2019 preliminary assessment for Pribilof Island red king crab

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Contents

Executive summary

1. Stock: Pribilof islands red king crab (PIRKC), *Paralithodes camtschaticus*
2. Catches: Retained catches have not occurred since 1998/1999. Bycatch and discard have been decreasing since 2012/2013 (though the 2018/2019 numbers appears to break that trend). In general, total bycatch is a very small fraction of the OFL.
3. Stock biomass: In recent years, observed mature male biomass (>120mm carapace width) peaked in 2015 and has steadily declined since then. The running average and random effects models indicate the stock was very close to the minimum stock size threshold in 2018.
4. Recruitment: Recruitment is only estimated in the integrated model and appears to be episodic. Based on survey length compositions, it is possible that a large new year class established in 2018, but additional years of data are needed to corroborate this given the variance in estimates of abundance.
5. Recent management statistics: PIRKC is now on a biennial assessment cycle and was last assessed in 2017. The 2017 recommended model was the random effects model with a prior on λ with CV = 2.24. (Tables to be inserted for September)
6. 2019/2020 OFL projections: (to come in September with new data)
7. Probability distributions of the OFL: (to come in September with new data)
8. Basis for ABC: ABCs are identified as the 49th percentile of the distributions of the OFL given a p-star of 0.49. A 25% buffer was also recommended by the CPT and SSC in 2017 and will be applied to the ABC.

Summary of major changes:

1. Management: This is the first assessment since PIRKC shifted to a biennial management cycle in 2017.
2. Input data: Survey and bycatch data were updated with the most recent data in this draft; additional data will be included in the final assessment in September. Some small adjustments were made to the recent years of bycatch data after a new download from AKFIN.
3. Assessment methodology: In addition to the 3 year running average and random effects model that were presented in 2017, results from an integrated assessment are also presented here. An attempt was made to use GMACS for PIRKC, but some difficulties were encountered.
4. Assessment results: Preliminary analysis based on the running average and random effects model indicate PIRKC MMB was very close to the Tier 4 minimum stock size threshold in 2018. However, the integrated model output suggested the stock was near B_{MSY}.

CPT comments September 2017

The CPT had one recommendation from September 2017:

"Information regarding the model should be included in the prsentation to the CPT (such as parameter tables and process error) in order to fully evaluate model performance."

I will do my best to fulfill this request at the meeting.

The key question this document tries to address is which model should be used (running average, random effects, or integrated assessment) to provide management advice in 2019.

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 and become established in the Barents Sea (Jorstad 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). The distribution of red king crab within the Pribilof District is concentrated around the islands (Figure 3 & Figure 4).

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).

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 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. 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).

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 5). 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.

Data

The following sources and years of data are available: NMFS trawl survey (1975-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 (Figure 6), 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 (Figure 7). 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.

Groundfish pot, trawl, and hook and line fisheries

The data through the present year 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 (Figure 7). 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.

Catch-at-length

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

Survey abundance and length composition

Historical survey data are available from 1975 to the present, and survey data analyses were standardized in 1980 (Stauffer, 2004). The most up-to-date 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. Male and female 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 8). Red king crab have been observed at 35 unique stations of the 44 stations in the Pribilof District over the years 1975 to 2017 (22 stations on the 400 nm^2 grid). The number of stations at which at least one crab was observed in a given year ranges from 0-14 over the period from 1975-present (Figure 8). Male crabs were observed at 10 stations in the Pribilof District during the 2018 survey; female crabs were observed at 5. Although estimated numbers at length are variable from year to year, 3 to 4 cohorts can be discerned in the length composition data (Figure 9 & Figure 10).

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 generally been located closer to St. Paul Island. Currently, the largest tows were observed north and east of St. Paul Island (Figure 3 & Figure 4).

Male and female survey abundance has declined in recent years (Figure 11). However, a potential recruitment event occurred in 2018 in both sexes (Figure 9 & Figure 10). Given the variability in the survey data, more years will be needed to corroborate this observation.

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 has been used in past years to set allowable catches. In 2017, biomass and derived management quantities were also estimated by several iterations of a random effects method, one of which was selected by the CPT as the chosen model. The Tier 4 harvest control rule (HCR) is used in conjunction with estimates of estimates of MMB to calculate management quantities. 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 estimated 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. This year, an integrated assessment is presented similar to the one presented in 2014 (Szuwalski and Turnock, 2015) for comparison with the other methods. Below are brief descriptions of each model.

Model descriptions

Running average

An inverse variance weighted 3 year running average of mature male biomass at survey time was calculated by:

$$RA_t = \frac{\sum_{t-1}^{t+1} MMB_t/\sigma_t^2}{\sum_{t-1}^{t+1} 1/\sigma_t^2} \tag{3}$$

where MMB_t is the estimated mature male biomass (>=120 mm carapace width) from the survey data and σ_t^2 are the associated variances (Table 3).

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. This model was developed for use in NPFMC groundfish assessments and uses the same input data as the running average model. The likelihood equation for the random effects model is:

$$\sum_{i=1} 0.5(log(2\pi\sigma_i^2) + \frac{(\hat{B}_i - B_i)^2}{\sigma_i^2}) + \sum_{t=2} 0.5(log(2\pi\sigma_p^2) + \frac{(\hat{B}_{t-1} - \hat{B}_t)^2}{\sigma_p^2}) \tag{4}$$

where B_i is the observed biomass in year i, $\hat{B}_t$ is the model estimated biomass in year t, σ_i^2 is the variance of observed 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.

Iterations performed to address problems in convergence for the 2017 assessment by adding priors on variance components contained an error in the modified .TPL file used (Turnock, pers. comm.). Turnock suggested trying to fit the original model with updated data to see if it converged; it did. Consequently, the presented random effect model is the 'standard' version of the random effects code used in NPFMC ground fish assessments. The general result of fitting of the running average and random effects model is a smoothing of the time series of biomass estimated from the survey (Figure 12).

Integrated assessment model

The running average and random effects models do not incorporate the survey length composition data. The length composition data contain information on the number of cohorts traversing the population. When coupled with very little fishing mortality and an assumed natural mortality, the length composition data can be informative in the face of high variability in abundance estimates.

The integrated assessment presented in this document for PIRKC fits to male abundance and length composition data from the NMFS summer survey, similar to Szuwalski et al. (2015). Retained catches and bycatch are also fit to using assumed selectivities from the BBRKC assessment. Growth is estimated and informed by 4 cohorts moving through the population and molting probabilities are fixed based on Wendel (1969). 92 parameters are estimated (Table 1) and 7 parameters are fixed (Table 2). See appendix 1 for a more complete description of the modeling framework. Three different scenarios are considered for the integrated assessment that vary in the assumed rate of natural mortality (M_0.18, M_0.23, M_0.29). Scenarios considering different values for natural mortality were chosen given natural mortalities influence of the 'persistence' of a cohort. The integrated assessment with M = 0.18 (as presented i n 2014/15) was unable to fit the higher values in the early years of the time series as a result of predicted cohorts 'persisting' longer than reflected in the data. The scenarios considered explore the possibility natural mortality is different than assumed and could account for the observed dynamics.

Calculation of reference points

Tier 4 OFL and B_{MSY}

Tier 4 control rules use natural mortality as a proxy for F_{MSY} and calculate a proxy for B_{MSY} by averaging the biomass over a period of time when the stock is thought to have been at B_{MSY}. A Tier 4 OFL is calculated by applying a fishing mortality determined by the harvest control rule below to the mature male biomass at the time of fishing.

$$F_{OFL} = \begin{cases} Bycatchonly & if \frac{MMB}{MMB_{MSY}} \leq 0.25 \\ \frac{\lambda M(\frac{MMB}{MMB_{MSY}} - \alpha)}{1-\alpha} & if 0.25 < \frac{MMB}{MMB_{MSY}} < 1 \\ \lambda M & if MMB > MMB_{MSY} \end{cases} \tag{5}$$

Where MMB is the mature male biomass projected to the time of mating, MMB_{MSY} is the average mature male biomass over the years 1991-present, M is natural mortality, and α determines the slope of the descending limb of the HCR (here set to 0.05). The running average and random effects model produce similar estimated trends in MMB (Figure 12). The running average model estimated MMB in 2018 as 909.59; the random effects model estimated MMB in 2018 as 1158.24. The estimated proxy for B_{MSY} was 3597.97 for the running average model and 4399.1 for the random effects model. The OFLs for the running average model and the random effects model were 34.29 and 45.87, respectively (Table 4).

The estimate of MMB for the integrated assessment was 5487.73 and the B_{MSY} was 5048.43. This resulted in a stock standing at 1.09 of B_{MSY} and an OFL of 1653.18 (Table 4). The large difference between the integrated assessment and the smoothing algorithms comes from a combination of a higher estimated B_{MSY} and higher estimated MMB based on the length composition data.

Acceptable biological catches

ABCs will be presented in the September assessment after a discussion of the available models. An acceptable biological catch (ABC) will be estimated below the OFL by a proportion based a predetermined probability that the ABC would exceed the OFL (P-star). Currently, P-star 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 (ABCmax). Any additional uncertainty outside of the assessment methods (σ_b) will be considered as a recommended ABC below ABCmax. Additional uncertainty will be included in the application of the ABC by adding the uncertainty components as:

$$\sigma_{total} = (\sigma_b^2 + \sigma_w^2)^{0.5} \tag{6}$$

Specifications of the disributions of the OFL used in the ABC

Distributions of the OFL were not calculated for this draft. They are generally calculated by bootstrapping values of MMB (assuming that MMB is log-normally distributed) with additional uncertainty added and calculating the OFL for each iteration. Additional uncertainty (σ_b) equal to 0.3 has been added in the past when bootstrapping values of MMB while calculating the distribution for the OFL for the tier 4 HCR. The random effects model outputs a confidence interval that can be used to describe the distribution of MMB, from which a distribution of the OFL can be calculated. A standard deviation can be calculated for the OFL in the integrated methods to develop a distribution from which the ABC can be identified.

