BRISTOL BAY RED KING CRAB STOCK ASSESSMENT IN FALL 2015

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Executive Summary

1. Stock: red king crab (RKC), *Paralithodes camtschaticus,* in Bristol Bay, Alaska.
2. Catches: The domestic RKC fishery began to expand in the late 1960s and peaked in 1980 with a catch of 129.95 million lbs (58,943 t). The catch declined dramatically in the early 1980s and remained at low levels during the last three decades. Catches during recent years until 2010/11 were among the high catches in last 15 years. The retained catch in 2014/15 was about 10 million lbs (4,500 t) less than it was in 2009/10. The magnitude of bycatch from groundfish trawl fisheries has been stable and small relative to stock abundance during the last 10 years.
3. Stock biomass: Estimated mature biomass increased dramatically in the mid 1970s and decreased precipitously in the early 1980s. Estimated mature crab abundance had increased during 1985-2009 with mature females being about 3 times more abundant in 2009 than in 1985 and mature males being about 2 times more abundant in 2009 than in 1985. Estimated mature abundance has steadily declined since 2009.
4. Recruitment: Estimated recruitment was high during 1970s and early 1980s and has generally been low since 1985 (1979 year class). During 1984-2015, only in 1984, 1986, 1995, 1999, 2002 and 2005 were estimated recruitments above the historical average for 1976-2015. Estimated recruitment was extremely low during the last 9 years.
5. Management performance:

Status and catch specifications (1,000 t) (scenarios 1 and 1a):

Year	MSST	Biomass (MMB)	TAC	Retained Catch	Total Catch	OFL	ABC
2011/12	13.77[A]	30.88[A]	3.55	3.61	4.09	8.80	7.92
2012/13	13.19[B]	29.05[B]	3.56	3.62	3.90	7.96	7.17
2013/14	12.85[C]	27.12[C]	3.90	3.99	4.56	7.07	6.36
2014/15[1]	13.03[D]	27.25[D]	4.49	4.54	5.44	6.82	6.14
2015/16[1]		24.69[D]				6.73	6.06
2014/15[1a]	13.23[D]	27.80[D]	4.49	4.54	5.44	6.82	6.14
2015/16[1a]		25.02[D]				6.82	6.14

The stock was above MSST in 2014/15 and is hence not overfished. Overfishing did not occur.

Status and catch specifications (million lbs):

Year	MSST	Biomass (MMB)	TAC	Retained Catch	Total Catch	OFL	ABC
2011/12	30.4[A]	68.1[A]	7.83	7.95	9.01	19.39	17.46
2012/13	29.1[B]	64.0[B]	7.85	7.98	8.59	17.55	15.80
2013/14	28.3[C]	59.9[C]	8.60	8.80	10.05	15.58	14.02
2014/15[1]	28.7[D]	60.1[D]	9.99	10.01	11.99	15.04	13.53
2015/16[1]		54.4[D]				14.84	13.36
2014/15[1a]	29.2[D]	61.3[D]	9.99	10.01	11.99	15.04	13.53
2015/16[1a]		55.2[D]				15.04	13.54

Notes:
A – Calculated from the assessment reviewed by the Crab Plan Team in September 2012
B – Calculated from the assessment reviewed by the Crab Plan Team in September 2013
C – Calculated from the assessment reviewed by the Crab Plan Team in September 2014
D – Calculated from the assessment reviewed by the Crab Plan Team in September 2015
1 – Scenario 1 and 1a – scenario 1a.

6. Basis for the OFL: All table values are in 1000 t (Scenarios 1 and 1a).

Year	Tier	B_{MSY}	Current MMB	B/B_{MSY} (MMB)	F_{OFL}	Years to define B_{MSY}	Natural Mortality
2011/12	3a	27.3	29.8	1.09	0.32	1984-2011	0.18
2012/13	3b	27.5	26.3	0.96	0.31	1984-2012	0.18
2013/14	3b	26.4	25.0	0.95	0.27	1984-2013	0.18
2014/15	3b	25.7	24.7	0.96	0.28	1984-2014	0.18
2015/16[1]	3b	26.1	24.7	0.95	0.27	1984-2015	0.18
2015/16[1a]	3b	26.5	25.0	0.95	0.27	1984-2015	0.18

Basis for the OFL: All table values are in million lbs.

Year	Tier	B_{MSY}	Current MMB	B/B_{MSY} (MMB)	F_{OFL}	Years to define B_{MSY}	Natural Mortality
2011/12	3a	60.1	65.6	1.09	0.32	1984-2011	0.18
2012/13	3b	60.7	58.0	0.96	0.31	1984-2012	0.18
2013/14	3b	58.2	55.0	0.95	0.27	1984-2013	0.18
2014/15	3b	56.7	54.4	0.96	0.28	1984-2014	0.18
2015/16[1]	3b	57.5	54.4	0.95	0.27	1984-2015	0.18
2015/16[1a]	3b	58.4	55.2	0.95	0.27	1984-2015	0.18

A. Summary of Major Changes

1. Change to management of the fishery: None.

2. Changes to the input data:

a. The new time series of NMFS trawl survey area-swept estimates provided by NMFS in 2015 with new 2015 trawl survey data were used.

b. Catch and biomass data were updated to present.

c. Bottom temperature data collected during the NMFS summer trawl surveys were used to estimate trawl survey catchability.

3. Changes to the assessment methodology:

Three model scenarios are evaluated in this report (See Section E.3.a for details):

Scenario 1: Scenario 1 is renamed from scenario 4nb in the SAFE report in September 2014 for simplicity with the new time series of the NMFS trawl survey data.

Scenario 1a: Scenario 1a is the same as scenario 1 except using the bottom temperature data to estimate annual trawl survey catchability with the "data method" described in Schirippa et al. (2009).

Scenario 1b: Scenario 1b is the same as scenario 1 except using the bottom temperature data to estimate annual trawl survey catchability with the "model method" based on Wilderbuer et al. (2013).

4. Changes to assessment results:

The population biomass estimates in 2015 are slightly lower than those in 2014. Among the three scenarios, model estimated relative survey biomasses are very similar between scenarios 1 and 1b and fluctuate a lot more for scenario 1a, primarily due to a much better fit of total survey biomass. The absolute population biomass estimates are slightly higher for scenario 1a than for scenarios 1 and 1b due to a slightly lower estimate of trawl survey catchability for scenario 1a.

B. Responses to SSC and CPT Comments

1. Responses to the most recent two sets of SSC and CPT comments on assessments in general:

None.

2. Responses to the most recent two sets of SSC and CPT comments specific to this assessment:

Response to CPT Comments (from September 2014)

"The CPT recommended that the assessment authors consider the affects of the final size bin used in the retained size composition data on model fitting (including the effects of the assumption of fixed sample size in the final bin) and consider the possibility of subdividing the final size bin into more than one bin."

This question comes from the difficulty of GMACS to fit the length composition data. The primary reason for the difficult fit is due to problems of estimating the growth transition matrix and survey selectivities. However, the final plus-length group does have impacts on the results. It is a trade-off between the numbers of empty length groups and relatively low impacts of large plus groups. We may consider examining this in the future.

Response to CPT Comments (from May 2015)

"1) Use new survey data for all runs."

Done.

"20. Do runs with stepwise changes from scenario 1 to 2, with one change for each scenario."

Due to lack of female juvenile growth data, we will not include scenario 2 in this report. Scenario 2 will be evaluated in future.

"3). Run a scenario with a temperature relationship to survey q. Use a method that allows variability in the index such as the "data method" described in Schirippa et al (2009)."

Scenario 1a is the "data method" to estimate annual trawl survey catchabilities with bottom temperature data. As a comparison, scenario 1b is the "model method" to estimate annual survey catchabilities based on Wilderbuer et al. (2013).

"4. Use egg code data in the survey to separate immature and mature females and input as data to the model as an alternative for tracking changes in maturity over time. Fit immature and mature females separately in the model."

Will follow this recommendation in future when working with scenario 2.

"*5). Label x axis on length composition plots with actual length in millimeters."*

Done.

Response to SSC Comments specific to this assessment (from October 2014)

"The SSC recommends that if Model 4n7 is brought forward in 2015 as an alternative model, that reference points for Model 4n7 be recalculated with the higher M = 0.27 estimated for 2006 – 2010. The SSC looks forward to the additional work planned by the author: implementing a random walk for natural mortality, investigation of recruitment dynamics, and investigation of survey weighting."

A scenario with random walk is not added in this report. We feel that the random walk approach may be used to examine the temporal trend of natural mortality, but the estimated natural mortality value may not be suitable for reference point estimates due to the mean recruitment estimated under different natural mortality.

In May 2015, we investigated a model scenario on examining female maturity as suggested by the SSC in 2013. This model scenario will be further developed in the future once juvenile red king crab female growth data are available.

We appreciate SSC suggestions on spatial statistical analysis similar to that conducted by Kotwicki and Lauth (2012) and incorporating bottom temperature as a covariate on survey Q using the method in Wilderbuer et al. (2013). We will consider conducting spatial statistical analysis in the future.

In this report, we examine annual trawl survey Q values with temperature data with two methods (scenarios 1a and 1b). Scenario 1b uses the method in Wilderbuer et al. (2013) to estimate survey Q.

Response to SSC Comments specific to this assessment (from June 2015):

No comments.

C. Introduction

1. Species

Red king crab (RKC), *Paralithodes camtschaticus*, in Bristol Bay, Alaska**.**

2. General distribution

Red king crab inhabit intertidal waters to depths >200 m of the North Pacific Ocean from British Columbia, Canada, to the Bering Sea, and south to Hokkaido, Japan, and are found in several areas of the Aleutian Islands and eastern Bering Sea.

3. Stock Structure

The State of Alaska divides the Aleutian Islands and eastern Bering Sea into three management registration areas to manage RKC fisheries: Aleutian Islands, Bristol Bay, and Bering Sea (Alaska Department of Fish and Game (ADF&G) 2012). The Bristol Bay area includes all waters north of the latitude of Cape Sarichef (54°36' N lat.), east of 168°00' W long., and south of the latitude of Cape Newenham (58°39' N lat.) and the fishery for RKC in this area is managed separately from fisheries for RKC outside of this area; i.e., the red king crab in the Bristol Bay area are assumed to be a separate stock from red king crab outside of this area. This report summarizes the stock assessment results for the Bristol Bay RKC stock.

4. Life History

Red king crab have a complex life history. Fecundity is a function of female size, ranging from several tens of thousands to a few hundreds of thousands (Haynes 1968; Swiney et al. 2012). The eggs are extruded by females, fertilized in the spring, and held by females for about 11 months (Powell and Nickerson 1965). Fertilized eggs are hatched in the spring, most during April-June (Weber 1967). Primiparous females are bred a few weeks earlier in the season than multiparous females.

Larval duration and juvenile crab growth depend on temperature (Stevens 1990; Stevens and Swiney 2007). Male and female RKC mature at 5–12 years old, depending on stock and temperature (Loher et al. 2001; Stevens 1990) and may live >20 years (Matsuura and Takeshita 1990). Males and females attain a maximum size of 227 and 195 mm carapace length (CL), respectively (Powell and Nickerson 1965). Female maturity is evaluated by the size at which females are observed to carry egg clutches. Male maturity can be defined by multiple criteria including spermataphore production and size, chelae vs. carapace allometry, and participation in mating *in situ* (reviewed by Webb 2014). For management purposes, females >89 mm CL and males >119 mm CL are assumed to be mature for Bristol Bay RKC. Juvenile RKC molt multiple times per year until age 3 or 4; thereafter, molting continues annually in females for life and in males until maturity. Male molting frequency declines after attaining functional maturity.

5. Fishery

The RKC stock in Bristol Bay, Alaska, supports one of the most valuable fisheries in the United States. A review of the history of the Bristol Bay RKC fishery is provided in Fitch et al. (2012) and Otto (1989). The Japanese fleet started the fishery in the early 1930s, stopped fishing from 1940 to 1952, and resumed the fishery from 1953 until 1974. The Russian fleet fished for RKC from 1959 to 1971. The Japanese fleet employed primarily tanglenets with a very small proportion of catch from trawls and pots. The Russian fleet used only tanglenets. United States trawlers started fishing Bristol Bay RKC in 1947, but the effort and catch declined in the 1950s. The domestic RKC fishery began to expand in the late 1960s and peaked in 1980 with a catch of 129.95 million lbs (58,943 t), worth an estimated $115.3 million ex-vessel value. The catch declined dramatically in the early 1980s and has remained at low levels during the last two decades (Table 1). After the early 1980s stock collapse, the Bristol Bay RKC fishery took place during a short period in the fall (usually lasting about a week) with the catch quota based on the stock assessment conducted the previous summer (Zheng and Kruse 2002). Beginning with the 2005/2006 season, new regulations associated with fishery rationalization resulted in an increase in the duration of the fishing season (October 15 to January 15). With the implementation of crab rationalization, historical guideline harvest levels (GHL) were changed to a total allowable catch (TAC). Before rationalization, the implementation errors were quite high for some years and total actual catch from 1980 to 2007 was about 6% less than the sum of GHL/TAC over that period.

6. Fisheries Management

King and Tanner crab stocks in the Bering Sea and Aleutian Islands are managed by the State of Alaska through a federal king and Tanner crab fishery management plan (FMP). Under the FMP, management measures are divided into three categories: (1) fixed in the FMP, (2) frame worked in the FMP, and (3) discretion of the State of Alaska. The State of Alaska is responsible for determining and establishing the GHL/TAC under the framework in the FMP.

Harvest strategies for the Bristol Bay RKC fishery have changed over time. Two major management objectives for the fishery are to maintain a healthy stock that ensures reproductive viability and to provide for sustained levels of harvest over the long term (ADF&G 2012). In attempting to meet these objectives, the GHL/TAC is coupled with size-sex-season restrictions. Only males ≥6.5-in carapace width (equivalent to 135-mm carapace length, CL) may be harvested and no fishing is allowed during molting and mating periods (ADF&G 2012). Specification of TAC is based on a harvest rate strategy. Before 1990, harvest rates on legal males were based on population size, abundance of prerecruits to the fishery, and postrecruit abundance, and rates varied from less than 20% to 60% (Schmidt and Pengilly 1990). In 1990, the harvest strategy was modified, and a 20% mature male harvest rate was applied to the abundance of mature-sized (≥120-mm CL) males with a maximum 60% harvest rate cap of legal (≥135-mm CL) males (Pengilly and Schmidt 1995). In addition, a minimum threshold of 8.4 million mature-sized females (≥90-mm CL) was added to existing management measures to avoid recruitment overfishing (Pengilly and Schmidt 1995). Based on a new assessment model and research findings (Zheng et al. 1995a, 1995b, 1997a, 1997b), the Alaska Board of Fisheries adopted a new harvest strategy in 1996. That strategy had two mature male harvest rates: 10% when effective spawning biomass (ESB) is between 14.5 and 55.0 million lbs and 15% when ESB is at or above 55.0 million lbs (Zheng et al. 1996). The maximum harvest rate cap of legal males was changed from 60% to 50%. A threshold of 14.5 million lbs of ESB was also added. In 1997, a minimum threshold of 4.0 million lbs was established as the minimum GHL for opening the fishery and maintaining fishery manageability when the stock abundance is low. The Board modified the current harvest strategy by adding a mature harvest rate of 12.5% when the ESB is between 34.75 and 55.0 million lbs in 2003 and eliminated the minimum GHL threshold in 2012. The current harvest strategy is illustrated in Figure 1.

D. Data

1. Summary of New Information

A new time series of NMFS trawl survey results was provided by NMFS in 2015. We compared the old and new time series of the NMFS trawl survey results in May 2015. The trawl survey data were updated to include the survey data in 2015.

Catch and biomass data were updated to present.

Mean annual bottom temperature data collected during the NMFS summer trawl surveys within the area of >54.75^{o}N and <58.75^{o}N, >-166^{o}W and <-158^{o}W were used to estimate trawl survey catchability. Bristol Bay red king crab primarily occur in this area.

2. Catch Data

Data on landings of Bristol Bay RKC by length and year and catch per unit effort from 1960 to 1973 were obtained from annual reports of the International North Pacific Fisheries Commission (Hoopes et al. 1972; Jackson 1974; Phinney 1975) and from the ADF&G from 1974 to 2014. Bycatch data are available starting from 1990 and were obtained from the ADF&G observer database and reports (Gaeuman 2013). Sample sizes for catch by length and shell condition are summarized in Table 2. Relatively large samples were taken from the retained catch each year. Sample sizes for trawl bycatch were the annual sums of length frequency samples in the National Marine Fisheries Service (NMFS) database.

(i). Catch Biomass

Retained catch and estimated bycatch biomasses are summarized in Table 1 and illustrated in Figure 2. Retained catch and estimated bycatch from the directed fishery include the general, open-access fishery (prior to rationalization), or the individual fishery quota (IFQ) fishery (after rationalization), as well as the Community Development Quota (CDQ) fishery and the ADF&G cost-recovery harvest. Starting in 1973, the fishery generally occurred during the late summer and fall. Before 1973, a small portion of retained catch in some years was caught from April to June. Because most crab bycatch from the groundfish trawl fisheries occurred during the spring, the years in Table 1 are one year less than those from the NMFS trawl bycatch database to approximate the annual bycatch for reporting years defined as June 1 to May 31; e.g., year 2002 in Table 1 for trawl bycatch corresponds to what is reported for year 2003 in the NMFS database. Catch biomass is shown in Figure 2. Bycatch data for the cost-recovery fishery before 2006 were not available. In this report, pot fisheries include both the directed fishery and RKC bycatch in the Tanner crab pot fishery and trawl fisheries are groundfish trawl fisheries.

(ii). Catch Size Composition

Retained catch by length and shell condition and bycatch by length, shell condition, and sex were obtained for stock assessments. From 1960 to 1966, only retained catch length compositions from the Japanese fishery were available. Retained catches from the Russian and U.S. fisheries were assumed to have the same length compositions as the Japanese fishery during this period. From 1967 to 1969, the length compositions from the Russian fishery were assumed to be the same as those from the Japanese and U.S. fisheries. After 1969, foreign catch declined sharply and only length compositions from the U.S. fishery were used to distribute catch by length.

(iii). Catch per Unit Effort

Catch per unit effort (CPUE) is defined as the number of retained crab per tan (a unit fishing effort for tanglenets) for the Japanese and Russian tanglenet fisheries and the number of retained crab per potlift for the U.S. fishery (Table 3). Soak time, while an important factor influencing CPUE, is difficult to standardize. Furthermore, complete historical soak time data from the U.S. fishery are not available. Based on the approach of Balsiger (1974), all fishing effort from Japan, Russia, and U.S. were standardized to the Japanese tanglenet from 1960 to 1971, and the CPUE was standardized as crab per tan. Except for the peak-to-crash years of late 1970s and early 1980s the correspondence between U.S. fishery CPUE and area-swept survey abundance is poor (Figure 3). Due to the difficulty in estimating commercial fishing catchability and crab availability to the NMFS annual trawl survey data, commercial CPUE data were not used in the model.

3. NMFS Survey Data

The NMFS has performed annual trawl surveys of the eastern Bering Sea since 1968. Two vessels, each towing an eastern otter trawl with an 83 ft headrope and a 112 ft footrope, conducted this multispecies, crab-groundfish survey during the summer. Stations were sampled in the center of a systematic 20 X 20 nm grid overlaid in an area of ≈140,000 nm^2. Since 1972, the trawl survey has covered the full stock distribution except in nearshore waters. The survey in Bristol Bay occurs primarily during late May and June. Tow-by-tow trawl survey data for Bristol Bay RKC during 1975-2015 were provided by NMFS.

Abundance estimates by sex, carapace length, and shell condition were derived from survey data using an area-swept approach (Figures 4 and 5). Spatial distributions of crab from the standard trawl surveys during recent years are shown in Appendix B. Until the late 1980s, NMFS used a post-stratification approach, but subsequently treated Bristol Bay as a single stratum; the estimates shown for Bristol Bay in Figures 4 and 5 were made without post-stratification. If multiple tows were made for a single station in a given year, the average of the abundances from all tows within that station was used as the estimate of abundance for that station. The new time series in 2015 discards all "hot spot" tows. We used the new area-swept estimates provided by NMFS in 2015.

In addition to standard surveys, NMFS also conducted some surveys after the standard surveys to better assess mature female abundance. In addition to the standard surveys conducted in early June (late May to early June in 1999 and 2000), a portion of the distribution of Bristol Bay RKC was re-surveyed in 1999, 2000, and 2006-2012. Resurveys performed in late July, about six weeks after the standard survey, included 31 stations (1999), 23 stations (2000), 31 stations (2006, 1 bad tow and 30 valid tows), 32 stations (2007-2009), 23 stations (2010) and 20 stations (2011 and 2012) with high female density. The resurveys were necessary because a high proportion of mature females had not yet molted or mated when sampled by the standard survey. Differences in area-swept estimates of abundance between the standard surveys and resurveys of these same stations are attributed to survey measurement errors or to seasonal changes in distribution between survey and resurvey. More large females were observed in the resurveys than during the standard surveys in 1999 and 2000 because most mature females had not molted prior to the standard surveys. As in 2006, area-swept estimates of males >89 mm CL, mature males, and legal males within the 32 resurvey stations in 2007 were not significantly different (P=0.74, 0.74 and 0.95; paired t-test of sample means) between the standard survey and resurvey tows. However, similar to 2006, area-swept estimates of mature females within the 32 resurvey stations in 2007 were significantly different (P=0.03; paired t-test) between the standard survey and resurvey tows. Resurvey stations were close to shore during 2010-2012, and mature and legal male abundance estimates were lower for the re-tow than the standard survey. Following the CPT recommendation, we used the standard survey data for male abundance estimates and only the resurvey data, plus the standard survey data outside the resurveyed stations, to assess female abundances during these resurvey years.

4. Bering Sea Fisheries Research Foundation Survey Data

The BSFRF conducted trawl surveys for Bristol Bay RKC in 2007 and 2008 with a small-mesh trawl net and 5-minute tows. The surveys occurred at similar times as the NMFS standard surveys and covered about 97% of the Bristol Bay area. Few Bristol Bay RKC were found outside of the BSFRF survey area. Because of the small mesh size, the BSFRF surveys were expected to catch more of RKC within the swept area. Crab abundances of different size groups were estimated by the kriging method. Mature male abundances were estimated to be 22.331 in 2007 and 19.747 million in 2008 with respective CVs of 0.0634 and 0.0765.

E. Analytic Approach

1. History of Modeling Approaches

To reduce annual measurement errors associated with abundance estimates derived from the area-swept method, ADF&G developed a length-based analysis (LBA) in 1994 that incorporates multiple years of data and multiple data sources in the estimation procedure (Zheng et al. 1995a). Annual abundance estimates of the Bristol Bay RKC stock from the LBA have been used to manage the directed crab fishery and to set crab bycatch limits in the groundfish fisheries since 1995 (Figure 1). An alternative LBA (research model) was developed in 2004 to include small size groups for federal overfishing limits. The crab abundance declined sharply during the early 1980s. The LBA estimated natural mortality for different periods of years, whereas the research model estimated additional mortality beyond a basic constant natural mortality during 1976-1993. In this report, we present only the research model that was fit to the data from 1975 to 2015.

2. Model Description

The original LBA model was described in detail by Zheng et al. (1995a, 1995b) and Zheng and Kruse (2002). The model combines multiple sources of survey, catch, and bycatch data using a maximum likelihood approach to estimate abundance, recruitment, selectivities, catches, and bycatch of the commercial pot fisheries and groundfish trawl fisheries. A full model description is provided in Appendix A.

a-f. See appendix A.

g. Critical assumptions of the model:

   i. The base natural mortality is constant over shell condition and length and was estimated assuming a maximum age of 25 and applying the 1% rule (Zheng 2005).

   ii. Survey and fisheries selectivities are a function of length and were constant over shell condition. Selectivities are also a function of sex except for trawl bycatch selectivities, which are the same for both sexes. Two different survey selectivities were estimated: (1) 1975-1981 and (2) 1982-2015, based on modifications to the trawl gear used in the assessment survey.

iii. Growth is a function of length and is assumed to not change over time for males. For females with scenarios 1, 1a, and 1b, growth-per-molt increments as a function of length were estimated for three periods (1975-1982, 1983-1993, and 1994-2015) based on sizes at maturity. Once mature, female red king crab grow with a much smaller growth increment per molt.

iv. Molting probabilities are an inverse logistic function of length for males. Females molt annually.

v. Annual fishing seasons for the directed fishery are short.

vi. The prior of survey catchability (*Q*) was estimated to be 0.896, based on a trawl experiment by Weinberg et al. (2004) with a standard deviation of 0.025. *Q* is assumed to be constant over time and is estimated in the model for scenario 1. Annual *Q* values for scenarios 1a and 1b are estimated with bottom temperature data.

vii. Males mature at sizes ≥120 mm CL. For convenience, female abundance was summarized at sizes ≥90 mm CL as an index of mature females.

viii. Measurement errors were assumed to be normally distributed for length compositions and were log-normally distributed for biomasses.

h. Changes to the above since previous assessment: see Section A.3. Changes to the assessment methodology.

i. Outline of methods used to validate the code used to implement the model and whether the code is available: The code is available.

3. Model Selection and Evaluation

a. Alternative model configurations:

Several scenarios were compared for this report:

Scenario 1 (renamed from previous scenario 4nb): base scenario. Scenario 1 includes:

(1) Basic M = 0.18, with an additional mortality level during 1980-1984 for males and two additional mortality levels (one for 1980-1984 and the other for 1976-1979 and 1985-1993) for females. For scenario 2, the additional mortality level for 1976-1979 and 1985-1993 is 0 based on the model estimate, and thus is fixed to 0.

(2) Including BSFRF survey data in 2007 and 2008.

(3) Survey catchability is estimated in the model and is assumed to be constant over time.

(4) Two levels of molting probabilities for males: one before 1980 and one after 1979, based on survey shell condition data. Each level has two parameters.

(5) Estimating effective sample size from observed sample sizes. Effective sample sizes are estimated as min(0.5*observed-size, N) for trawl surveys and min(0.1* observed-size, N) for catch and bycatch, where N is the maximum sample size (200 for trawl surveys, 100 for males from the pot fishery and 50 for females from pot fishery and both males and females from the trawl fisheries. The effective sample sizes are plotted against the implied effective sample sizes in Figures 6 and 7, where the implied effective sample sizes are estimated as follows:

$$n_y = \sum_l \hat{P}_{y,l}(1-\hat{P}_{y,l}) / \sum_l (P_{y,l} - \hat{P}_{y,l})^2$$

where $\hat{P}_{y,l}$ and $P_{y,l}$ are estimated and observed size compositions in year y and length group l, respectively.

(6) Standard survey data for males and retow data for females.

(7) Estimating initial year length compositions.

Scenario 1a: Scenario 1a differs with scenario 1 by using the bottom temperature data to estimate annual trawl survey catchability with the "data method" described in Schirippa et al. (2009):

$T_t = \beta\, \varepsilon_t$,

where β is a parameter, $\varepsilon_t \sim$ N(0, σ_ε^2), the process error deviation for year t and T_t is the estimated bottom temperature deviation for year t. Annual survey Q_t are

$Q_t = Q \exp(\varepsilon_t)$,

where Q is a parameter. The negative log likelihood value is

$L = \sum [\ln(\sigma_T^2\, \beta^2)^{0.5} + (T_t^{obs} - T_t)^2 / (2\,\sigma_T^2\, \beta^2)]$,

where T_t^{obs} is the observed bottom temperature deviation for year t, and σ_T is the assumed standard deviation value of the residual error for the bottom temperatures. σ_T is assumed to be 0.3 for a reasonable trade-off between the over-fitting and under-fitting of the trawl survey biomass.

Scenario 1b: Scenario 1b differs with scenario 1 by using the bottom temperature data to estimate annual trawl survey catchability with the "model method" based on Wilderbuer et al. (2013):

$Q_t = Q \exp(b^* T_t^{obs})$, where Q and b are parameters and T_t^{obs} is the observed temperature deviation in year t.

Only the full results for scenarios 1 and 1a are presented in this report, since the results of scenarios 1 and 1b are about the same. Each figure or table is indicated with a scenario.

b. Progression of results: See the new results at the beginning of the report.

c. Evidence of search for balance between realistic and simpler models: NA.

d. Convergence status/criteria: ADMB default convergence criteria.

e. Sample sizes for length composition data: observed sample sizes are summarized in Table 2, and estimated implied sample sizes and effective sample sizes are illustrated in Figures 6 and 7.

f. Credible parameter estimates: All estimated parameters seem to be credible.

g. Model selection criteria: The likelihood values were used to select among alternatives that could be legitimately compared by that criterion.

h. Residual analysis: Residual plots are illustrated in figures.

i. Model evaluation is provided under Results, below.

4. Results

a. Effective sample sizes and weighting factors.

i. The effective sample sizes are:

(1) Trawl surveys: 200 for males and females except for females: 184 in 1986, 180 in 1992, and 133 in 1994.
(2) Retained catch: 100.
(3) Pot male discard: 100 except 87 in 1990 and 23 in 1996.
(4) Pot female discard: 50 except 38 in 1991, 1 in 1996, 4 in 1999, and 30 in 2002.
(5) Trawl bycatch: 50 for males and females except for males 44 in 1988, 21 in 1991 and 1992, 33 in 1994, 10 in 1995, and for females 28 in 1986 and 1988, 19 in 1989, 40 in 1991, 11 in 1992, 25 in 1994, 5 in 1995, 48 in 1997.
(6) Tanner fishery bycatch: 50 for males and females except for males 28 in 1992, 23 in 1993, and 22 in 2013, and for females 27 in 1993.
(7) BSFRF survey: 200 for the BSFRF survey males and females.

For scenario 1, effective sample sizes are illustrated in Figures 6 and 7.

ii. Weights are assumed to be 500 for retained catch biomass, and 100 for all bycatch biomasses, 2 for recruitment variation, and 10 for recruitment sex ratio.

iii. Initial trawl survey catchability (*Q*) is estimated to be 0.896 with a standard deviation of 0.025 (CV about 0.03) based on the double-bag experiment results. These values are used as a prior for estimating *Q* in the model.

b. Tables of estimates.

i. Parameter estimates for scenarios 1 and 1a are summarized in Tables 4 and 5.

ii. Abundance and biomass time series are provided in Table 6 for scenarios 1 and 1a.

iii. Recruitment time series for scenarios 1 and 1a are provided in Table 6.

iv. Time series of catch biomass is provided in Table 1.

Negative log-likelihood values and parameter estimates are summarized in Tables 4 and 5, respectively. Length-specific fishing mortality is equal to selectivity-at-length times the full fishing mortality. Estimated full pot fishing mortalities for females and full fishing mortalities for trawl bycatch were very low due to low bycatch as well as handling mortality rates less than 1.0. Estimated recruits varied greatly from year to year (Table 6). Estimated low selectivities for male pot bycatch, relative to the retained catch, reflected the 20% handling mortality rate (Figure 8). Both selectivities were applied to the same level of full fishing mortality. Estimated selectivities for female pot bycatch were close to 1.0 for all mature females, and the estimated full fishing mortalities for female pot bycatch were lower than for male retained catch and bycatch (Table 5).

c. Graphs of estimates.

  i. Selectivities and molting probabilities by length are provided in Figures 8 and 9 for scenarios 1 and 1a.

     One of the most important results is estimated trawl survey selectivity/catchability (Figure 8). Survey selectivity affects not only the fitting of the data but also the absolute abundance estimates. Estimated survey selectivities in Figure 8 are generally smaller than the capture probabilities in Figure A1 because survey selectivities include capture probabilities and crab availability. The NMFS survey catchability was estimated to be 0.896 from the trawl experiment, which is higher than that estimated from the BSFRF surveys (0.854). The reliability of estimated survey selectivities will greatly affect the application of the model to fisheries management. Under- or overestimates of survey selectivities will cause a systematic upward or downward bias of abundance estimates. Information about crab availability to the survey area at survey times will help estimate the survey selectivities.

     For scenarios 1 and 1a, estimated molting probabilities during 1975-2015 (Figure 9) were generally lower than those estimated from the 1954-1961 and 1966-1969 tagging data (Balsiger 1974). Lower molting probabilities mean more oldshell crab, possibly due to changes in molting probabilities over time or shell aging errors. Overestimates or underestimates of oldshell crab will result in lower or higher estimates of male molting probabilities.

  ii. Estimated total survey biomass and mature male and female abundances are plotted in Figure 10. Absolute mature male biomasses are illustrated in Figure 11.

     Model estimated relative survey biomasses are very similar between scenarios 1 and 1b and fluctuate a lot more for scenario 1a, primarily due to a much better fit of total survey biomass. The absolute population biomass estimates are slightly higher for scenario 1a than for scenarios 1 and 1b due to a slightly lower estimate of trawl survey catchability for scenario 1a.

     Although the model did not fit the mature crab abundances directly, trends in the mature abundance estimates agree well with observed survey values except in 2014 (Figure 10b). Estimated mature crab abundance increased dramatically in the mid 1970s then decreased precipitously in the early 1980s. Estimated mature crab abundance had increased during 1985-2009 with mature females being about 3 times more abundant in 2009 than in 1985 and mature males being about 2 times more abundant in 2009 than in 1985. Estimated mature abundance has declined since 2009 (Figure 10b). Model estimates of both male and female mature abundances have steadily declined since the late 2000s. Absolute mature male biomasses for scenarios 1, 1a and 1b are similar over time (Figure 11).

The fit to BSFRF survey data and estimated survey selectivities are illustrated in Figures 10c-e.

iii. Estimated recruitment time series are plotted in Figure 12 for scenarios 1 and 1a.

iv. Estimated fishing mortality rates are plotted against mature male biomass in Figure 13 for scenarios 1 and 1a.

The average of estimated male recruits from 1984 to 2015 (Figure 12) and mature male biomass per recruit were used to estimate $B_{35\%}$. Alternative periods of 1976-present and 1976-1983 were compared in our report. The full fishing mortalities for the directed pot fishery at the time of fishing were plotted against mature male biomass on Feb. 15 (Figure 13). Estimated fishing mortalities in most years before the current harvest strategy was adopted in 1996 were above $F_{35\%}$ (Figure 13). Under the current harvest strategy, estimated fishing mortalities were at or above the $F_{35\%}$ limits in 1998, 2005, 2007-2009 for both scenarios 1 and 1a but below the $F_{35\%}$ limits in the other post-1995 years. The estimated higher survey catchabilities with scenarios 1 and 1b result in relatively higher fishing mortalities than those with scenario 1a.

