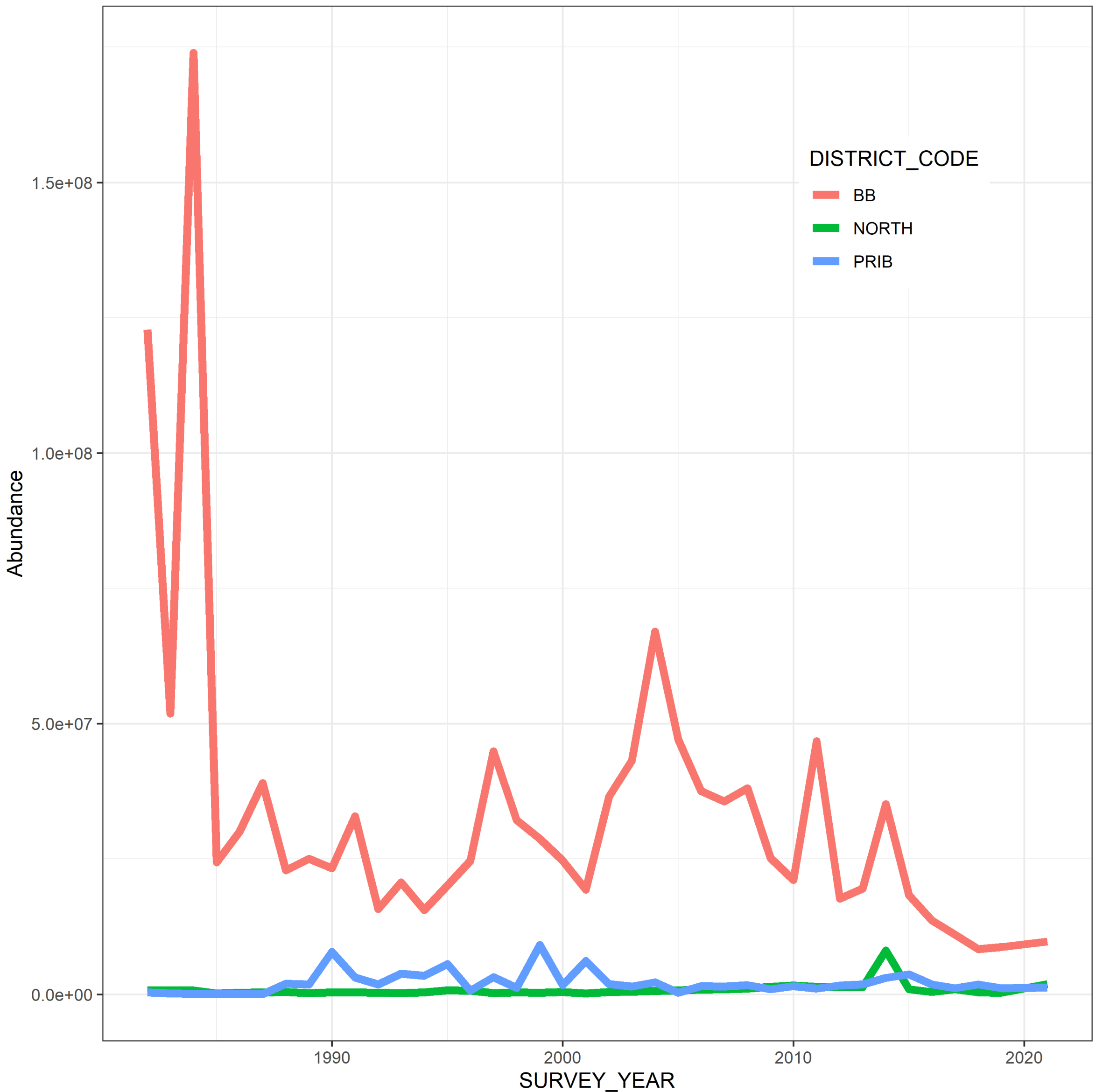

Figure 6: The survey estimated abundance of red king crab by district.

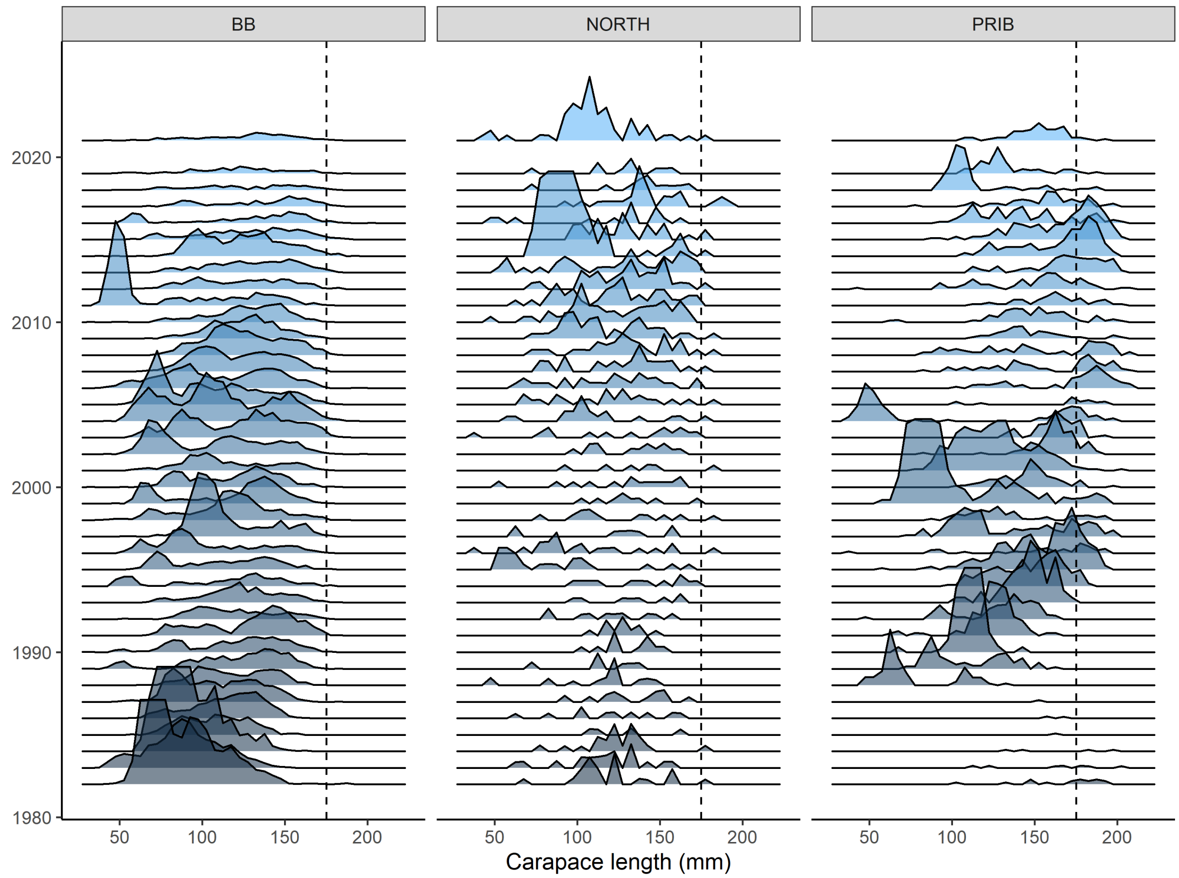

Figure 7: The number by size of male red king crab at carapace length by district. Each district is scaled to the maximum observed in a district, refer to above figure for relative differences. Data were capped in some years and size classes to allow for better resolution of cohorts (e.g. 60-70 mm carapace length in 1982 for Bristol Bay.