Variables related to scientific uncertainty in the OFL probability distribution

Uncertainty in estimates of biomass and abundance for Pribilof Islands red king crab was relatively high due to small sample sizes. The coefficient of variation for the estimate of male abundance for 2018 was 0.41 and has ranged between 0.36 and 0.92 since the 1991 peak in numbers (Table 3). 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) may increase the CVs. Recruitment, growth and survey selectivity were estimated within the integrated assessment, but maturity, survey catchability, fishery selectivity, and natural mortality were fixed. Fitting to data to inform these processes would likely increase the uncertainty in estimates of management quantities. 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 HCR (1991-present). The majority of these years there was no directed fishery for PIRKC, so designating them as years in which biomass was at B_{MSY} is internally contradictory. 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 (but probably not much given their small magnitudes).

Author Recommendation

I look forward to discussion among the CPT about the relative merits of each model. The smoothing algorithms (running average or random effects) require very few assumptions and input data, but they also ignore the length composition data (and other studies on red king crab) used in the integrated assessment that could add valuable information to the analysis. A tradeoff likely exists between the additional information and the number of assumptions made due to a lack of PIRKC-specific data. For example, length composition data do not exist for retained catch or bycatch of PIRKC, so retained fishery selectivity was assumed to be knife-edge at the legal size and bycatch selectivity was fixed at the values estimated in the Bristol Bay red king crab (BBRKC) fishery. However, without knowing the underlying dynamics, it is difficult to understand the impact of misspecifying these processes on management quantities.

I lean toward the integrated assessment for two reasons. First, the signal in the length composition data is quite clear (arguably clearer than the survey abundance data). There appear to be four large cohorts moving through the population. With an assumed natural mortality and estimated growth, the cohorts in the length composition data can provide the dynamics of the population (something that is difficult to discern without them) and the survey abundance estimates can provide the scale. Second, the decreases seen in the random effects model imposed by fitting to the higher observations are inconsistent with information available on natural mortality for red king crab. The time elapsed from the peaks of biomass to the troughs in the running average and random effects models is shorter than would be expected with a natural mortality of 0.18.

The appropriateness of the Tier 4 rules for PIRKC should also be discussed The period of time over which biomass is averaged to find the proxy for B_{MSY} for PIRKC is 1991 to present. The stock was only fished from 1993 to 1998, so this formulation of B_{MSY} is closer to an estimate of unfished biomass. Tier 3 rules that use spawning biomass per recruit proxies for B_{MSY} could be applied using the integrated assessment output and provide a more internally consistent measure of B_{MSY} than the Tier 4 rules. Although the Tier 3 rules would be more internally consistent, the Tier 4 rules would be considerably more precautionary. The adoption of Tier 3 rules would also necessitate the acceptance of the assumptions made by the integrated assessment (which may or may not be more appropriate than the smoothing models).

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 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. Catch-at-length data for the trawl fishery are also currently unavailable, but their inclusion would allow trawl fishery selectivity to be estimated and discard mortality specific to PIRKC to be incorporated into the integrated model. 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.

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.

Literature cited

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Appendix 1: size-structured population dynamics model for the integrated assessment

Basic dynamics

The integrated assessment tracks numbers of Pribilof Island red king crabs by sex and length. The survey initiates the beginning of the mode year and survey to fishery dynamics are described by:

$$N_{s,y,l} = N_{s,y,l}e^{-M/12} \tag{7}$$

where $N_{s,y,l}$ is the number of animals of sex s in length-class l at time step y, and –M/12 decrements the population by one month of natural mortality. A pulse fishery is modeled one month after the survey (the fishery lasted on average two weeks, so this is a reasonable assumption) in which numbers are updated by:

$$N_{s,y,l} = N_{s,y,l}e^{-F_{dir,y}+F_{trawl,y}} \tag{8}$$

where $N_{s,y,l}$ is the number of animals of sex s in length-class l at time step y, and $\breve{}M/12$ decrements the population by one month of natural mortality. A pulse fishery is modeled one month after the survey (the fishery lasted on average two weeks, so this is a reasonable assumption) in which numbers are updated by:

$$N_{s,y,l} = N_{s,y,l}e^{-F_{dir,y}+F_{trawl,y}} \tag{9}$$

Molting, growth, and recruitment, in that order, after the fishery:

$$N_{s,y,l} = K_l N_{s,y,l} X_{l,l'} + (1 - K_l)N_{s,y,l} + \phi R_y \tag{10}$$

Where K_l is the probability of an animal molting at length l, $N_{s,y,l}$ is the number of animals in sex s in length class l at time step y, $X_{l,l'}$ is the size transition matrix, R_y is recruitment furing ye y and ϕ is a vector containing the proportion of recruitment allocated to length class l.

The remaining months of natural mortality are applied to the population between the fishery and the survey:

$$N_{s,y,l} = N_{s,y,l}e^{-11M/12} \tag{11}$$

Fishing mortality and selectivity

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

$$F_{dir,y,l} = S_{dir,l}e^{-(F_{dir}+F_{dev,y})} \tag{12}$$

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

Fishery selectivity is assumed to be a logistic function of size and constant over time, with the parameters fixed so that selectivity is knife-edged at the legal size:

$$S_{dir,l} = \frac{1}{1 + exp(-ln(19)\frac{L_l - L_{50,dir}}{L_{95,dir} - L_{50,dir}})} \tag{13}$$

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

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

$$F_{trawl,y,l} = S_{trawl,l}e^{-(F_{trawl} + F_{dev,y})} \tag{14}$$

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

$$S_{trawl,l} = \frac{1}{1 + exp(-ln(19)\frac{L_l - L_{50,trawl}}{L_{95,trawl} - L_{50,trawl}})} \tag{15}$$

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

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

$$S_{trawl,l} = \frac{q_{srv}}{1 + exp(-ln(19)\frac{L_l - L_{50,srv}}{L_{95,srv} - L_{50,srv}})} \tag{16}$$

where q is the catchability coefficient for the survey gear, $L_{50,srv}$ is the length at which 50% of animals are selected, L_l is the midpoint of length class l, and $L_{95,srv}$ is the length at which 95% of animals are selected. Survey selectivity parameters are estimated, except for q, which is fixed to a value of 1. Catchabilty is fixed because, when estimated, it decreases to the lower bound, regardless of where it is set.

Survey numbers at length

The model prediction of the number of male crab at length at the time of the survey, $N_{s,y,l}^{srv}, is given by:

$$\hat{N}_{s,y,l} = S_{l,srv}N_{s,y,l} \tag{17}$$

Catch

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

$$\hat{C}_{dir,y,l} = S_{l,dir}N_{s,y=fish,l}(1 - e^{-F_{y,l}}) \tag{18}$$

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

Growth

Molting and growth occur before the survey. Female crab are assumed to molt every year, but the probability of molting for male crab is a declining logistic function of length. The parameters are fixed based on Wendel (1969) such that the probability of molting is 1 until approximately the age of maturity at which time it steadily declines:

$$P_l = 1 - \frac{1}{1 + exp(-ln(19)\frac{L_l - L_{50,molt}}{L_{95,molt} - L_{50,molt}})} \tag{19}$$

where $L_{50,molt}$ is the length at which 50% of animals molt, and $L_{95,molt}$ is the length at which 95% of animals molt. For crab that do molt, the growth increment within the size-transition matrix, $X_{l,l'}$, was based on a linear relationship between predicted pre- and post-molt length, ($\hat{L}_l^{pred}$ and $\hat{L}_l^{post}$, respectively) and the variability around that relationship was characterized by a discretized and renormalized gamma function, $Y_{l,l'}$.

$$X_{l,l'} = \frac{Y_{l,l'}}{\sum_{l'} Y_{l,l'}} \tag{20}$$

$$Y_{l,l'} = (\Delta_{l,l'})^{\frac{\hat{L_l} - (\bar{L}_l - 2.5)}{\beta}} \tag{21}$$

$$\hat{L}_l^{post,1} = \alpha + \beta_1 L_l \tag{22}$$

$$\Delta_{l,l'} = \bar{L}_{l'} + 2.5 - L_l \tag{23}$$

$\hat{L}_{s,l}^{post,1}$ and $\hat{L}_{s,l}^{post,2}$ were predicted post-molt lengths from each piece of the piece-wise relationship, and $\Phi()$ was a cumulative normal distribution in which $\delta_{a,x}$ was an estimated change point. The model in which linear growth was estimated removed equations 26 and 27 from the model.

Recruitment

An average recruitment for the assessment period (1982-present) and yearly deviations around this average were estimated within the assessment for models in which only a single vector of recruitment deviations was estimated. Each year's estimated recruitment was allocated to length bins based on a discretized and renormalized gamma function with parameters specified in the control file.

$$Rec_y = e^{(Rec_{avg} + Rec_{dev,y})} \tag{24}$$

$$Pr_l = \frac{(\Delta_{1,l})^{\alpha_{rec}/\beta_{rec}} e^{-\Delta_{1,l'}/\beta_{rec}}}{\sum_{l'} (\Delta_{1,l'})^{\alpha_{rec}/\beta_{rec}} e^{(-\Delta_{1,l'}/\beta_{rec})}} \tag{25}$$

Recruitment deviation and fishing mortality vectors were subject to a smoothing penalty.

Likelihood components

Three general types of likelihood components were used to fit to the available data. Multinomial likelihoods were used for size composition data, log-normal likelihoods were used for indices of abundance data, and normal likelihoods were used for catch data, growth data, priors, and penalties. Multinomial likelihoods were implemented in the form:

$$L_x = \sum_y N_{x,y}^{eff} \sum_l p_{x,y,l}^{obs} ln(\hat{p}_{x,y,l}/p_{x,y,l}^{obs}) \tag{26}$$

L$_x$ was the likelihood associated with data component x, where $N_{x,y}^{eff}$ was the effective sample sizes for the likelihood, $p_{x,y,l}^{obs}$ was the observed proportion in size bin l during year y for data component x, and $\hat{p}_{x,y,l}$ was the predicted proportion in size bin l during year y for data component x. `r` multinomial likelihood components were included in the assessment.

Log normal likelihoods were implemented in the form:

$$L_x = \sum_y \frac{\left(ln(\hat{I}_{x,y}) - ln(I_{x,y})\right)^2}{2(ln(CV_{x,y}^2 + 1))} \tag{27}$$

L_x was the contribution to the objective function of data component x, $\hat{I}_{x,y}$ was the predicted value of quantity I from data component x during year y, I$_{x,y}$ was the observed value of quantity I from data component x during year y and CV$_{x,y}$ was the coefficient of variation for data component x during year y.