For scenario 1, estimated full pot fishing mortalities ranged from 0.00 to 1.52 during 1975-2014, with estimated values over 0.40 during 1975-1981, 1986-1987 and 2008 (Table 5, Figure 13). For scenario 1a, estimated full pot fishing mortalities ranged from 0.00 to 1.46 during 1975-2014, with estimated values over 0.40 during 1975-1981, 1986 and 2008 (Figure 13). Estimated fishing mortalities for pot female bycatch and trawl bycatch were generally less than 0.06.

v. Estimated mature male biomass and recruitment are plotted to illustrate their relationships with scenario 1 (Figure 14a). Annual stock productivities are illustrated in Figure 14b.

Stock productivity (recruitment/mature male biomass) was generally lower during the last 20 years (Figure 14c).

Egg clutch data collected during summer surveys may provide information about mature female reproductive conditions. Although egg clutch data are subject to rating errors as well as sampling errors, data trends over time may be useful. Proportions of empty clutches for newshell mature females >89 mm CL were high in some years before 1990, but have been low since 1990 (Figure 15). The highest proportion of empty clutches (0.2) was in 1986, and primarily involved soft shell females (shell condition 1). Clutch fullness fluctuated annually around average levels during two periods: before 1991 and after 1990 (Figure 15). The average clutch fullness was similar for these two periods (Figure 15).

d. Graphic evaluation of the fit to the data.

i. Observed vs. estimated catches are plotted in Figure 16.

ii. Model fits to total survey biomass are shown in Figure 10 with a standardized residual plot in Figure 17.

iii. Model fits to catch and survey proportions by length are illustrated in Figures 18-24 and residual bubble plots are shown in Figures 25-26.

The model (scenarios 1 and 1a) fit the fishery biomass data well and the survey biomass reasonably well, especially for scenario 1a (Figures 10 and 16). Because the model estimates annual fishing mortality for directed pot male catch, undirected pot male bycatch, pot female bycatch, and trawl bycatch, the deviations of observed and predicted (estimated) fishery biomass are mainly due to size composition differences.

The model also fit the length composition data well (Figures 18-24). The model also fit the length proportions of the pot male bycatch well with two simple linear selectivity functions (Figure 21). We explored a logistic selectivity function, but due to the long left tail of the pot male bycatch selectivity, the logistic selectivity function did not fit the data well.

Modal progressions are tracked well in the trawl survey data, particularly beginning in the mid-1990s (Figures 18 and 19). Cohorts first seen in the trawl survey data in 1975, 1986, 1990, 1995, 1999, 2002 and 2005 can be tracked over time. Some cohorts can be tracked over time in the pot bycatch as well (Figure 21), but the bycatch data did not track the cohorts as well as the survey data. Groundfish trawl bycatch data provide little information to track modal progression (Figures 23 and 24).

Standardized residuals of total survey biomass and proportions of length are plotted to examine their patterns. Residuals were calculated as observed minus predicted and standardized by the estimated standard deviation. Standardized residuals of total survey biomass did not show any consistent patterns (Figure 17). Standardized residuals of proportions of survey males appear to be random over length and year (Figure 25). There is an interesting pattern for residuals of proportions of survey females. Residuals were generally negative for large-sized mature females during 1975-1987 for scenarios 1 and 1a (Figure 26). Changes in growth over time or increased mortality may cause this pattern. The inadequacy of the model can be corrected by adding parameters to address these factors or with improved growth data.

iv. Temperature deviations and use of temperature data to estimate annual trawl survey catchability (Q_t) are summarized in Figure 27. The choice of $\sigma_T = 0.3$ for temperature measurement errors and process errors is supported by the relationship between total negative log likelihood, negative log trawl survey biomass likelihood and assumed σ_T values (Figure 27a). σ_T =0.3 is a good trade-off between the over-fitting and under-fitting. Furthermore, the estimated mature biomass is not sensitive to the σ_T values (Figure 27a).

    As expected, annual estimated Q_t values are much more variable for scenario 1a than for scenario 1b (Figure 27b). In fact, very little change of estimated Q_t values occurs over time for scenario 1b. The standardized residuals of temperatures look reasonable (Figure 27c). The correlation between estimated Q_t values and temperatures depends on the σ_T values. Generally, high temperature values increase the estimated survey Q_t values (Figure 27c).

e. Retrospective and historic analyses.

Two kinds of retrospective analyses were conducted for this report: (1) the 2015 model (scenarios 1 and 1a) hindcast results and (2) historical results. The 2015 model results are based on sequentially excluding one-year of data to evaluate the current model performance with fewer data. The historical results are the trajectories of biomass and abundance from previous assessments that capture both new data and changes in methodology over time. Treating the 2015 estimates as the baseline values, we can also evaluate how well the model had done in the past.

i. Retrospective analysis (retrospective bias in base model or models).

The performance of the 2015 model includes sequentially excluding one-year of data. The models with scenarios 1 and 1a performed reasonably well during 2008-2014 with a lower terminal year estimates in 2012 and 2013 and higher estimates during 2008-2010 (Figure 28).

ii. Historic analysis (plot of actual estimates from current and previous assessments).

The model first fit the data from 1985 to 2004 in the terminal year of 2004. Thus, sequentially incrementing the terminal year provided 10 historical assessments for comparison with the 2015 assessment model results (Figure 29). The main differences of the 2004 model were weighting factors and effective sample sizes for the likelihood functions. In 2004, the weighting factors were 1,000 for survey biomass, 2,000 for retained catch biomass and 200 for bycatch biomasses. The effective sample sizes were set to be 200 for all proportion data but weighting factors of 5, 2, and 1 were also respectively applied to retained catch proportions, survey proportions and bycatch proportions. Estimates of time series of abundance in 2004 were generally higher than those estimated after 2004 (Figure 29).

In 2005, to improve the fit for retained catch data, the weight for retained catch biomass was increased to 3,000 and the weight for retained catch proportions was increased to 6. All other weights were not changed. In 2006, all weights were re-configured. No weights were used for proportion data, and instead, effective sample sizes were set to 500 for retained catch, 200 for survey data, and 100 for bycatch data. Weights for biomasses were changed to 800 for retained catch, 300 for survey and 50 for bycatch. The weights in 2007 were the same as 2006. Generally, estimates of time series of abundance in 2005 were slightly lower than in 2006 and 2007, and there were few differences between estimates in 2006 and 2007 (Figure 29).

In 2008, estimated coefficients of variation for survey biomass were used to compute likelihood values as suggested by the CPT in 2007. Thus, weights were re-configured to: 500 for retained catch biomass, 50 for survey biomass, and 20 for bycatch biomasses. Effective sample size was lowered to 400 for the retained catch data. These changes were necessary for the estimation to converge and for a relatively good balanced fit to both biomasses and proportion data. Also, sizes at

50% selectivities for all fisheries data were allowed to change annually, subject to a random walk pattern, for all assessments before 2008. The 2008 model does not allow annual changes in any fishery selectivities. Except for higher estimates of abundance during the late 1980s and early 1990s, estimates of time series of abundance in 2008 were generally close to those in 2006 and 2007 (Figure 29).

During 2009-2013, the model was extended to the data through 1968. No weight factors were used for the NMFS survey biomass during 2009-2013 assessments. Since 2013, the model has fitted the data only back to 1975 for consistence of trawl survey data. Two levels of molting probabilities over time were used, shell conditions for males were combined, and length composition data of the BSFRF survey were used as well. In 2014 and 2015, the trawl survey time series were re-estimated and a trawl survey catchability was estimated for some scenarios.

Overall, both historical results (historic analysis) and the 2015 model results (retrospective analysis) performed reasonably well. No great overestimates or underestimates occurred as was observed in assessments for Pacific halibut (*Hippoglossus stenolepis*) (Parma 1993) and some eastern Bering Sea groundfish stocks (Zheng and Kruse 2002; Ianelli et al. 2003). Since the most recent model was not used to set TAC or overfishing limits until 2009, historical implications for management from the stock assessment errors cannot be evaluated at the current time. However, management implications of the ADF&G stock assessment model were evaluated by Zheng and Kruse (2002).

f. Uncertainty and sensitivity analyses

i. Estimated standard deviations of parameters are summarized in Table 5 for scenarios 1 and 1a. Estimated standard deviations of mature male biomass are listed in Table 6.

ii. Probabilities for trawl survey catchability *Q* are illustrated in Figure 30 for scenarios 1 and 1a using the mcmc approach; estimated *Q*s are generally less than 1.0. Probabilities for mature male biomass and OFL in 2014 are illustrated in Figure 31 for scenarios 1 and 1a using the mcmc appproach. The confidence intervals are quite narrow.

iii. Sensitivity analysis for handling mortality rate was reported in the SAFE report in May 2010. The baseline handling mortality rate for the directed pot fishery was set at 0.2. A 50% reduction and 100% increase respectively resulted in 0.1 and 0.4 as alternatives. Overall, a higher handling mortality rate resulted in slightly higher estimates of mature abundance, and a lower rate resulted in a minor reduction of estimated mature abundance. Differences of estimated legal abundance and mature male biomass were small among these handling mortality rates.

iv. Sensitivity of weights. Sensitivity of weights was examined in the SAFE report in May 2010. Weights to biomasses (trawl survey biomass, retained catch biomass, and bycatch biomasses) were reduced to 50% or increased to 200% to examine their sensitivity to abundance estimates. Weights to the penalty terms (recruitment variation and sex ratio) were also reduced or increased. Overall, estimated biomasses were very close under different weights except during the mid-1970s. The variation of estimated biomasses in the mid-1970s was mainly caused by the changes in estimates of additional mortalities in the early 1980s.

g. Comparison of alternative model scenarios

These comparisons, based on the data through 2010, were reported in the SAFE report in May 2011. Estimating length proportions in the initial year (scenario 1a) results in a better fit of survey length compositions at an expense of 36 more parameters than scenario 1. Abundance and biomass estimates with scenario 1a are similar between scenarios. Using only standard survey data (scenario 1b) results in a poorer fit of survey length compositions and biomass than scenarios using both standard and re-tow data (scenarios 1, 1a, and 1c) and has the lowest likelihood value. Although the likelihood value is higher for using both standard survey and re-tow data for males (scenario 1) than using only standard survey for males (scenario 1c), estimated abundances and biomasses are almost identical. The higher likelihood value for scenario 1 over scenario 1c is due to trawl bycatch length compositions.

In this report (September 2015), three scenarios are compared. Model estimated relative survey biomasses are very similar between scenarios 1 and 1b and fluctuate a lot more for scenario 1a, primarily due to much better fit of total survey biomass. The absolute population biomass estimates are slightly higher for scenario 1a than for scenarios 1 and 1b due to a slightly lower estimate of trawl survey catchability for scenario 1a. Overall, the results for all three scenarios are similar.

F. Calculation of the OFL and ABC

1. Bristol Bay RKC is currently placed in Tier 3b (NPFMC 2007).
2. For Tier 3 stocks, estimated biological reference points include $B_{35\%}$ and $F_{35\%}$. Estimated model parameters were used to conduct mature male biomass-per-recruit analysis.
3. Specification of the OFL:

   The Tier 3 can be expressed by the following control rule:

   a) $\frac{B}{B^*} > 1$ $\quad F_{OFL} = F^*$

   b) $\beta < \frac{B}{B^*} \le 1$ $\quad F_{OFL} = F^* \left(\frac{B / B^* - \alpha}{1 - \alpha} \right)$ (1)

   c) $\frac{B}{B^*} \le \beta$ $\quad$ directed fishery $F = 0$ and $F_{OFL} \le F^*$

   Where

   B = a measure of the productive capacity of the stock such as spawning biomass or fertilized egg production. A proxy of B, MMB estimated at the time of primiparous female mating (February 15) is used as a default in the development of the control rule.

F^* = $F_{35\%}$, a proxy of F_{MSY}, which is a full selection instantaneous F that will produce MSY at the MSY producing biomass,

B^* = $B_{35\%}$, a proxy of B_{MSY}, which is the value of biomass at the MSY producing level,

β = a parameter with restriction that $0 \le \beta < 1$. A default value of 0.25 is used.

α = a parameter with restriction that $0 \le \alpha \le \beta$. A default value of 0.1 is used.

Because trawl bycatch fishing mortality was not related to pot fishing mortality, average trawl bycatch fishing mortality during 2005 to 2014 was used for the per recruit analysis as well as for projections in the next section. Pot female bycatch fishing mortality was set equal to pot male fishing mortality times 0.02, an intermediate level during 1990-2014. Some discards of legal males occurred since the IFQ fishery started in 2005, but the discard rates were much lower during 2007-2013 than in 2005 after the fishing industry minimized discards of legal males. However, due to the high proportion of large oldshell males, the discard rate increased greatly in 2014. The average of retained selectivities and discard male selectivities during 2012-2014 were used to represent current trends for per recruit analysis and projections. Average molting probabilities during 2005-2014 were used for per recruit analysis and projections.

Average recruitments during three periods were used to estimate $B_{35\%}$: 1976-1983, 1976-2015, and 1984-2015 (Figure 12). Estimated $B_{35\%}$ is compared with historical mature male biomass in Figure 13a. We recommend using the average recruitment during 1984-present, corresponding to the 1976/77 regime shift. Note that recruitment period 1984-present has been used since 2011 to set the overfishing limits. Several factors support our recommendation. First, estimated recruitment was lower after 1983 than before 1984, which corresponded to brood years 1978 and later, after the 1976/77 regime shift. Second, high recruitments during the late 1960s and 1970s generally occurred when the spawning stock was primarily located in the southern Bristol Bay, whereas the current spawning stock is mainly in the middle of Bristol Bay. The current flows favor larvae hatched in the southern Bristol Bay (see the section on Ecosystem Considerations for SAFE reports in 2008 and 2009). Finally, stock productivity (recruitment/mature male biomass) was higher before the 1976/1977 regime shift.

If we believe that differences in productivity and other population characteristics before 1978 were caused by fishing, not by the regime shift, then we should use the recruitment from 1976-1983 (corresponding to brood years before 1978) as the baseline to estimate B35%. If we believe that the regime shift during 1976/77 caused the productivity differences, then we should select the recruitments from period 1984-2015 as the baseline.

The control rule is used for stock status determination. If total catch exceeds OFL estimated at B, then “overfishing” occurs. If B equals or declines below 0.5 B_{MSY} (i.e., MSST), the stock is “overfished.” If B equals or declines below β*B_{MSY} or β*a proxy B_{MSY}, then the stock productivity is severely depleted and the fishery is closed.

The estimated probability distribution of MMB in 2015 is illustrated in Figure 30. Based the SSC suggestion in 2011, ABC = 0.9*OFL is used to estimate ABC.

Status and catch specifications (1,000 t) (scenarios 1 and 1a):

Year	MSST	Biomass (MMB)	TAC	Retained Catch	Total Catch	OFL	ABC
2011/12	13.77[A]	30.88[A]	3.55	3.61	4.09	8.80	7.92
2012/13	13.19[B]	29.05[B]	3.56	3.62	3.90	7.96	7.17
2013/14	12.85[C]	27.12[C]	3.90	3.99	4.56	7.07	6.36
2014/15[1]	13.03[D]	27.25[D]	4.49	4.54	5.44	6.82	6.14
2015/16[1]		24.69[D]				6.73	6.06
2014/15[1a]	13.23[D]	27.80[D]	4.49	4.54	5.44	6.82	6.14
2015/16[1a]		25.02[D]				6.82	6.14

The stock was above MSST in 2014/15 and is hence not overfished. Overfishing did not occur.

Status and catch specifications (million lbs):

Year	MSST	Biomass (MMB)	TAC	Retained Catch	Total Catch	OFL	ABC
2011/12	30.4[A]	68.1[A]	7.83	7.95	9.01	19.39	17.46
2012/13	29.1[B]	64.0[B]	7.85	7.98	8.59	17.55	15.80
2013/14	28.3[C]	59.9[C]	8.60	8.80	10.05	15.58	14.02
2014/15[1]	28.7[D]	60.1[D]	9.99	10.01	11.99	15.04	13.53
2015/16[1]		54.4[D]				14.84	13.36
2014/15[1a]	29.2[D]	61.3[D]	9.99	10.01	11.99	15.04	13.53
2015/16[1a]		55.2[D]				15.04	13.54

Notes:

A – Calculated from the assessment reviewed by the Crab Plan Team in September 2012
B – Calculated from the assessment reviewed by the Crab Plan Team in September 2013
C – Calculated from the assessment reviewed by the Crab Plan Team in September 2014
D – Calculated from the assessment reviewed by the Crab Plan Team in September 2015
1 – Scenario 1 and 1a – scenario 1a.

4. Based on the $B_{35\%}$ estimated from the average male recruitment during 1984-2015, the biological reference points and OFL were estimated as follows:

	Scenario 1		Scenario 1a		Scenario 1b	
	1,000t	Mill. lbs	1,000t	Mill. lbs	1,000t	Mill. lbs
$B_{35\%}$	26.064	57.462	26.467	58.350	26.075	57.486
$F_{35\%}$	0.29		0.29		0.29	
MMB_{2015}	24.691	54.433	25.019	55.156	24.778	54.626
OFL_{2015}	6.732	14.841	6.824	15.044	6.783	14.954
ABC_{2015}	6.059	13.357	6.141	13.539	6.105	13.459

5. Based on the 10% buffer rule used last year, ABC = 0.9*OFL. If P*=49% is used, the ABC will be higher.

G. Rebuilding Analyses

NA.

H. Data Gaps and Research Priorities

1. The following data gaps exist for this stock:
   a. Information about changes in natural mortality in the early 1980s;
   b. Un-observed trawl bycatch in the early 1980s;
   c. Natural mortality;
   d. Crab availability to the trawl surveys;
   e. Juvenile crab abundance;
   f. Female growth per molt as a function of size and maturity;
   g. Changes in male molting probability over time.
2. Research priorities:
   a. Estimating natural mortality;
   b. Estimating crab availability to the trawl surveys;
   c. Surveying juvenile crab abundance in nearshore;
   d. Studying environmental factors that affect the survival rates from larvae to recruitment.

I. Projections and Future Outlook

1. Projections

Future population projections primarily depend on future recruitment, but crab recruitment is difficult to predict. Therefore, annual recruitment for the projections was a random selection from estimated recruitments during 1984-2015. Besides recruitment, the other major uncertainty for the projections is estimated abundance in 2015. The 2015 abundance was randomly selected from the estimated normal distribution of the assessment model output for each replicate. Three scenarios of fishing mortality for the directed pot fishery were used in the projections:

(1) No directed fishery. This was used as a base projection.

(2) $F_{40\%}$. This fishing mortality creates a buffer between the limits and target levels.

(3) $F_{35\%}$. This is the maximum fishing mortality allowed under the current overfishing definitions.

Each scenario was replicated 1,000 times and projections made over 10 years beginning in 2015 (Table 7).

As expected, projected mature male biomasses are much higher without the directed fishing mortality than under the other scenarios. At the end of 10 years, projected mature male biomass is above $B_{35\%}$ for all scenarios (Table 7; Figure 32). Projected retained catch for the $F_{35\%}$ scenario is higher than those for the $F_{40\%}$ scenario (Table 7, Figure 33). Due to the poor recruitment in recent years, the projected biomass and retained catch are expected to decline during the next few years.

2. Near Future Outlook

The near future outlook for the Bristol Bay RKC stock is a declining trend. The three recent above-average year classes (hatching years 1990, 1994, and 1997) had entered the legal population by 2006 (Figure 34). Most individuals from the 1997 year class will continue to gain weight to offset loss of the legal biomass to fishing and natural mortalities. The above-average year class (hatching year 2000) with lengths centered around 87.5 mm CL for both males and females in 2006 and with lengths centered around 112.5-117.5 mm CL for males and around 107.5 mm CL for females in 2008 has largely entered the mature male population in 2009 and the legal population by 2014 (Figure 34). No strong cohorts have been observed in the survey data after this cohort through 2010 (Figure 34). There was a huge tow of juvenile crab of size 45-55 mm in 2011, but these juveniles were not observed during 2012-2015 surveys. This singe tow is unlikely to be an indicator for a strong cohort. The high survey abundance of large males and mature females in 2014 cannot be explained by the survey data during the previous years and were not followed with the 2015 survey results (Figure 34). Due to lack of recruitment, mature and legal crab should continue to decline next year. Current crab abundance is still low relative to the late 1970s, and without favorable environmental conditions, recovery to the high levels of the late 1970s is unlikely.

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Table 1. Bristol Bay red king crab annual catch and bycatch mortality biomass (t) from June 1 to May 31. A handling mortality rate of 20% for the directed pot, 25% for the Tanner fishery, and 80% for trawl was assumed to estimate bycatch mortality biomass.

Year	Retained Catch				Pot Bycatch		Trawl Bycatch	Tanner Fishery Bycatch	Total Catch
	U.S.	Cost-Recovery	Foreign	Total	Males	Females			
1953	1331.3		4705.6	6036.9					6036.9
1954	1149.9		3720.4	4870.2					4870.2
1955	1029.2		3712.7	4741.9					4741.9
1956	973.4		3572.9	4546.4					4546.4
1957	339.7		3718.1	4057.8					4057.8
1958	3.2		3541.6	3544.8					3544.8
1959	0.0		6062.3	6062.3					6062.3
1960	272.2		12200.7	12472.9					12472.9
1961	193.7		20226.6	20420.3					20420.3
1962	30.8		24618.7	24649.6					24649.6
1963	296.2		24930.8	25227.0					25227.0
1964	373.3		26385.5	26758.8					26758.8
1965	648.2		18730.6	19378.8					19378.8
1966	452.2		19212.4	19664.6					19664.6
1967	1407.0		15257.0	16664.1					16664.1
1968	3939.9		12459.7	16399.6					16399.6
1969	4718.7		6524.0	11242.7					11242.7
1970	3882.3		5889.4	9771.7					9771.7
1971	5872.2		2782.3	8654.5					8654.5
1972	9863.4		2141.0	12004.3					12004.3
1973	12207.8		103.4	12311.2					12311.2
1974	19171.7		215.9	19387.6					19387.6
1975	23281.2		0	23281.2					23281.2
1976	28993.6		0	28993.6			682.8		29676.4
1977	31736.9		0	31736.9			1249.9		32986.8
1978	39743.0		0	39743.0			1320.6		41063.6
1979	48910.0		0	48910.0			1331.9		50241.9
1980	58943.6		0	58943.6			1036.5		59980.1
1981	15236.8		0	15236.8			219.4		15456.2
1982	1361.3		0	1361.3			574.9		1936.2
1983	0.0		0	0.0			420.4		420.4
1984	1897.1		0	1897.1			1094.0		2991.1
1985	1893.8		0	1893.8			390.1		2283.8
1986	5168.2		0	5168.2			200.6		5368.8
1987	5574.2		0	5574.2			186.4		5760.7
1988	3351.1		0	3351.1			597.8		3948.9
1989	4656.0		0	4656.0			174.1		4830.1
1990	9236.2	36.6	0	9272.8	526.9	651.5	247.6		10698.7
1991	7791.8	93.4	0	7885.1	407.8	75.0	316.0	1401.8	10085.7
1992	3648.2	33.6	0	3681.8	552.0	418.5	335.4	244.4	5232.2
1993	6635.4	24.1	0	6659.6	763.2	637.1	426.6	54.6	8541.0
1994	0.0	42.3	0	42.3	3.8	1.9	88.9	10.8	147.8
1995	0.0	36.4	0	36.4	3.3	1.6	194.2	0.0	235.5
1996	3812.7	49.0	0	3861.7	164.6	1.0	106.5	0.0	4133.9
1997	3971.9	70.2	0	4042.1	244.7	19.6	73.4	0.0	4379.8
1998	6693.8	85.4	0	6779.2	959.7	864.9	159.8	0.0	8763.7
1999	5293.5	84.3	0	5377.9	314.2	8.8	201.6	0.0	5902.4
2000	3698.8	39.1	0	3737.9	360.8	40.5	100.4	0.0	4239.5
2001	3811.5	54.6	0	3866.2	417.9	173.5	164.6	0.0	4622.1
2002	4340.9	43.6	0	4384.5	442.7	7.3	155.1	0.0	4989.6

2003	7120.0	15.3	0	7135.3	918.9	430.4	172.3	0.0	8656.9
2004	6915.2	91.4	0	7006.7	345.5	187.0	119.6	0.0	7658.8
2005	8305.0	94.7	0	8399.7	1359.5	498.3	155.2	0.0	10412.8
2006	7005.3	137.9	0	7143.2	563.8	37.0	116.7	3.8	7864.4
2007	9237.9	66.1	0	9303.9	1001.3	186.1	138.5	1.8	10631.6
2008	9216.1	0.0	0	9216.1	1165.5	148.4	159.5	4.0	10693.5
2009	7226.9	45.5	0	7272.5	888.1	85.2	103.7	1.6	8351.2
2010	6728.5	33.0	0	6761.5	797.5	122.6	85.3	0.0	7767.0
2011	3553.3	53.8	0	3607.1	395.0	24.0	68.8	0.0	4094.9
2012	3560.6	61.1	0	3621.7	205.2	12.3	61.2	0.0	3900.5
2013	3901.1	89.9	0	3991.0	310.6	99.8	136.2	28.5	4566.0
2014	4530.0	8.6	0	4538.6	584.7	86.2	186.1	42.0	5437.6

Table 2. Annual sample sizes (>64 mm CL) in numbers of crab for trawl surveys, retained catch and pot and trawl fishery bycatch of Bristol Bay red king crab.

Year	Trawl Survey		Retained Catch	Pot Bycatch		Trawl Bycatch		Tanner Fishery Bycatch	
	Males	Females		Males	Females	Males	Females	Males	Females
1968	3,684	2,165	18,044						
1969	6,144	4,992	22,812						
1970	1,546	1,216	3,394						
1971			10,340						
1972	1,106	767	15,046						
1973	1,783	1,888	11,848						
1974	2,505	1,800	27,067						
1975	2,943	2,139	29,570						
1976	4,724	2,956	26,450			2,327	676		
1977	3,636	4,178	32,596			14,014	689		
1978	4,132	3,948	27,529			8,983	1,456		
1979	5,807	4,663	27,900			7,228	2,821		
1980	2,412	1,387	34,747			47,463	39,689		
1981	3,478	4,097	18,029			42,172	49,634		
1982	2,063	2,051	11,466			84,240	47,229		
1983	1,524	944	0			204,464	104,910		
1984	2,679	1,942	4,404			357,981	147,134		
1985	792	415	4,582			169,767	30,693		
1986	1,962	367	5,773			1,199	284		
1987	1,168	1,018	4,230			723	927		
1988	1,834	546	9,833			437	275		
1989	1,257	550	32,858			3,147	194		
1990	858	603	7,218	873	699	761	1,570		
1991	1,378	491	36,820	1,801	375	208	396	885	2,198
1992	513	360	23,552	3,248	2,389	214	107	280	685
1993	1,009	534	32,777	5,803	5,942			232	265
1994	443	266	0	0	0	330	247		
1995	2,154	1,718	0	0	0	103	35		
1996	835	816	8,896	230	11	1,025	968		
1997	1,282	707	15,747	4,102	906	1,202	483		
1998	1,097	1,150	16,131	11,079	9,130	1,627	915		
1999	764	540	17,666	1,048	36	2,154	858		
2000	731	1,225	14,091	8,970	1,486	994	671		
2001	611	743	12,854	9,102	4,567	4,393	2,521		
2002	1,032	896	15,932	9,943	302	3,372	1,464		
2003	1,669	1,311	16,212	17,998	10,327	1,568	1,057		
2004	2,871	1,599	20,038	8,258	4,112	1,689	1,506		
2005	1,283	1,682	21,938	55,019	26,775	1,815	1,872		
2006	1,171	2,672	18,027	32,252	3,980	1,481	1,983		
2007	1,219	2,499	22,387	59,769	12,661	1,011	1,097		
2008	1,221	3,352	14,567	49,315	8,488	1,867	1,039		
2009	830	1,857	16,708	52,359	6,041	1,482	870		
2010	705	1,633	20,137	36,654	6,868	734	846		
2011	525	994	10,706	20,629	1,920	600	1,069		
2012	580	707	8,956	7,206	561	1,577	1,752		
2013	633	560	10,197	13,828	6,048	4,681	4,198	218	596
2014	1,106	1,255	9,618	13,040	1,950	1958	2580	256	381
2015	600	677							

Table 3. Annual retained catch (millions of crab) and catch per unit effort of the Bristol Bay red king crab fishery.

Year	Japanese Tanglenet		Russian Tanglenet		U.S. Pot/Trawl		Standardized Crab/tan
	Catch	Crab/tan	Catch	Crab/tan	Catch	Crab/Potlift	
1960	1.949	15.2	1.995	10.4	0.088		15.8
1961	3.031	11.8	3.441	8.9	0.062		12.9
1962	4.951	11.3	3.019	7.2	0.010		11.3
1963	5.476	8.5	3.019	5.6	0.101		8.6
1964	5.895	9.2	2.800	4.6	0.123		8.5
1965	4.216	9.3	2.226	3.6	0.223		7.7
1966	4.206	9.4	2.560	4.1	0.140	52	8.1
1967	3.764	8.3	1.592	2.4	0.397	37	6.3
1968	3.853	7.5	0.549	2.3	1.278	27	7.8
1969	2.073	7.2	0.369	1.5	1.749	18	5.6
1970	2.080	7.3	0.320	1.4	1.683	17	5.6
1971	0.886	6.7	0.265	1.3	2.405	20	5.8
1972	0.874	6.7			3.994	19	
1973	0.228				4.826	25	
1974	0.476				7.710	36	
1975					8.745	43	
1976					10.603	33	
1977					11.733	26	
1978					14.746	36	
1979					16.809	53	
1980					20.845	37	
1981					5.308	10	
1982					0.541	4	
1983					0.000		
1984					0.794	7	
1985					0.796	9	
1986					2.100	12	
1987					2.122	10	
1988					1.236	8	
1989					1.685	8	
1990					3.130	12	
1991					2.661	12	
1992					1.208	6	
1993					2.270	9	
1994					0.015		
1995					0.014		
1996					1.264	16	
1997					1.338	15	
1998					2.238	15	
1999					1.923	12	
2000					1.272	12	
2001					1.287	19	
2002					1.484	20	
2003					2.510	18	
2004					2.272	23	
2005					2.763	30	
2006					2.477	31	
2007					3.154	28	
2008					3.064	22	
2009					2.553	21	
2010					2.410	18	
2011					1.298	28	
2012					1.176	30	
2013					1.272	27	
2014					1.501	26	

Table 4. Summary of statistics for the model (Scenarios 1 and 1a).

Parameter counts	**Scenario 1**	**Scenario 1a**
Fixed growth parameters	9	9
Fixed recruitment parameters	2	2
Fixed length-weight relationship parameters	6	6
Fixed mortality parameters	4	4
Fixed survey catchability parameter	1	1
Fixed high grading parameters	10	10
Total number of fixed parameters	32	32
Free survey catchability parameter	1	1
Free growth parameters	6	6
Initial abundance (1975)	1	1
Recruitment-distribution parameters	2	2
Mean recruitment parameters	1	1
Male recruitment deviations	40	40
Female recruitment deviations	40	40
Natural and fishing mortality parameters	4	4
Pot male fishing mortality deviations	42	42
Bycatch mortality from the Tanner crab fishery	10	10
Pot female bycatch fishing mortality deviations	27	27
Trawl bycatch fishing mortality deviations	41	41
Initial (1975) length compositions	35	35
Free selectivity parameters	22	22
Temperature deviation	0	42
Total number of free parameters	272	314
Total number of fixed and free parameters	304	346
Negative log likelihood components (see table 4)		
Length compositions---retained catch		
Length compositions---pot male discard		
Length compositions---pot female discard		
Length compositions---survey		
Length compositions---trawl discard		
Length compositions---Tanner crab discards		
Pot discard male biomass		
Retained catch biomass		
Pot discard female biomass		
Trawl discard		
Survey biomass		
Recruitment variation		
Others		
Total		

Table 4. Negative log likelihood components for scenarios 1, 1a, and 1b and differences in negative log-likelihood components among model scenarios.

	Scenario					
Negative log likelihood	1	1a	1b	1 – 1a	1 - 1b	1a – 1b
R-variation	80.61	78.40	80.09	2.21	0.52	-1.69
Length-like-retained	-979.49	-979.04	-979.53	-0.45	0.04	0.49
Length-like-discmale	-998.27	-999.01	-998.23	0.74	-0.04	-0.78
Length-like-discfemale	-2334.30	-2336.26	-2333.88	1.96	-0.42	-2.38
Length-like-survey	-46200.10	-46198.50	-46200.40	-1.60	0.30	1.90
Length-like-disctrawl	-2027.93	-2027.24	-2027.70	-0.69	-0.23	0.46
Length-like-discTanner	-398.41	-397.76	-398.49	-0.65	0.08	0.74
Length-like-bsfrfsurvey	-237.78	-237.57	-237.86	-0.21	0.08	0.29
Catchbio_retained	47.31	47.22	47.44	0.10	-0.13	-0.23
Catchbio_discmale	219.50	219.35	219.57	0.15	-0.06	-0.22
Catchbio-discfemale	0.13	0.10	0.12	0.03	0.00	-0.02
Catchbio-disctrawl	0.90	0.90	0.90	0.00	0.00	0.00
Catchbio-discTanner	0.13	0.12	0.13	0.01	-0.01	-0.02
Biomass-trawl survey	95.08	27.81	94.44	67.27	0.64	-66.64
Biomass-bsfrfsurvey	-4.95	-5.40	-4.96	0.45	0.01	-0.44
Q-trawl survey	0.64	0.22	0.64	0.43	0.01	-0.42
Temperature deviation		24.70				
Others	20.82	20.86	20.70	-0.04	0.12	0.16
Total	-52716.10	-52761.10	-52717.00	45.00	0.90	-44.10
Free parameters	272	314	273	-42	-1	41

Table 5(1). Summary of model parameter estimates (scenario 1) for Bristol Bay red king crab. Estimated values and standard deviations. All values are on a log scale. Male recruit is exp(mean+males), and female recruit is exp(mean+males+females).