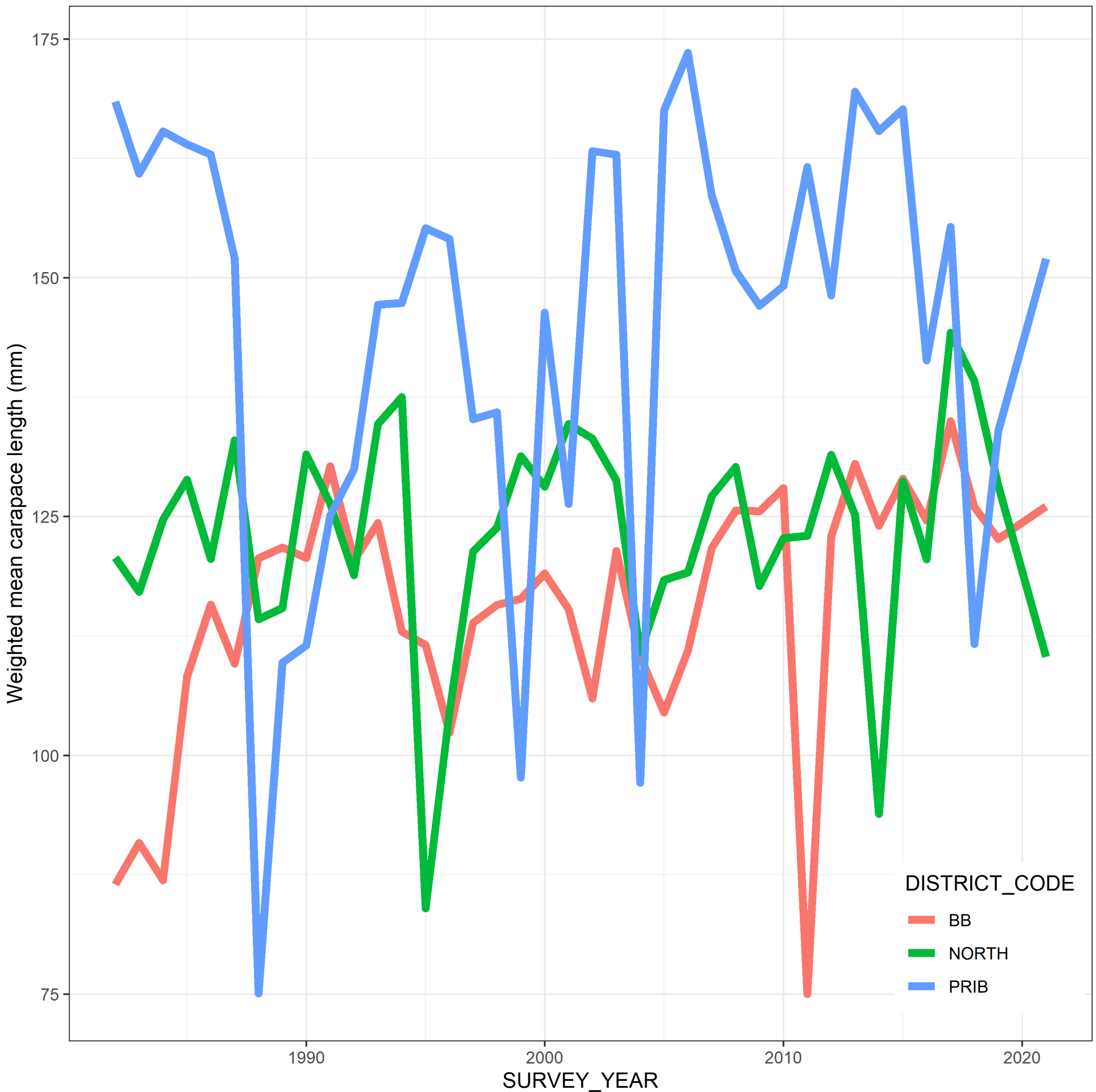

Figure 8: The mean size over time by district for red king crab in the Bering Sea.

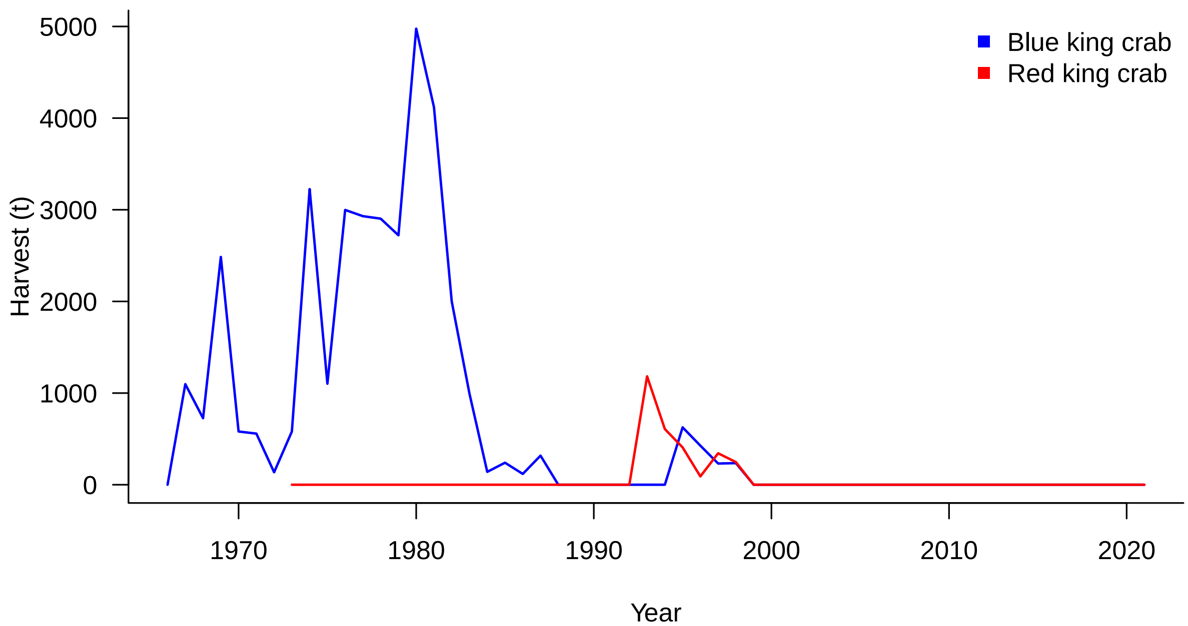

Figure 9: Historical directed harvests of blue king crab and red king crab around the Pribilof Islands.