Normal likelihoods were implemented in the form:

$$L_x = \lambda_x \sum_y \frac{(\hat{I}_{x,y} - I_{x,y})^2}{\sigma_x^2} \tag{28}$$

L_x was the contribution to the objective function of data component x, λ_x was represents the weight applied to the data component (and can be translated to a standard deviation), $\hat{I}_{x,y}$ was the predicted value of quantity I from data component x during year y, I$_{x,y}$ was the observed value of quantity I from data component x during year y. `r` normal likelihood components were included in the base assessment (see **??** for descriptions, weighting factors, and translated standard deviations).

Small smoothing penalties placed on some estimated vectors of parameters took the form of normal likelihoods on the first or second differences of the vector.

Table 1: Maximum likelihood estimates of parameter values by scenario.

Parameter	M_0.18	M_0.23	M_0.29
srv_sel50:	105.32	110.74	116.44
srv_sel95:	143.67	149.25	154.82
log_avg_fmort_dir:	-1.95	-2	-2.05
fmort_dir_dev:	vector	vector	vector
log_avg_fmort_trawl:	-7.81	-7.73	-7.66
fmort_trawl_dev:	vector	vector	vector
mean_log_rec:	12.56	13.06	13.66
rec_dev:	vector	vector	vector
am:	5.36	4.97	4.49
bm:	1.14	1.14	1.15
growth_beta:	vector	vector	vector
alpha1_rec:	1.48	0.98	0.69
beta_rec:	0.21	0.18	0.16

Table 2: Fixed parameter values in the integrated model.

Parameter	Value
srv_q	1
fish_sel50	138
fish_sel95	138.5
trawl_sel50	164.84
trawl_slope	0.053
molt_sel50	140.19
molt_slope	0.101

Table 3: Observed survey mature male biomass >=120mm in metric tons.

Year	MMB	CV
1976	165.7	0.83
1977	118.6	0.83
1978	1250	0.72
1979	555.8	0.49
1980	1269	0.37
1981	312.3	0.54
1982	1464	0.63
1983	526.7	0.5
1984	317.2	0.51
1985	61.48	0.83
1986	137.6	0.63
1987	53.58	0.83
1988	106.6	0.83
1989	1529	0.78
1990	1141	0.79
1991	4430	0.7
1992	3305	0.55
1993	9873	0.78
1994	9139	0.68
1995	18056	0.56
1996	2362	0.36
1997	6159	0.57
1998	2324	0.35
1999	5523	0.61
2000	4320	0.36
2001	8603	0.69
2002	7037	0.62
2003	5373	0.6
2004	3622	0.55
2005	1238	0.54
2006	7003	0.37
2007	5224	0.47
2008	5462	0.48
2009	2500	0.58
2010	4405	0.42
2011	3834	0.59
2012	4477	0.53
2013	7749	0.57
2014	12047	0.69
2015	15173	0.66
2016	4150	0.63
2017	3658	0.59
2018	928.7	0.41

Table 4: Estimated management quantities (in tons) for each scenario presented.

Model	MMB	B35	F35	FOFL	OFL
M_0.18	5488	1916	0.49	0.49	1653
M_0.23	4703	1706	0.79	0.79	1853
M_0.29	4195	1590	1.47	1.47	2122
Running average	909.6	3598	0.18	0.04	34.29
Random effects	1158	4399	0.18	0.04	45.87

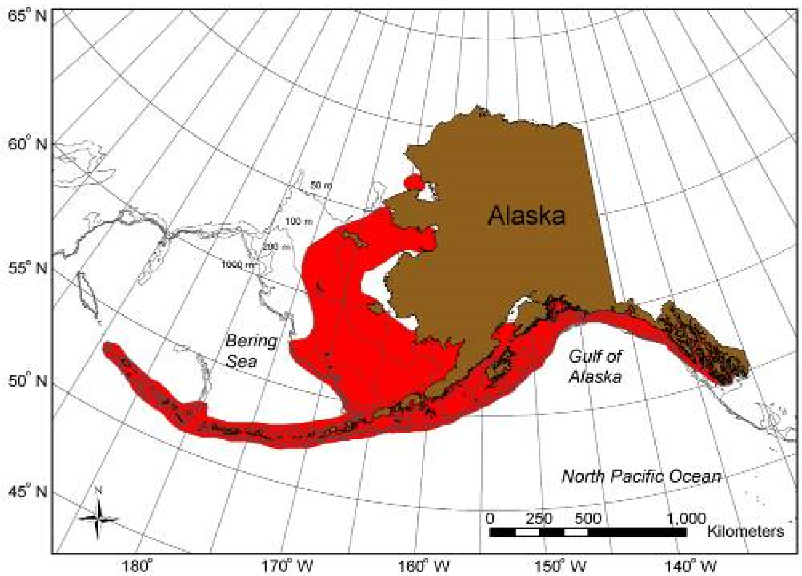

Figure 1: Red king crab distribution in the North Pacific

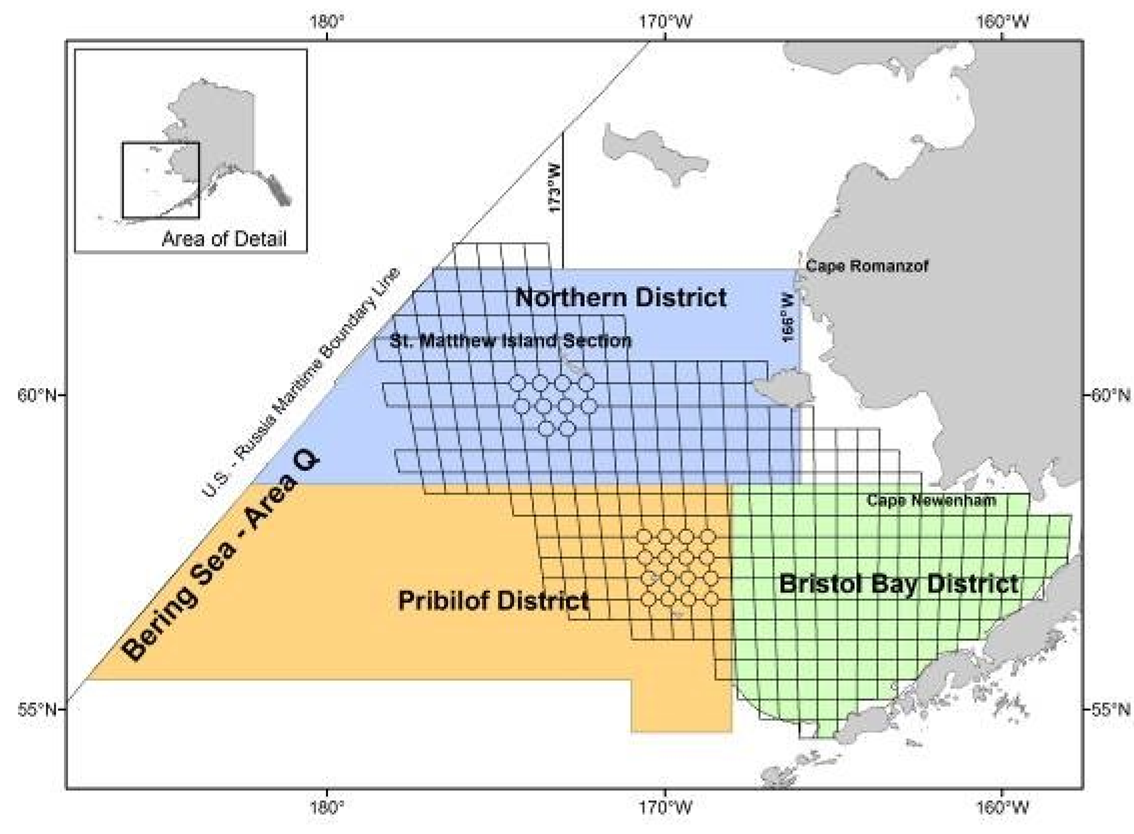

Figure 2: Pribilof Island management area in the Bering Sea

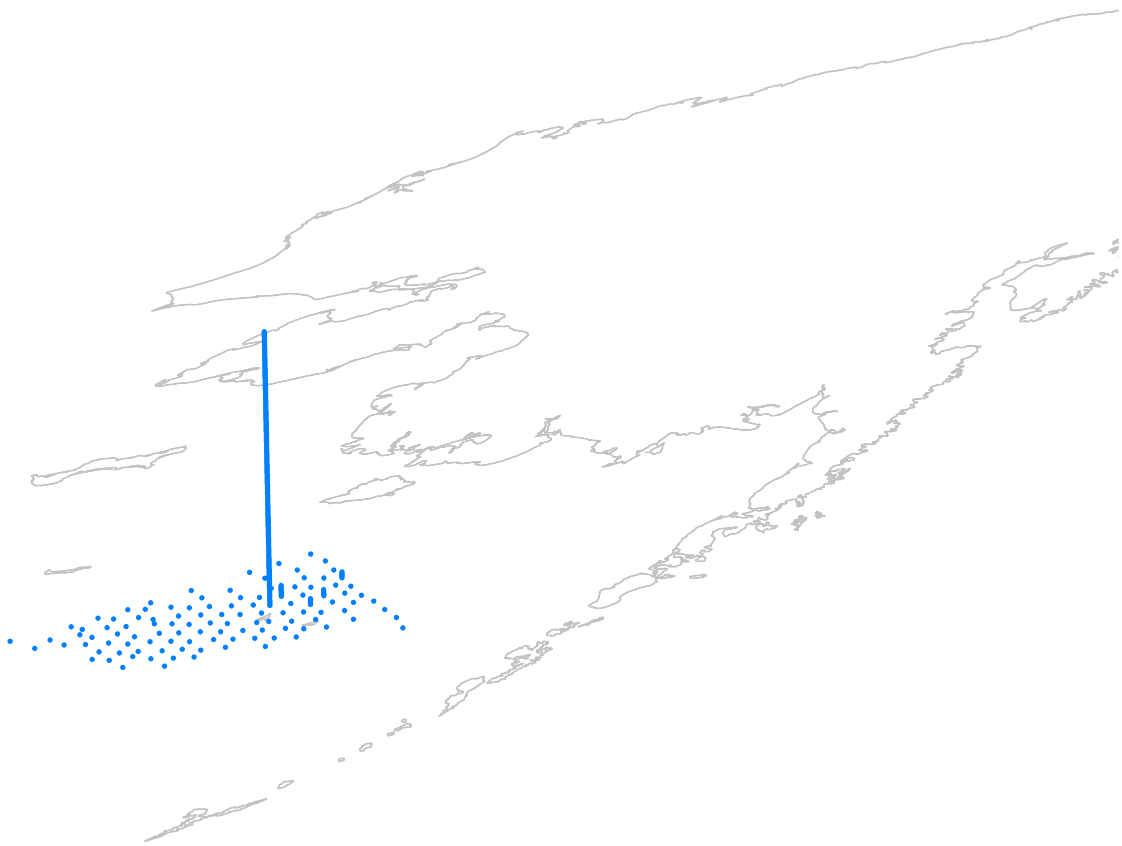

Figure 3: Observed relative male abundance by survey stations in 2018.