Year	Recruits				F for Directed Pot Fishery				F for Trawl	
	Females	SD	Males	SD	Males	SD	Females	SD	Estimate	SD
Mean	15.913	0.026	15.913	0.026	-2.011	0.043	0.011	0.001	-5.300	0.062
Limits↑	13,18		13,18		-4.0,0.0		.001,0.1		-8.5,-1.0	
Limits↓	-15,15		-15,15		-15,2.43		-6.0,3.5		-10,10	
1975					1.118	0.099				
1976	0.157	0.246	0.734	0.142	1.126	0.071			0.175	0.107
1977	0.557	0.158	0.648	0.104	1.127	0.061			0.702	0.105
1978	0.486	0.134	0.865	0.085	1.339	0.056			0.698	0.104
1979	0.751	0.102	1.140	0.077	1.613	0.052			0.735	0.104
1980	0.278	0.115	1.333	0.077	2.413	0.049			0.777	0.105
1981	0.150	0.146	0.515	0.105	2.425	0.007			0.342	0.104
1982	-0.001	0.051	2.155	0.050	0.563	0.047			2.056	0.106
1983	-0.033	0.071	1.430	0.051	-	0.725			1.935	0.105
1984	0.431	0.060	1.394	0.053	0.938	0.057			2.900	0.103
1985	0.161	0.182	-0.663	0.123	1.032	0.064			1.840	0.105
1986	0.518	0.059	0.667	0.048	1.549	0.063			0.769	0.104
1987	-0.062	0.136	-0.215	0.075	1.154	0.059			0.453	0.104
1988	0.274	0.169	-0.906	0.108	0.211	0.051			1.429	0.102
1989	0.150	0.146	-0.750	0.089	0.315	0.047			0.025	0.102
1990	-0.081	0.068	0.382	0.046	0.919	0.044	2.046	0.101	0.318	0.102
1991	-0.130	0.096	-0.082	0.056	0.892	0.045	-0.097	0.101	0.652	0.103
1992	-0.355	0.346	-1.831	0.173	0.372	0.047	2.209	0.101	0.824	0.103
1993	-0.307	0.100	-0.306	0.056	1.015	0.049	2.115	0.102	1.081	0.103
1994	-0.078	0.376	-2.191	0.201	-4.126	0.048	1.482	0.129	-0.388	0.104
1995	-0.022	0.039	1.253	0.036	-4.457	0.045	1.594	0.133	0.249	0.103
1996	-0.637	0.234	-0.585	0.115	0.092	0.043	-3.674	0.150	-0.454	0.103
1997	-0.755	0.361	-1.447	0.171	0.202	0.043	-0.970	0.102	-0.836	0.103
1998	-0.319	0.122	-0.186	0.069	0.893	0.044	2.135	0.100	-0.112	0.102
1999	0.044	0.060	0.643	0.044	0.448	0.043	-2.003	0.105	0.107	0.102
2000	-0.114	0.143	-0.322	0.082	0.081	0.042	-0.233	0.100	-0.645	0.102
2001	0.718	0.182	-0.974	0.142	0.105	0.042	1.145	0.099	-0.194	0.102
2002	0.185	0.055	1.078	0.041	0.210	0.042	-2.184	0.106	-0.288	0.101
2003	0.077	0.229	-0.700	0.149	0.736	0.042	1.190	0.100	-0.223	0.101
2004	-0.184	0.150	0.061	0.083	0.599	0.042	0.417	0.099	-0.568	0.102
2005	0.317	0.061	0.978	0.047	1.022	0.043	0.950	0.100	-0.336	0.101
2006	-0.692	0.161	0.354	0.067	0.743	0.043	-1.492	0.101	-0.621	0.102
2007	-0.308	0.154	-0.199	0.085	1.073	0.044	-0.250	0.100	-0.501	0.102
2008	0.083	0.160	-0.673	0.105	1.169	0.047	-0.555	0.100	-0.364	0.102
2009	0.225	0.143	-0.678	0.100	0.879	0.049	-0.784	0.101	-0.804	0.104
2010	-0.074	0.103	-0.065	0.066	0.745	0.052	-0.250	0.101	-1.026	0.105
2011	-0.012	0.107	-0.091	0.071	0.075	0.053	-1.184	0.103	-1.226	0.106
2012	-0.253	0.147	-0.346	0.084	-0.025	0.056	-1.726	0.105	-1.348	0.107
2013	-0.758	0.192	-0.458	0.089	0.157	0.059	0.221	0.103	-0.539	0.107
2014	-0.204	0.376	-1.943	0.217	0.400	0.065	-0.100	0.104	-0.201	0.108
2015	-0.181	0.151	-0.015	0.104						

Table 5(1) (continued). Summary of model parameter estimates for Bristol Bay red king crab (scenario 1). Estimated values and standard deviations. For initial year length composition deviations, the first 20 length groups are for males and the last 16 length groups are for females.

				Initial Length Composition 1975			
Parameter	Value	SD	Limits	Length	Value	SD	Limits
Mm80-84	0.464	0.016	0.184, 1.0	68	1.159	0.103	-5, 5
Mf80-84	0.813	0.021	0.276, 1.5	73	1.178	0.090	-5, 5
Mf76-79,85-93	0.086	0.006	0.0, 0.108	78	0.512	0.108	-5, 5
log_betal, females	0.220	0.055	-0.67, 1.32	83	0.586	0.090	-5, 5
log_betal, males	0.646	0.082	-0.67, 1.32	88	0.396	0.089	-5, 5
log_betar, females	-0.620	0.062	-1.14, 0.5	93	0.205	0.094	-5, 5
log_betar, males	-0.620	0.050	-1.14, 0.5	98	0.211	0.093	-5, 5
Bsfrf_CV	0.069	0.071	0.00, 0.40	103	-0.001	0.105	-5, 5
moltp_slope, 75-78	0.132	0.021	0.01, 0.207	108	0.076	0.104	-5, 5
moltp_slope, 79-14	0.104	0.004	0.01, 0.207	113	0.207	0.101	-5, 5
log_moltp_L50, 75-78	4.968	0.013	4.47, 5.62	118	0.008	0.119	-5, 5
log_moltp_L50, 79-14	4.947	0.004	4.47, 5.62	123	0.051	0.124	-5, 5
log_N75	20.010	0.034	15.0, 21.0	128	-0.030	0.139	-5, 5
log_avg_L50_ret	4.920	0.002	4.78, 5.05	133	-0.041	0.148	-5, 5
ret_fish_slope	0.536	0.032	0.05, 0.70	138	-0.140	0.138	-5, 5
pot disc.males, φ	-0.345	0.015	-0.40, 0.00	143	-0.251	0.142	-5, 5
pot disc.males, κ	0.004	0.000	0.0, 0.005	148	-0.436	0.153	-5, 5
pot disc.males, γ	-0.016	0.001	-0.025, 0.0	153	-0.775	0.188	-5, 5
pot disc.fema., slope	0.454	0.216	0.05, 0.69	158	-1.304	0.260	-5, 5
log_pot disc.fema., L50	4.391	0.012	4.24, 4.61	163	-1.318	0.273	-5, 5
trawl disc slope	0.063	0.003	0.01, 0.20	68	1.614	0.105	-5, 5
log_trawl disc L50	4.939	0.028	4.40, 5.20	73	1.525	0.102	-5, 5
log_srv_L50, m, bsfrf	4.394	0.045	3.59, 5.49	78	1.498	0.094	-5, 5
srv_slope, f, bsfrf	0.012	0.005	0.01, 0.435	83	1.337	0.093	-5, 5
log_srv_L50, f, bsfrf	5.331	0.510	4.09, 5.54	88	1.291	0.086	-5, 5
log_srv_L50, m, 75-81	4.350	0.010	4.09, 5.54	93	0.830	0.102	-5, 5
srv_slope, f, 75-81	0.068	0.004	0.01, 0.33	98	0.453	0.124	-5, 5
log_srv_L50, f, 75-81	4.491	0.018	4.09, 4.70	103	0.156	0.148	-5, 5
log_srv_L50, m, 82-14	4.485	0.009	4.09, 5.10	108	0.007	0.152	-5, 5
srv_slope, f, 82-14	0.061	0.002	0.01, 0.30	113	-0.249	0.179	-5, 5
log_srv_L50, f, 82-14	4.513	0.011	4.09, 4.90	118	-0.825	0.278	-5, 5
TC_slope, females	0.365	0.135	0.02, 0.40	123	-0.942	0.318	-5, 5
log_TC_L50, females	4.535	0.015	4.24, 4.90	128	-1.218	0.411	-5, 5
TC_slope, males	0.231	0.093	0.05, 0.90	133	-2.139	0.899	-5, 5
log_TC_L50, males	4.585	0.022	4.25, 5.14	138	-2.150	0.990	-5, 5
Q	0.924	0.021	0.6, 1.2	143	NA	NA	
log_TC_F, males, 91	-4.177	0.087	-10.0, 1.00				
log_TC_F, males, 92	-6.146	0.088	-10.0, 1.00				
log_TC_F, males, 93	-6.877	0.091	-10.0, 1.00				
log_TC_F, males, 13	-8.245	0.099	-10.0, 1.00				
log_TC_F, males, 14	-7.390	0.098	-10.0, 1.00				
log_TC_F, females, 91	-2.920	0.086	-10.0, 1.00				
log_TC_F, females, 92	-4.569	0.086	-10.0, 1.00				
log_TC_F, females, 93	-6.457	0.087	-10.0, 1.00				
log_TC_F, females, 13	-7.680	0.085	-10.0, 1.00				
log_TC_F, females, 14	-7.529	0.085	-10.0, 1.00				

Table 5(1a). Summary of model parameter estimates (scenario 1a) for Bristol Bay red king crab. Estimated values and standard deviations (SD). All values are on a log scale. Male recruit is exp(mean+males), and female recruit is exp(mean+males+females).

	Recruits				F for Directed Pot Fishery				F for Trawl	
Year	Females	SD	Males	SD	Males	SD	Females	SD	Estimate	SD
Mean	15.916	0.027	15.916	0.027	-2.047	0.036	0.012	0.001	-5.342	0.061
Limits↑	13,18		13,18		-4.0,0.0		.001,0.1		-8.5,-1.0	
Limits↓	-15,15		-15,15		-15,2.43		-6.0,3.5		-10,10	
1975					1.184	0.102				
1976	0.083	0.244	0.721	0.136	1.177	0.072			0.226	0.108
1977	0.523	0.158	0.594	0.104	1.168	0.060			0.750	0.106
1978	0.461	0.134	0.801	0.087	1.373	0.054			0.745	0.105
1979	0.728	0.102	1.068	0.079	1.647	0.048			0.785	0.105
1980	0.249	0.115	1.254	0.079	2.425	0.014			0.827	0.105
1981	0.131	0.146	0.444	0.106	2.425	0.006			0.384	0.104
1982	0.010	0.051	2.115	0.051	0.571	0.047			2.081	0.106
1983	-0.025	0.071	1.417	0.052	-10.026	0.595			1.945	0.105
1984	0.445	0.060	1.398	0.055	0.923	0.057			2.892	0.104
1985	0.165	0.182	-0.628	0.123	1.000	0.065			1.819	0.105
1986	0.527	0.059	0.697	0.050	1.518	0.063			0.751	0.105
1987	-0.055	0.136	-0.182	0.076	1.124	0.059			0.433	0.104
1988	0.280	0.168	-0.873	0.109	0.188	0.050			1.409	0.103
1989	0.158	0.145	-0.720	0.090	0.296	0.047			0.008	0.103
1990	-0.074	0.068	0.416	0.048	0.893	0.043	2.038	0.101	0.302	0.103
1991	-0.125	0.096	-0.045	0.058	0.855	0.046	-0.094	0.101	0.629	0.104
1992	-0.344	0.348	-1.810	0.175	0.330	0.047	2.214	0.101	0.792	0.104
1993	-0.299	0.100	-0.277	0.058	0.965	0.049	2.126	0.101	1.046	0.103
1994	-0.077	0.378	-2.162	0.202	-4.174	0.049	1.492	0.129	-0.429	0.105
1995	-0.018	0.040	1.280	0.038	-4.490	0.045	1.592	0.133	0.219	0.103
1996	-0.645	0.238	-0.575	0.116	0.065	0.042	-3.677	0.150	-0.477	0.103
1997	-0.748	0.362	-1.431	0.172	0.174	0.042	-0.968	0.102	-0.858	0.103
1998	-0.314	0.123	-0.173	0.069	0.863	0.043	2.143	0.100	-0.133	0.102
1999	0.055	0.061	0.654	0.044	0.422	0.042	-2.000	0.105	0.087	0.102
2000	-0.109	0.144	-0.312	0.083	0.062	0.041	-0.234	0.100	-0.660	0.102
2001	0.723	0.183	-0.966	0.142	0.090	0.040	1.143	0.099	-0.205	0.102
2002	0.191	0.056	1.086	0.042	0.198	0.040	-2.186	0.106	-0.296	0.101
2003	0.072	0.229	-0.682	0.148	0.728	0.039	1.186	0.100	-0.227	0.101
2004	-0.182	0.150	0.069	0.083	0.592	0.040	0.420	0.099	-0.571	0.102
2005	0.318	0.062	0.992	0.047	1.013	0.041	0.950	0.100	-0.337	0.101
2006	-0.691	0.161	0.361	0.068	0.738	0.041	-1.494	0.101	-0.621	0.102
2007	-0.296	0.155	-0.200	0.087	1.069	0.042	-0.250	0.100	-0.498	0.102
2008	0.098	0.161	-0.680	0.107	1.161	0.046	-0.550	0.100	-0.361	0.103
2009	0.234	0.144	-0.684	0.102	0.873	0.050	-0.781	0.101	-0.801	0.104
2010	-0.067	0.103	-0.068	0.069	0.744	0.054	-0.250	0.101	-1.019	0.106
2011	-0.004	0.107	-0.098	0.074	0.079	0.057	-1.188	0.103	-1.217	0.107
2012	-0.251	0.148	-0.353	0.086	-0.016	0.059	-1.733	0.105	-1.336	0.109
2013	-0.753	0.192	-0.468	0.092	0.169	0.064	0.212	0.103	-0.524	0.109
2014	-0.199	0.376	-1.954	0.218	0.415	0.071	-0.110	0.105	-0.184	0.110
2015	-0.174	0.151	-0.027	0.107						

Table 5(1a) (continued). Summary of model parameter estimates for Bristol Bay red king crab (scenario 1a). Estimated values and standard deviations. For initial year length composition deviations, the first 20 length groups are for males and the last 16 length groups are for females.

				Initial Length Comp. 1975			Temperature Deviation		
Parameter	Value	SD	Limits	Length	Value	SD	Year	Value	SD
Mm80-84	0.438	0.017	0.184, 1.00	68	1.154	0.101	1975	-0.186	0.127
Mf80-84	0.792	0.022	0.276, 1.50	73	1.181	0.088	1976	0.008	0.101
Mf76-79,85-93	0.085	0.006	0.0, 0.108	78	0.521	0.107	1977	0.291	0.104
log_betal, females	0.225	0.055	-0.67, 1.32	83	0.601	0.089	1978	0.281	0.100
log_betal, males	0.630	0.082	-0.67, 1.32	88	0.417	0.089	1979	-0.252	0.111
log_betar, females	-0.614	0.062	-1.14, 0.50	93	0.228	0.094	1980	0.047	0.139
log_betar, males	-0.624	0.050	-1.14, 0.50	98	0.236	0.093	1981	0.405	0.124
Bsfrf_CV	0.050	0.062	0.00, 0.40	103	0.025	0.105	1982	0.628	0.152
moltp_slope, 75-79	0.133	0.019	0.01, 0.168	108	0.102	0.103	1983	0.060	0.135
moltp_slope, 80-14	0.102	0.004	0.01, 0.168	113	0.234	0.101	1984	0.452	0.234
log_moltp_L50, 75-79	4.975	0.012	4.47, 5.52	118	0.034	0.119	1985	-0.154	0.108
log_moltp_L50, 80-14	4.942	0.004	4.47, 5.52	123	0.075	0.123	1986	-0.294	0.203
log_N75	19.967	0.035	15.0, 21.00	128	-0.007	0.138	1987	0.199	0.132
log_avg_L50_ret	4.920	0.002	4.78, 5.05	133	-0.020	0.147	1988	-0.099	0.140
ret_fish_slope	0.538	0.032	0.05, 0.70	138	-0.129	0.138	1989	-0.240	0.142
pot disc.males, φ	-0.350	0.015	-0.40, 0.00	143	-0.239	0.142	1990	-0.055	0.146
pot disc.males, κ	0.004	0.000	0.0, 0.005	148	-0.424	0.154	1991	0.142	0.208
pot disc.males, γ	-0.016	0.001	-0.025, 0.0	153	-0.763	0.189	1992	-0.367	0.115
pot disc.fema., slope	0.472	0.209	0.05, 0.69	158	-1.300	0.264	1993	0.029	0.127
log_pot disc.fema., L50	4.390	0.011	4.24, 4.61	163	-1.317	0.277	1994	-0.392	0.115
trawl disc slope	0.063	0.004	0.01, 0.20	68	1.574	0.106	1995	-0.372	0.157
log_trawl disc L50	4.936	0.028	4.40, 5.20	73	1.488	0.103	1996	-0.177	0.129
log_srv_L50, m, bsfrf	4.390	0.045	3.59, 5.49	78	1.464	0.095	1997	0.147	0.155
srv_slope, f, bsfrf	0.012	0.005	0.01, 0.435	83	1.308	0.094	1998	0.260	0.118
log_srv_L50, f, bsfrf	5.319	0.508	4.09, 5.54	88	1.266	0.086	1999	-0.210	0.129
log_srv_L50, m, 75-81	4.346	0.011	4.09, 5.54	93	0.810	0.102	2000	-0.073	0.137
srv_slope, f, 75-81	0.069	0.004	0.01, 0.33	98	0.435	0.126	2001	-0.227	0.120
log_srv_L50, f, 75-81	4.478	0.018	4.09, 4.70	103	0.139	0.149	2002	-0.069	0.127
log_srv_L50, m, 82-14	4.474	0.009	4.09, 5.10	108	-0.004	0.154	2003	0.335	0.163
srv_slope, f, 82-14	0.062	0.002	0.01, 0.30	113	-0.258	0.182	2004	0.344	0.176
log_srv_L50, f, 82-14	4.504	0.012	4.09, 4.90	118	-0.835	0.283	2005	0.241	0.113
TC_slope, females	0.364	0.135	0.02, 0.40	123	-0.950	0.324	2006	0.016	0.111
log_TC_L50, females	4.534	0.015	4.24, 4.90	128	-1.227	0.421	2007	0.013	0.132
TC_slope, males	0.238	0.098	0.05, 0.90	133	-2.158	0.930	2008	0.027	0.139
log_TC_L50, males	4.581	0.021	4.25, 5.14	138	-2.180	1.035	2009	-0.186	0.178
Q	0.912	0.021	0.6, 1.2	143	NA	NA	2010	-0.149	0.139
Beta, temperature	3.115	0.334			Limits	(-5,5)	2011	-0.204	0.134
log_TC_F, males, 91	-4.253	0.087	-10.0, 1.00				2012	-0.364	0.144
log_TC_F, males, 92	-6.222	0.088	-10.0, 1.00				2013	-0.265	0.149
log_TC_F, males, 93	-6.960	0.090	-10.0, 1.00				2014	0.407	0.126
log_TC_F, males, 13	-8.267	0.102	-10.0, 1.00				2015	0.004	0.135
log_TC_F, males, 14	-7.409	0.103	-10.0, 1.00						
log_TC_F, females, 91	-2.976	0.086	-10.0, 1.00						
log_TC_F, females, 92	-4.625	0.086	-10.0, 1.00						
log_TC_F, females, 93	-6.515	0.088	-10.0, 1.00						
log_TC_F, females, 13	-7.698	0.087	-10.0, 1.00						
log_TC_F, females, 14	-7.545	0.087	-10.0, 1.00						

Table 6(1). Annual abundance estimates (millions of crab), mature male biomass (MMB, 1000 t), and total survey biomass (1000 t) for red king crab in Bristol Bay estimated by length-based analysis (scenario 1) from 1975-2015. Mature male biomass for year *t* is on Feb. 15 of year *t*+1. Size measurements are mm carapace length.

Year (t)	Males				Females	Total Recruits	Trawl Survey Biomass	
	Mature (>119 mm)	Legal (>134 mm)	MMB (>119 mm)	SD MMB	Mature (>89 mm)		Model Est. (>64 mm)	Area-Swept
1975	56.544	29.673	83.547	5.406	75.729		247.095	202.731
1976	61.901	35.966	92.900	4.584	114.592	36.805	283.885	331.868
1977	63.401	38.539	95.840	3.842	143.620	42.747	294.188	375.661
1978	69.567	39.527	98.692	3.186	137.306	50.808	286.326	349.545
1979	65.614	41.036	84.270	2.677	119.716	79.437	264.621	167.627
1980	47.110	33.884	25.260	1.023	109.495	71.679	229.457	249.322
1981	14.771	8.599	8.632	0.485	50.436	29.466	94.758	132.669
1982	7.541	3.226	8.428	0.440	23.387	140.497	53.145	143.740
1983	6.735	3.137	8.810	0.420	14.746	66.968	45.803	49.320
1984	6.364	3.132	6.683	0.393	15.005	83.319	45.765	155.311
1985	7.747	2.596	10.990	0.585	13.772	9.131	37.790	34.535
1986	12.695	5.000	16.291	0.890	20.294	42.510	50.347	48.158
1987	16.172	7.219	23.021	1.086	24.063	12.748	57.376	70.263
1988	16.958	9.650	29.036	1.189	28.945	7.621	61.640	55.372
1989	18.397	11.484	32.738	1.247	26.581	8.320	64.853	55.941
1990	18.578	12.497	30.622	1.272	22.848	22.938	64.938	60.321
1991	15.147	11.242	25.642	1.251	20.769	14.102	59.235	85.055
1992	12.033	9.092	23.437	1.198	20.474	2.221	53.258	37.687
1993	12.598	8.244	20.866	1.172	18.297	10.416	51.387	53.703
1994	12.415	7.627	26.346	1.199	15.104	1.753	45.657	32.335
1995	12.831	9.437	29.032	1.165	14.647	56.436	51.986	38.396
1996	12.794	10.023	26.898	1.106	19.854	6.935	59.340	44.649
1997	12.007	9.042	24.935	1.055	28.763	2.818	63.795	85.277
1998	16.330	8.723	27.240	1.143	26.882	11.684	67.090	85.176
1999	17.979	10.345	31.814	1.255	23.504	31.692	66.745	65.604
2000	15.984	11.749	31.595	1.241	25.774	11.168	68.720	68.342
2001	14.871	11.213	30.284	1.189	29.796	9.377	71.145	53.188
2002	16.450	10.671	31.996	1.181	29.457	52.744	75.427	69.786
2003	17.106	11.432	30.504	1.164	34.791	8.414	80.008	116.794
2004	15.211	10.815	28.211	1.118	42.019	15.858	81.627	131.910
2005	17.453	10.204	28.279	1.138	40.259	51.420	86.391	107.341
2006	17.620	10.680	30.051	1.195	43.965	17.406	89.175	95.676
2007	16.962	11.166	27.100	1.218	50.850	11.589	93.930	104.841
2008	18.413	10.298	27.958	1.361	47.706	8.672	93.514	114.430
2009	19.423	10.970	31.366	1.570	43.245	9.313	90.277	91.673
2010	18.309	12.053	31.296	1.696	39.509	14.725	86.919	81.642
2011	15.696	11.583	31.198	1.732	37.101	14.782	82.479	67.053
2012	14.194	11.034	29.788	1.721	36.059	10.239	80.813	61.248
2013	13.832	10.226	28.453	1.744	34.694	7.565	78.898	62.410
2014	13.935	9.753	27.254	1.815	31.776	2.120	75.332	114.103
2015	13.417	9.425	24.691	1.502	27.947	14.718	70.766	64.240

Table 6(1a). Annual abundance estimates (million crab), mature male biomass (MMB, 1000 t), and total survey biomass (1000t) for red king crab in Bristol Bay estimated by length-based analysis (scenario 1a) from 1975-2015. Mature male biomass for year *t* is on Feb. 15, year *t*+1. Size measurements are mm carapace length.

Year (t)	Males				Females	Total Recruits	Total Survey Biomass	
	Mature (>119 mm)	Legal (>134mm)	MMB (>119 mm)	SD MMB	Mature (>89 mm)		Model Est. (>64 mm)	Area-Swept (>64 mm)
1975	55.546	28.972	81.338	5.079	72.112		198.950	202.731
1976	60.860	35.415	91.029	4.326	108.445	35.040	276.719	331.868
1977	62.265	38.024	94.246	3.648	135.225	39.760	379.414	375.661
1978	68.099	38.998	96.975	3.058	129.049	47.051	364.798	349.545
1979	63.964	40.418	82.400	2.586	112.356	73.009	197.014	167.627
1980	45.585	33.186	25.183	1.007	102.471	65.319	228.809	249.322
1981	14.506	8.505	8.816	0.448	47.985	27.245	136.577	132.669
1982	7.553	3.265	8.652	0.415	22.598	136.133	97.839	143.740
1983	6.845	3.205	9.140	0.417	14.569	66.588	48.812	49.320
1984	6.558	3.245	7.096	0.413	15.222	84.631	73.699	155.311
1985	8.132	2.745	11.674	0.620	14.346	9.503	33.950	34.535
1986	13.310	5.248	17.379	0.942	21.179	44.185	39.207	48.158
1987	16.999	7.607	24.538	1.167	25.160	13.256	73.233	70.263
1988	17.867	10.178	30.812	1.290	30.279	7.928	58.403	55.372
1989	19.360	12.096	34.695	1.362	27.843	8.638	53.267	55.941
1990	19.556	13.167	32.699	1.394	23.967	23.889	64.179	60.321
1991	16.070	11.937	27.726	1.371	21.837	14.698	71.705	85.055
1992	12.893	9.781	25.449	1.311	21.562	2.285	38.988	37.687
1993	13.463	8.899	22.860	1.279	19.294	10.786	55.930	53.703
1994	13.296	8.266	28.401	1.302	15.957	1.811	32.753	32.335
1995	13.663	10.079	31.021	1.259	15.441	58.224	37.761	38.396
1996	13.562	10.643	28.762	1.190	20.791	7.008	52.112	44.649
1997	12.715	9.624	26.674	1.128	29.923	2.879	77.269	85.277
1998	17.131	9.265	29.057	1.210	27.924	11.890	90.702	85.176
1999	18.820	10.901	33.705	1.315	24.417	32.320	56.295	65.604
2000	16.760	12.323	33.391	1.291	26.689	11.347	66.283	68.342
2001	15.568	11.776	31.938	1.230	30.754	9.512	58.628	53.188
2002	17.102	11.189	33.545	1.215	30.352	53.508	72.584	69.786
2003	17.711	11.895	31.923	1.192	35.725	8.572	114.945	116.794
2004	15.750	11.232	29.492	1.142	43.016	16.046	118.108	131.910
2005	17.975	10.586	29.487	1.166	41.181	52.282	112.519	107.341
2006	18.126	11.029	31.206	1.230	44.920	17.584	92.682	95.676
2007	17.451	11.498	28.203	1.261	51.864	11.666	97.171	104.841
2008	18.935	10.631	29.099	1.432	48.632	8.704	97.976	114.430
2009	19.963	11.310	32.533	1.681	44.062	9.336	76.337	91.673
2010	18.812	12.393	32.401	1.842	40.226	14.765	76.156	81.642
2011	16.132	11.914	32.177	1.902	37.730	14.781	68.254	67.053
2012	14.554	11.334	30.622	1.910	36.613	10.200	56.890	61.248
2013	14.123	10.480	29.144	1.955	35.168	7.526	61.142	62.410
2014	14.160	9.950	27.803	2.053	32.167	2.106	114.123	114.103
2015	13.587	9.566	25.019	1.712	28.270	14.635	71.416	64.240

Table 7(1). Comparison of projected mature male biomass (1000 t) on Feb. 15, retained catch (1000 t), their 95% limits, and mean fishing mortality with no directed fishery, $F_{40\%}$, and $F_{35\%}$ harvest strategy with $F_{35\%}$ constraint during 2015-2024. Parameter estimates with scenario 1 are used for the projection.

			No Directed Fishery			
Year	MMB	95% LCI	95% UCI	Catch	95% LCI	95% UCI
2015	30.724	27.489	33.779	0.000	0.000	0.000
2016	33.018	29.541	36.301	0.000	0.000	0.000
2017	33.484	29.957	36.813	0.000	0.000	0.000
2018	34.705	31.111	38.305	0.000	0.000	0.000
2019	38.166	32.836	48.627	0.000	0.000	0.000
2020	42.649	33.256	61.471	0.000	0.000	0.000
2021	47.243	32.996	73.521	0.000	0.000	0.000
2022	51.505	33.146	83.714	0.000	0.000	0.000
2023	55.307	33.345	89.071	0.000	0.000	0.000
2024	58.542	34.355	93.149	0.000	0.000	0.000
			$F_{40\%}$			
2015	25.529	23.229	27.896	5.172	4.241	5.857
2016	23.707	21.842	25.554	4.531	3.783	5.333
2017	21.351	19.838	22.808	3.768	3.209	4.342
2018	20.602	19.202	22.039	3.298	2.850	3.776
2019	22.186	18.845	30.387	3.397	2.745	4.437
2020	24.524	17.955	39.313	3.825	2.518	5.972
2021	26.621	17.322	46.211	4.383	2.297	7.665
2022	28.171	17.079	49.689	4.874	2.206	8.999
2023	29.235	16.998	50.926	5.233	2.154	9.776
2024	29.866	17.177	50.513	5.469	2.210	10.025
			$F_{35\%}$			
2015	24.725	22.587	26.828	5.972	4.880	6.920
2016	22.554	20.869	24.159	4.936	4.159	5.731
2017	20.083	18.738	21.340	3.987	3.426	4.542
2018	19.315	18.059	20.639	3.442	2.999	3.902
2019	20.835	17.680	28.639	3.575	2.856	4.912
2020	23.009	16.765	36.907	4.088	2.611	6.659
2021	24.861	16.188	43.158	4.725	2.375	8.538
2022	26.148	16.010	45.651	5.247	2.279	9.998
2023	26.972	15.912	46.628	5.606	2.237	10.574
2024	27.409	16.092	45.946	5.820	2.294	10.781

Table 7(1a). Comparison of projected mature male biomass (1000 t) on Feb. 15, retained catch (1000 t), their 95% limits, and mean fishing mortality with no directed fishery, $F_{40\%}$, and $F_{35\%}$ harvest strategy with $F_{35\%}$ constraint during 2015-2024. Parameter estimates with scenario 1a are used for the projection.

Year	MMB	95% LCI	95% UCI	Catch	95% LCI	95% UCI
No Directed Fishery						
2015	31.144	27.449	34.633	0.000	0.000	0.000
2016	33.310	29.358	37.042	0.000	0.000	0.000
2017	33.667	29.673	37.440	0.000	0.000	0.000
2018	34.795	30.738	38.880	0.000	0.000	0.000
2019	38.225	32.479	48.850	0.000	0.000	0.000
2020	42.739	33.120	61.812	0.000	0.000	0.000
2021	47.386	32.948	73.669	0.000	0.000	0.000
2022	51.708	33.164	83.504	0.000	0.000	0.000
2023	55.573	33.515	89.813	0.000	0.000	0.000
2024	58.866	34.452	93.604	0.000	0.000	0.000
$F_{40\%}$						
2015	25.878	23.247	28.584	5.240	4.182	6.018
2016	23.925	21.798	26.025	4.545	3.701	5.455
2017	21.490	19.768	23.142	3.752	3.125	4.399
2018	20.688	19.130	22.288	3.268	2.767	3.802
2019	22.270	18.829	30.468	3.365	2.684	4.436
2020	24.653	18.017	39.290	3.798	2.468	5.956
2021	26.799	17.474	46.388	4.367	2.254	7.654
2022	28.391	17.146	50.203	4.868	2.188	9.060
2023	29.489	17.147	51.148	5.237	2.140	9.789
2024	30.140	17.353	50.856	5.481	2.220	9.962
$F_{35\%}$						
2015	25.060	22.611	27.486	6.053	4.814	7.111
2016	22.759	20.837	24.598	4.950	4.073	5.860
2017	20.214	18.682	21.646	3.969	3.339	4.597
2018	19.395	17.990	20.815	3.410	2.915	3.925
2019	20.917	17.639	28.652	3.541	2.799	4.926
2020	23.138	16.825	36.821	4.059	2.569	6.628
2021	25.038	16.335	43.423	4.707	2.348	8.488
2022	26.366	16.083	45.953	5.240	2.260	9.965
2023	27.220	16.051	46.908	5.609	2.223	10.631
2024	27.676	16.302	46.266	5.832	2.293	10.830

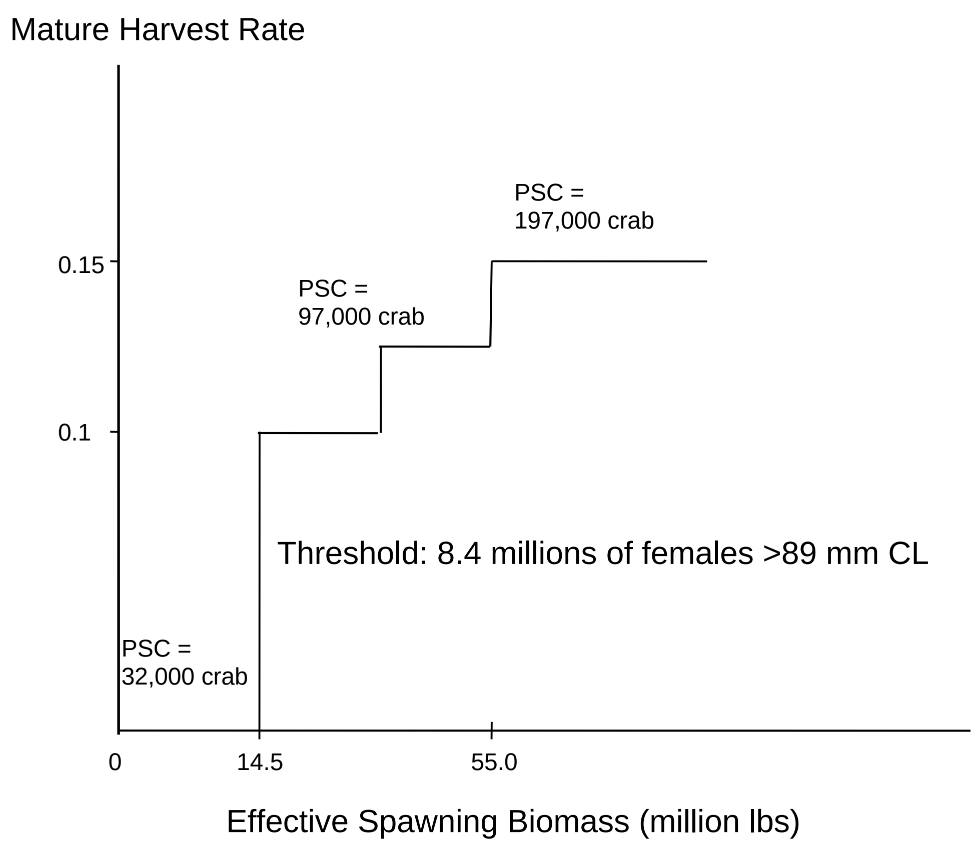


Figure 1. Current harvest rate strategy (line) for the Bristol Bay red king crab fishery and annual prohibited species catch (PSC) limits (numbers of crab) of Bristol Bay red king crab in the groundfish fisheries in zone 1 in the eastern Bering Sea. Harvest rates are based on current-year estimates of effective spawning biomass (ESB), whereas PSC limits apply to previous-year ESB.