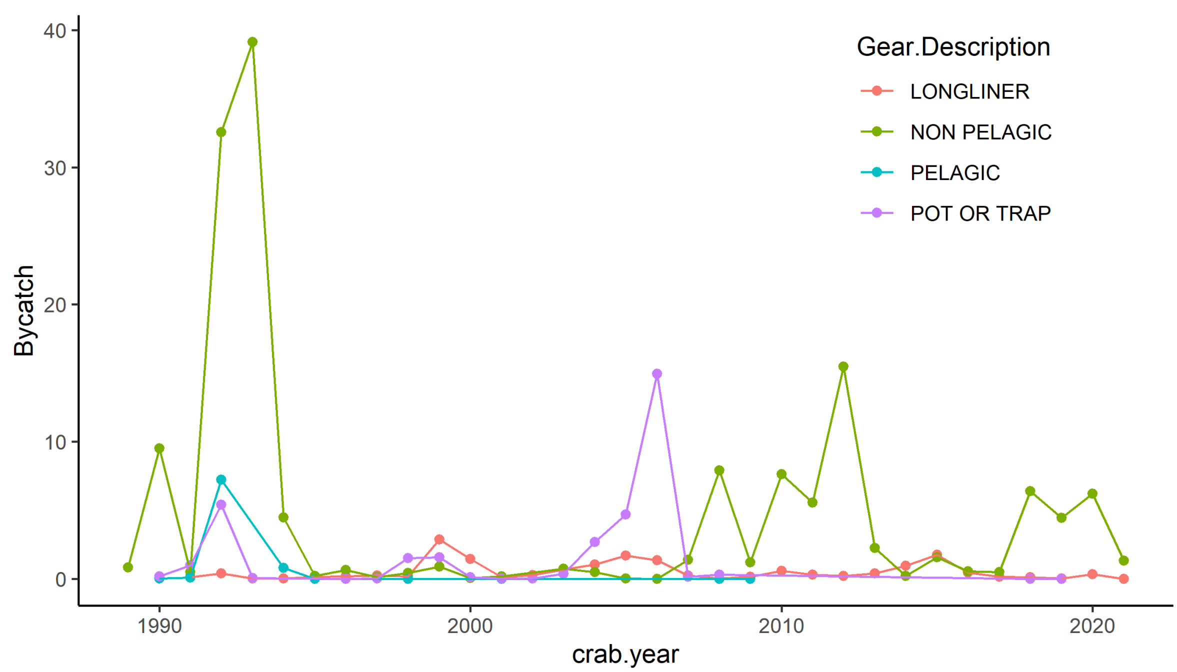

Figure 10: Bycatch by fleet by year in metric tonnes of PIRKC.

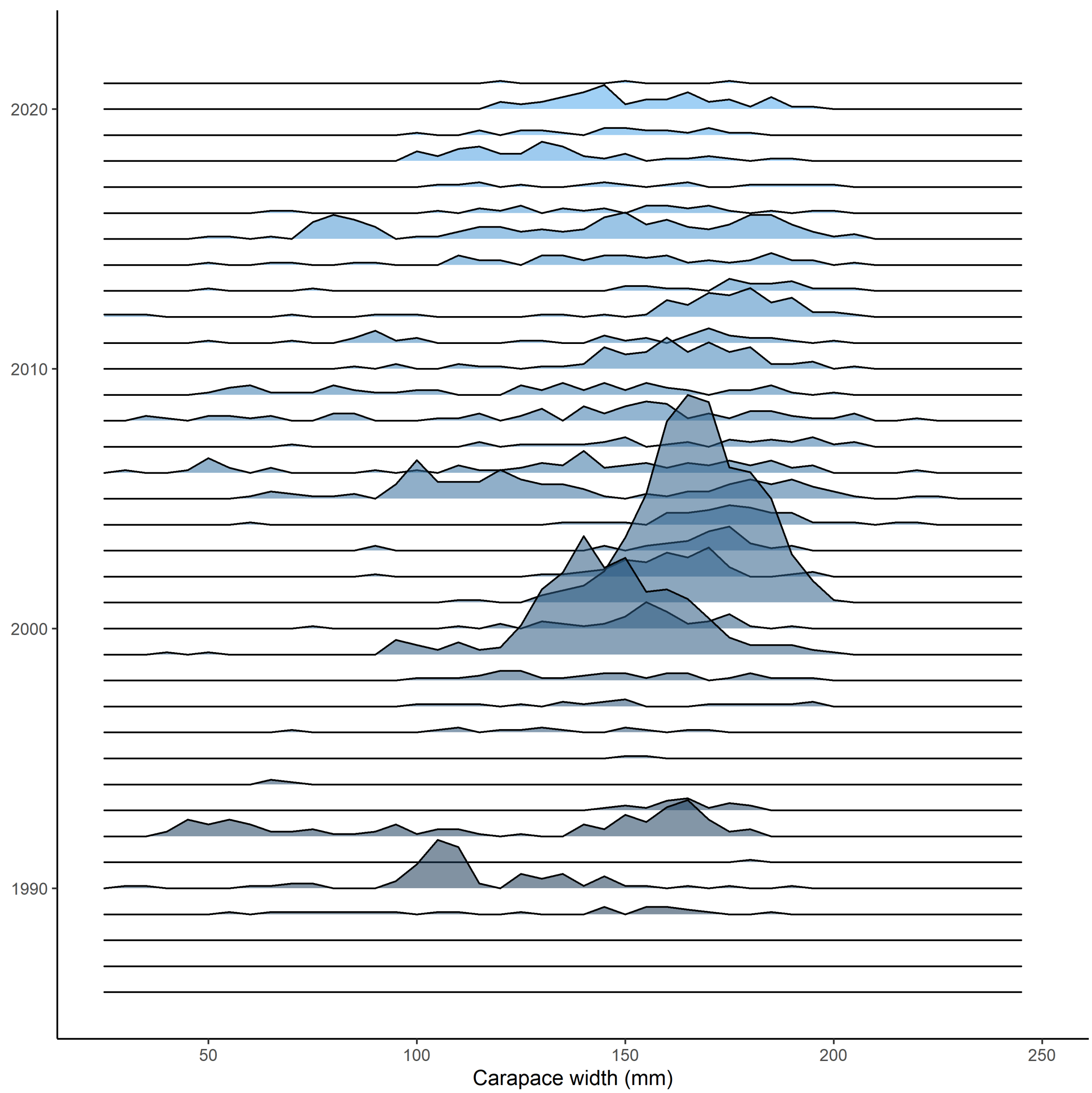

Figure 11: Size composition of the aggregate bycatch by year for red king crab in the Pribilof District.