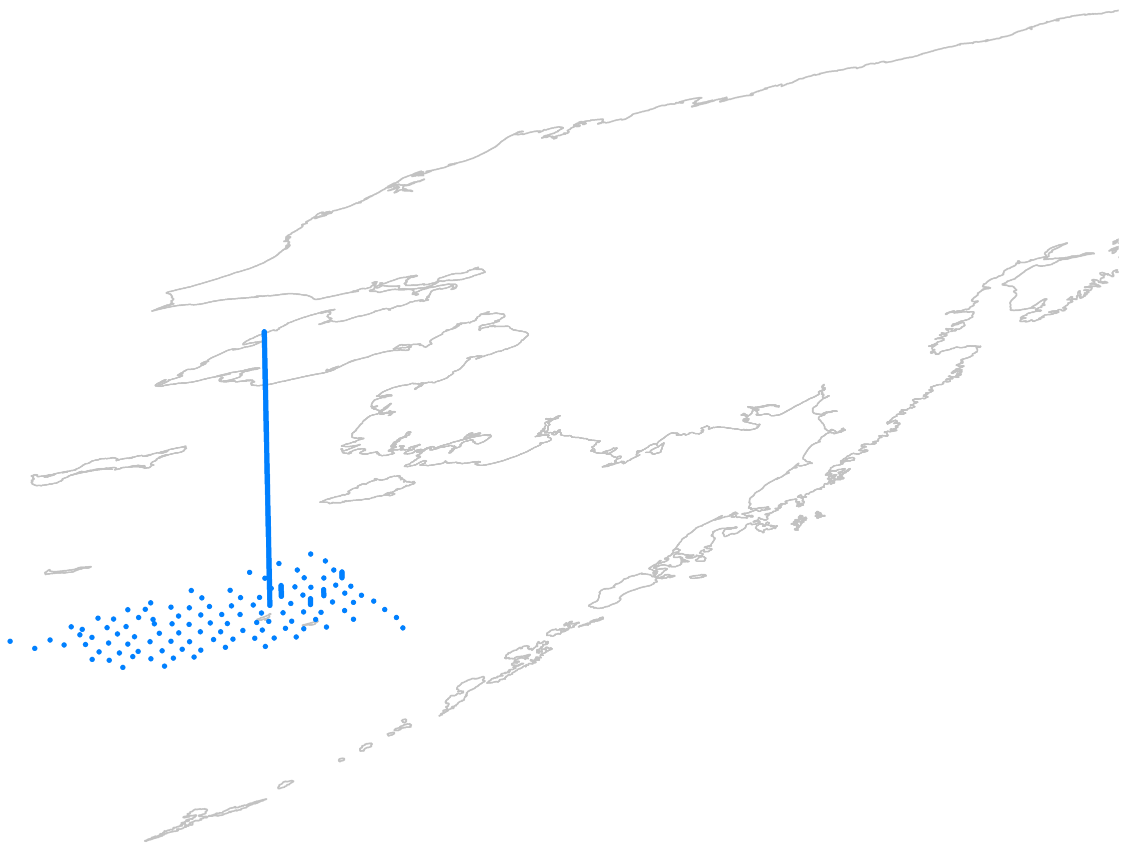

Figure 4: Observed relative female abundance by survey stations in 2018.

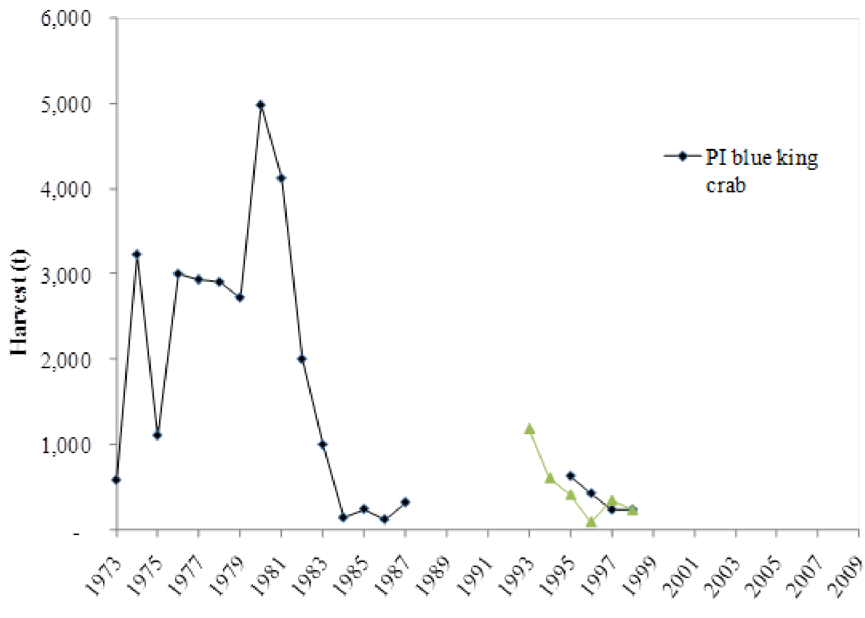

Figure 5: Pribilof Island management area in the Bering Sea

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 2018/2019	0	0	0

Figure 6: Observed retained catch

	Crab pot fisheries			Groundfish fisheries	
Year	Legal male (t)	Sublegal (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	0.12	1.19
2010/2011	0.00	0.00	0.00	0.25	6.05
2011/2012	0.00	0.00	0.00	0.29	4.57
2012/2013	0.00	0.00	0.00	0.10	12.11
2013/2014	0.00	0.00	0.00	0.24	1.99
2014/2015	0.00	0.00	0.00	0.41	0.19
2015/2016	0.167	0.00	0.053	0.73	1.03
2016/2017	0.00	0.00	0.00	0.26	0.43
2017/2018	0.00	0.00	0.00	0.09	0.39
2018/2019	0.00	0.00	0.00	0.07	4.75

Figure 7: Observed bycatches by fishery

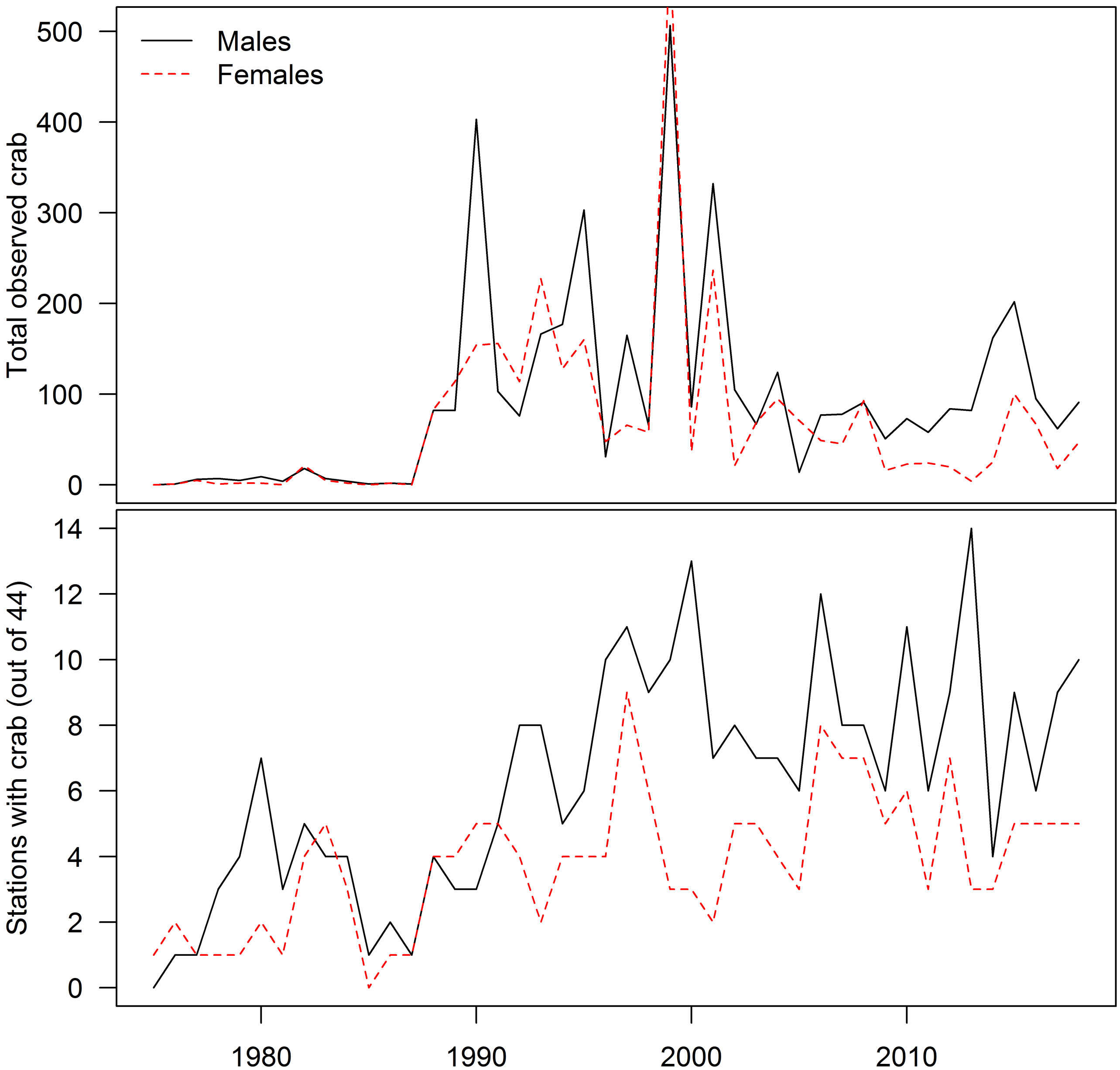

Figure 8: Total number of observed crab by year (top) and the number of stations at which crab were observed (bottom) by male (black solid line) and females (red dashed line).