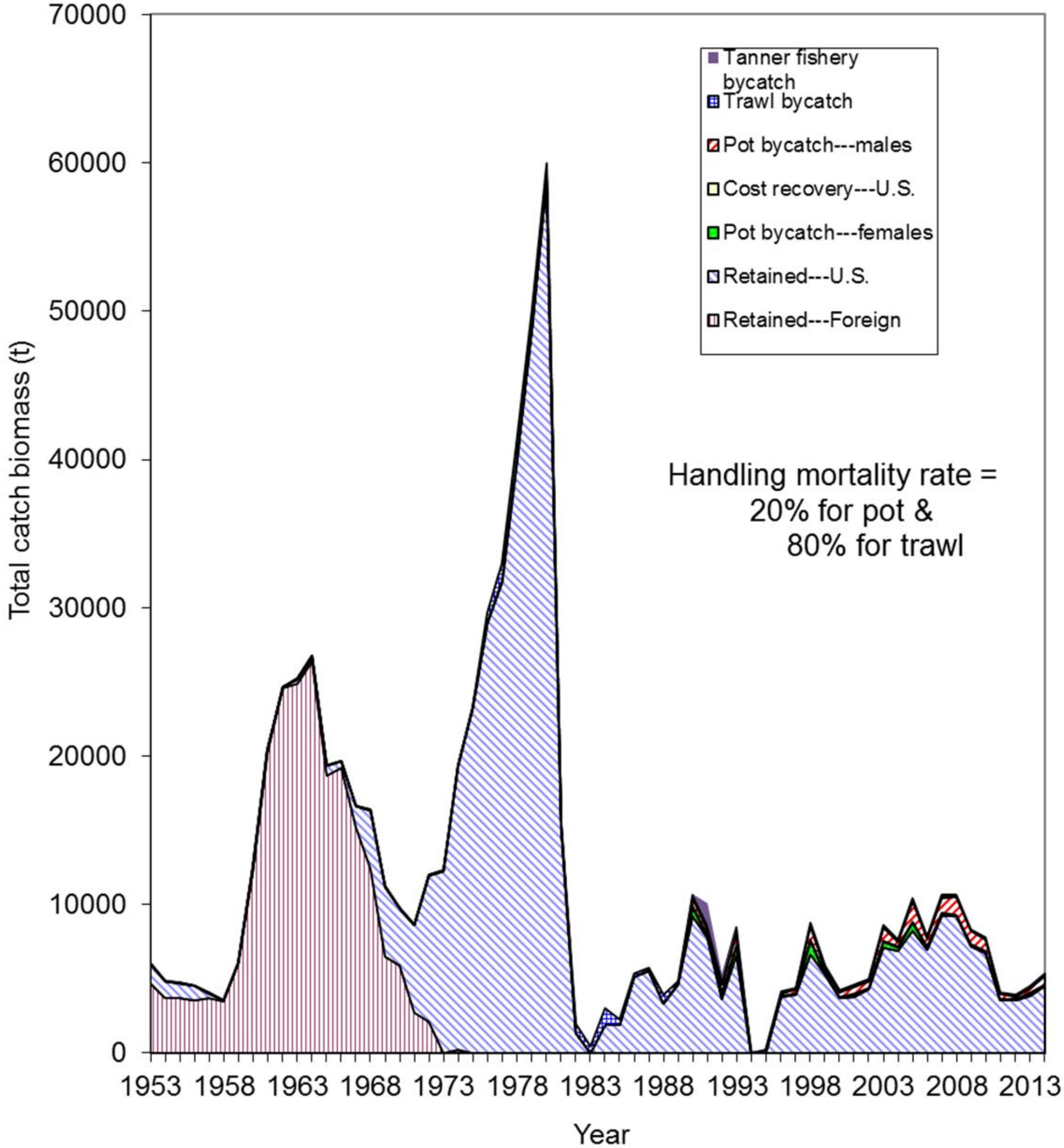


Figure 2. Retained catch biomass and bycatch mortality biomass (t) for Bristol Bay red king crab from 1953 to 2014. Handling mortality rates were assumed to be 0.2 for the directed pot fishery 0.25 for the Tanner crab fishery and 0.8 for the trawl fisheries.

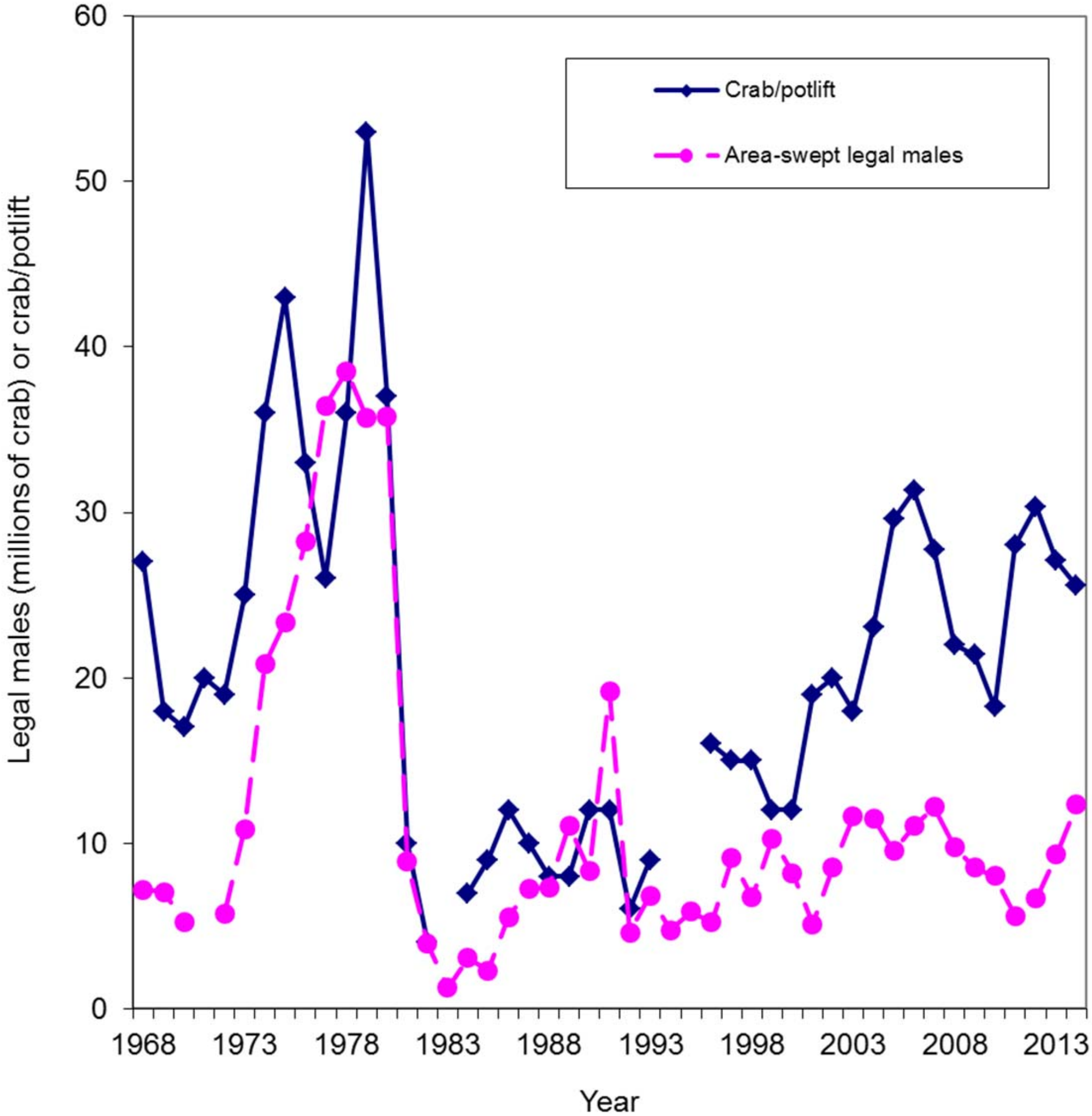


Figure 3. Comparison of survey legal male abundances and catches per unit effort for Bristol Bay red king crab from 1968 to 2014.

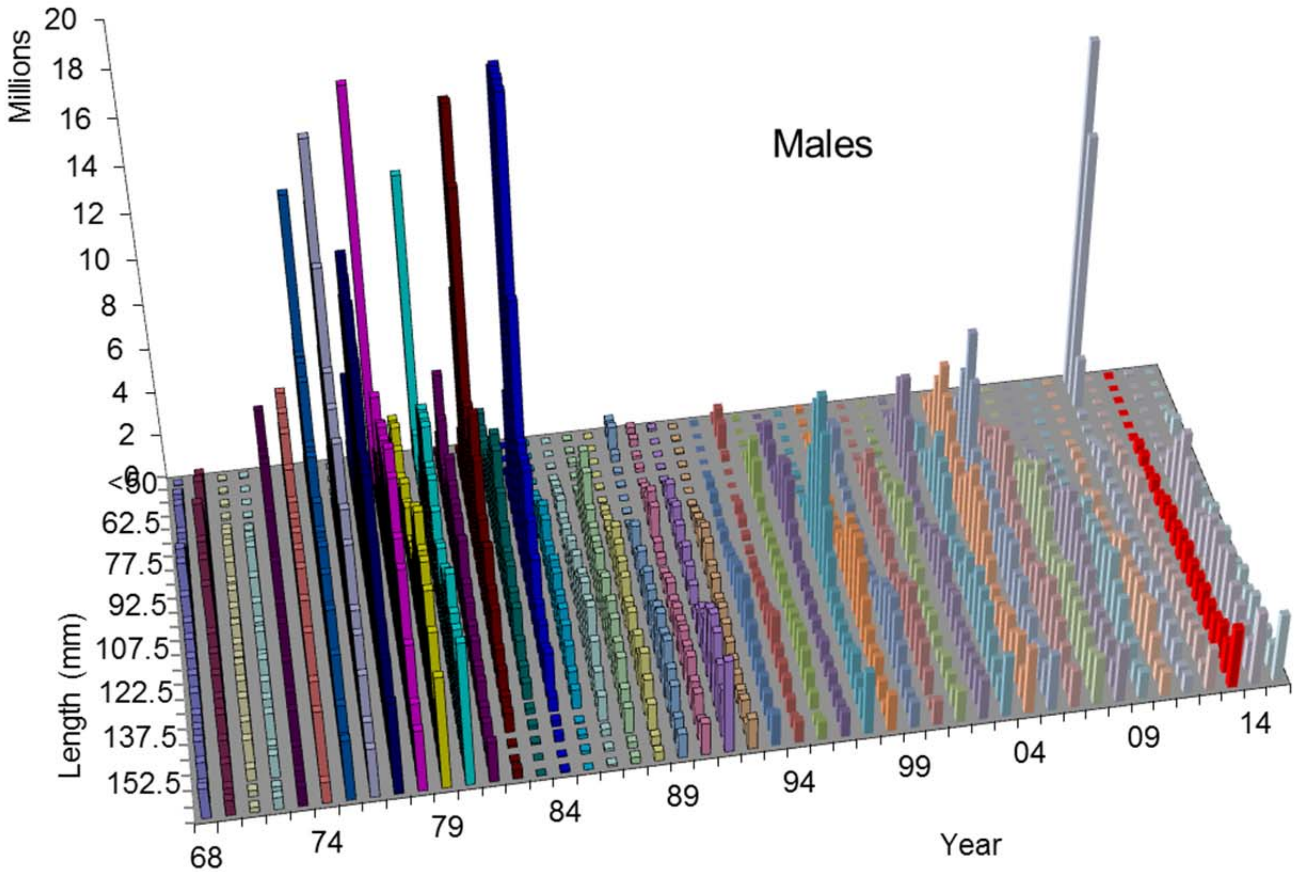


Figure 4. Survey abundances by 5-mm carapace length bin for male Bristol Bay red king crab from 1968 to 2015.

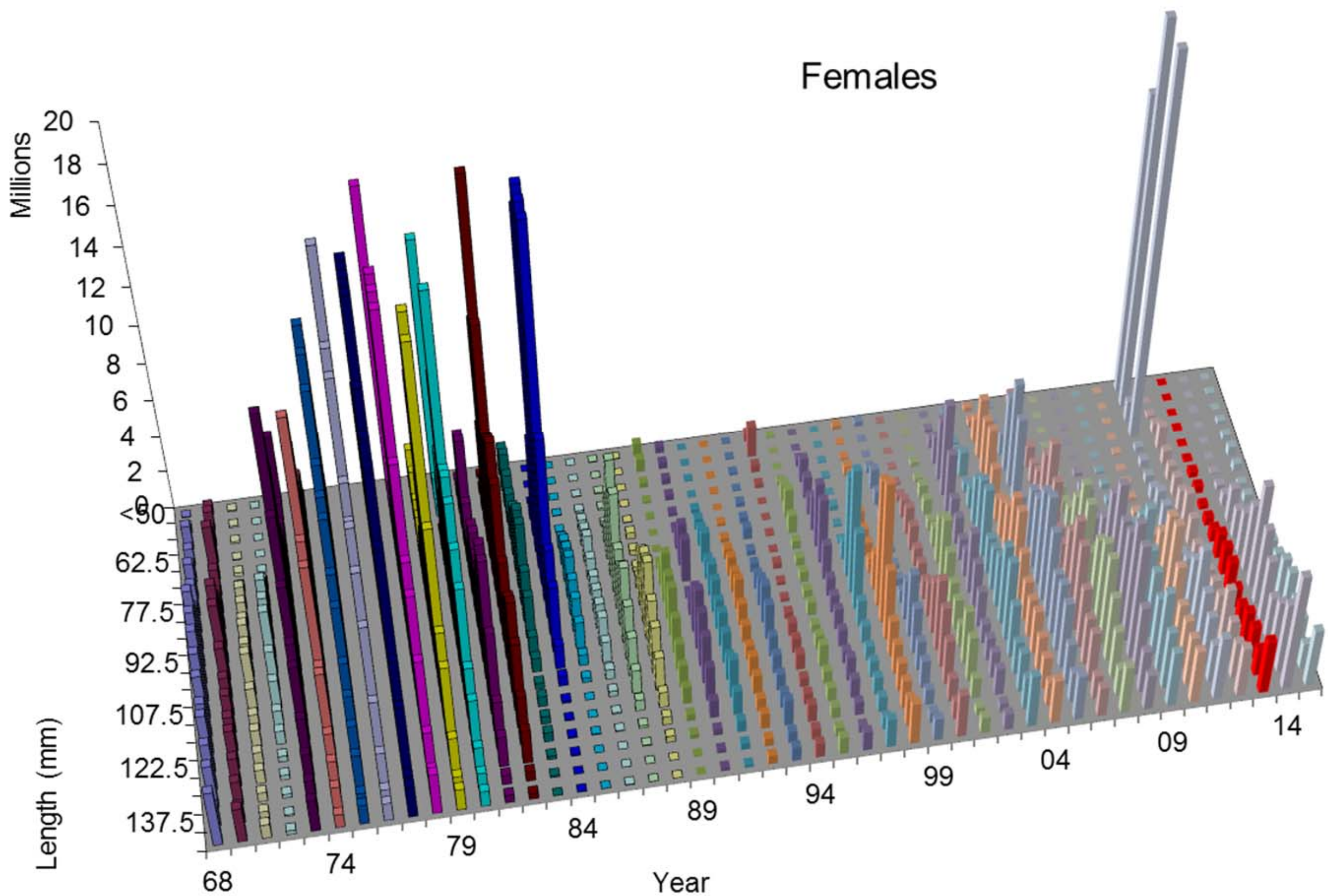
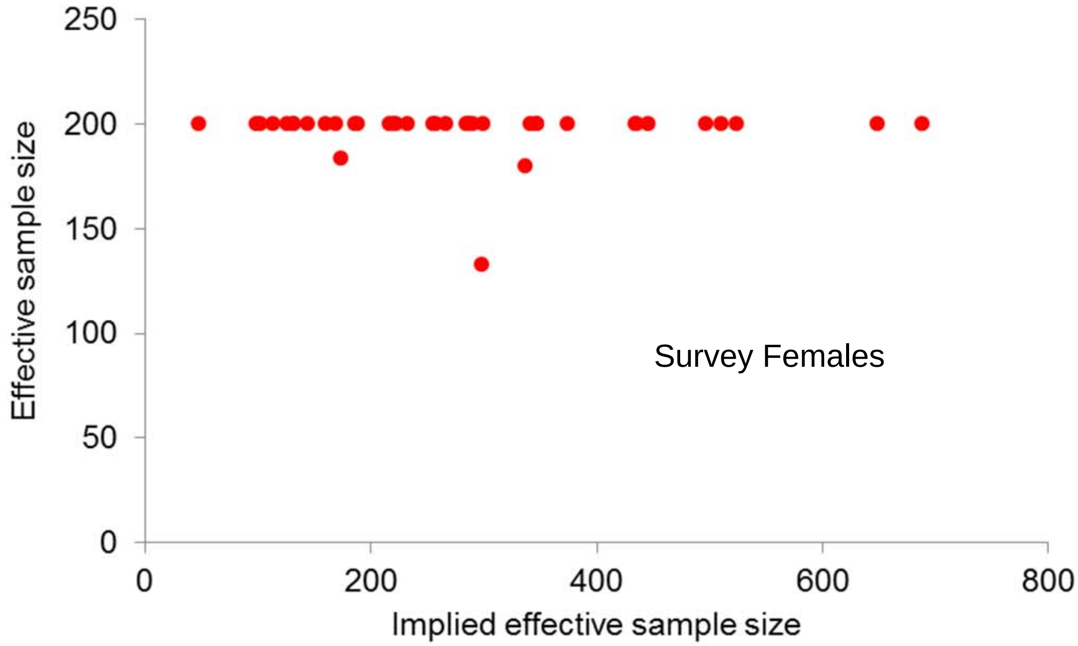


Figure 5. Survey abundances by 5 mm carapace length bin for female Bristol Bay red king crab from 1968 to 2015.



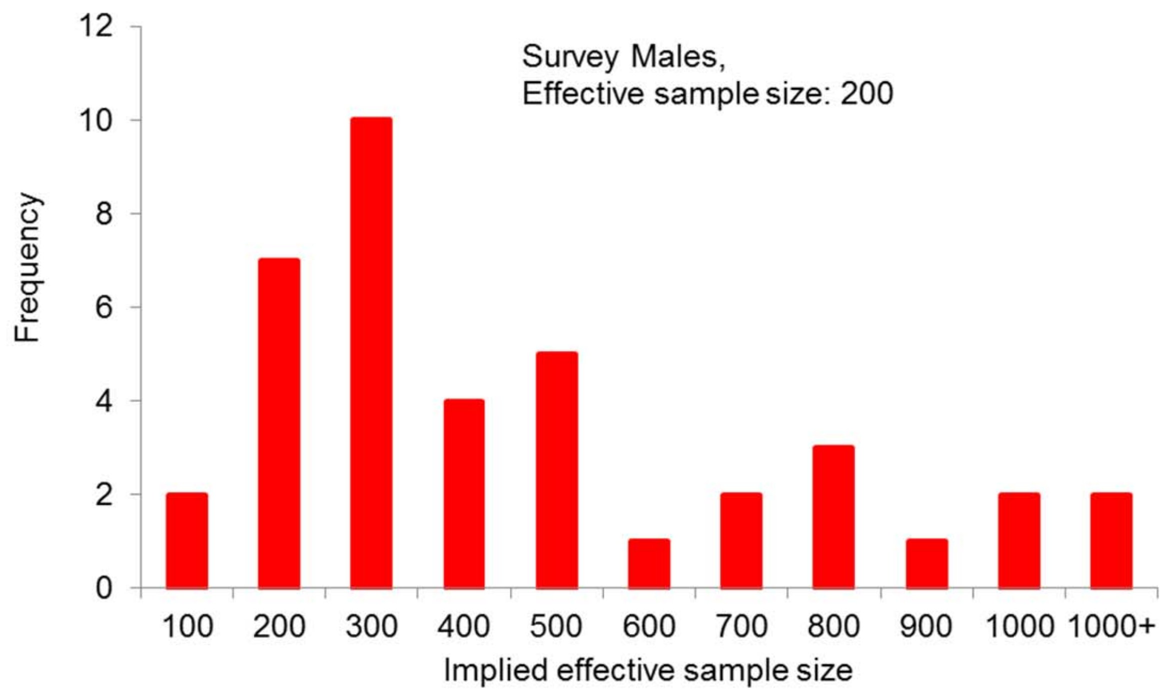


Figure 6. Relationship between implied effective sample sizes (section 3(a)(5)(i)) and effective sample sizes (see effective sample sizes for scenario 1) for length/sex composition data with scenario 1: trawl survey data.

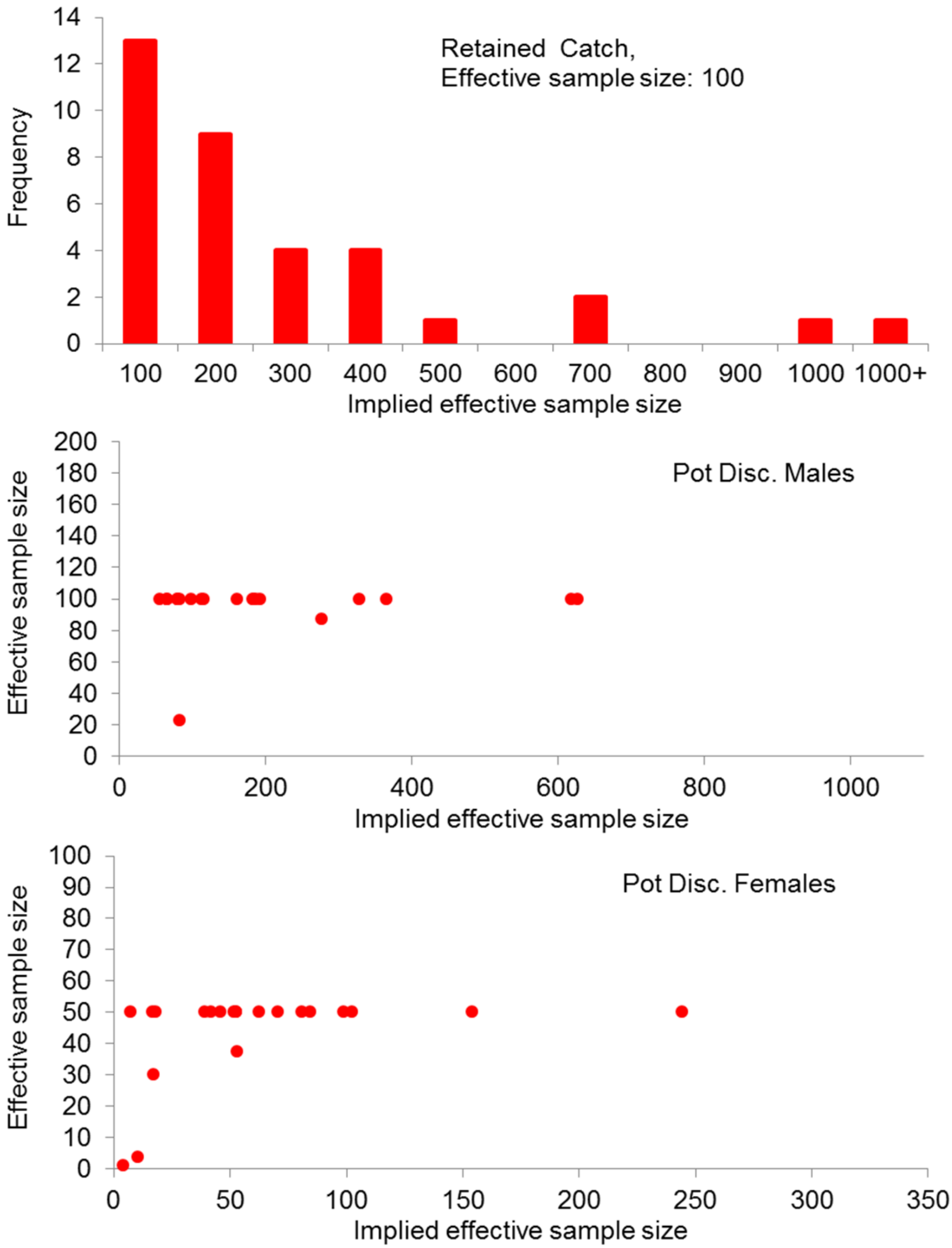


Figure 7. Relationship between implied effective sample sizes (section 3(a)(5)(i)) and effective sample sizes (see effective sample sizes for scenario 1) for length/sex composition data with scenario 1: directed pot fishery data.

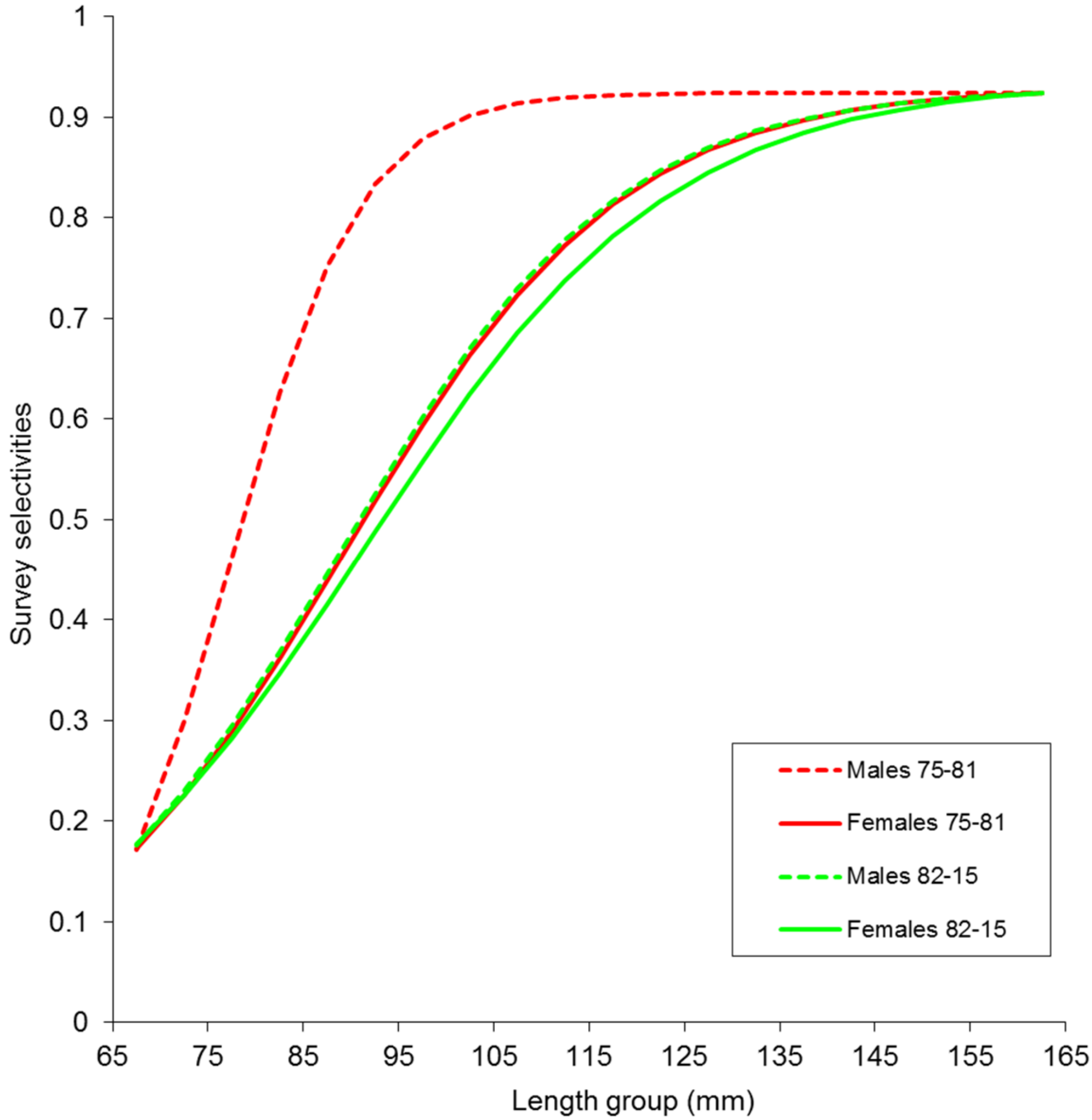


Figure 8a(1). Estimated trawl survey selectivities/catchability under scenario 1. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

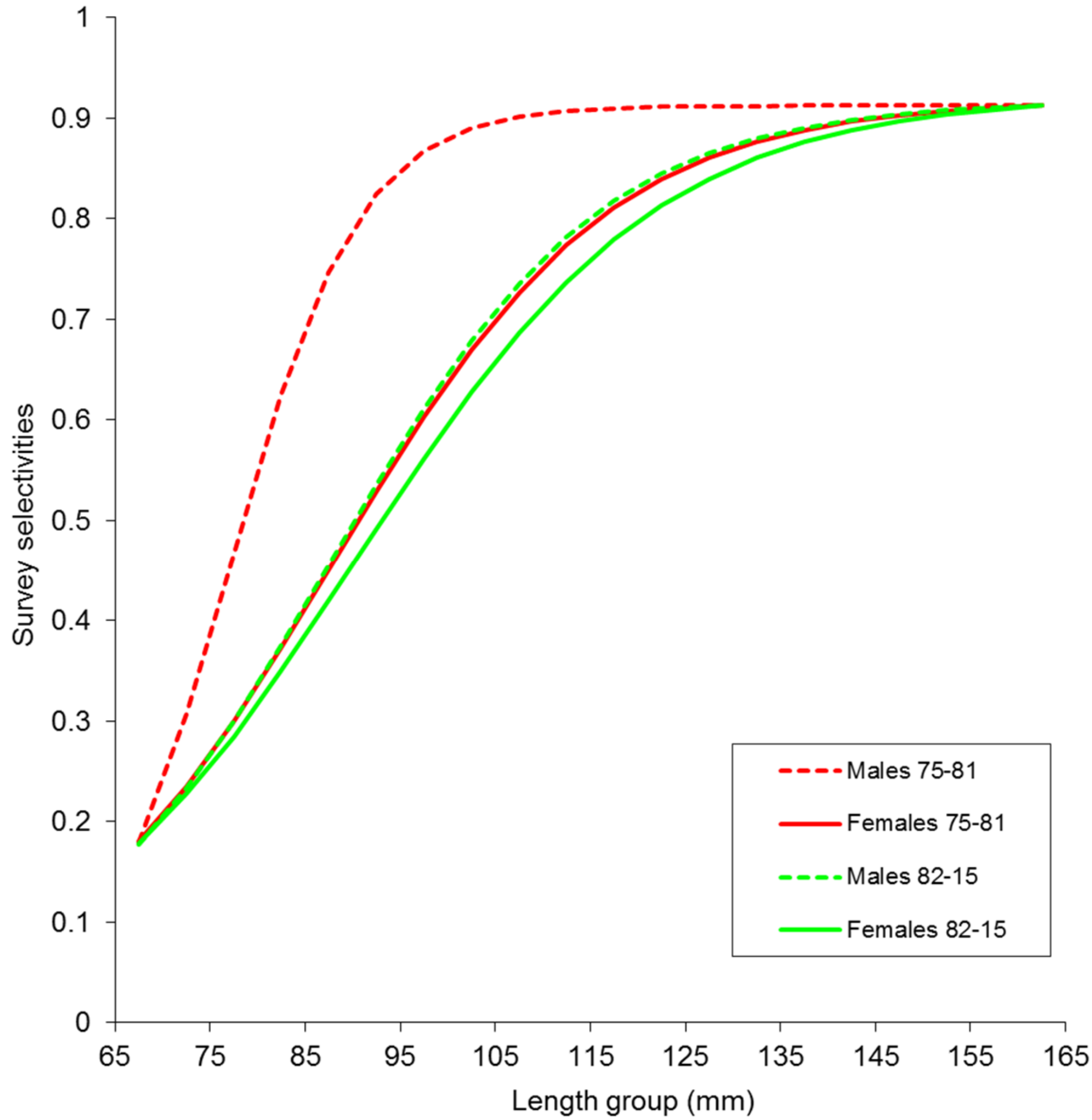
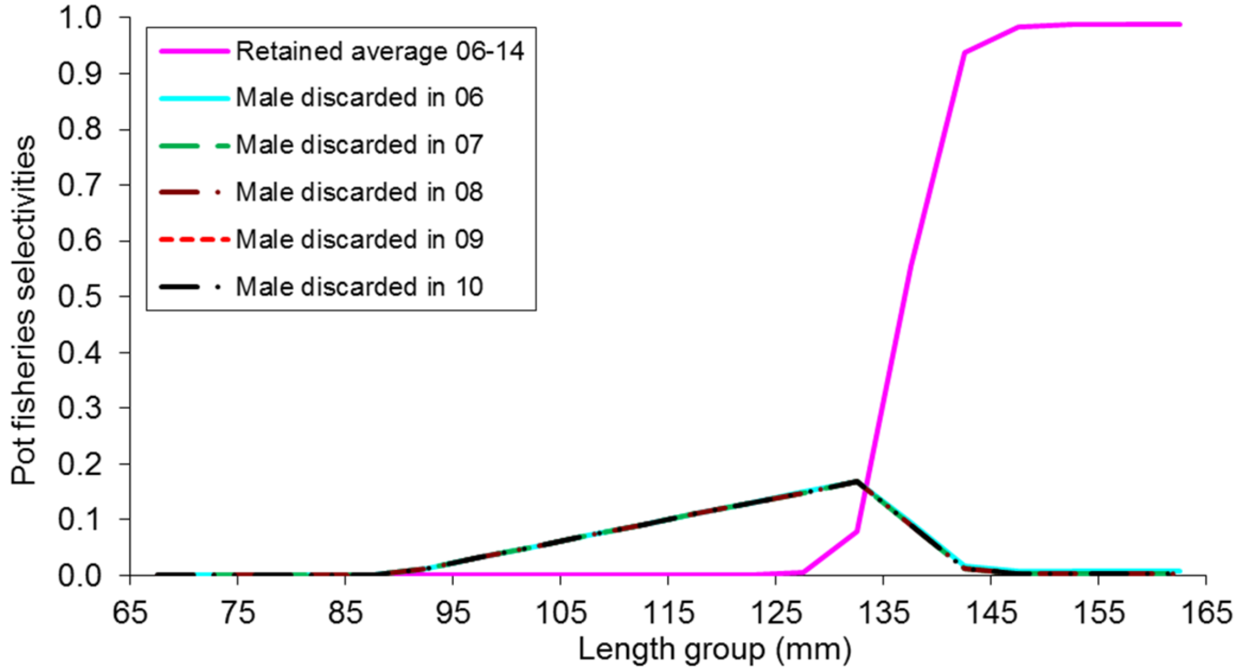


Figure 8a(1a). Estimated trawl survey selectivities/catchability under scenario 1a. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.