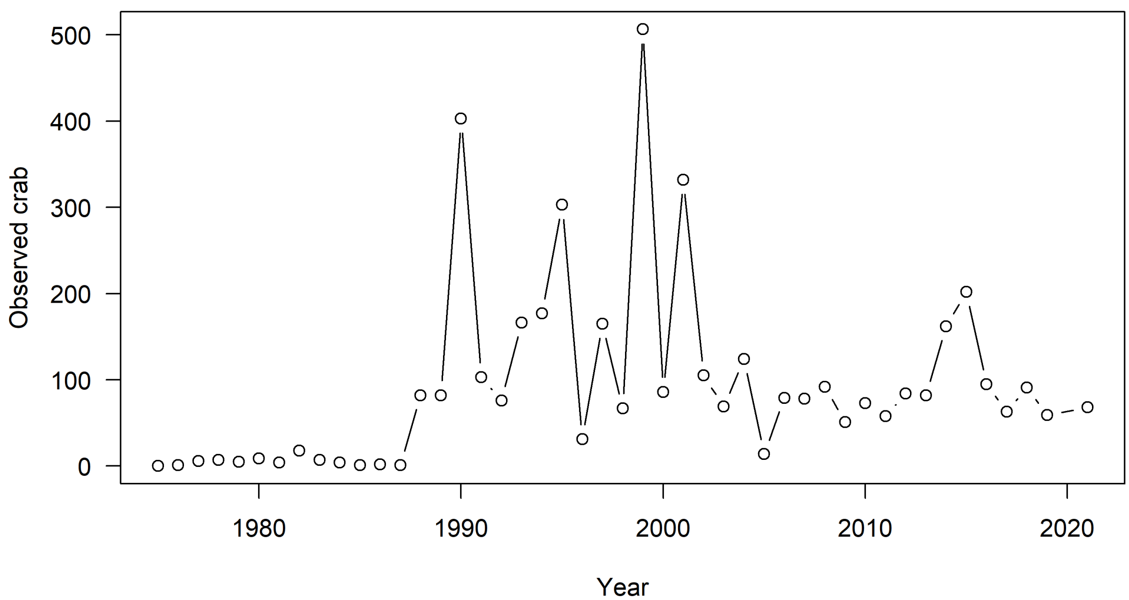

Figure 12: Total number of observed crab by year in the NMFS summer survey.

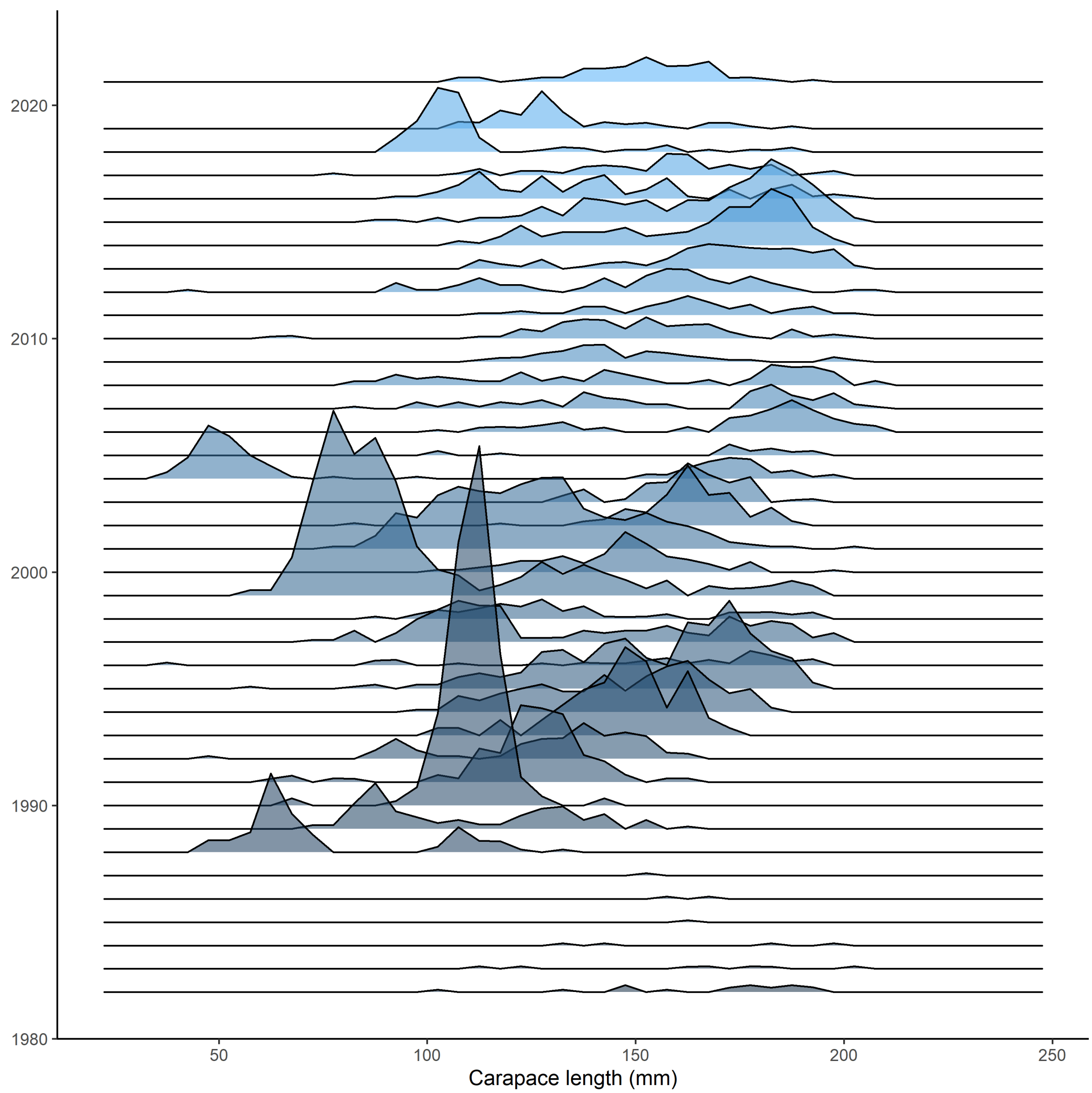

Figure 13: Observed numbers at length by year of male PIRKC.