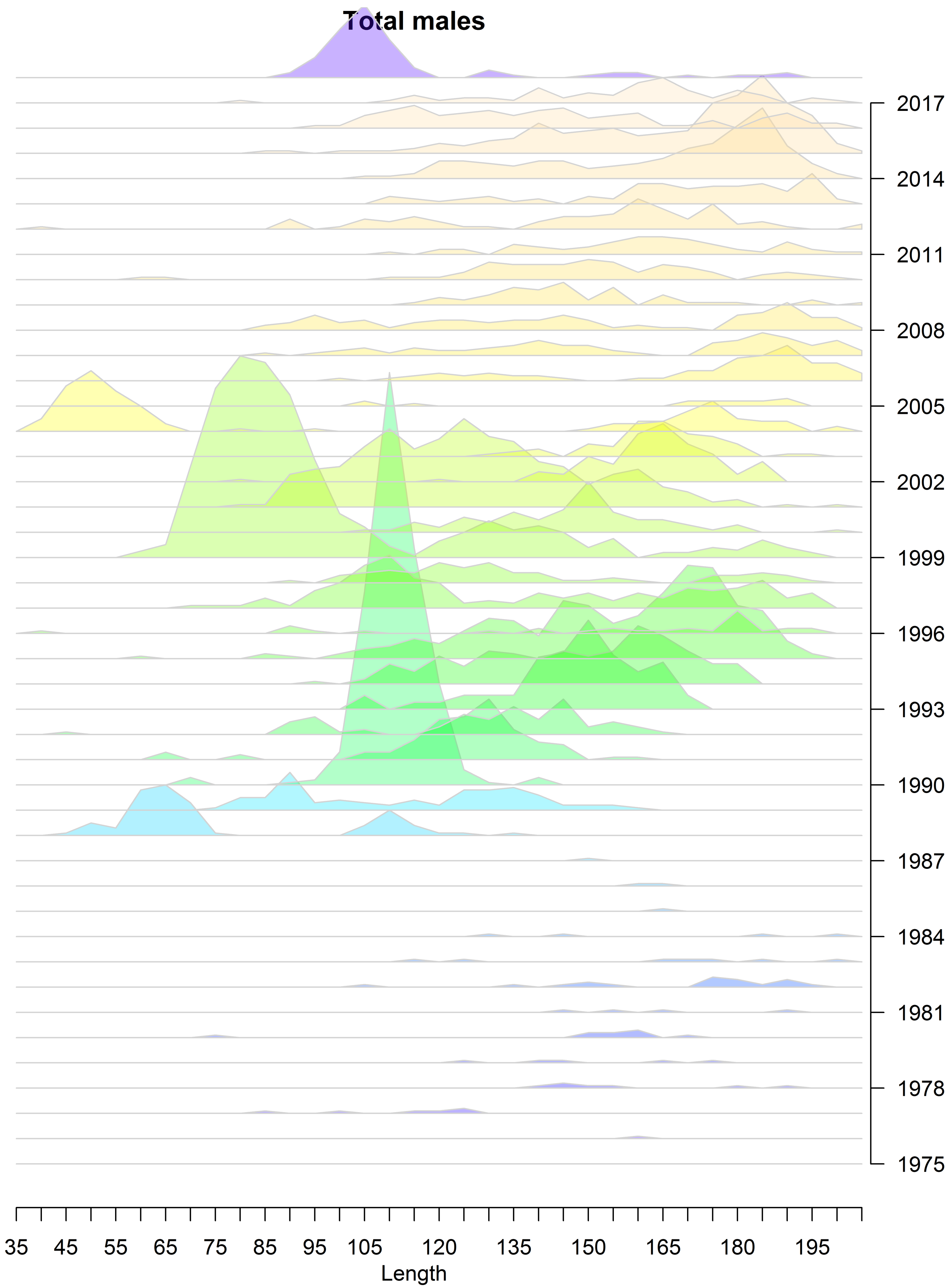

Figure 9: Observed male numbers at length by year.