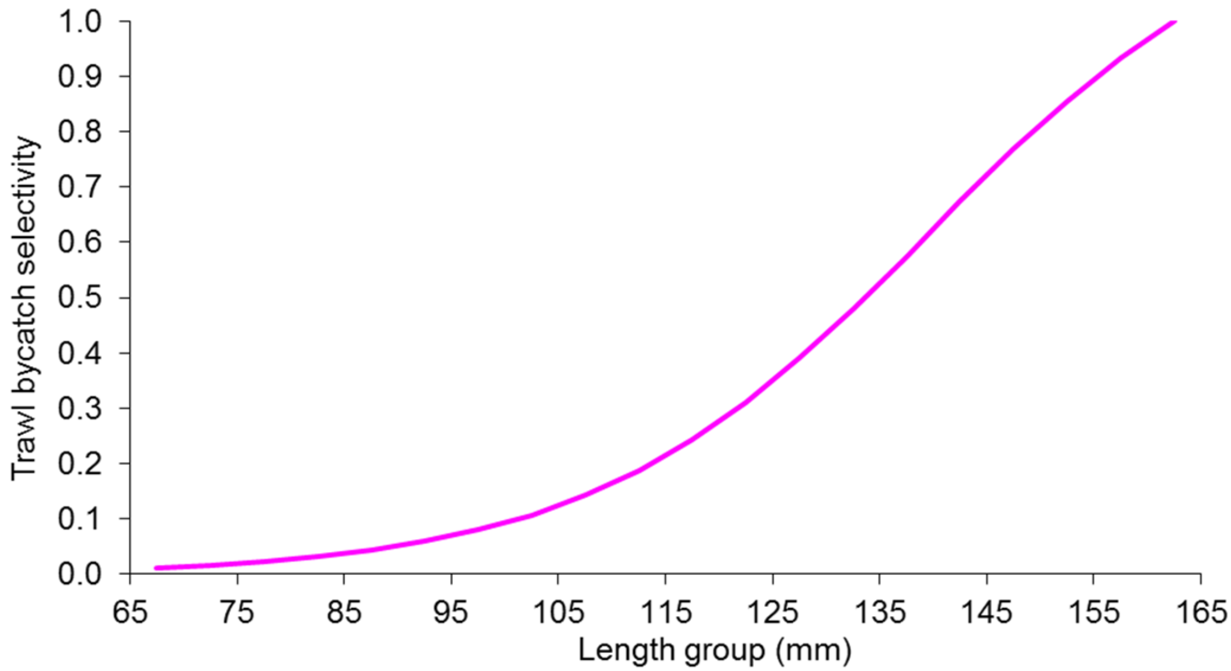


Figure 8b. Estimated pot fishery selectivities and groundfish trawl bycatch selectivities under scenario 1. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

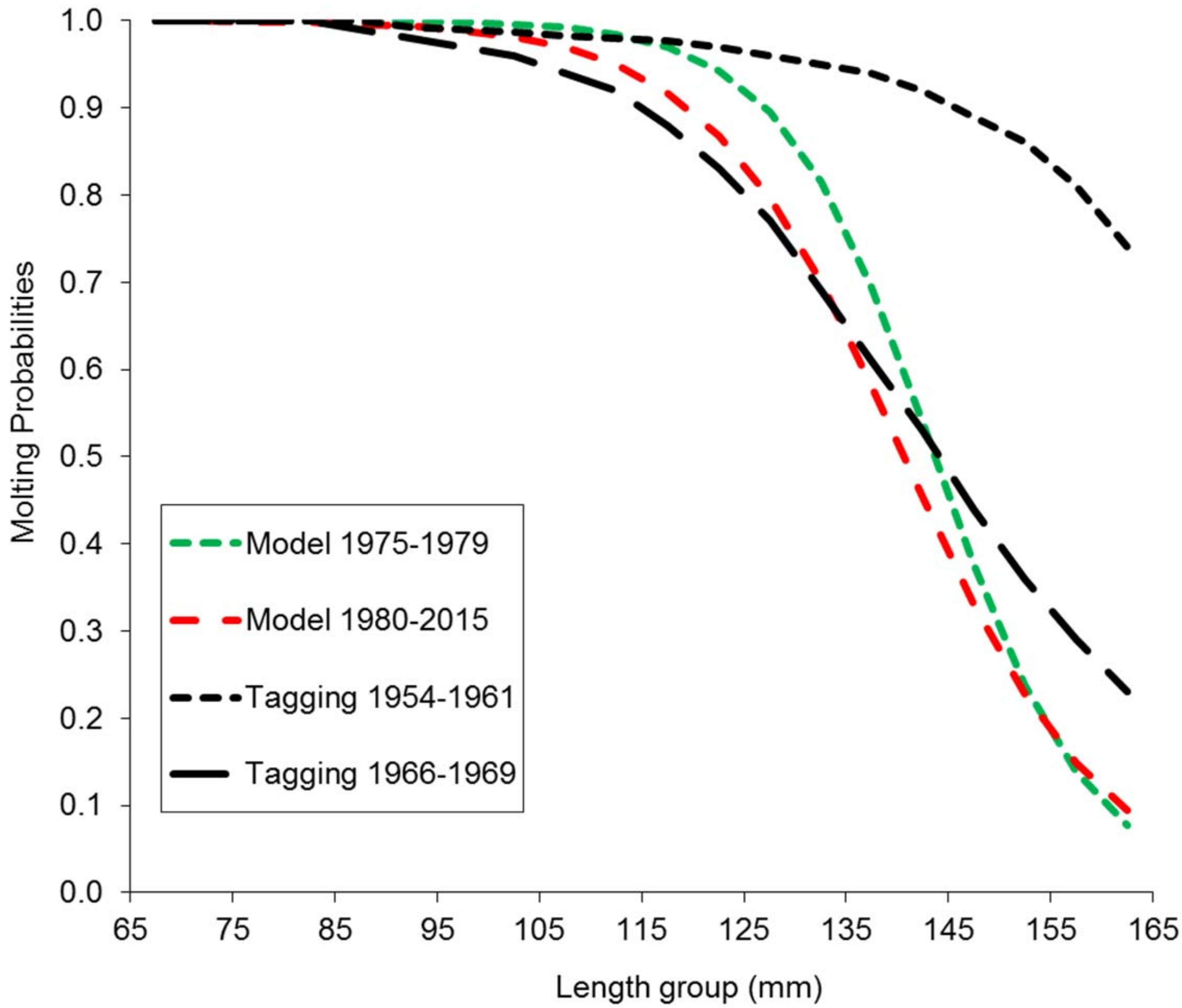


Figure 9(1). Comparison of estimated probabilities of molting of male red king crab in Bristol Bay for different periods. Molting probabilities for periods 1954-1961 and 1966-1969 were estimated by Balsiger (1974) from tagging data. Molting probabilities for 1975-2015 were estimated with a length-based model with a pot handling mortality rate of 0.2 under scenario 1.

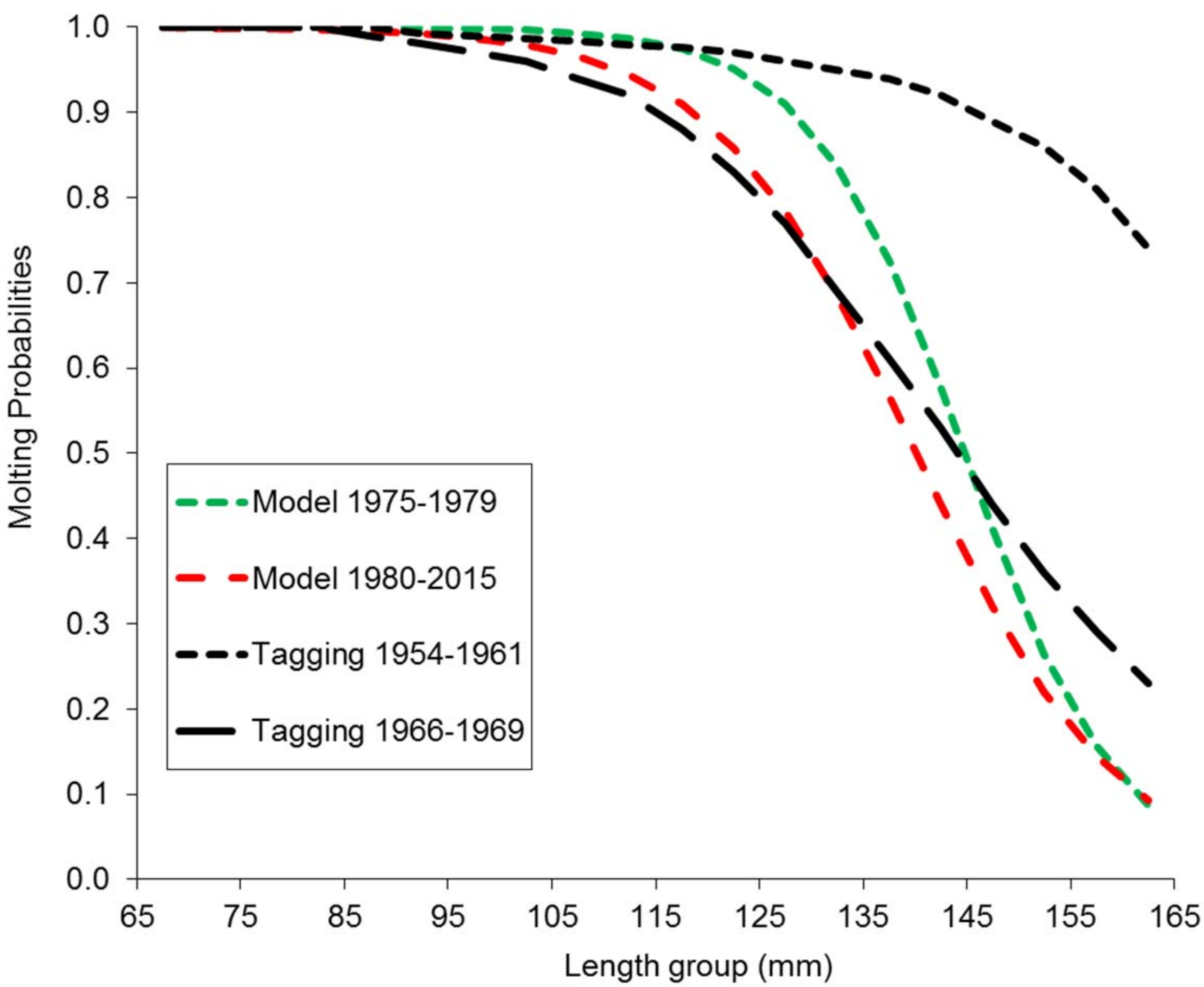


Figure 9(1a). Comparison of estimated probabilities of molting of male red king crab in Bristol Bay for different periods. Molting probabilities for periods 1954-1961 and 1966-1969 were estimated by Balsiger (1974) from tagging data. Molting probabilities for 1975-2015 were estimated with a length-based model with pot handling mortality rate of 0.2 under scenario 1a.

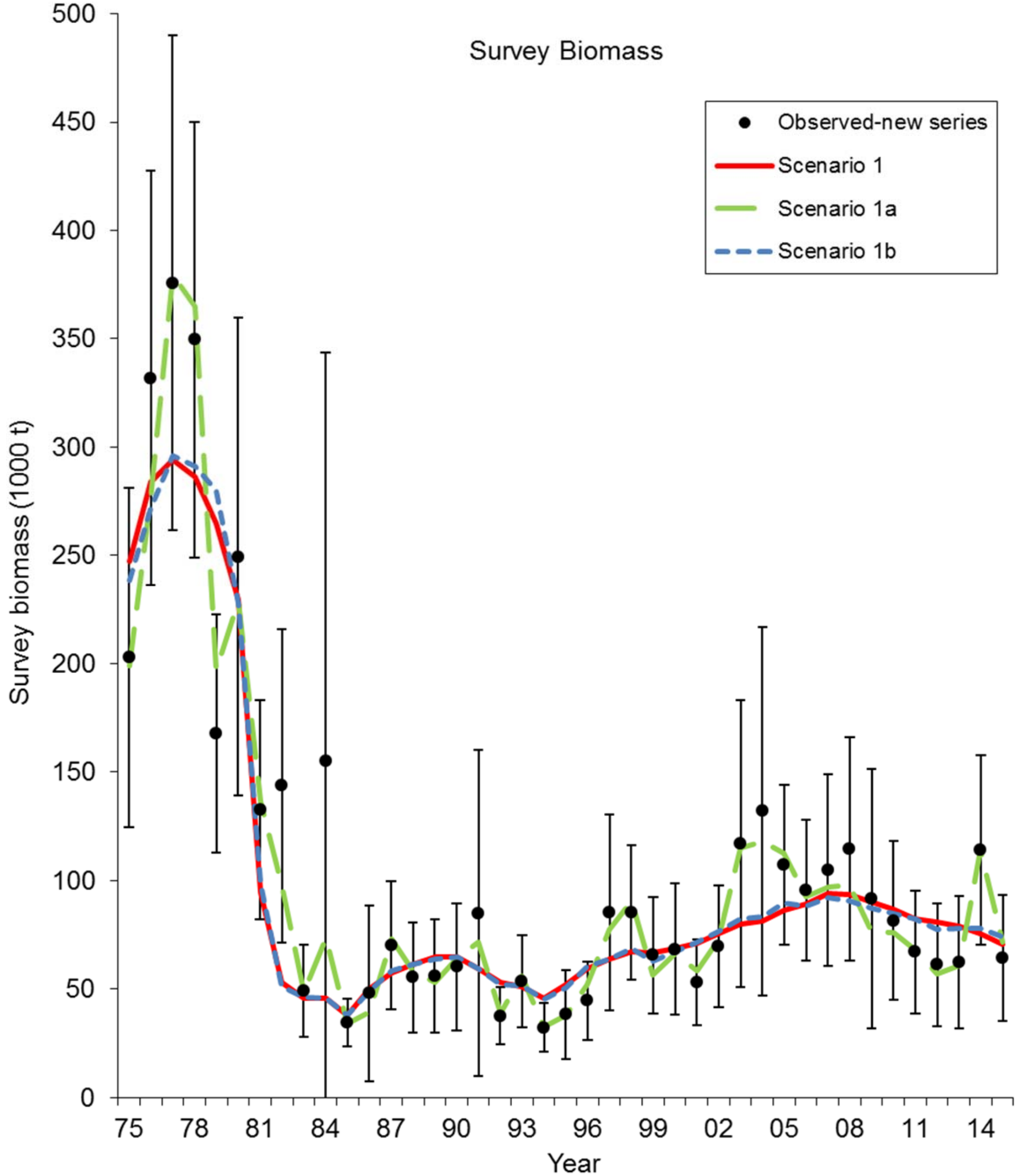
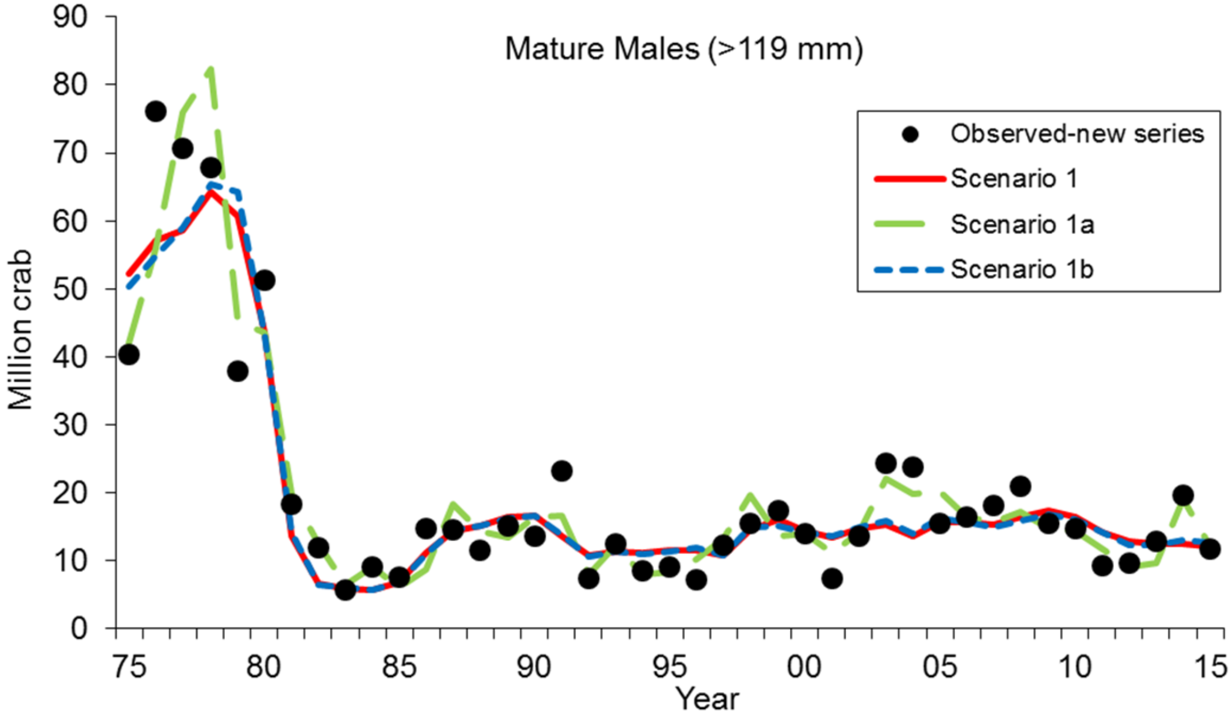


Figure 10a(1, 1a & 1b). Comparisons of area-swept estimates of total survey biomass and model prediction for model estimates in 2015 under scenarios 1, 1a and 1b. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively. The error bars are plus and minus 2 standard deviations.



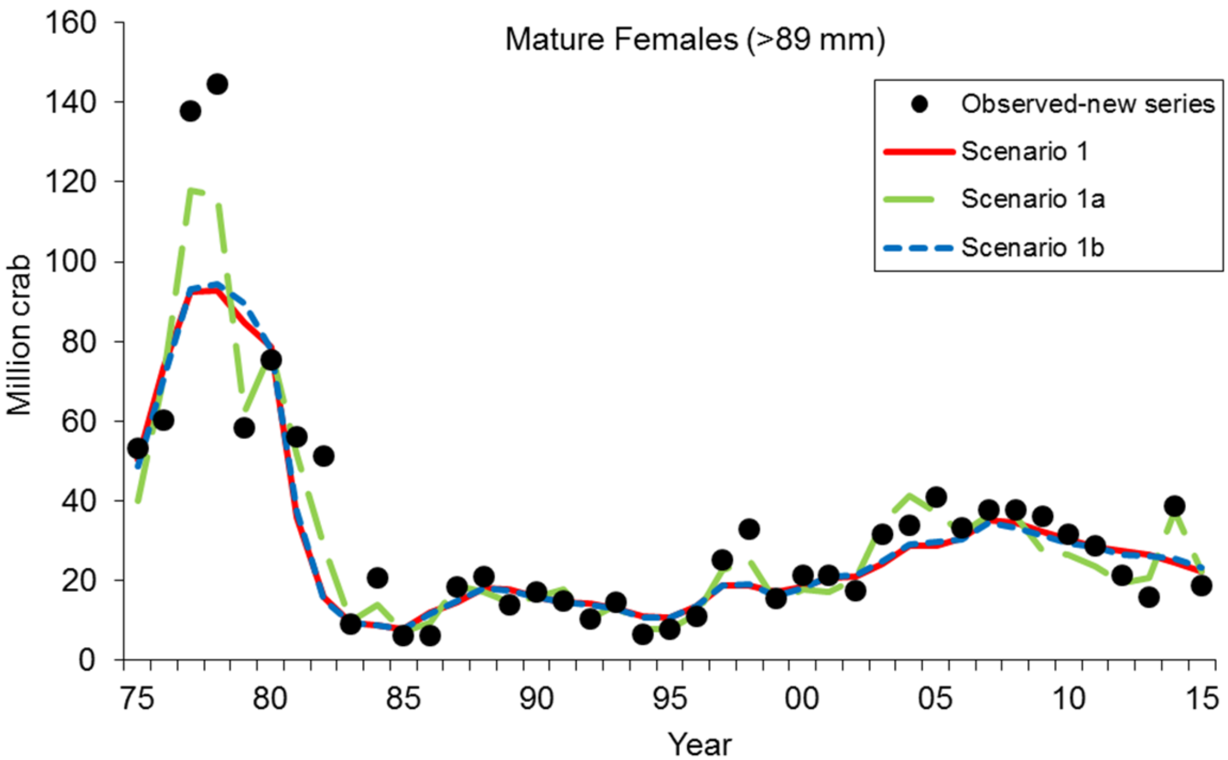


Figure 10b(1, 1a & 1b). Comparisons of area-swept estimates of male (>119 mm) and female (>89 mm) abundance and model prediction for model estimates in 2014 under scenarios 1, 1a and 1b. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

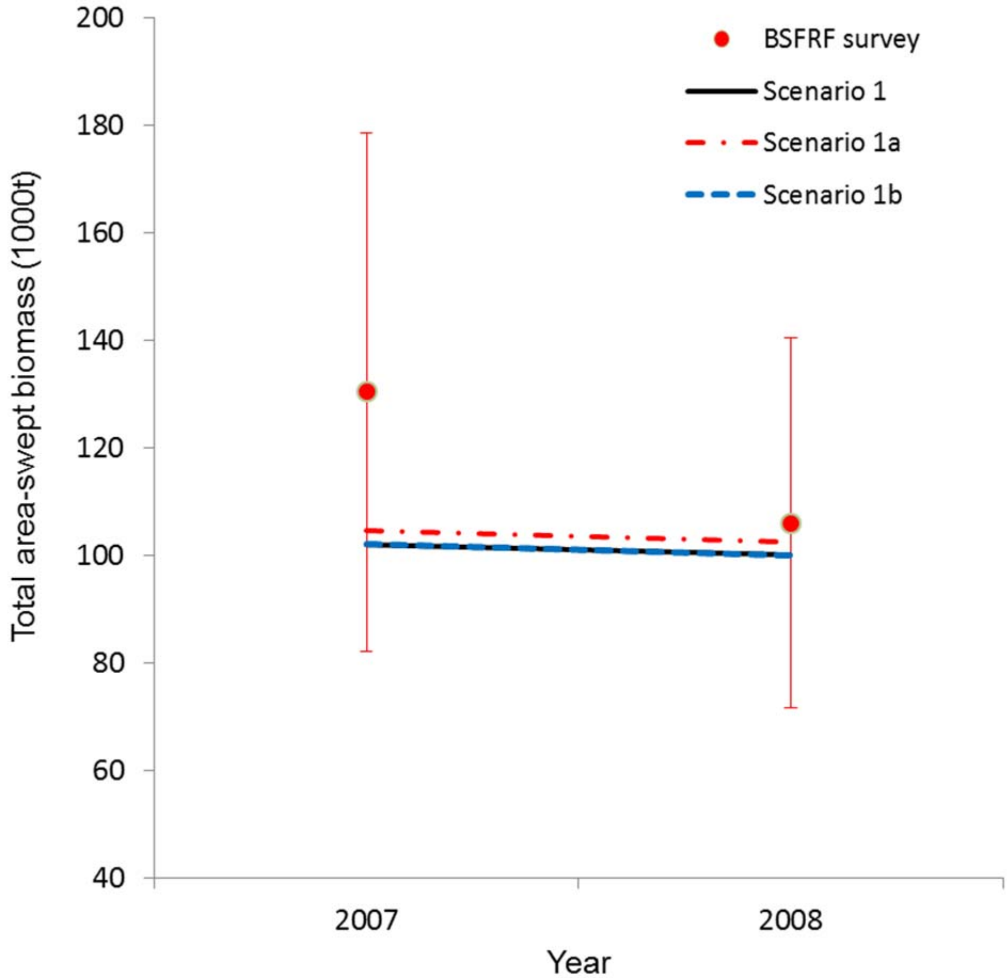


Figure 10c. Comparisons of total survey biomass estimates by the BSFRF survey and the model for model estimates in 2015 (scenarios 1, 1a & 1b). The error bars are plus and minus 2 standard deviations of scenario 1.

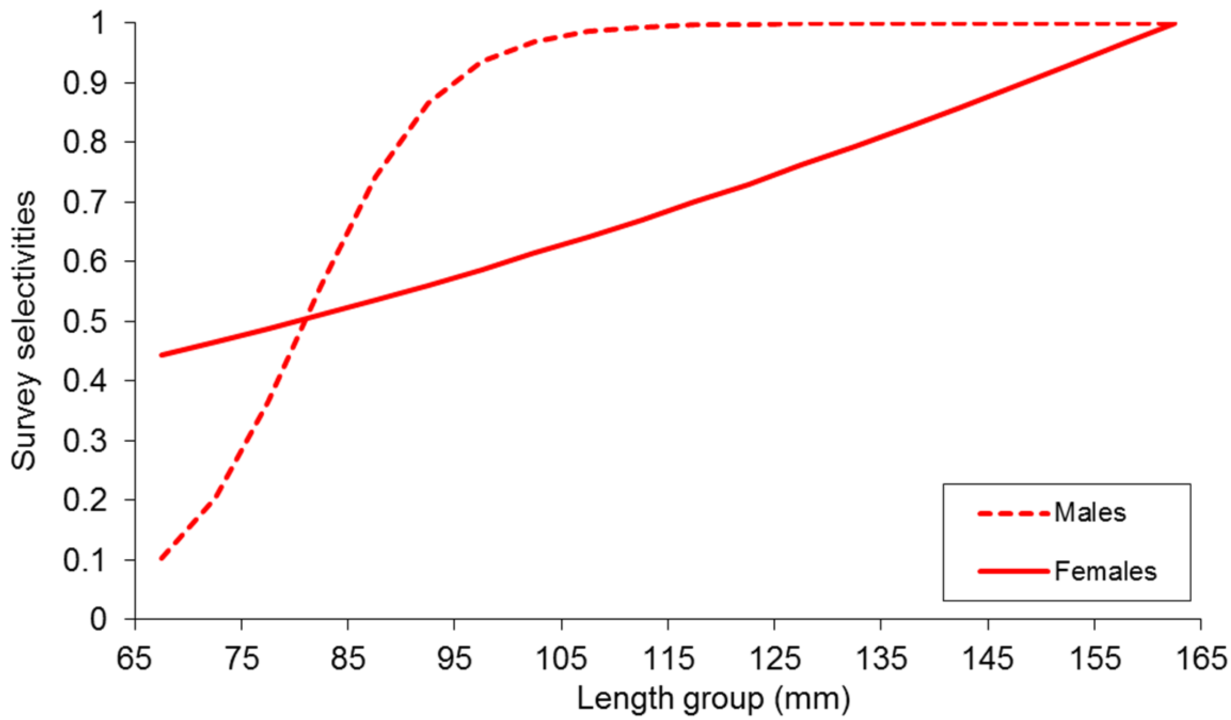


Figure 10d(1). Estimated BSFRF survey selectivities with scenario 1. The catchability is assumed to be 1.0.

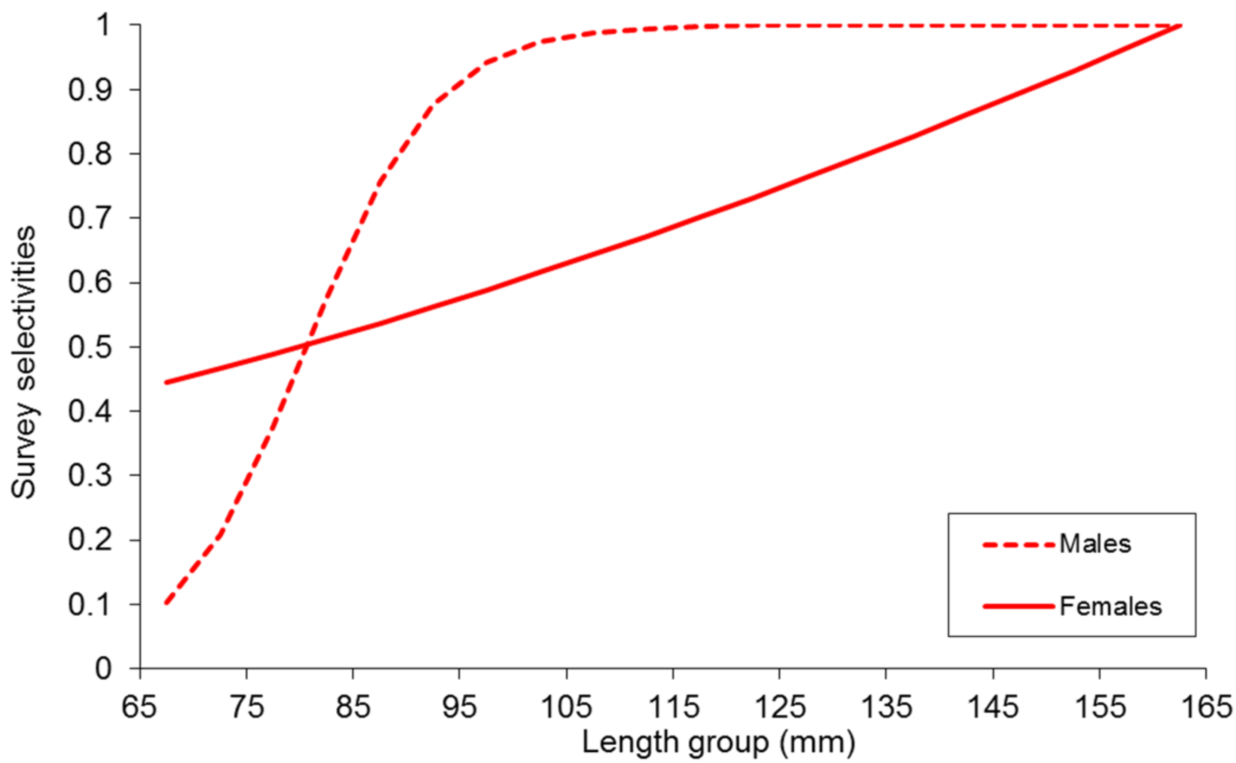


Figure 10d(1a). Estimated BSFRF survey selectivities with scenario 1a. The catchability is assumed to be 1.0.

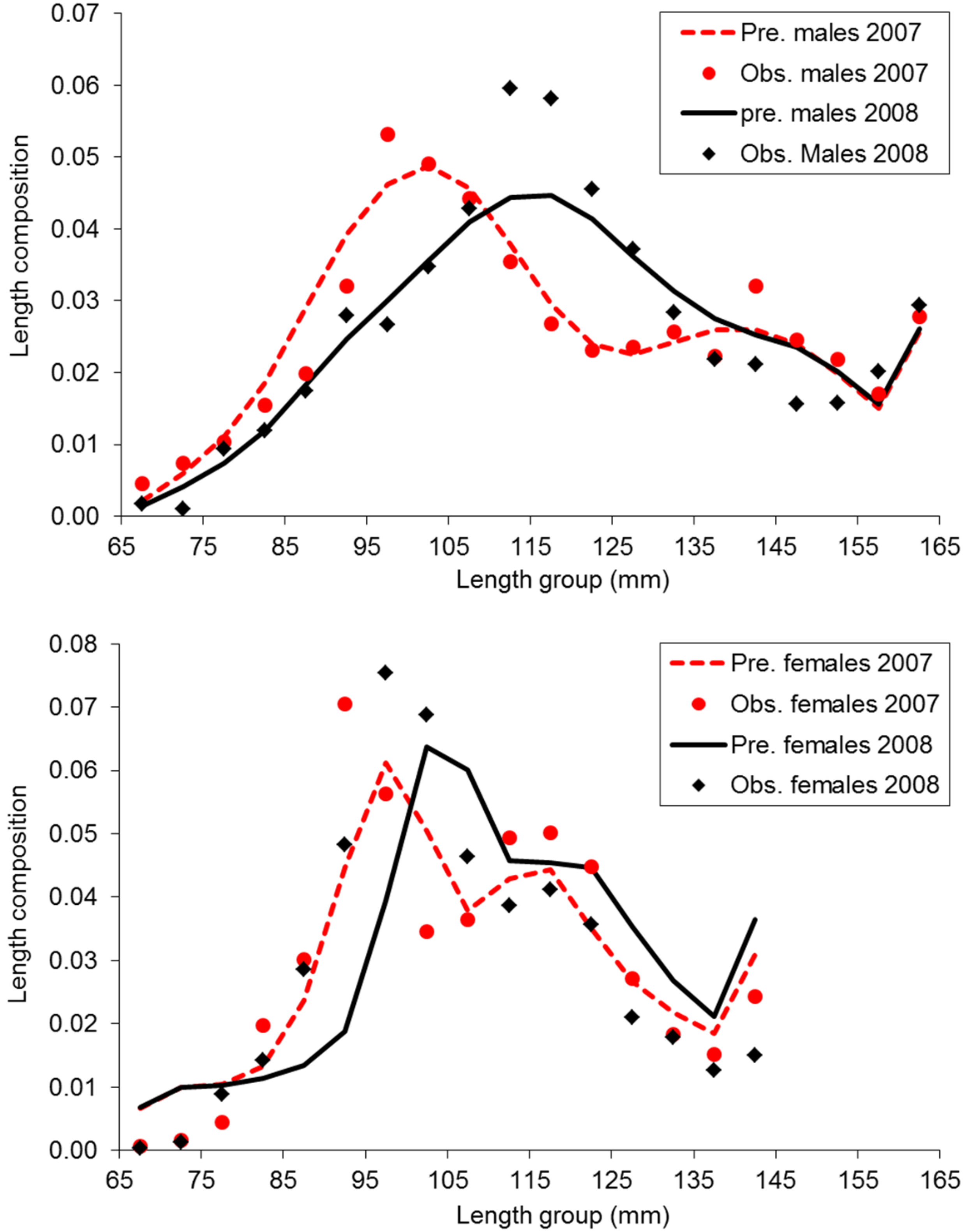


Figure 10e(1). Comparisons of length compositions by the BSFRF survey and the model estimates in 2007 and 2008 with scenario 1.