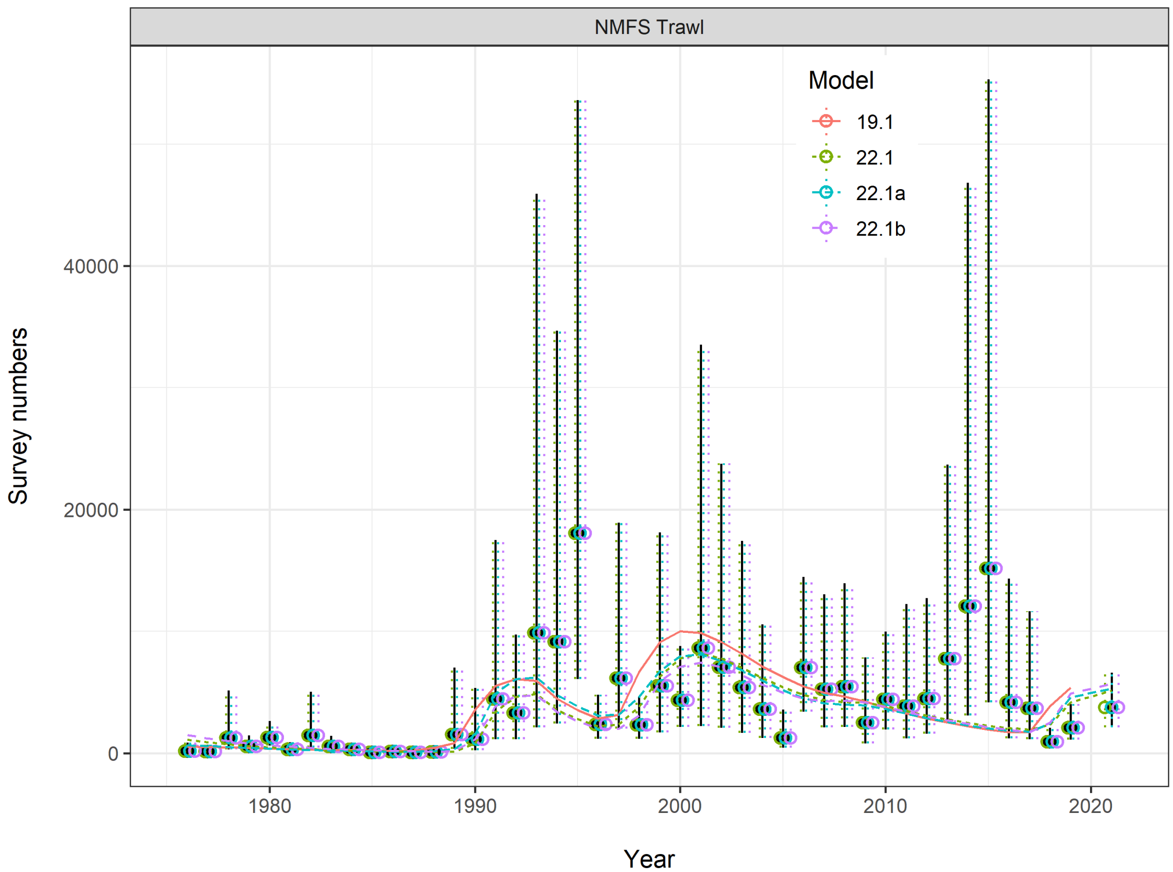

Figure 14: Model fits to mature male biomass from the NMFS summer trawl survey.

Figure 15: Model fits to survey size composition data.

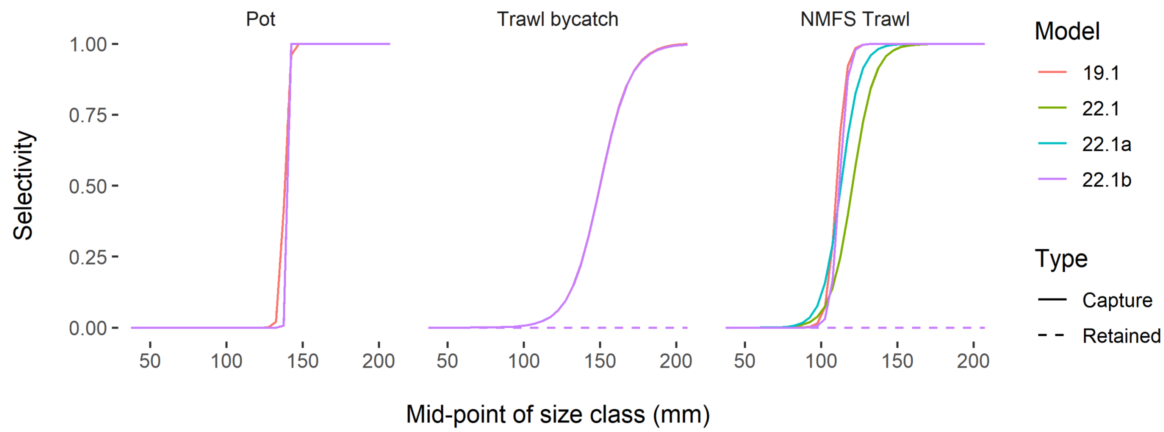

Figure 16: Estimated survey selectivity, assumed directed pot fishery selectivity, assumed bycatch selectivity.