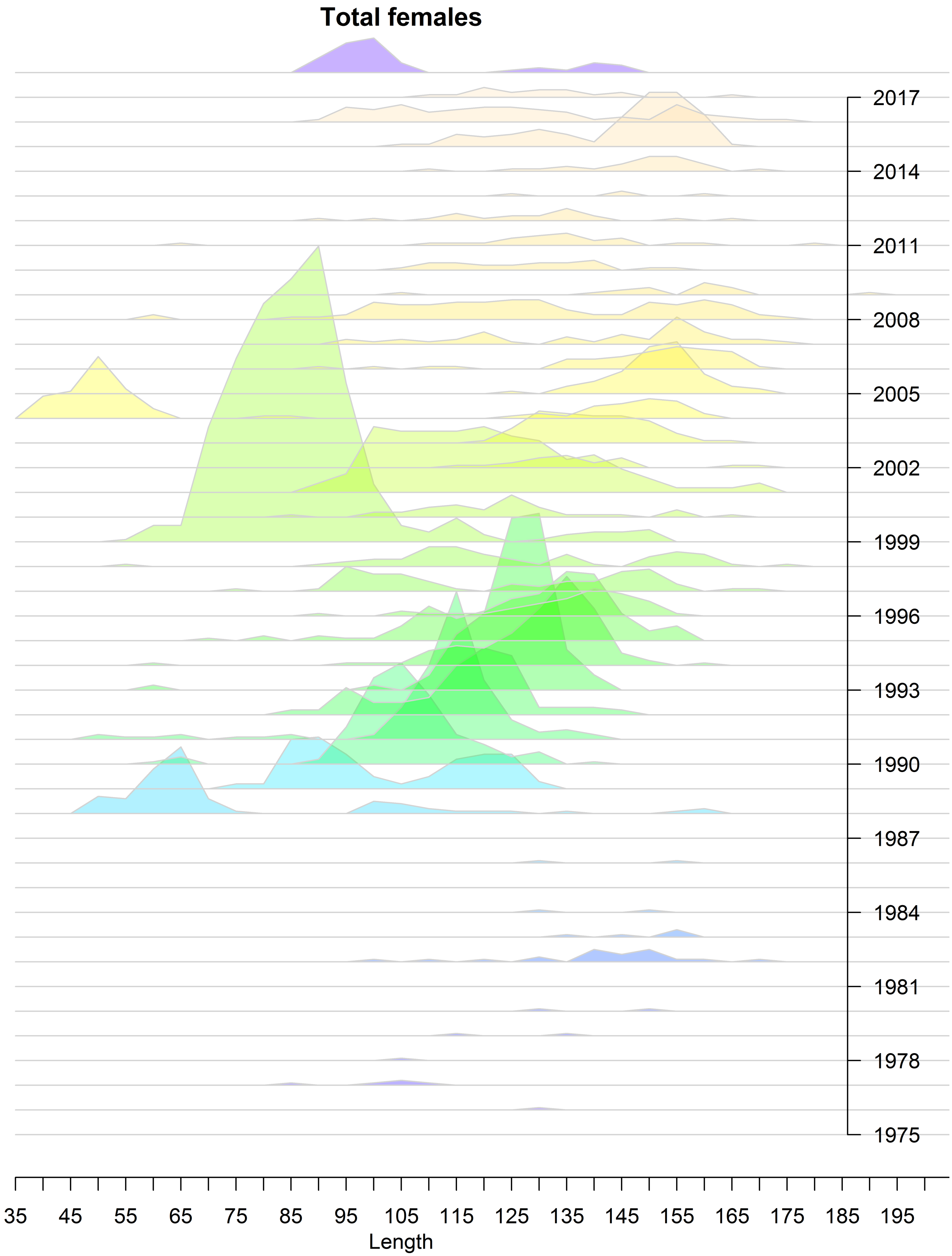

Figure 10: Observed female numbers at length by year

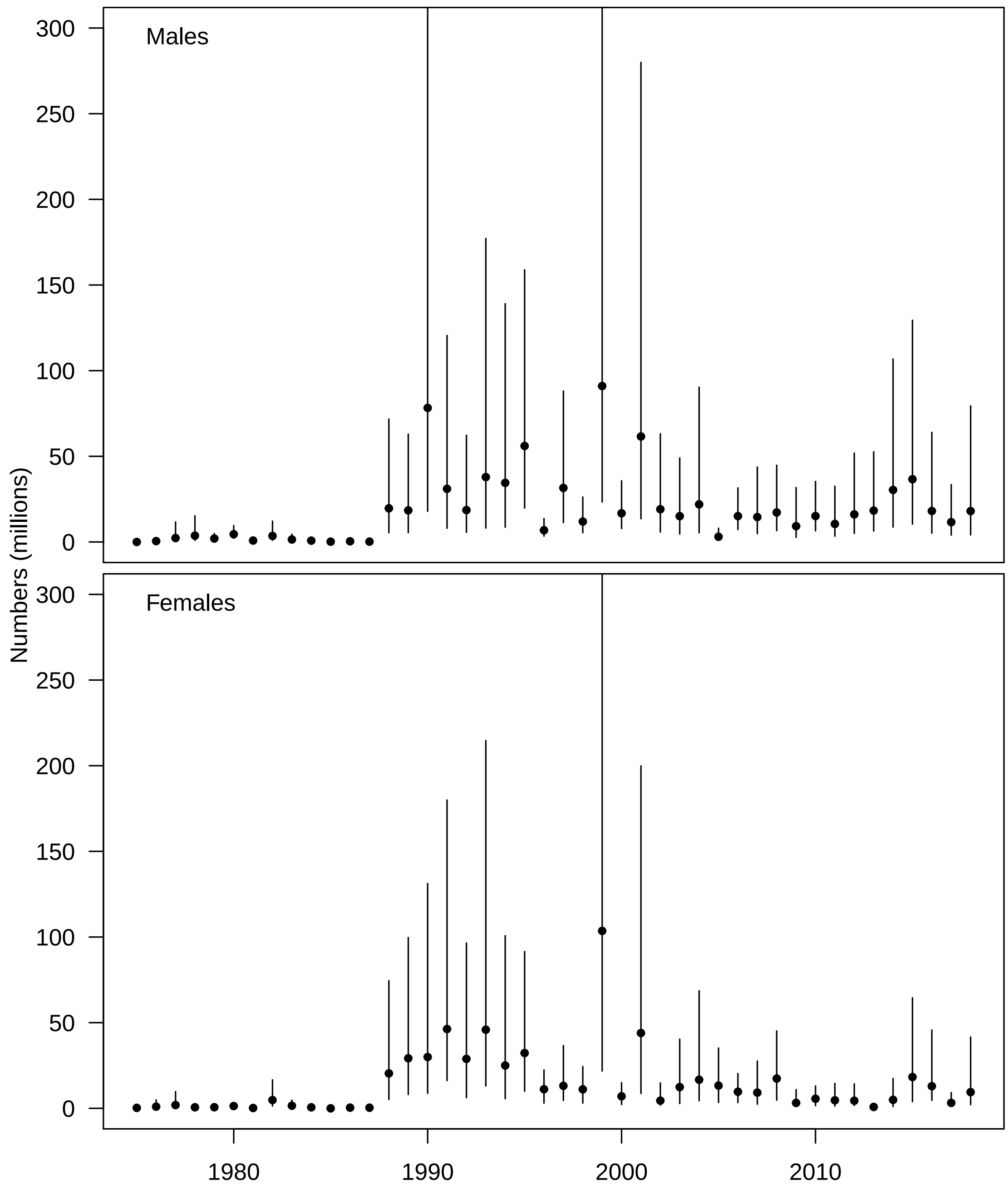

Figure 11: Yearly estimated abundance from the NMFS summer survey for male and female red king crab.

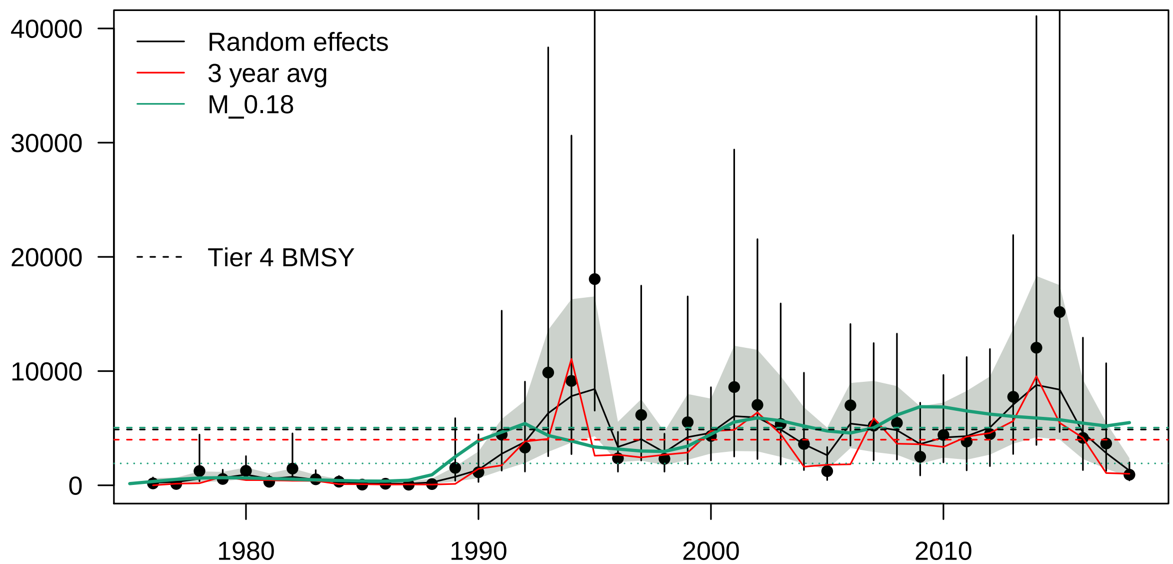

Figure 12: Comparison of estimated MMB among all models. The estimates from the integrated assessment are not fit to MMB, but it produces MMB.