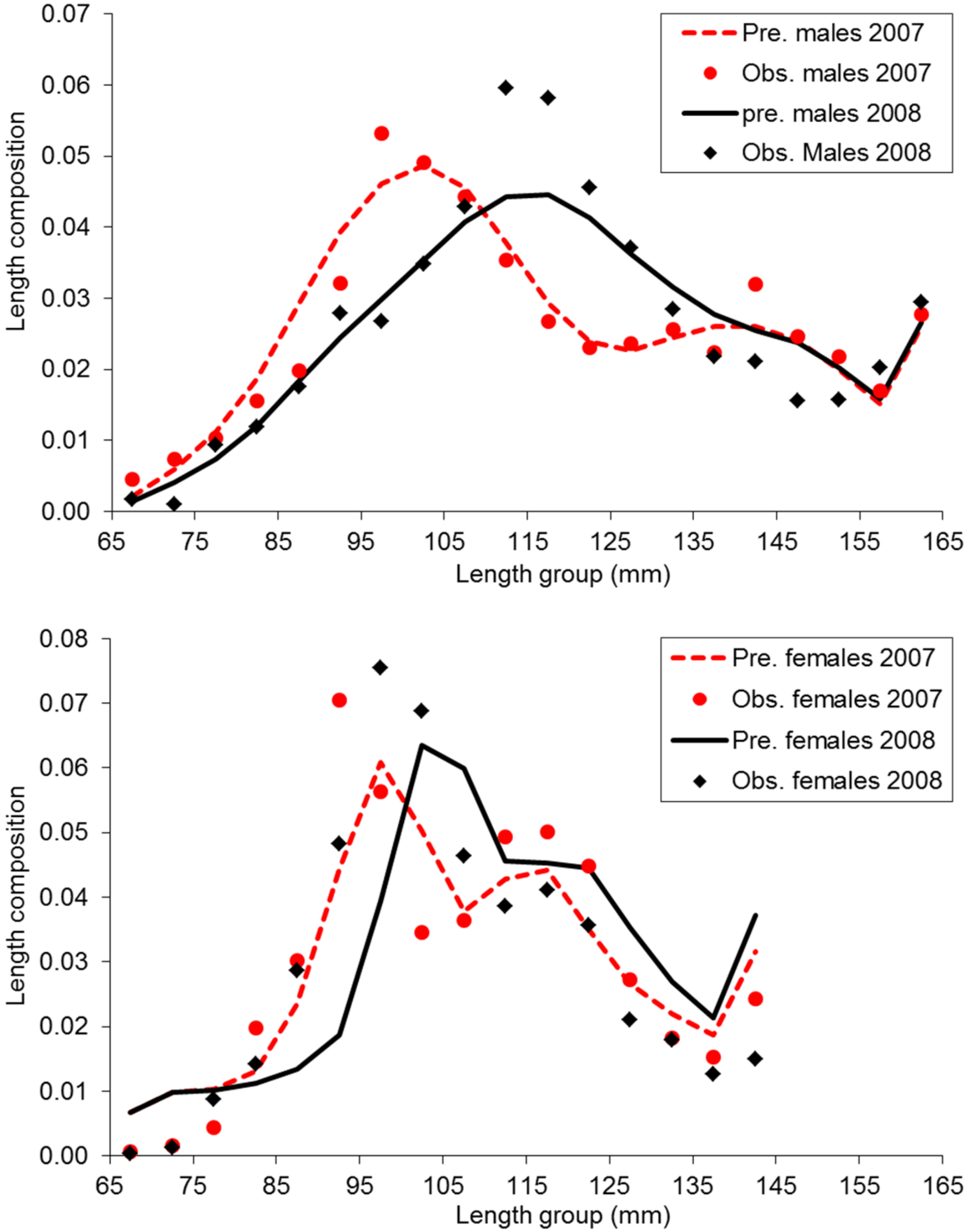


Figure 10e(1a). Comparisons of length compositions by the BSFRF survey and the model estimates in 2007 and 2008 with scenario 1a.

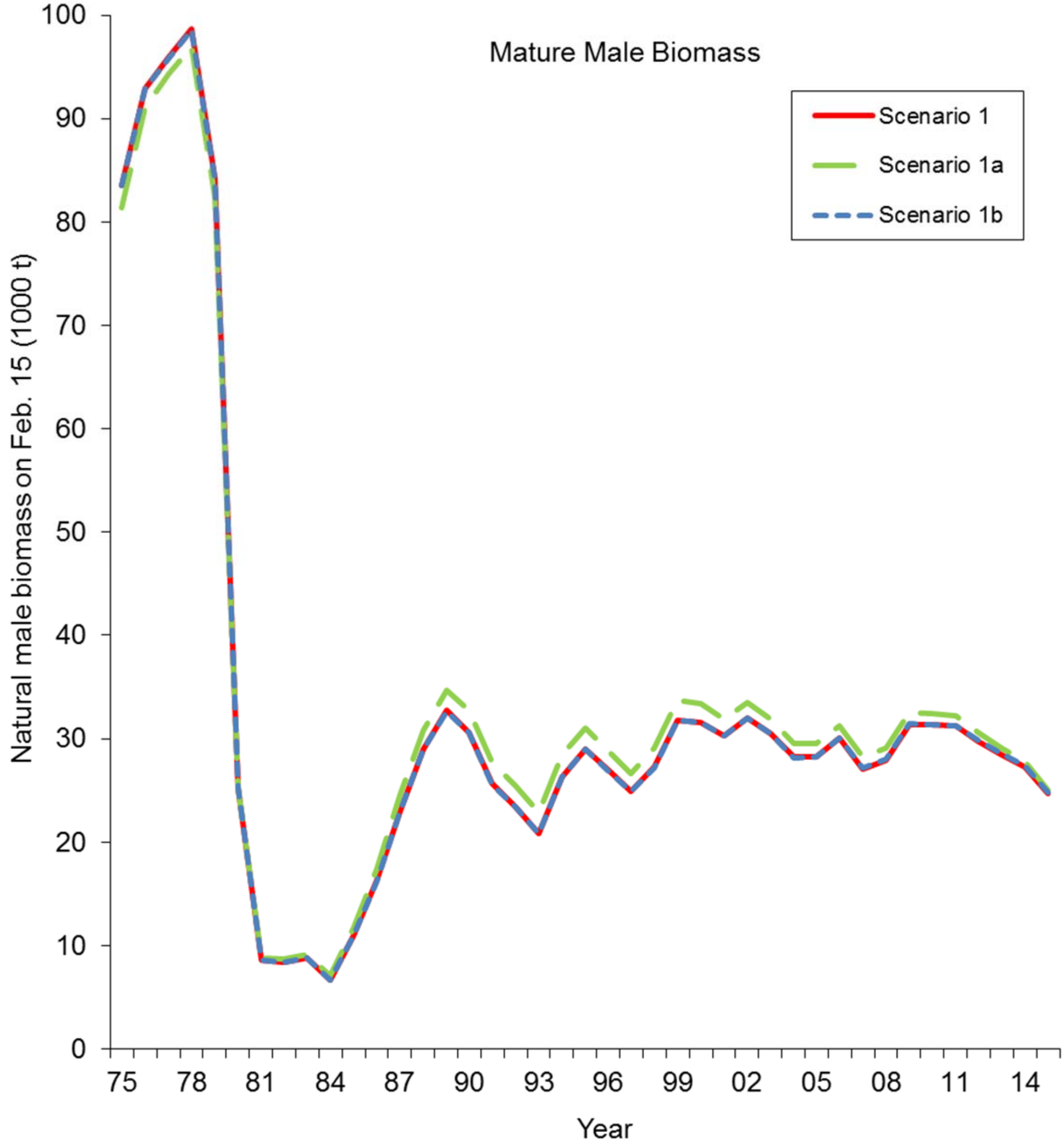


Figure 11. Estimated absolute mature male biomasses during 1975-2015 for scenarios 1, 1a and 1b.

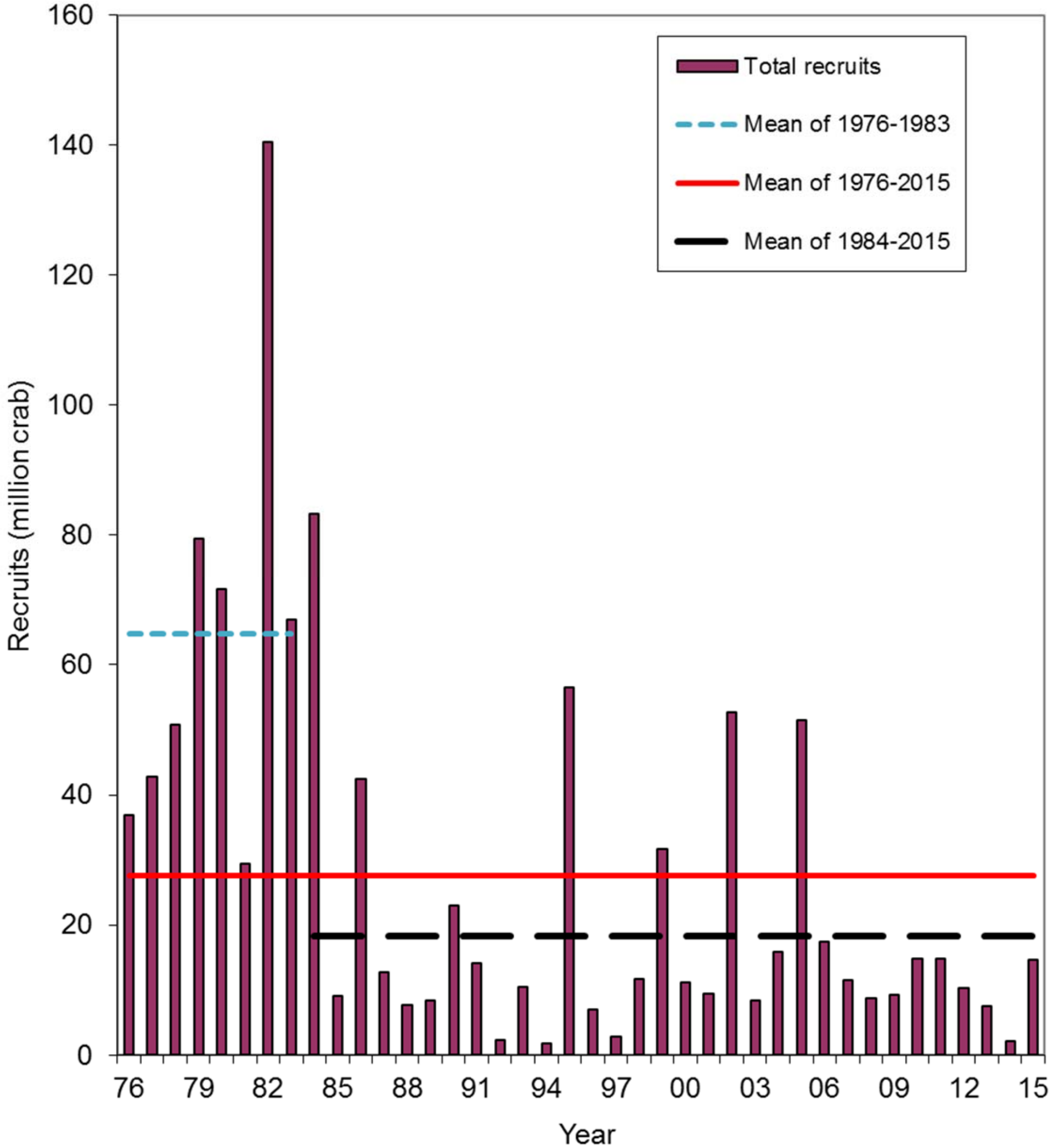


Figure 12(1). Estimated recruitment time series during 1976-2015 with scenario 1. Mean male recruits during 1984-2015 was used to estimate $B_{35\%}$.

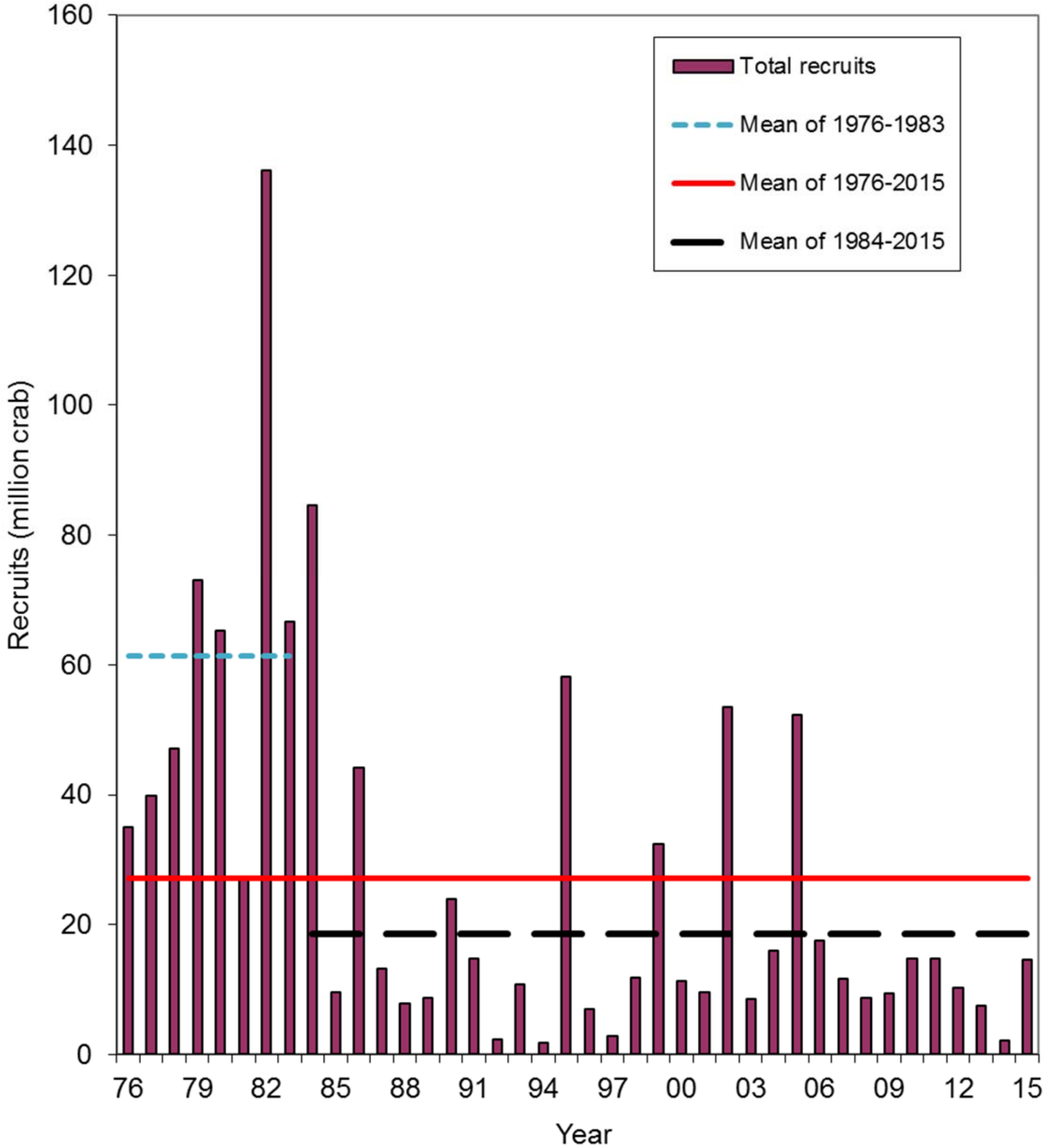


Figure 12(1a). Estimated recruitment time series during 1976-2015 with scenario 1a. Mean male recruits during 1984-2015 was used to estimate $B_{35\%}$.

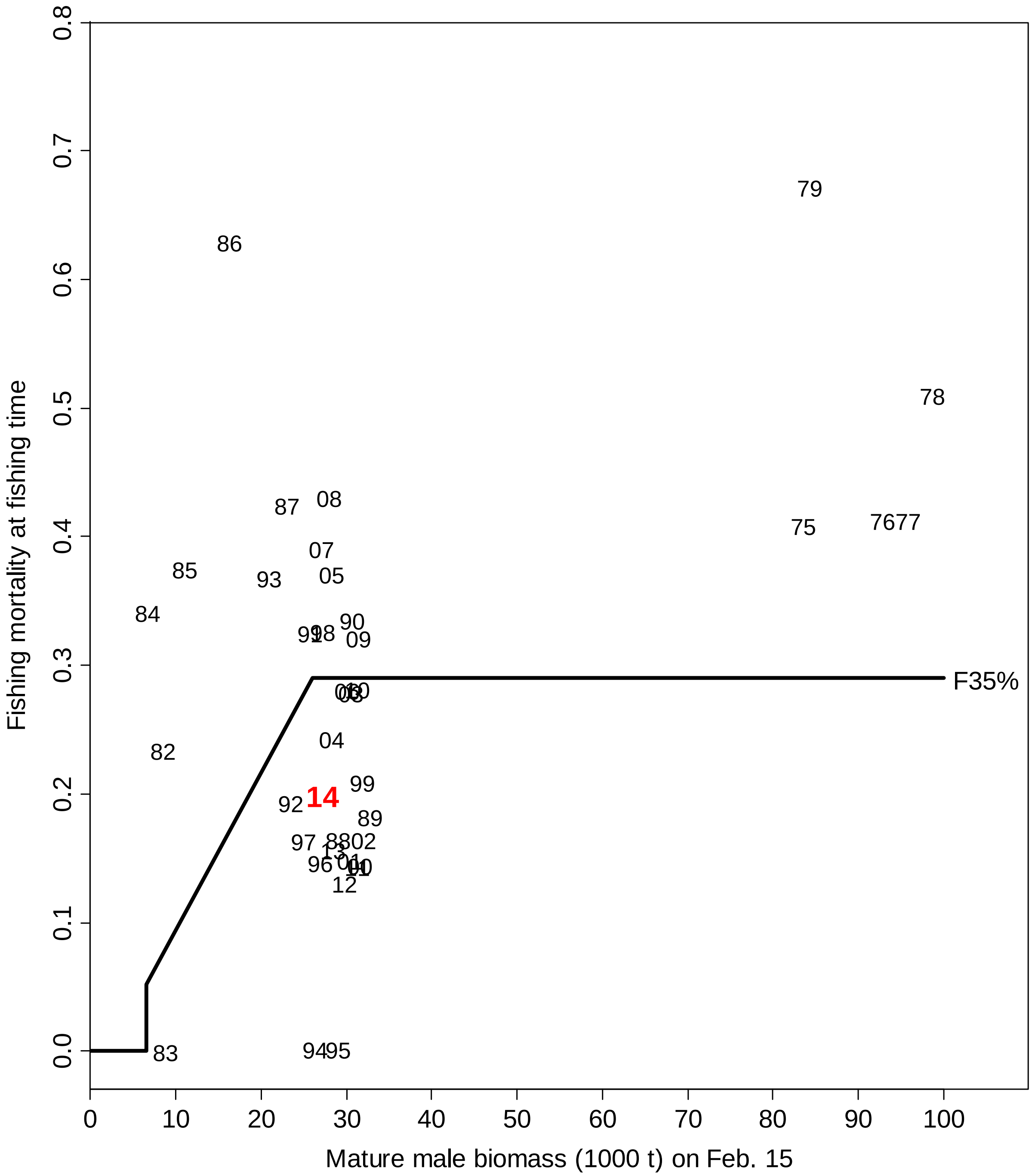


Figure 13(1). Relationships between full fishing mortalities for the directed pot fishery and mature male biomass on Feb. 15 during 1975-2014 under scenario 1. Average of recruitment from 1984 to 2015 was used to estimate B_{MSY}. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

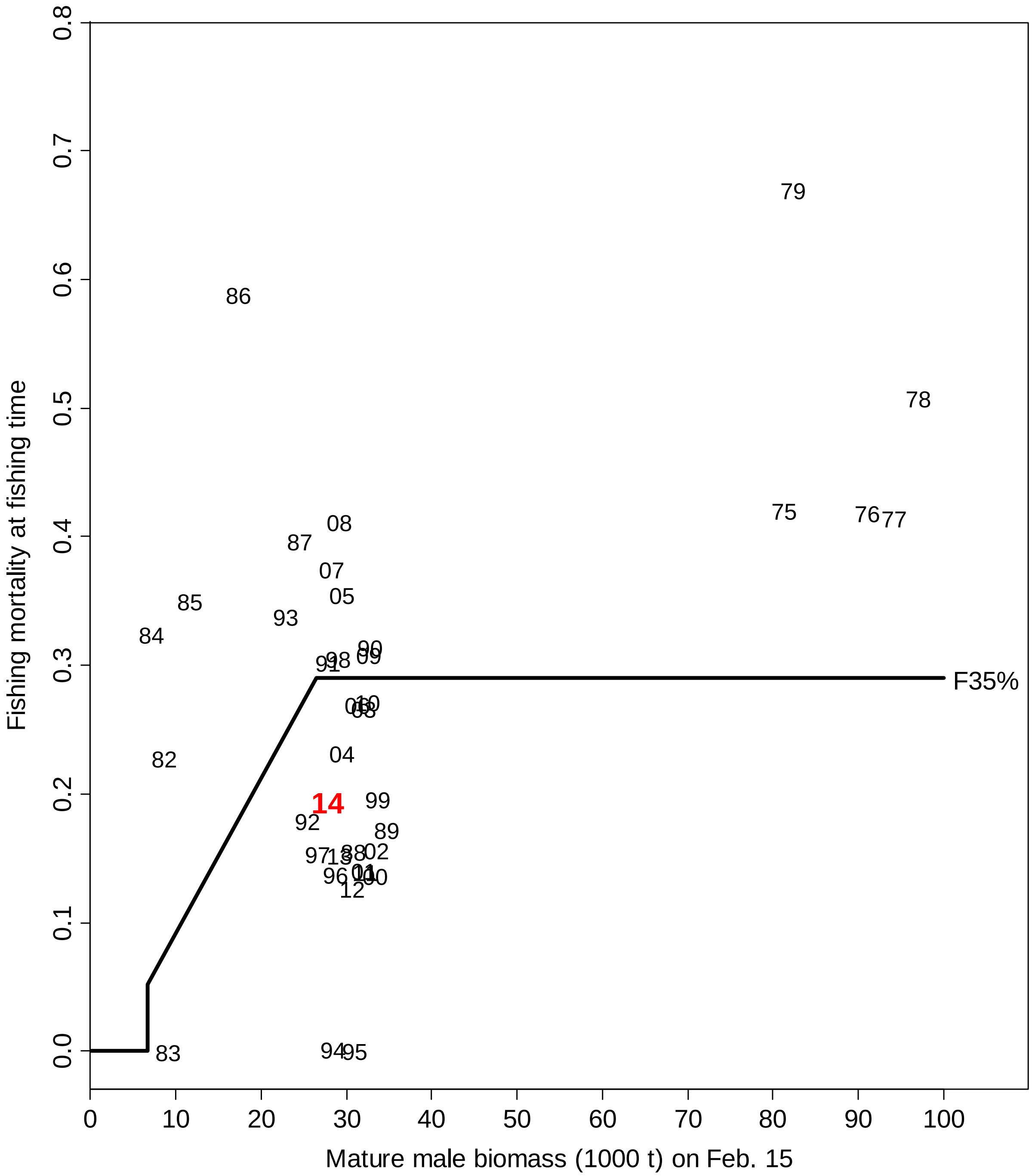


Figure 13(1a). Relationships between full fishing mortalities for the directed pot fishery and mature male biomass on Feb. 15 during 1975-2014 under scenario 1a. Average of recruitment from 1984 to 2015 was used to estimate B_{MSY}. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

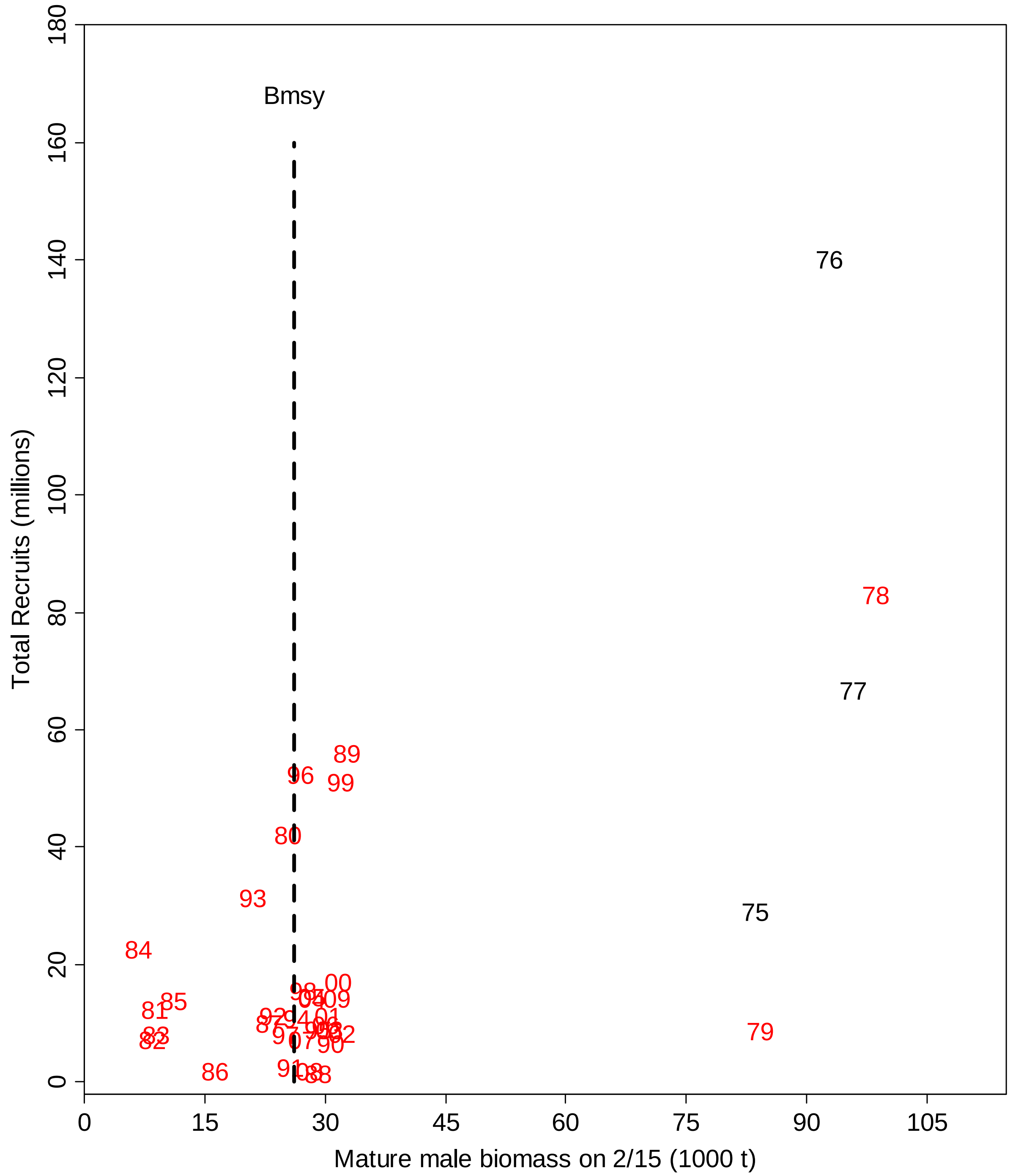


Figure 14a. Relationships between mature male biomass on Feb. 15 and total recruits at age 5 (i.e., 6-year time lag) for Bristol Bay red king crab with pot handling mortality rate of 0.2 under scenario 1. Numerical labels are years of mating, and the vertical dotted line is the estimated $B_{35\%}$ based on the mean recruitment level during 1984 to 2015.

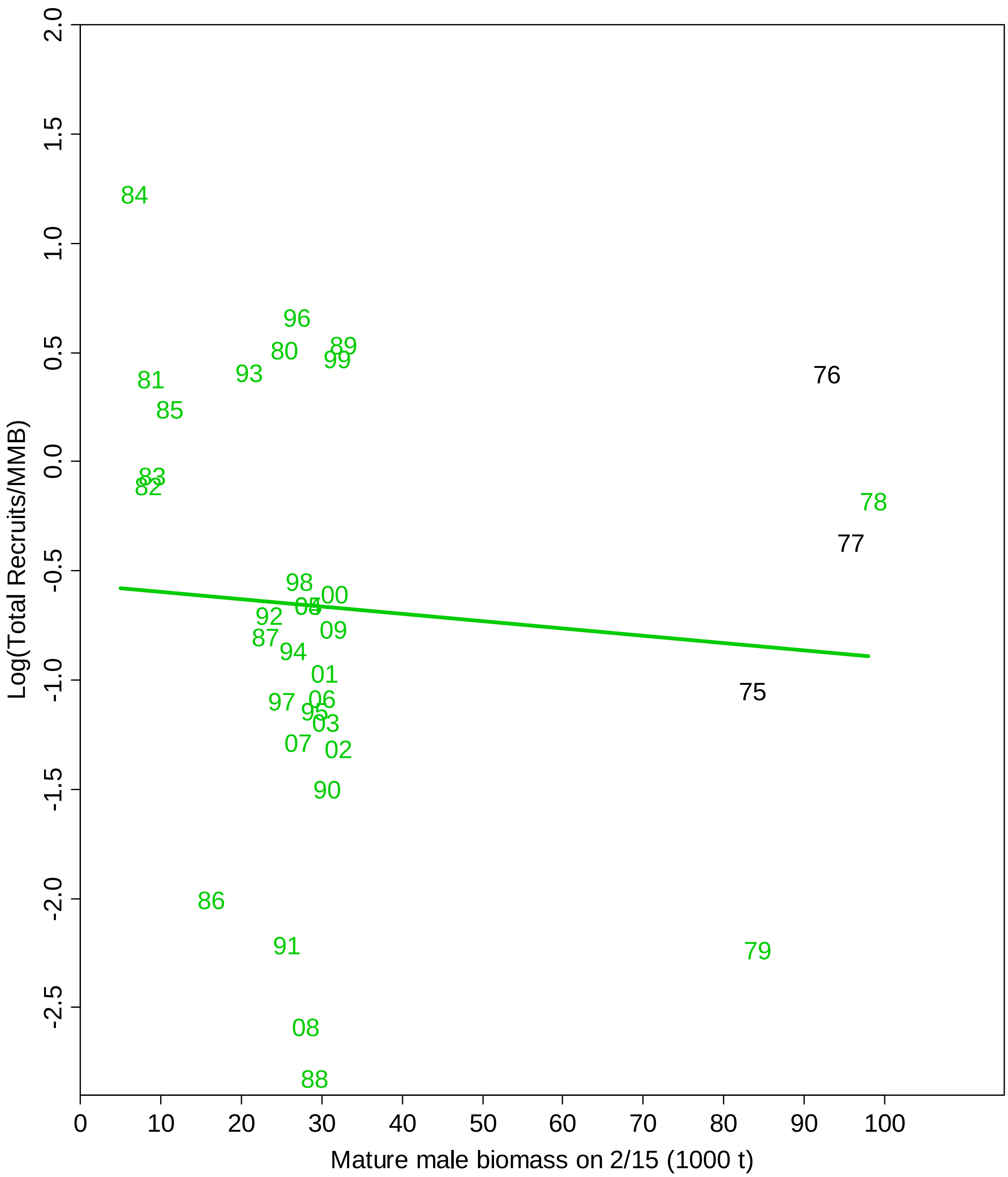


Figure 14b. Relationships between log recruitment per mature male biomass and mature male biomass on Feb. 15 for Bristol Bay red king crab with pot handling mortality rate of 0.2 under scenario 1. Numerical labels are years of mating, and the line is the regression line for data of 1978-2009.

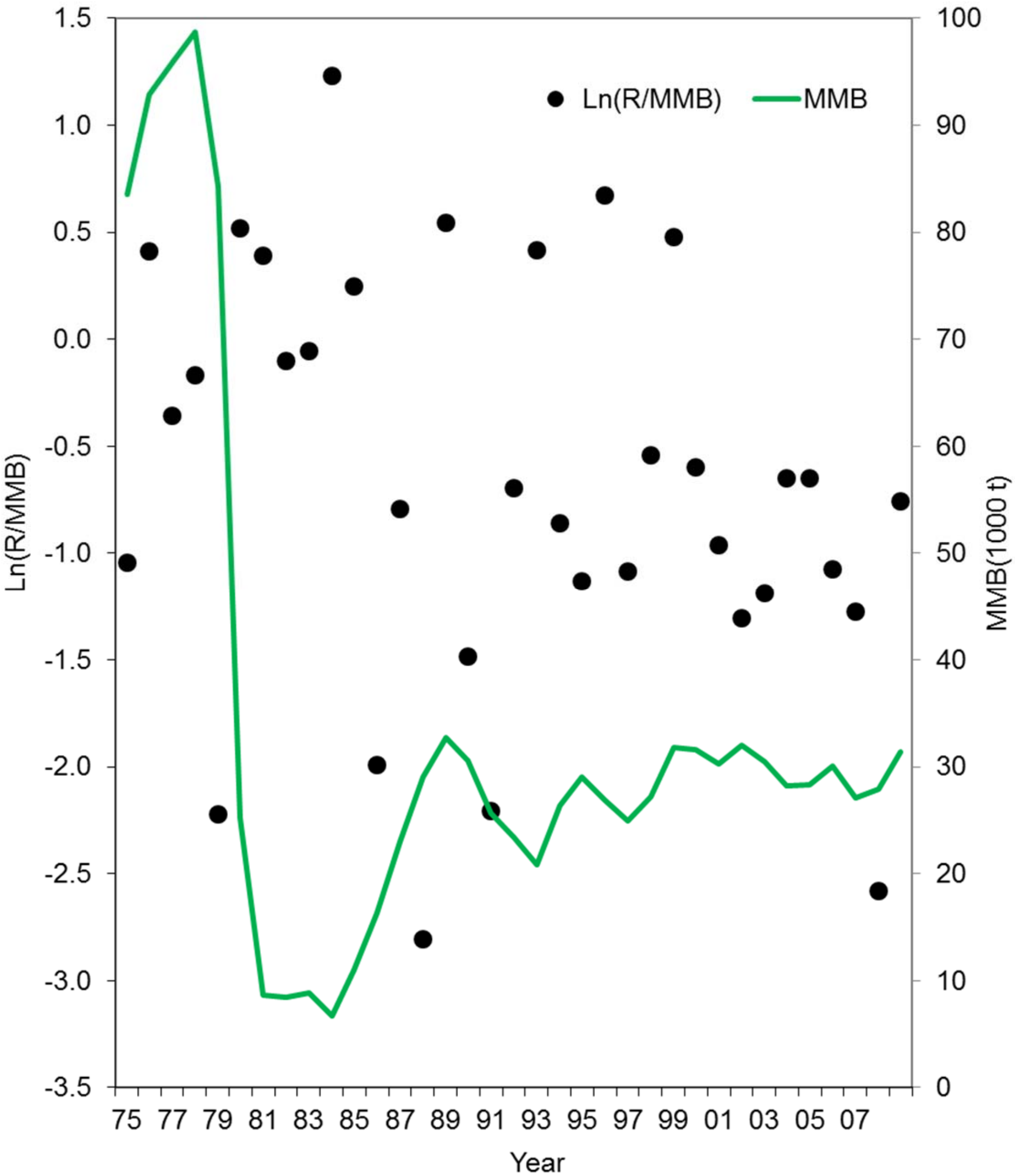


Figure 14c. Time series of log recruitment per mature male biomass and mature male biomass on Feb. 15 for Bristol Bay red king crab with pot handling mortality rate of 0.2 under scenario 1.