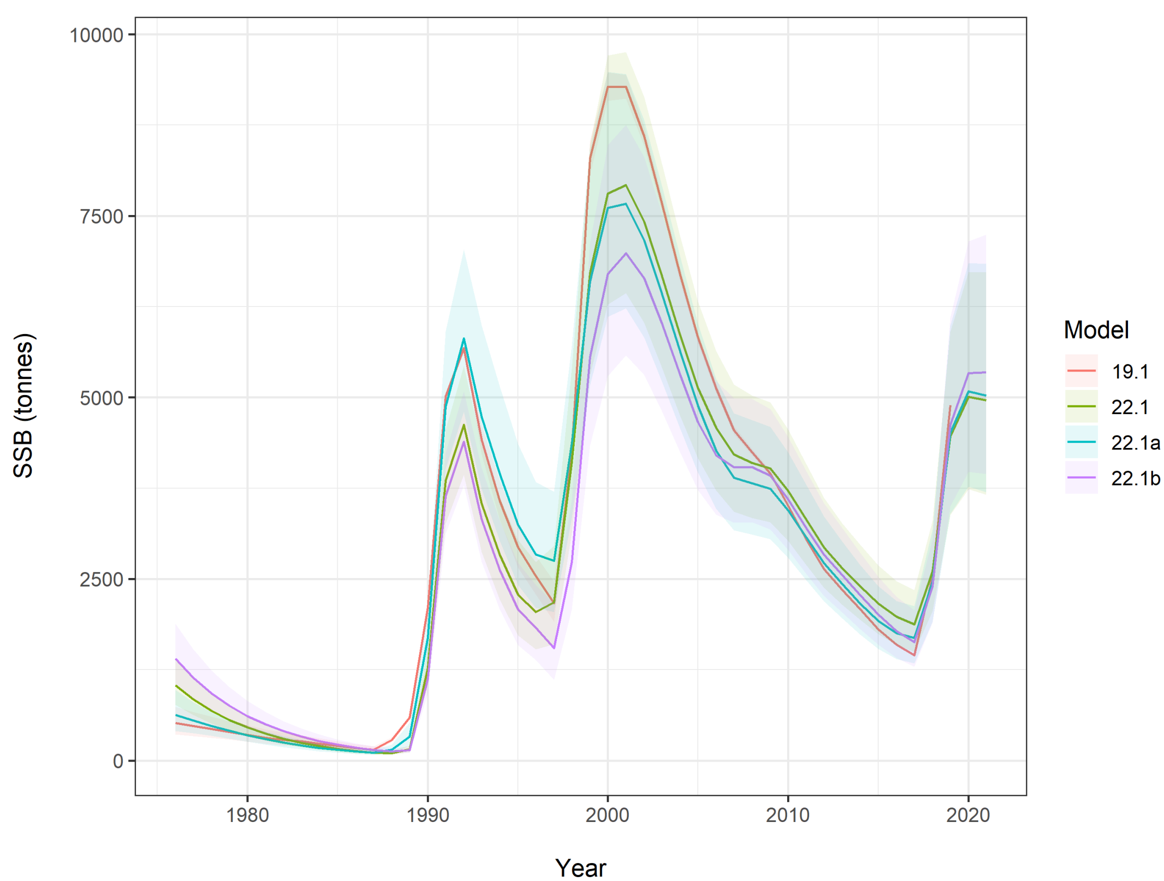

Figure 17: Model predicted mature male biomass at mating time

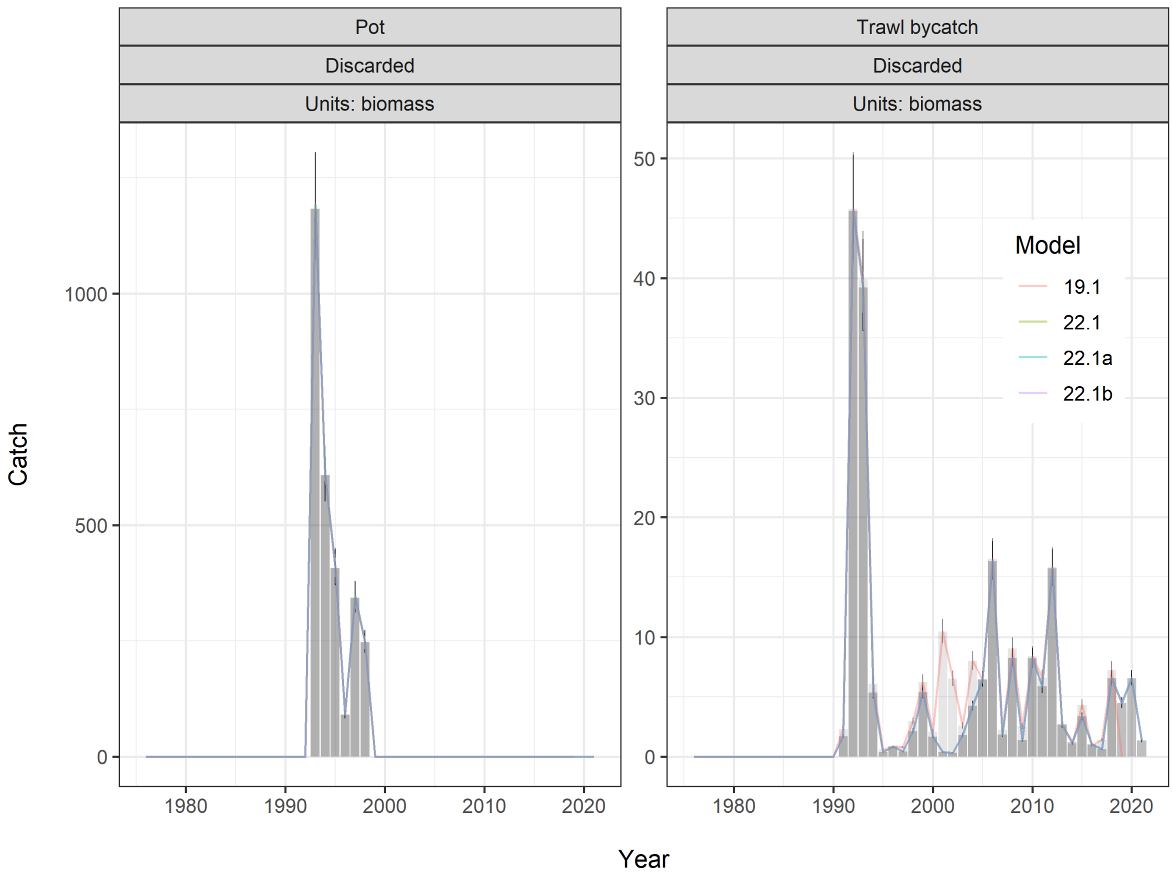

Figure 18: Model fits to catch data. note a