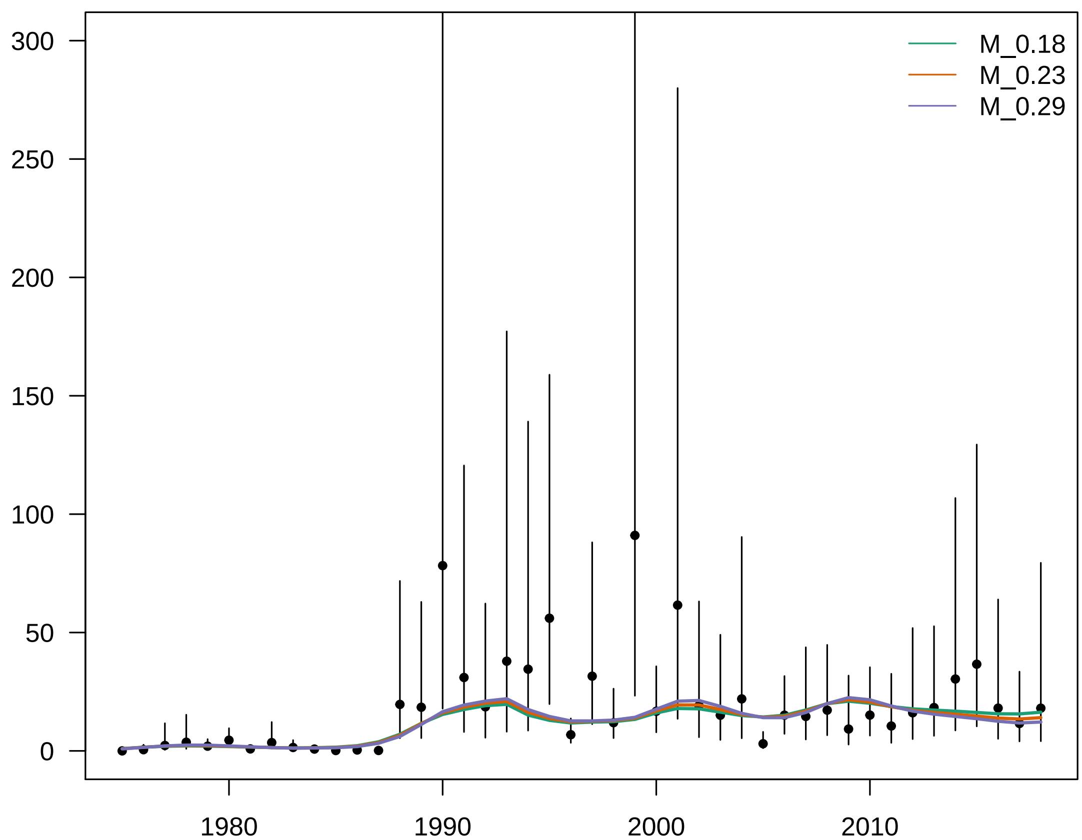

Figure 13: Model fits to the observed male numbers at the time of the survey

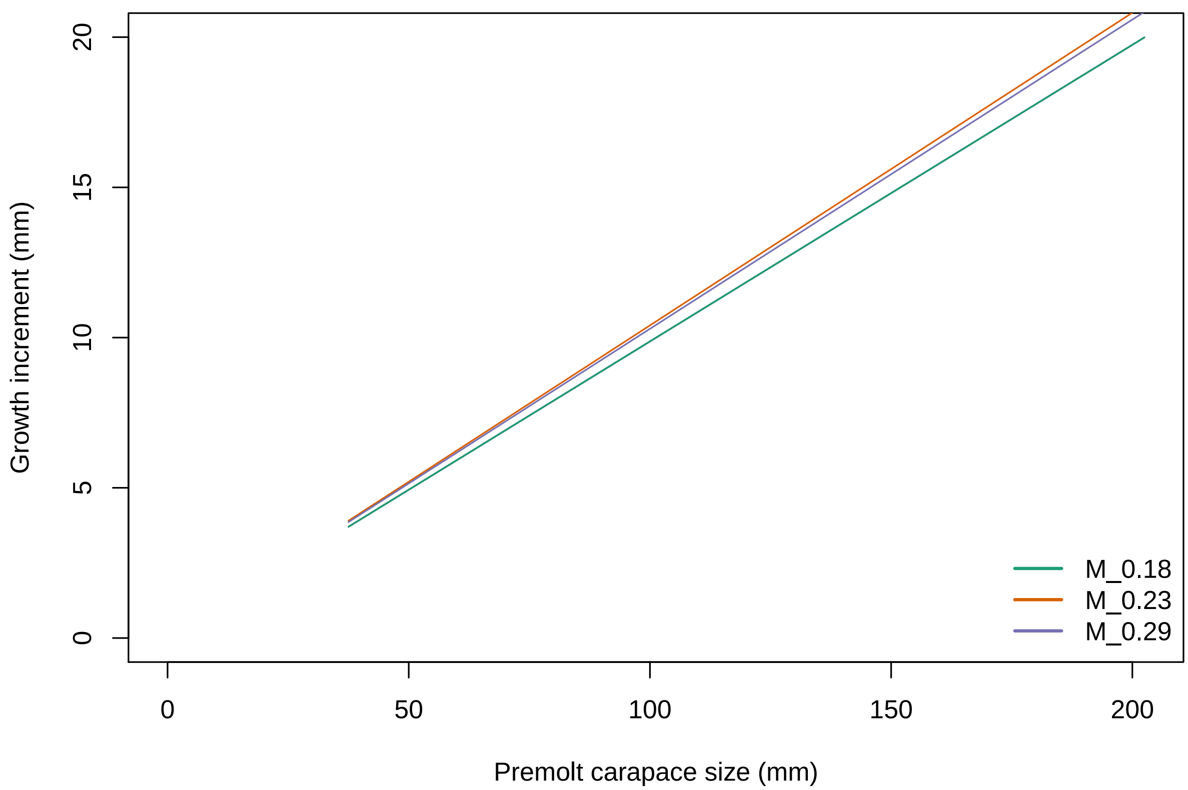

Figure 14: Predicted molt increments

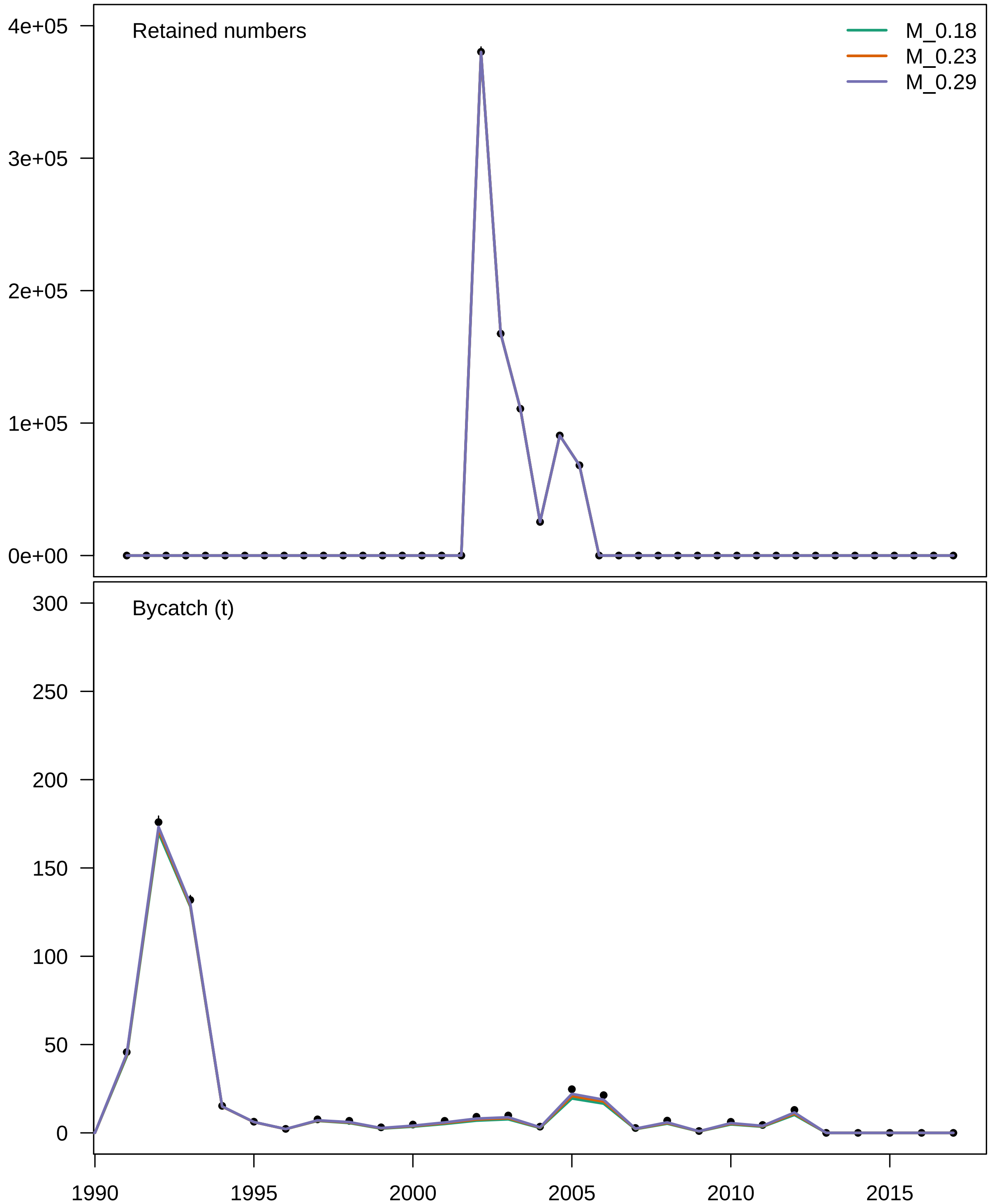

Figure 15: Model fits to catch data.

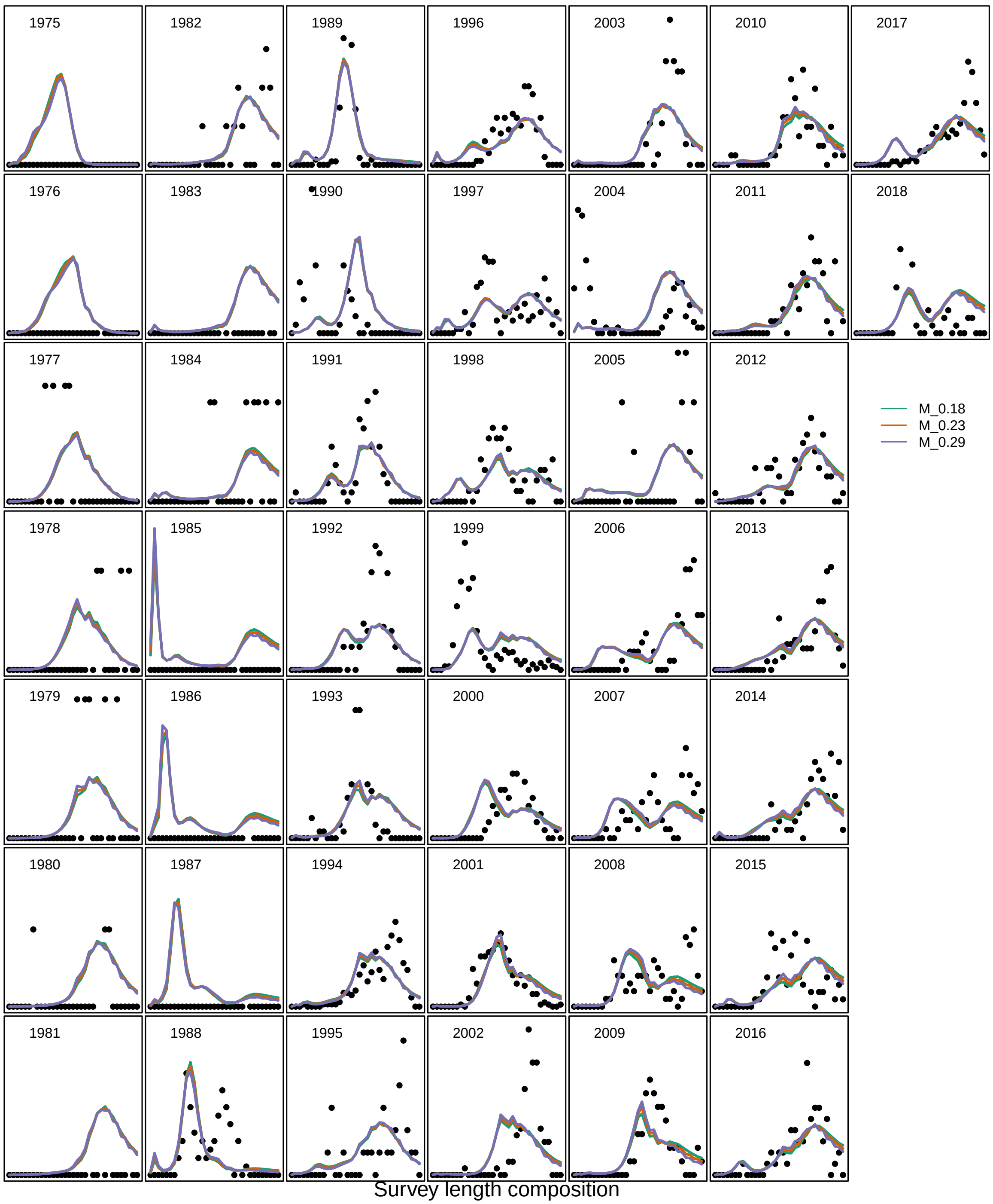

Figure 16: Model fits to survey size composition data.