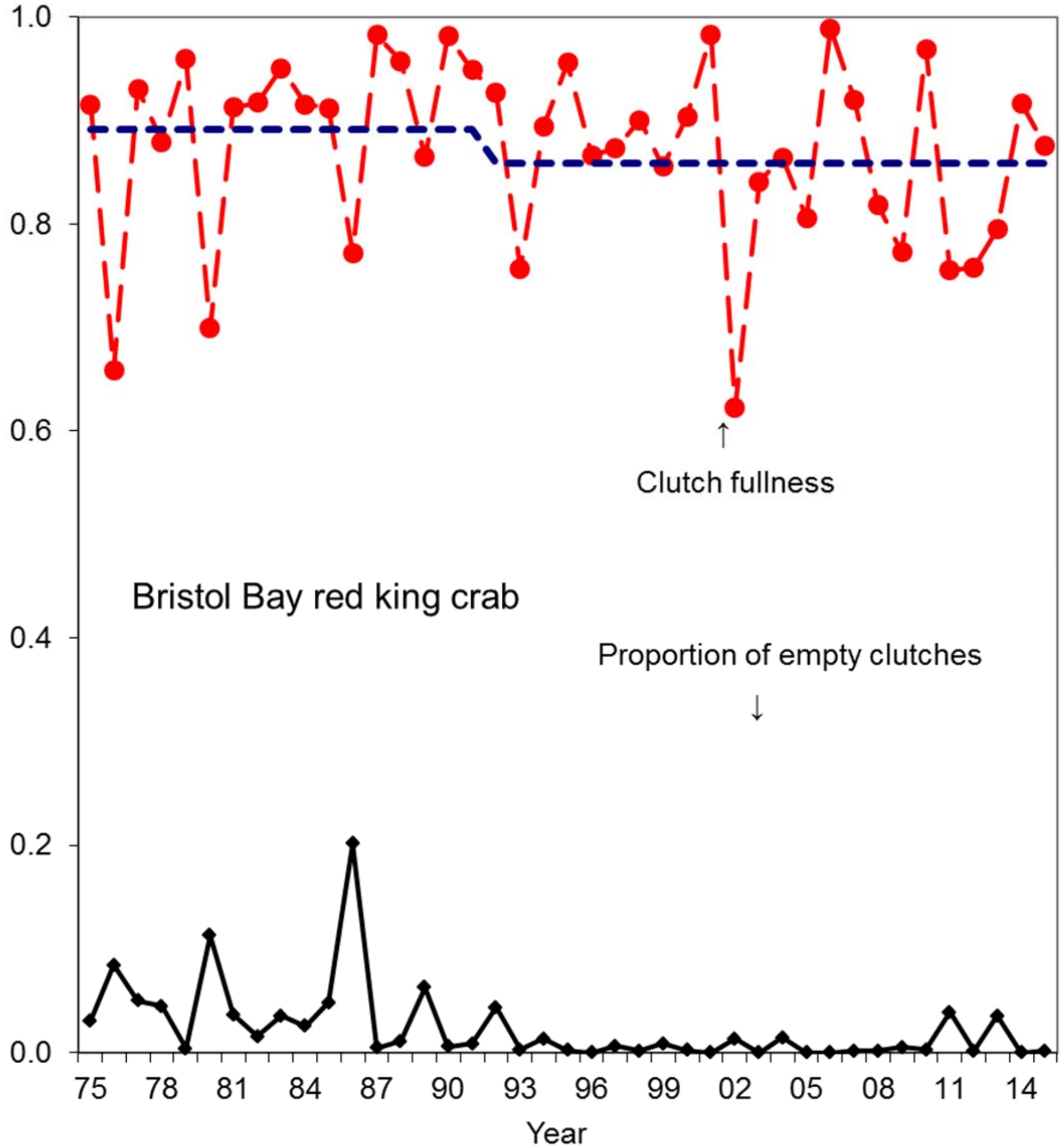


Figure 15. Average clutch fullness and proportion of empty clutches of newshell (shell conditions 1 and 2) mature female crab >89 mm CL from 1975 to 2015 from survey data. Oldshell females were excluded.

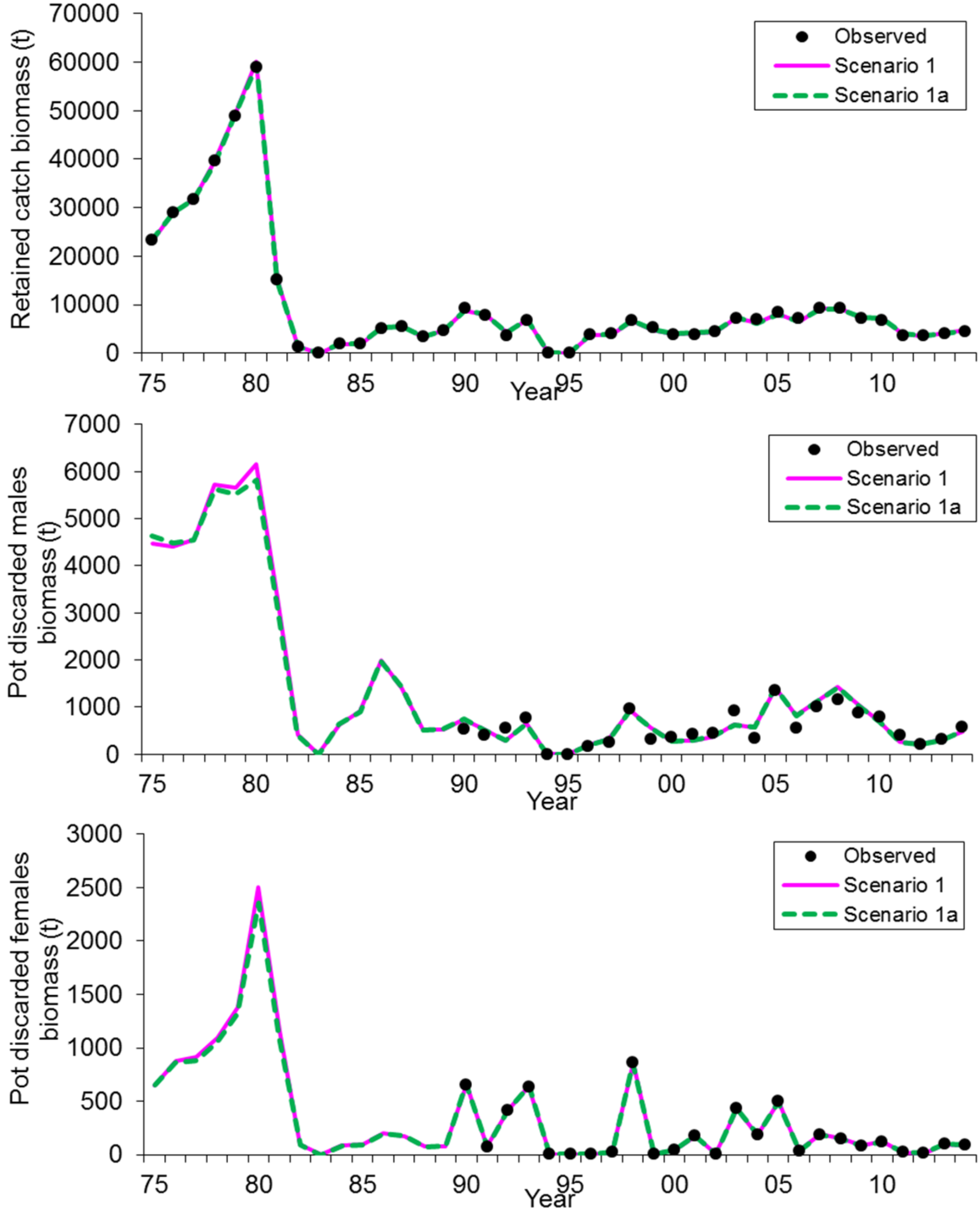
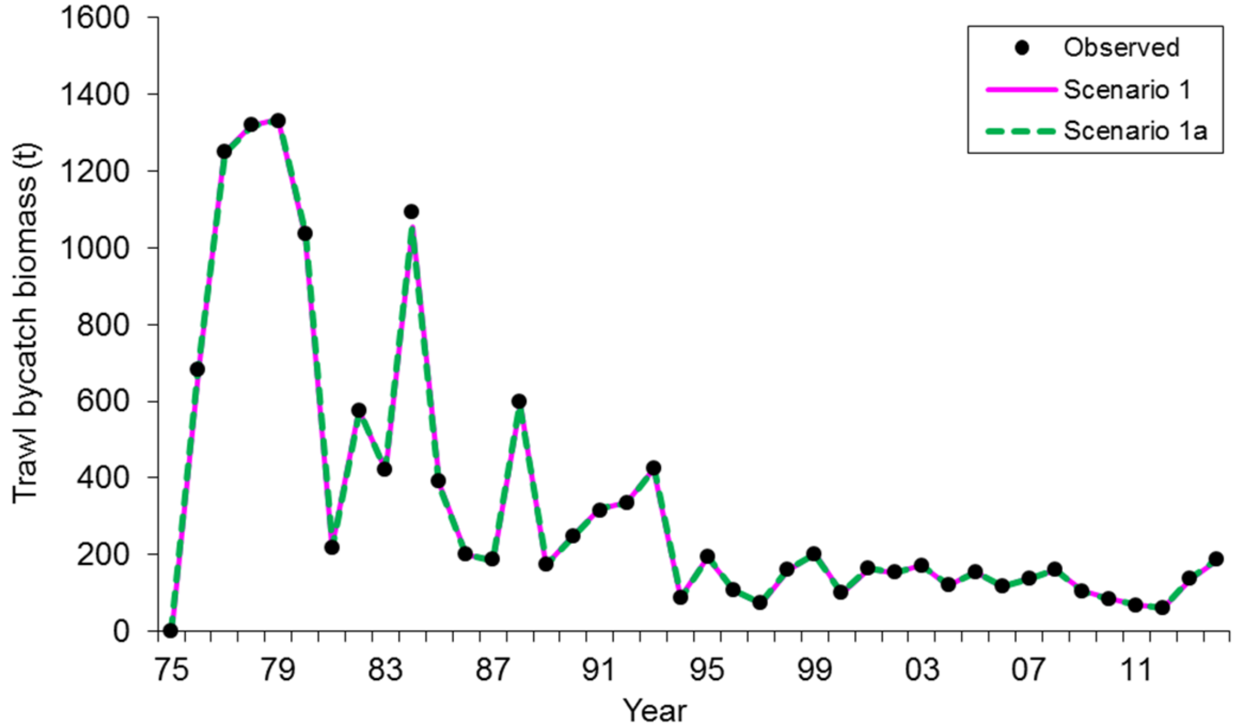


Figure 16a. Observed and predicted catch mortality biomass under scenarios 1 and 1a. Mortality biomass is equal to caught biomass times a handling mortality rate. Pot handling mortality rate is 0.2.



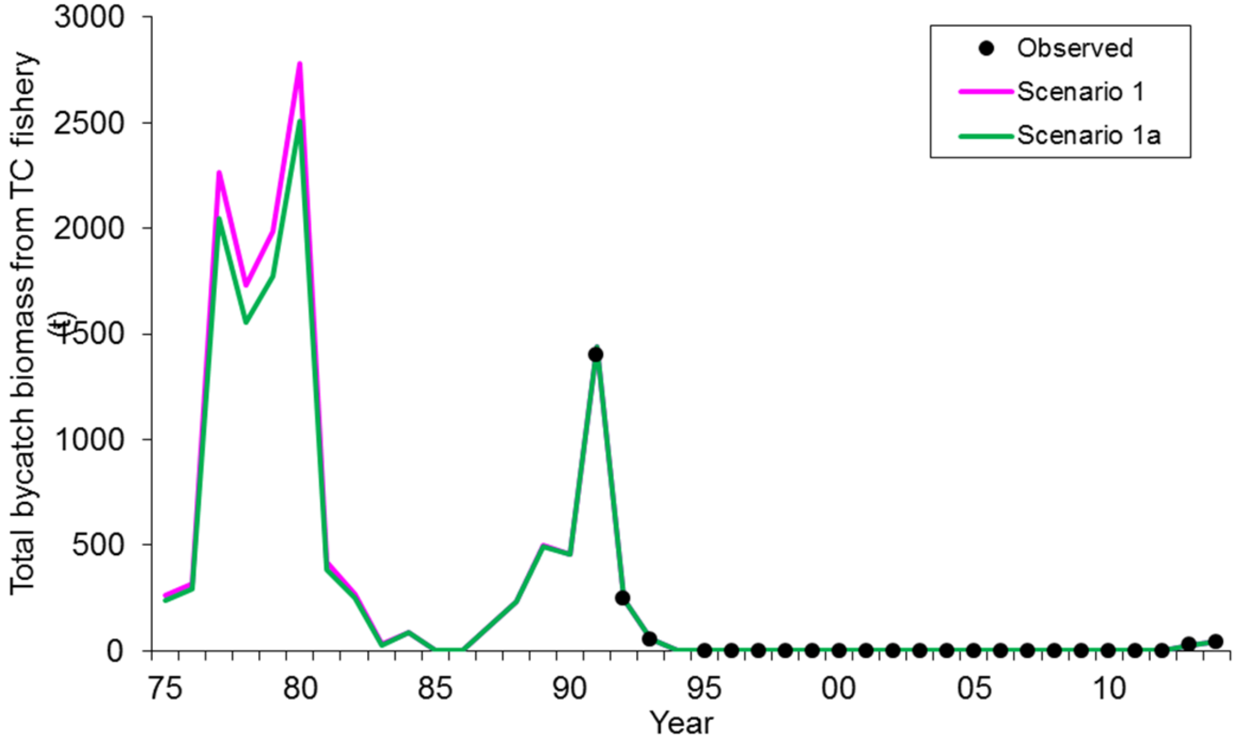


Figure 16b. Observed and predicted bycatch mortality biomass from trawl fisheries and the Tanner crab fishery under scenarios 1 and 1a. Mortality biomass is equal to caught biomass times a handling mortality rate. Trawl handling mortality rate is 0.8, and Tanner crab pot handling mortality is 0.25. Trawl bycatch biomass was 0 before 1976.

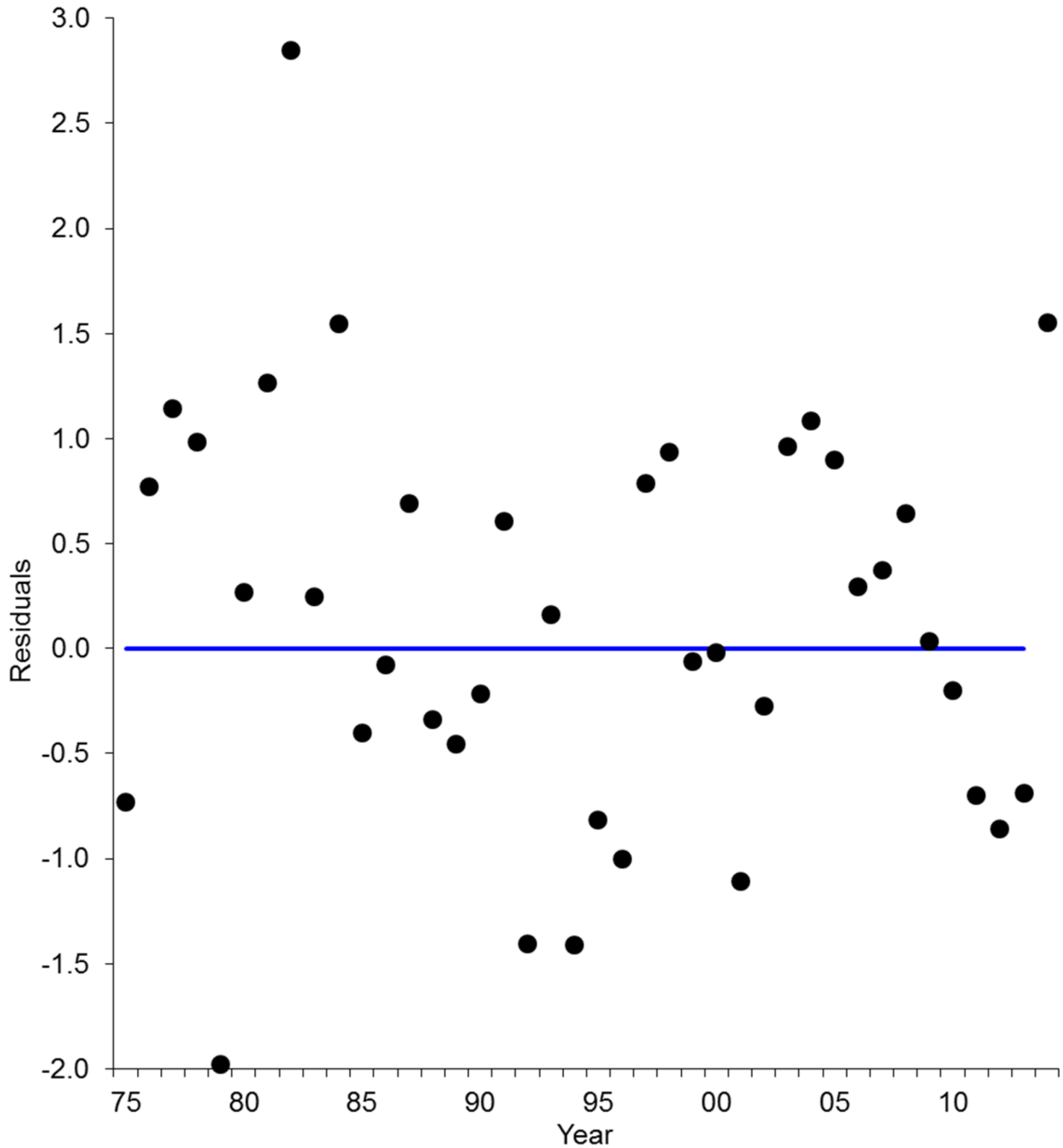


Figure 17(1). Standardized residuals of total survey biomass under scenario 1. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

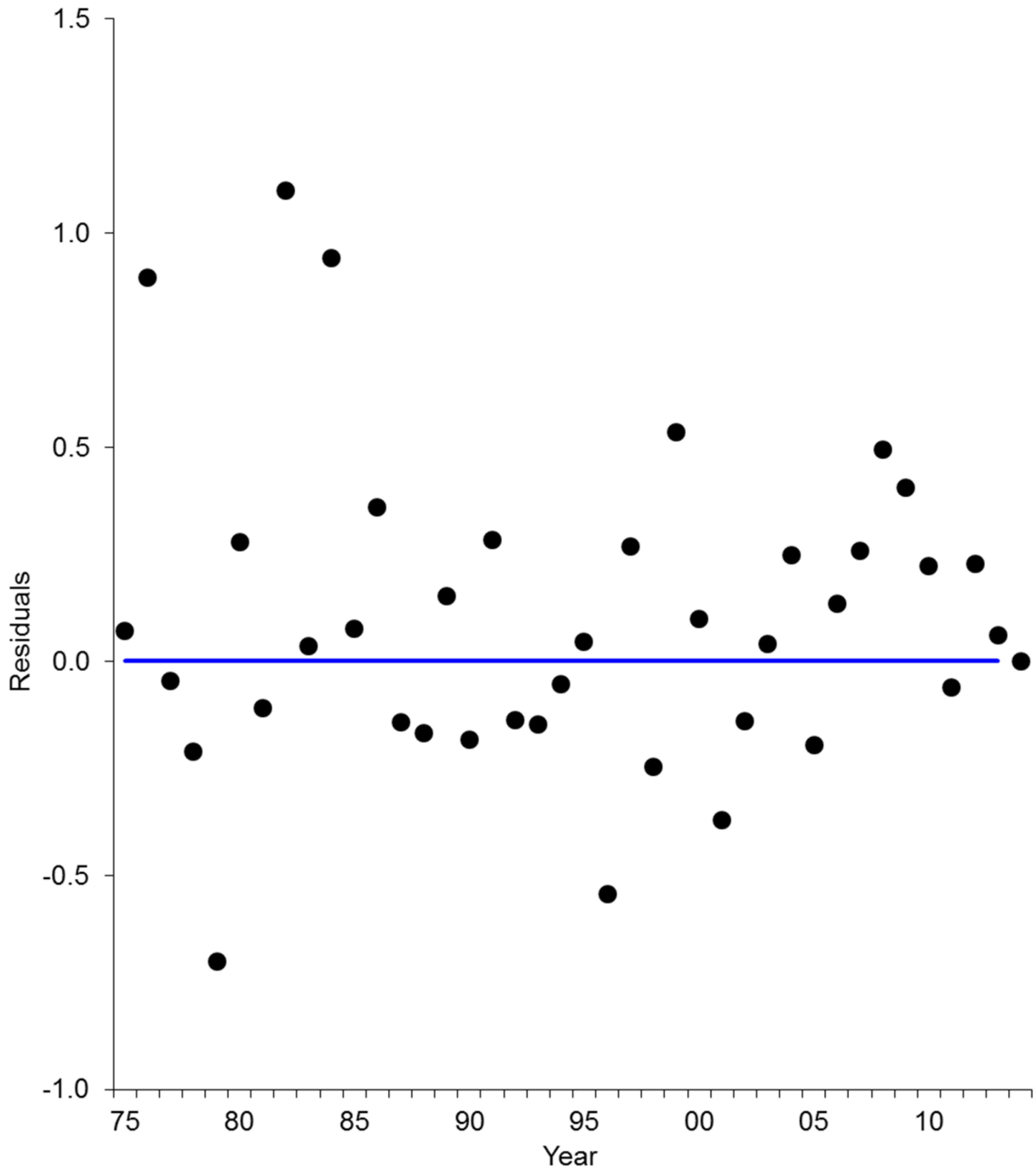


Figure 17(1a). Standardized residuals of total survey biomass under scenario 1a. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

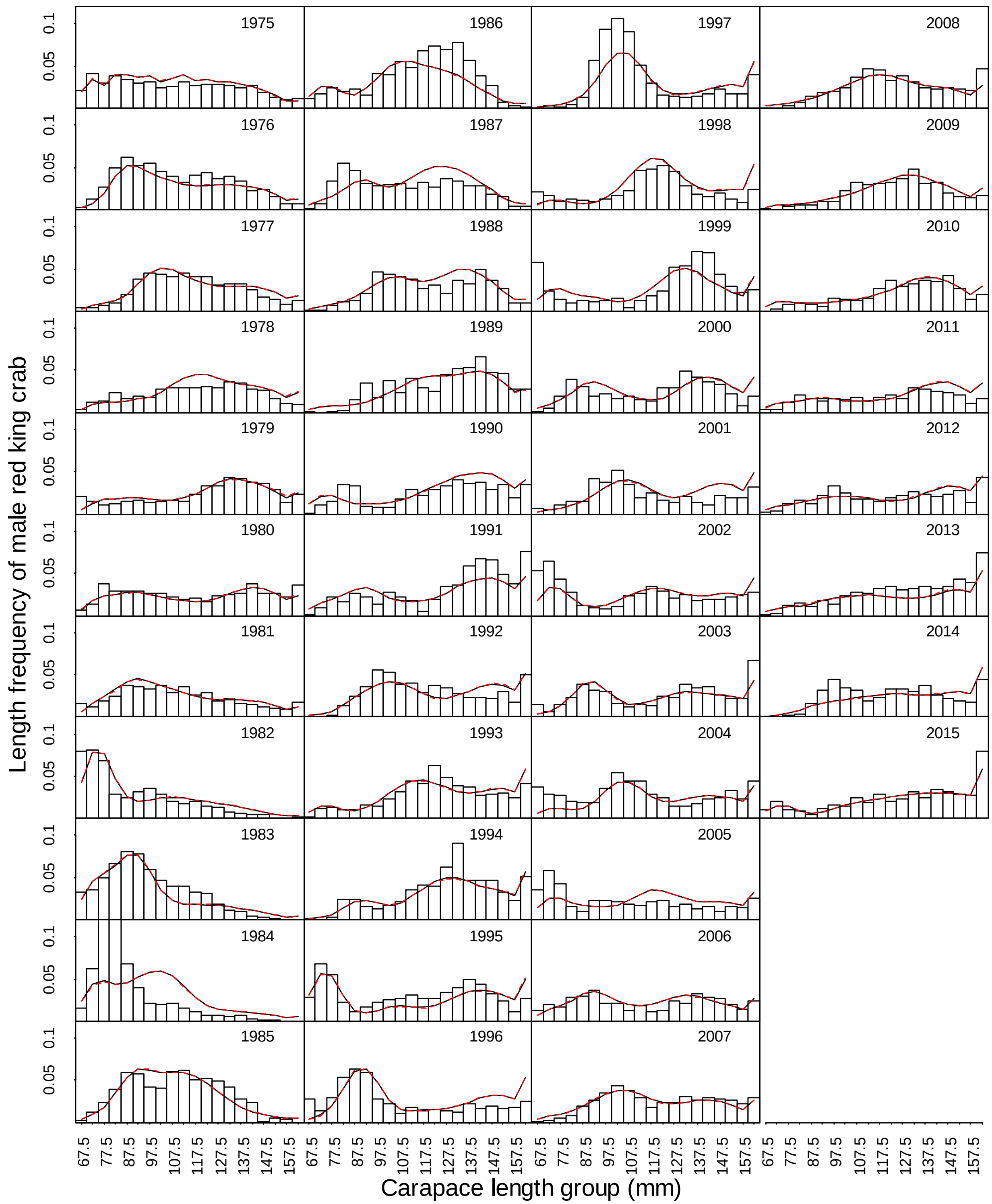


Figure 18(1 & 1a). Comparison of area-swept and model estimated survey length frequencies of Bristol Bay male red king crab by year under scenarios 1(solid black) and 1a(dashed red). Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8.

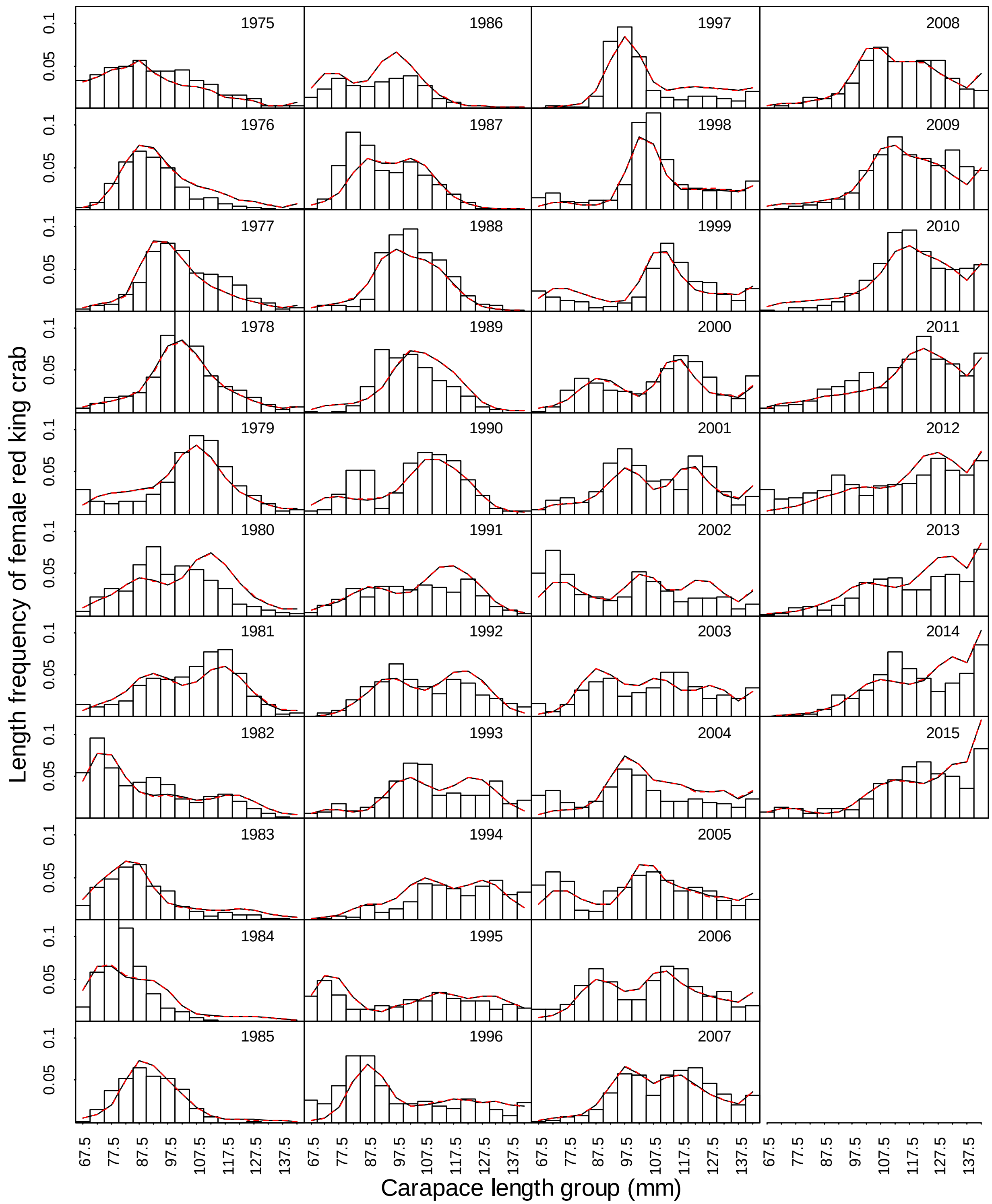


Figure 19(1 & 1a). Comparison of area-swept and model estimated survey length frequencies of Bristol Bay female red king crab by year under scenarios 1(solid black) and 1a(dashed red). Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

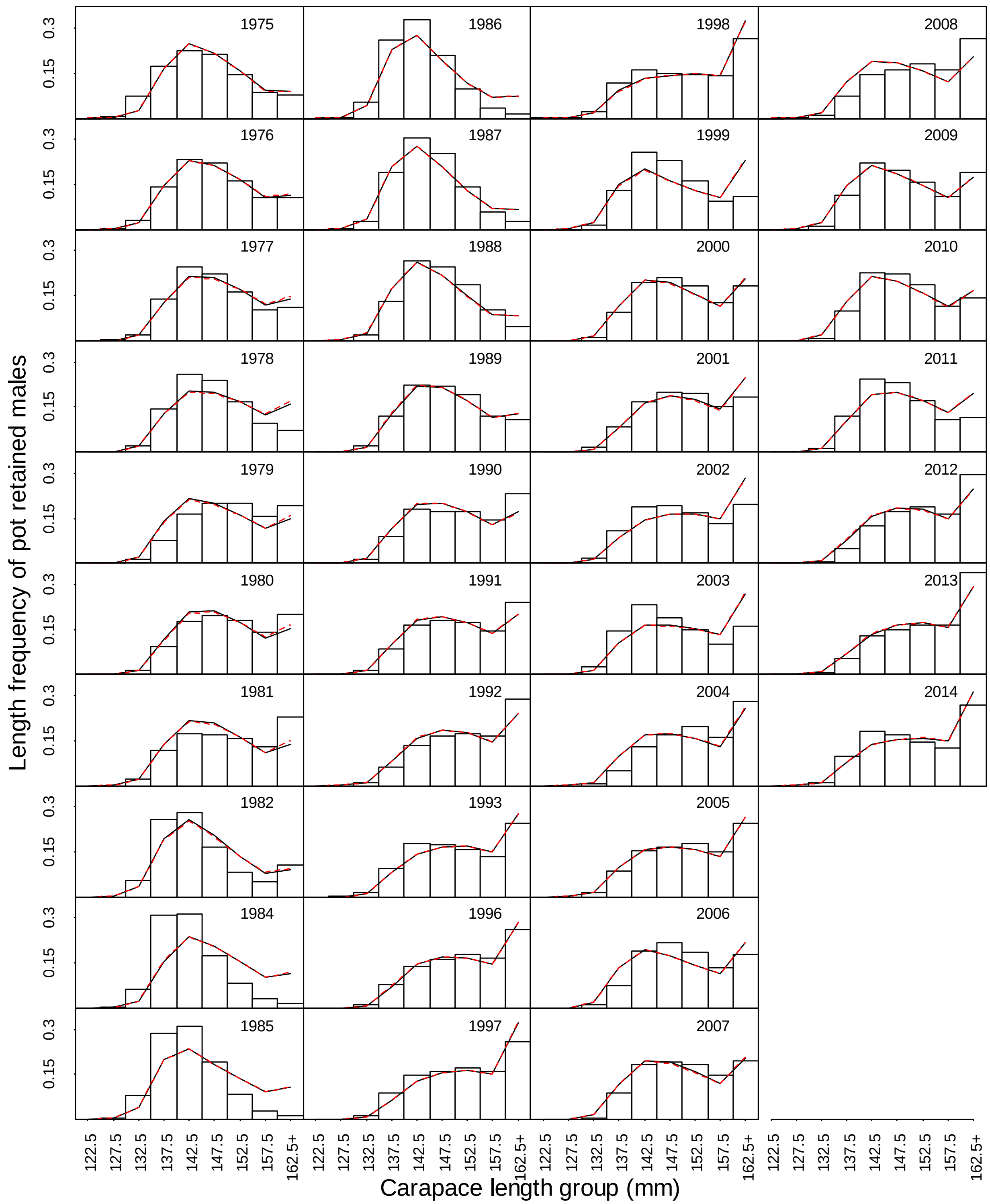


Figure 20(1 & 1a). Comparison of observed and model estimated retained length frequencies of Bristol Bay male red king crab by year in the directed pot fishery under scenarios 1 (solid black) and 1a(dashed red). Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