difference in scales between figures

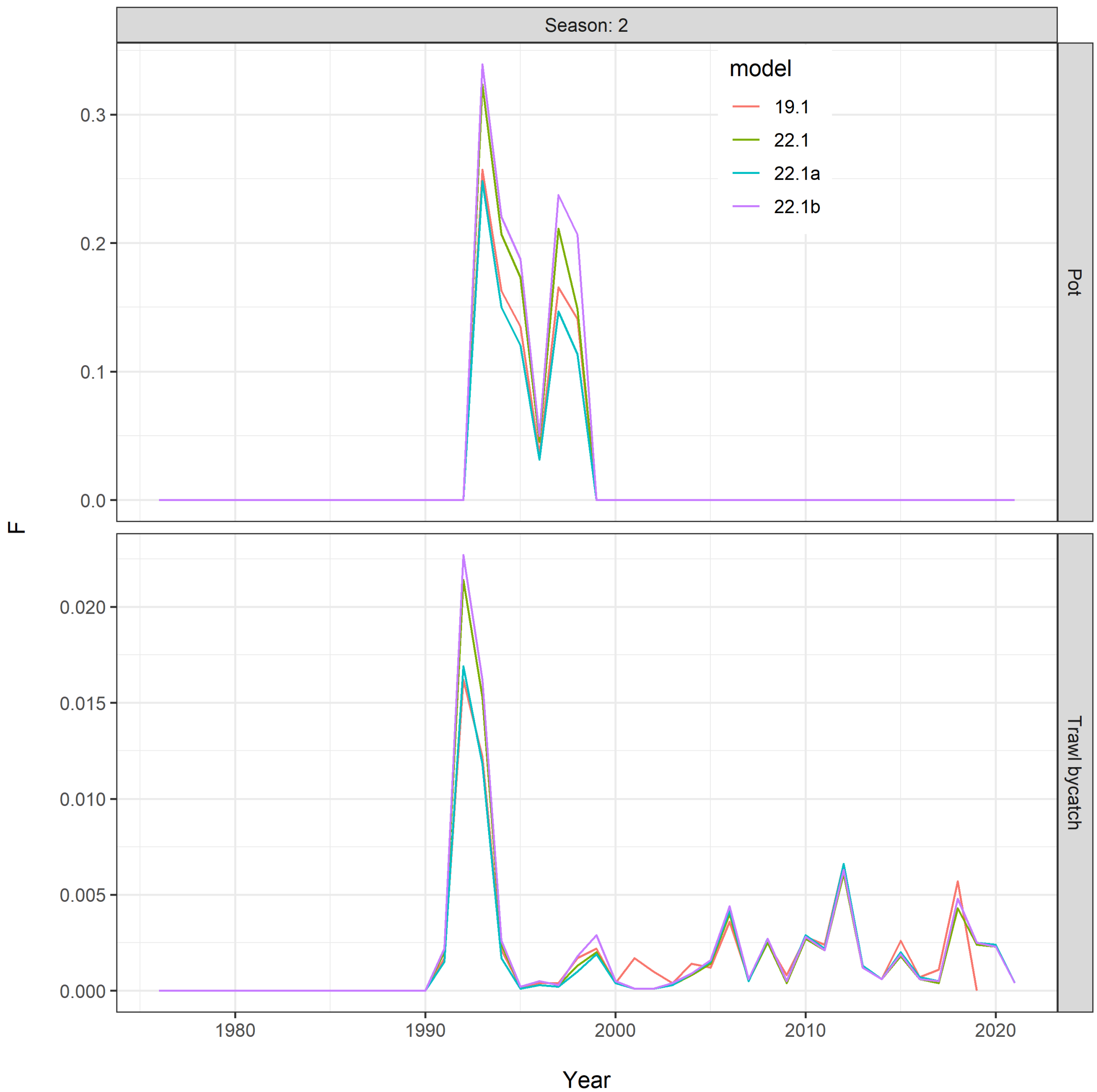

Figure 19: Model predicted fishing mortalities

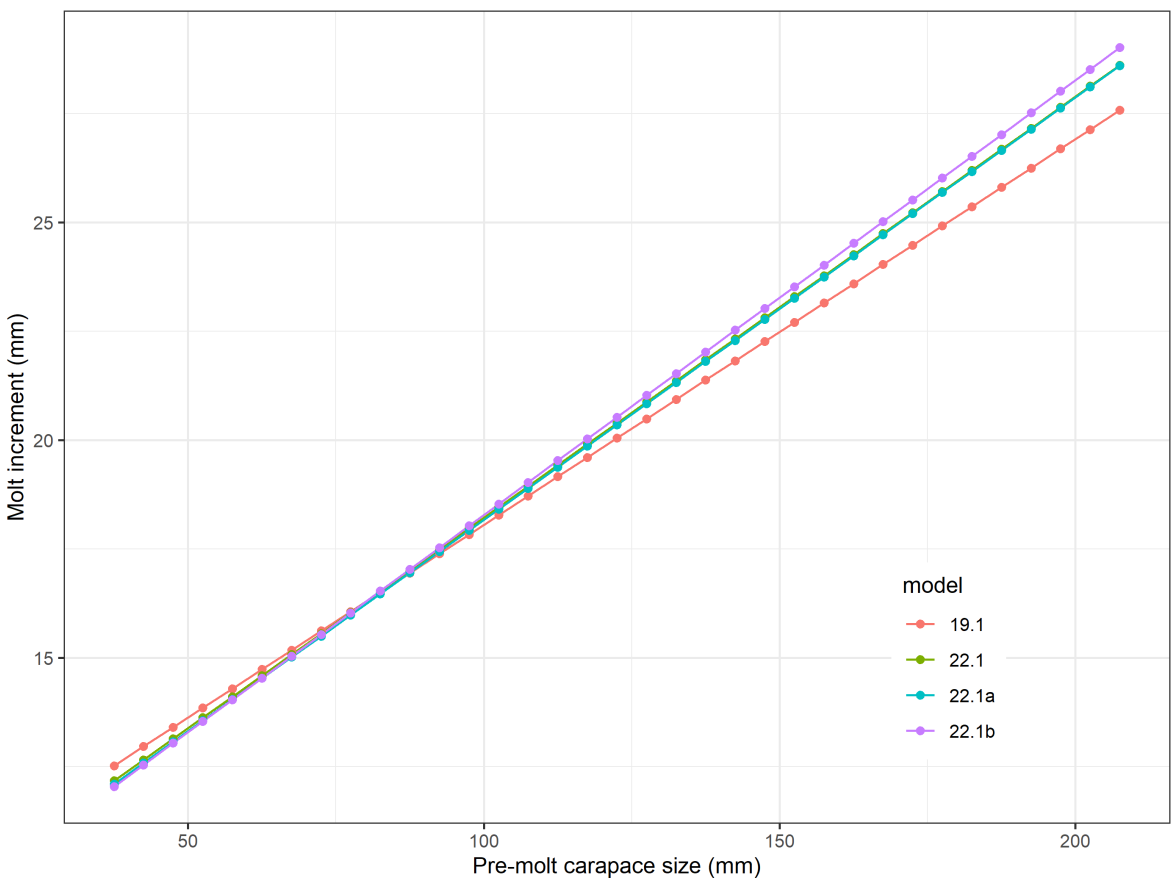

Figure 20: Predicted molt increments