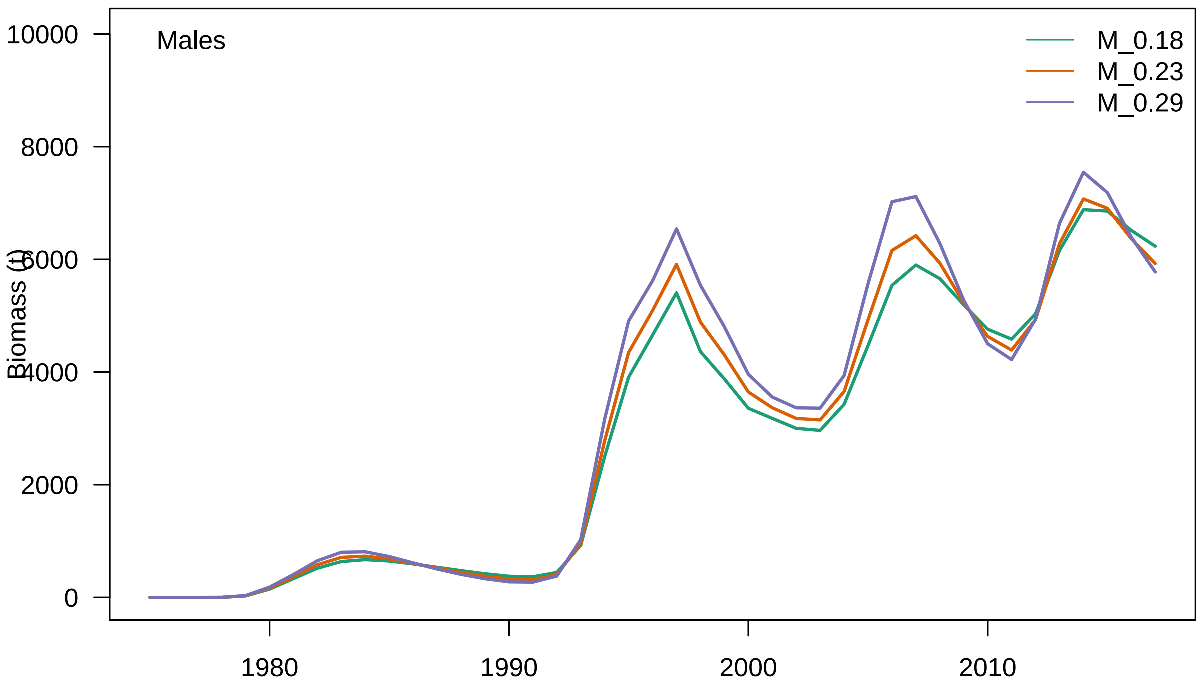

Figure 17: Model predicted mature male biomass at mating time

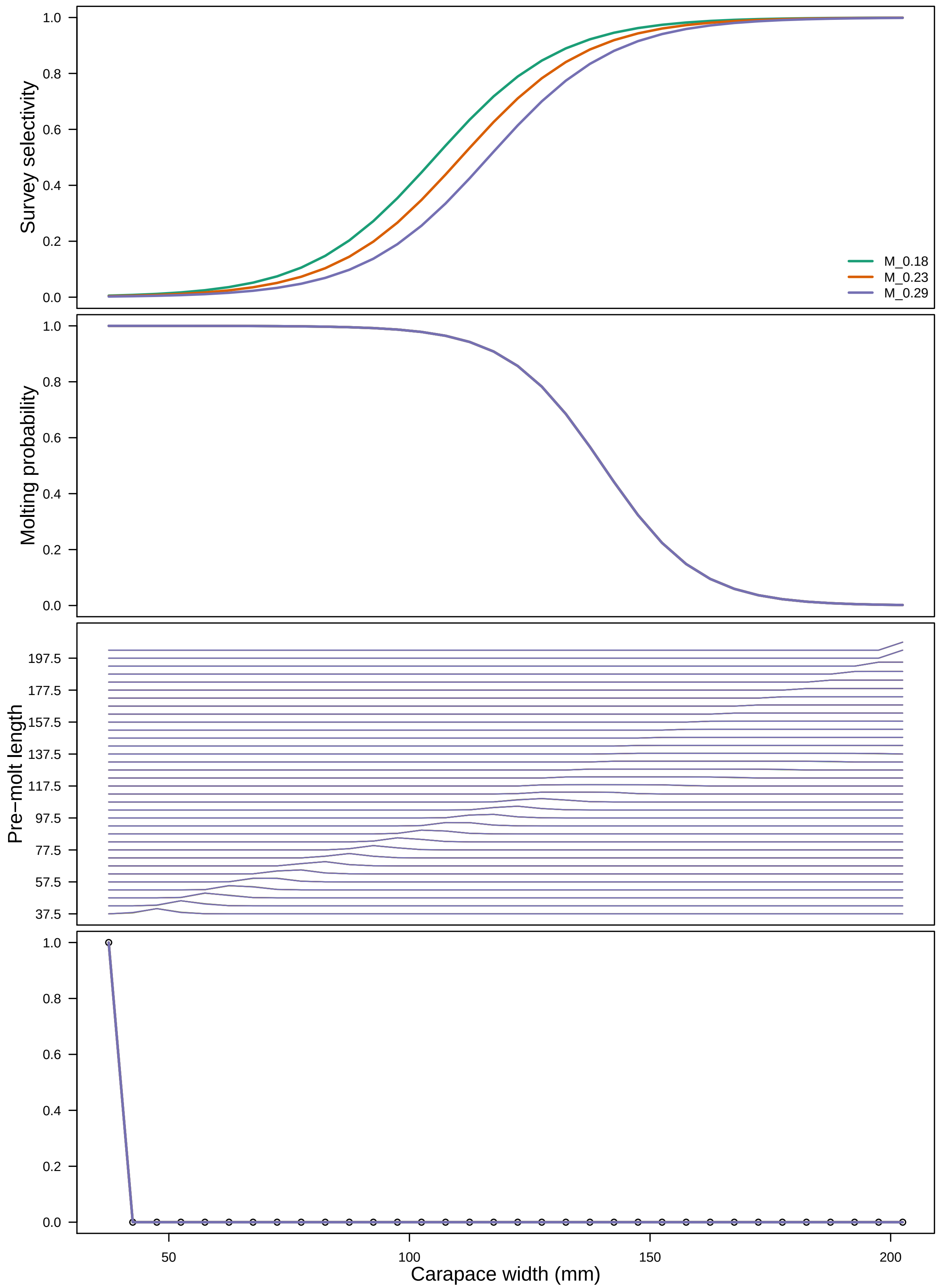

Figure 18: Estimated survey selectivity, probability of molting, size transition matrix, and fraction recruiting to length bin.

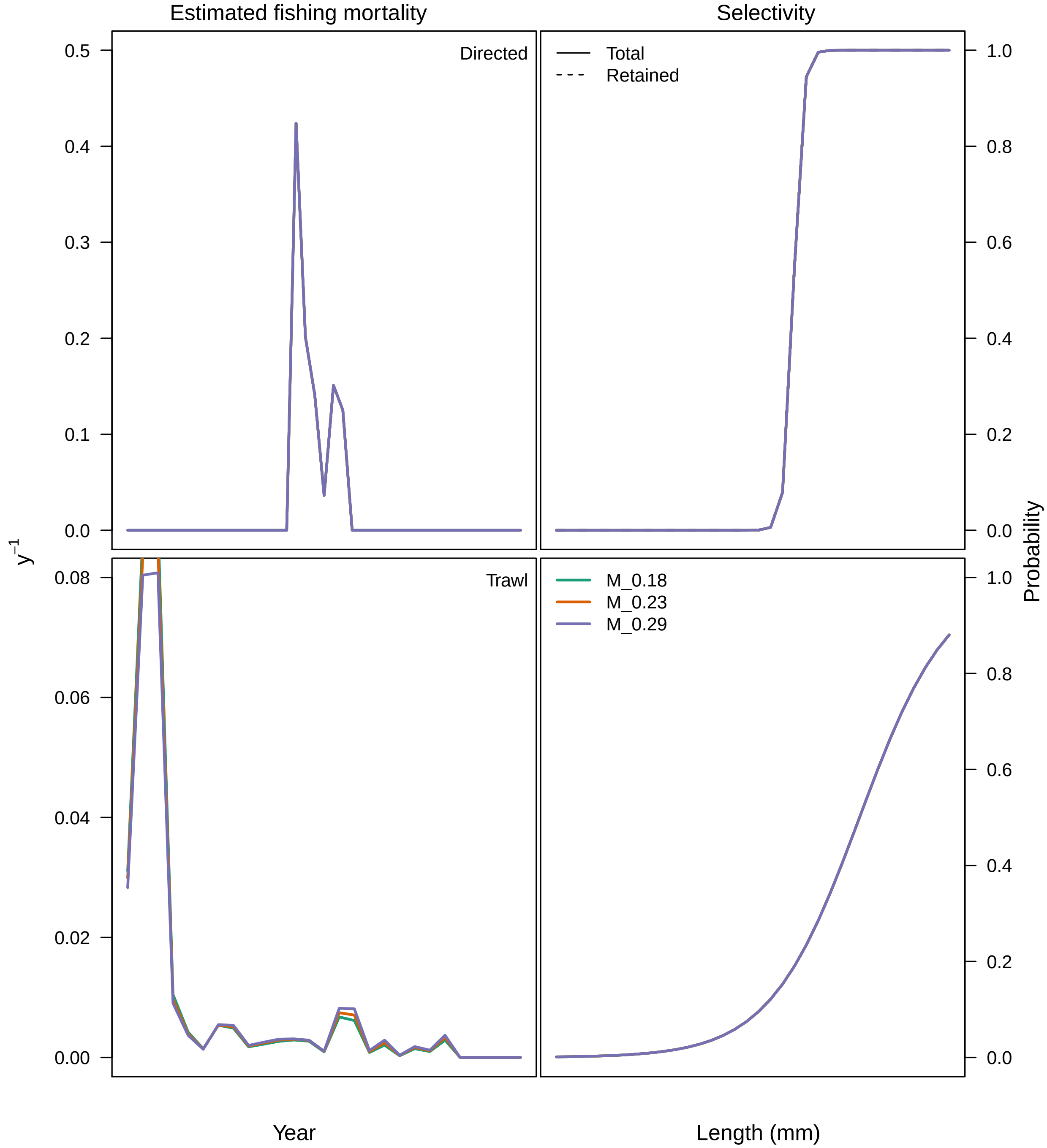

Figure 19: Model predicted fishing mortalities and selectivities for all sources of mortality

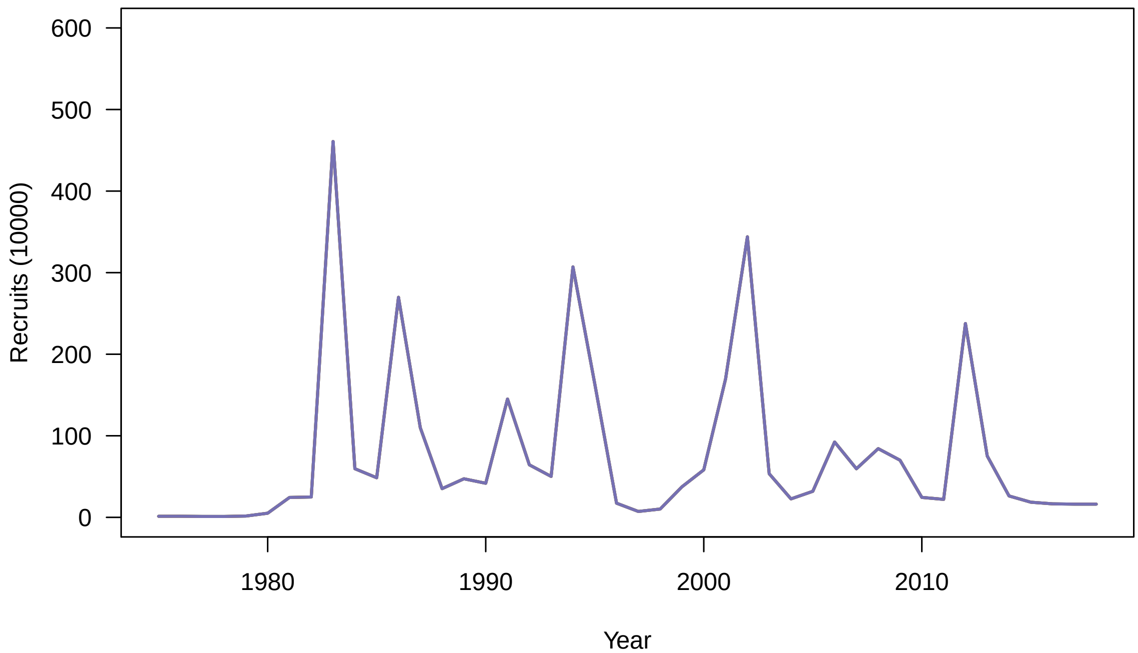

Figure 20: Estimated recruitment.