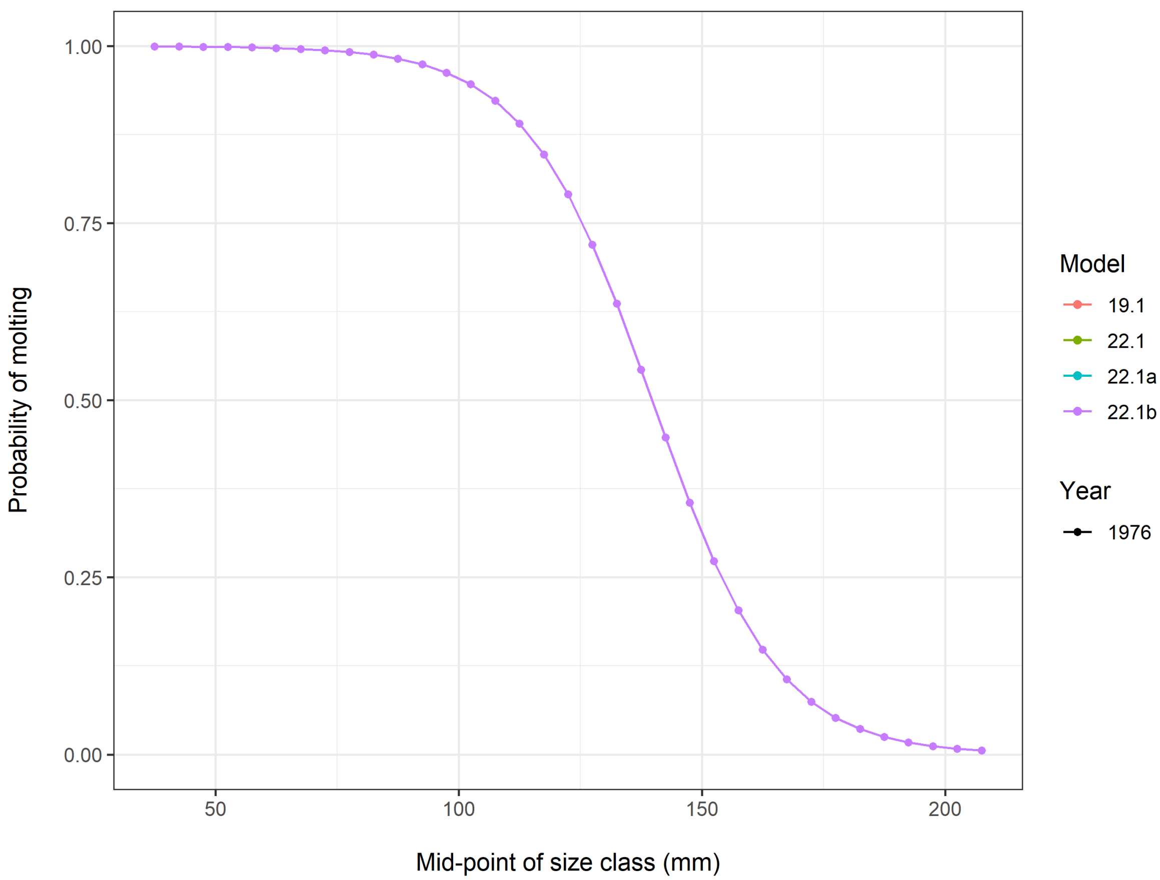

Figure 21: Specified probability of molting by size (mm)

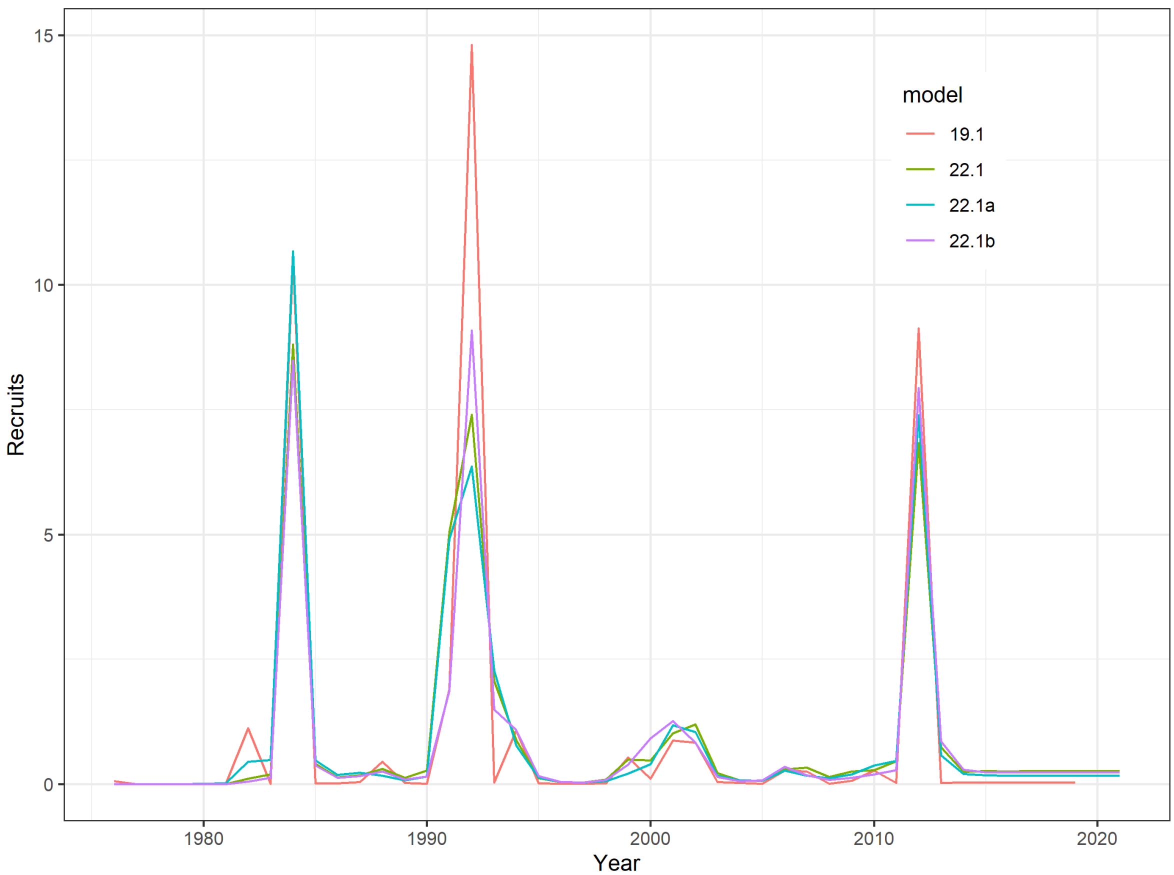

Figure 22: Estimated recruitment.