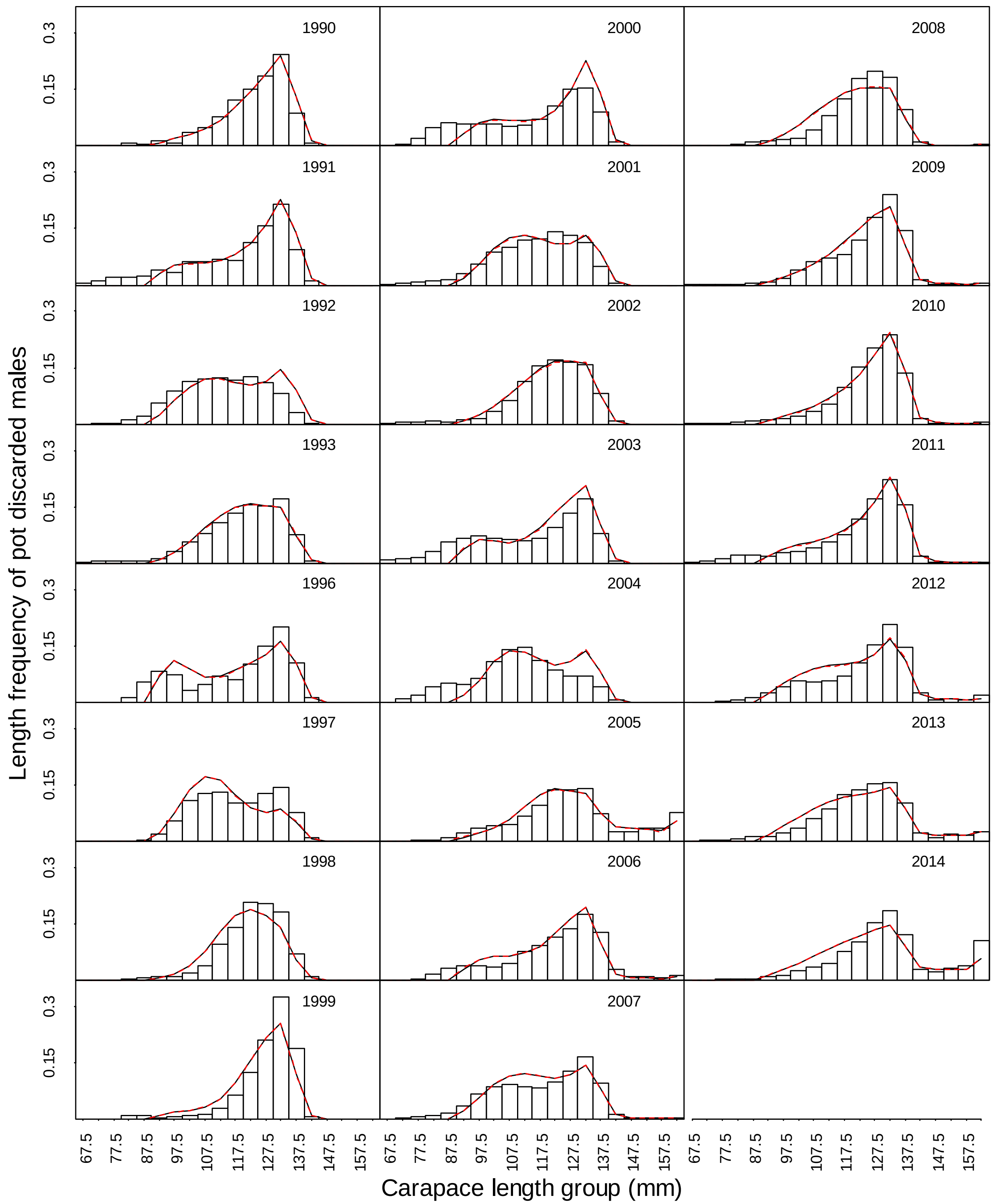


Figure 21(1 & 1a). Comparison of observer and model estimated discarded length frequencies of Bristol Bay male red king crab by year in the directed pot fishery under scenarios 1 (solid black) and 1a (dashed red). Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

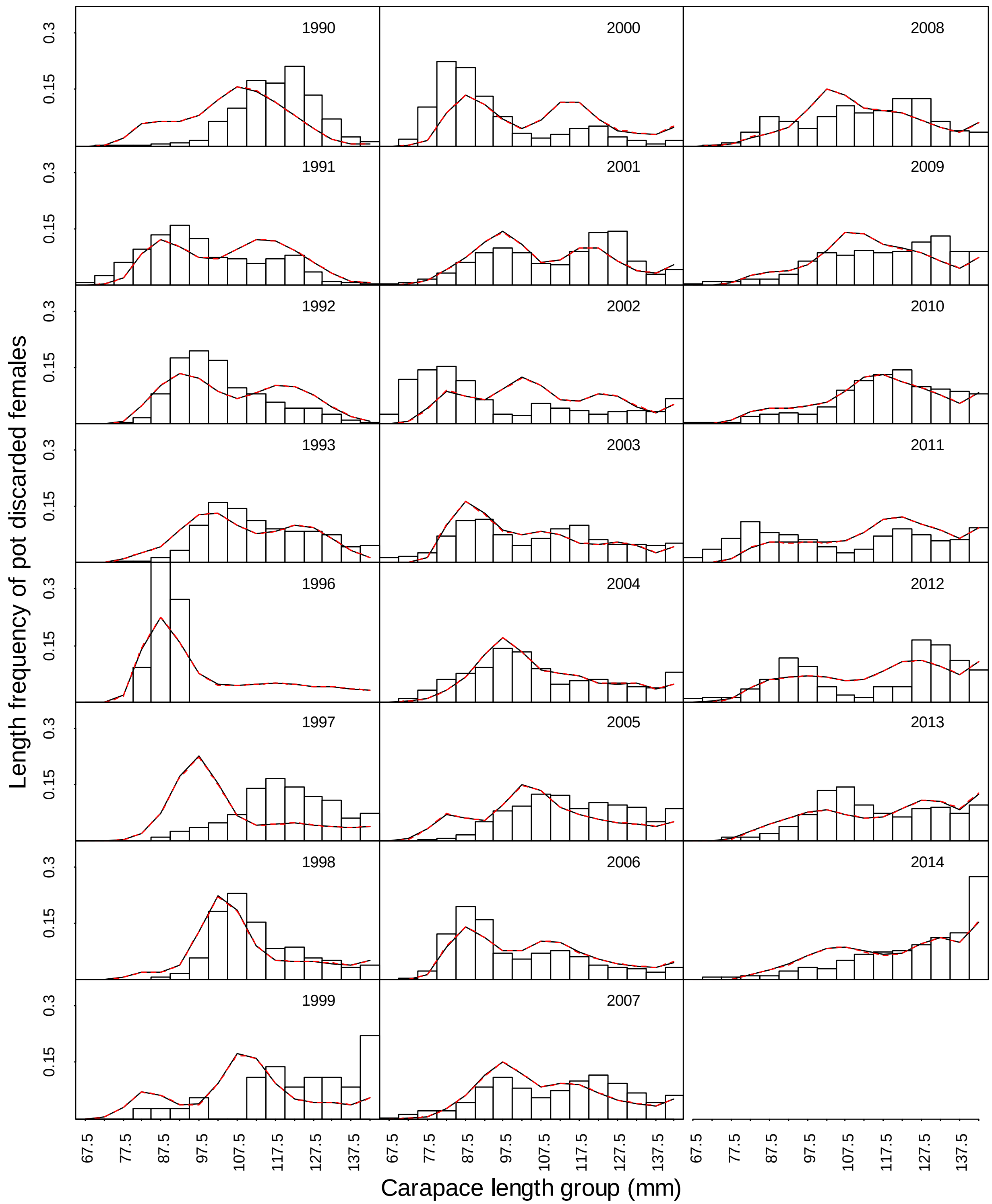


Figure 22(1 & 1a). Comparison of observer and model estimated discarded length frequencies of Bristol Bay female red king crab by year in the directed pot fishery under scenarios 1 (solid black) and 1a (dashed red). Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

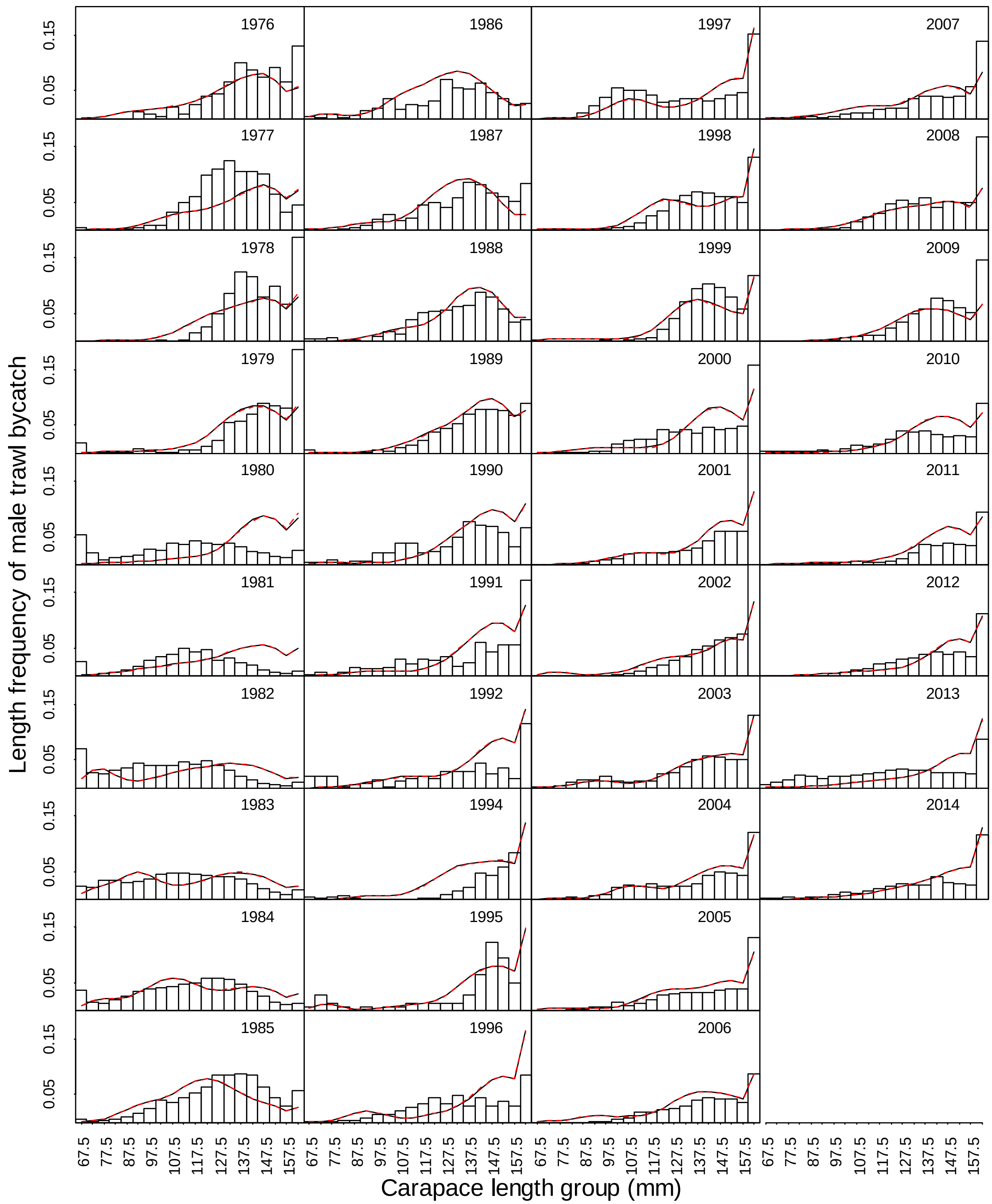


Figure 23(1 & 1a). Comparison of observer and model estimated discarded length frequencies of Bristol Bay male red king crab by year in the groundfish trawl fisheries under scenarios 1 (solid black) and 1a (dashed red). Pot handling mortality rate is 0.2, and trawl bycatch mortality rate is 0.8.

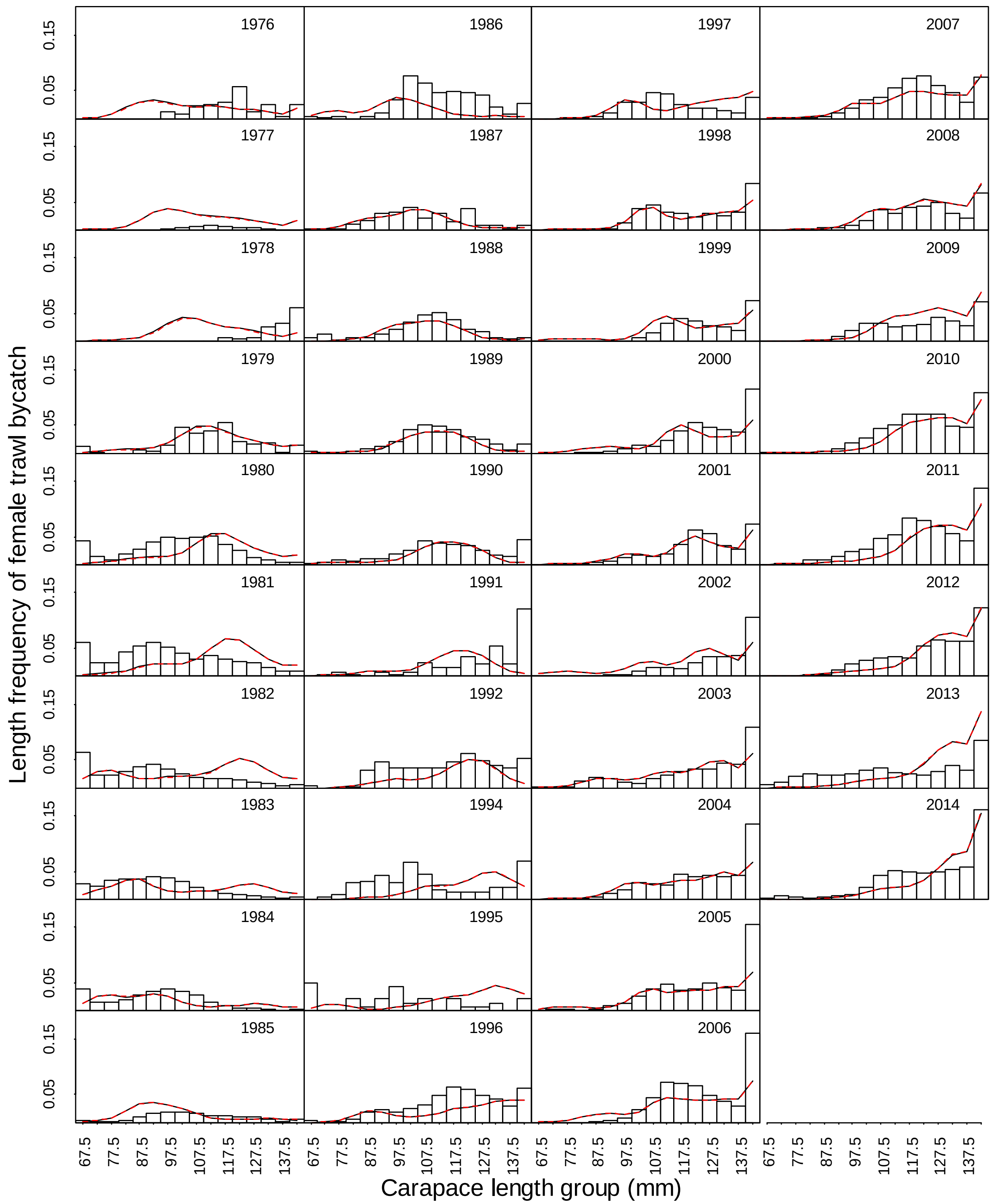


Figure 24(1 & 1a). Comparison of observer and model estimated discarded length frequencies of Bristol Bay female red king crab by year in the groundfish trawl fisheries under scenarios 1 (solid black) and 1a (dashed red). Pot handling mortality rate is 0.2, and trawl bycatch mortality rate is 0.8.

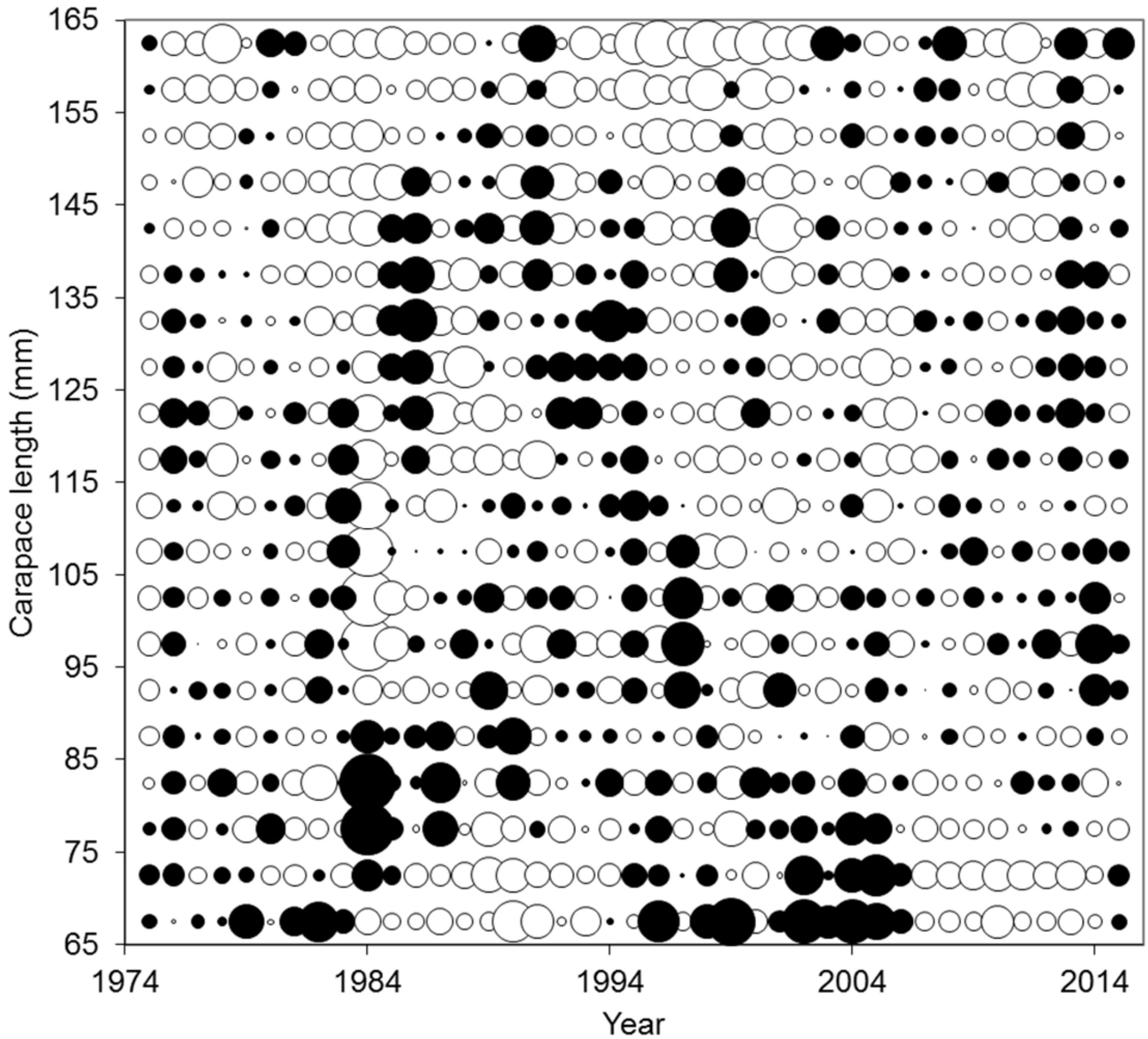


Figure 25(1). Standardized residuals of proportions of survey male red king crab under scenario 1. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

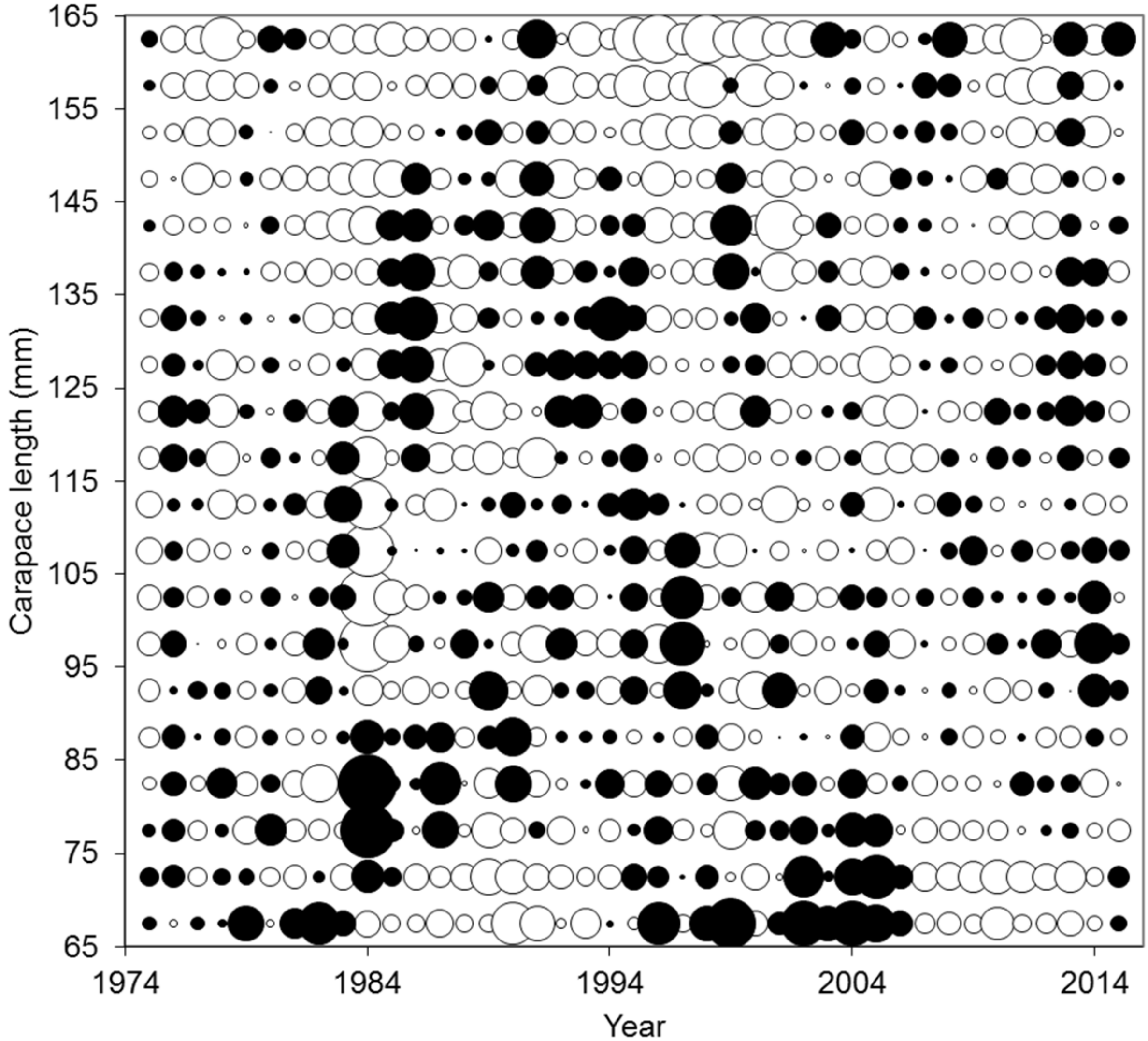


Figure 25(1a). Standardized residuals of proportions of survey male red king crab under scenario 1a. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

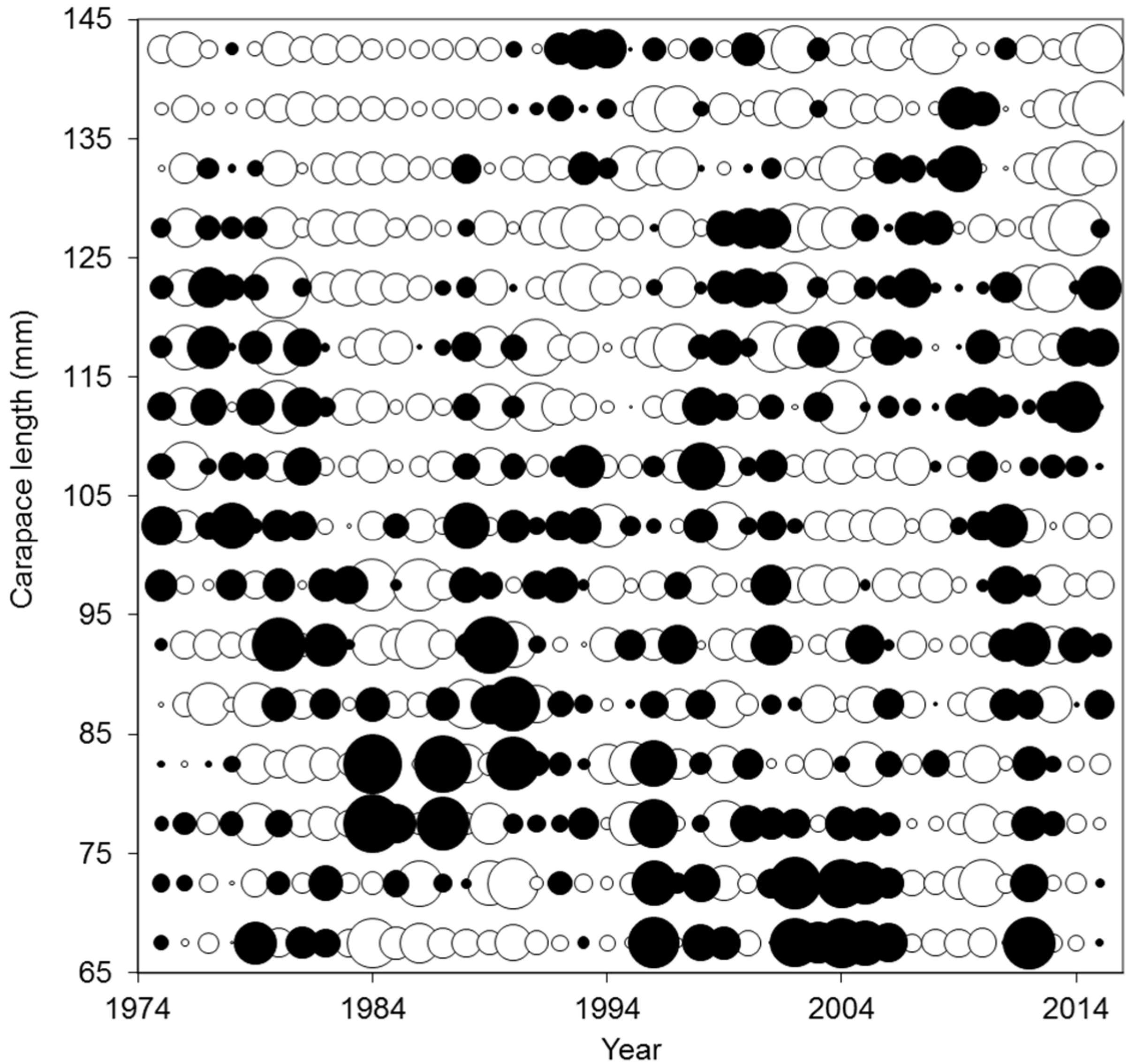


Figure 26(1). Standardized residuals of proportions of survey female red king crab under scenario 1. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

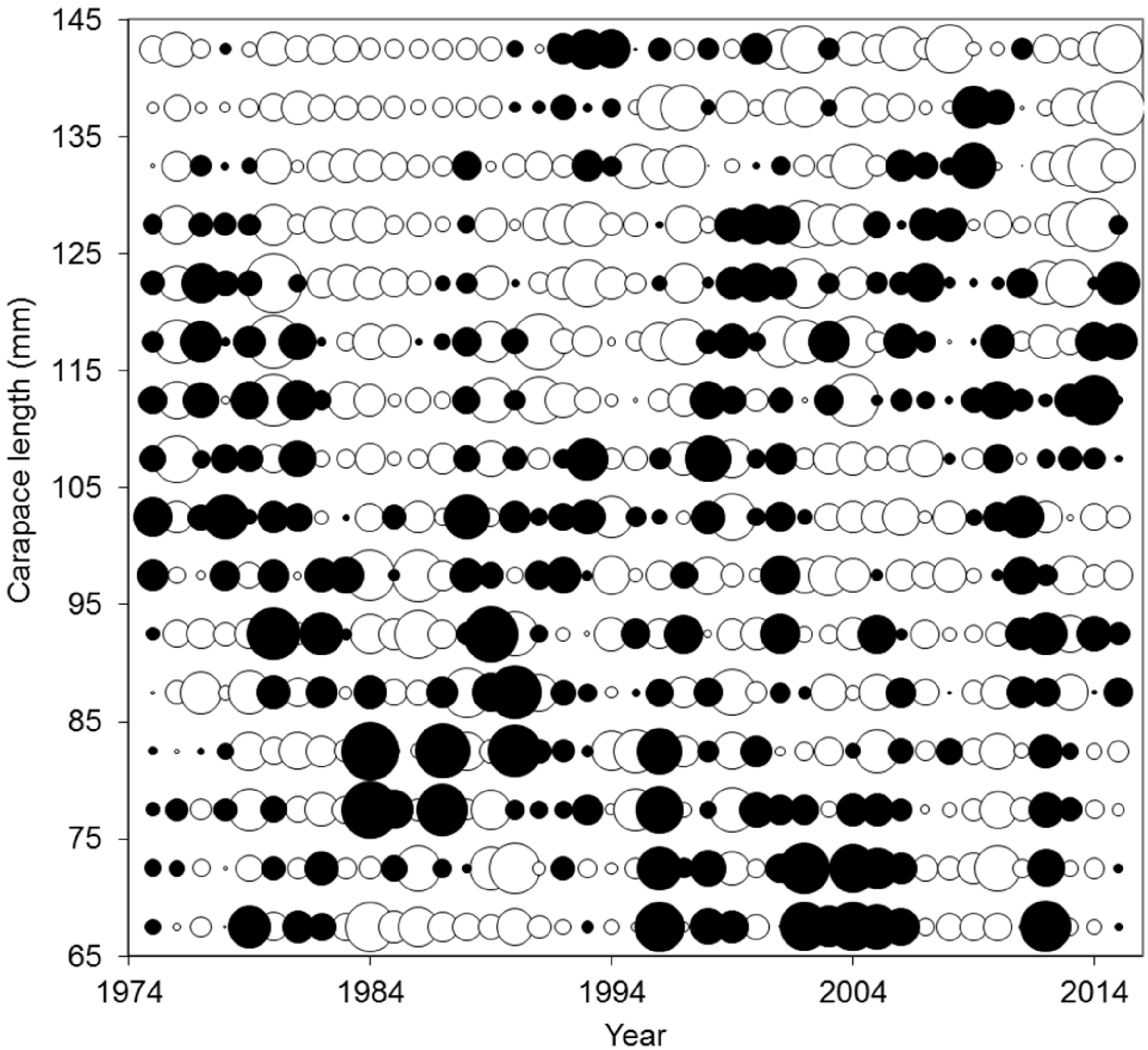


Figure 26(1a). Standardized residuals of proportions of survey female red king crab under scenario 1a. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

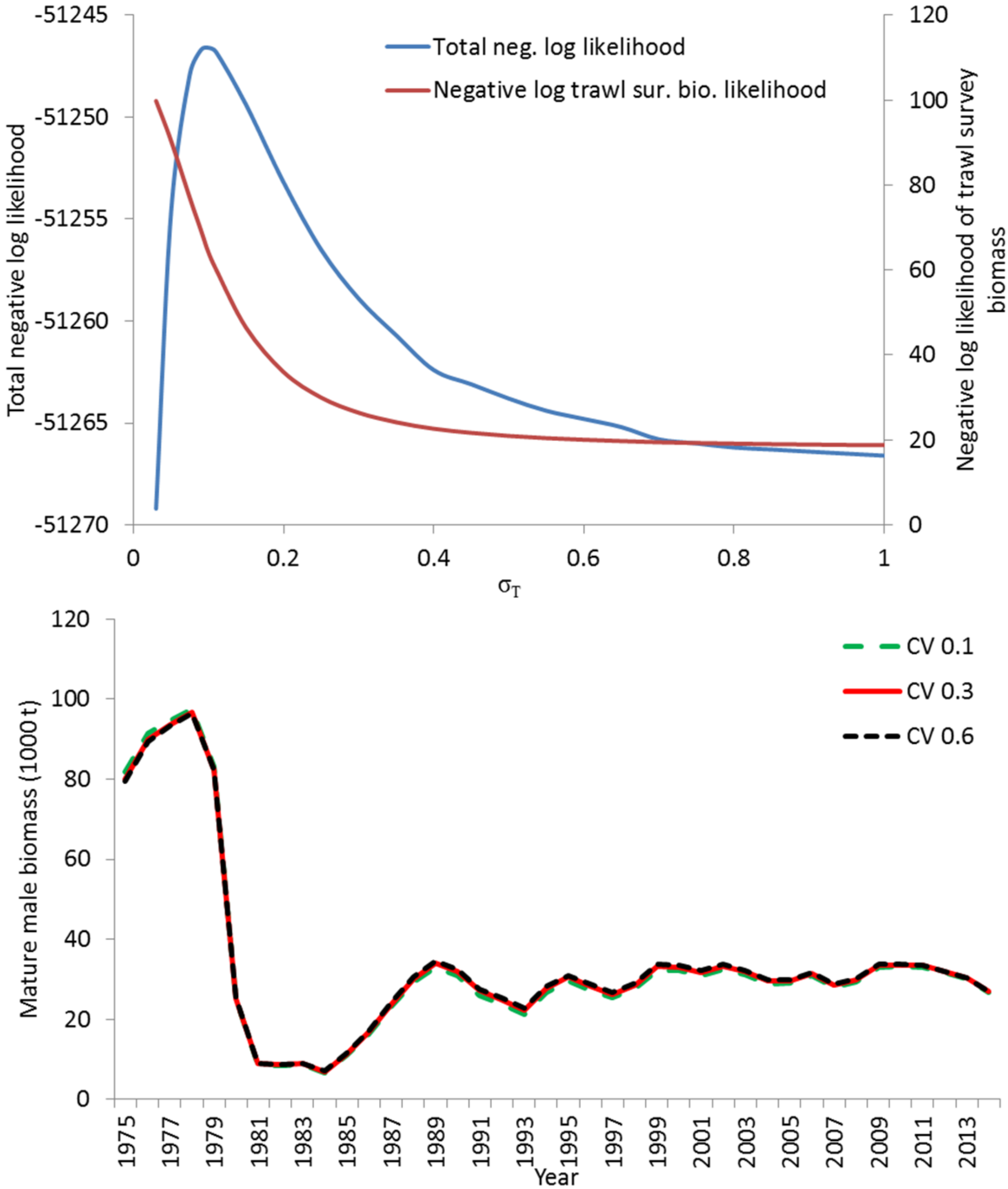


Figure 27a. Relationships among assumed temperature σ_T, total negative log likelihood and negative log trawl survey biomass likelihood (upper panel) and comparison of mature male biomass over time with assumed σ_T of 0.1, 0.3 and 0.6 (lower panel) for scenario 1a, based on data during 1975-2014.

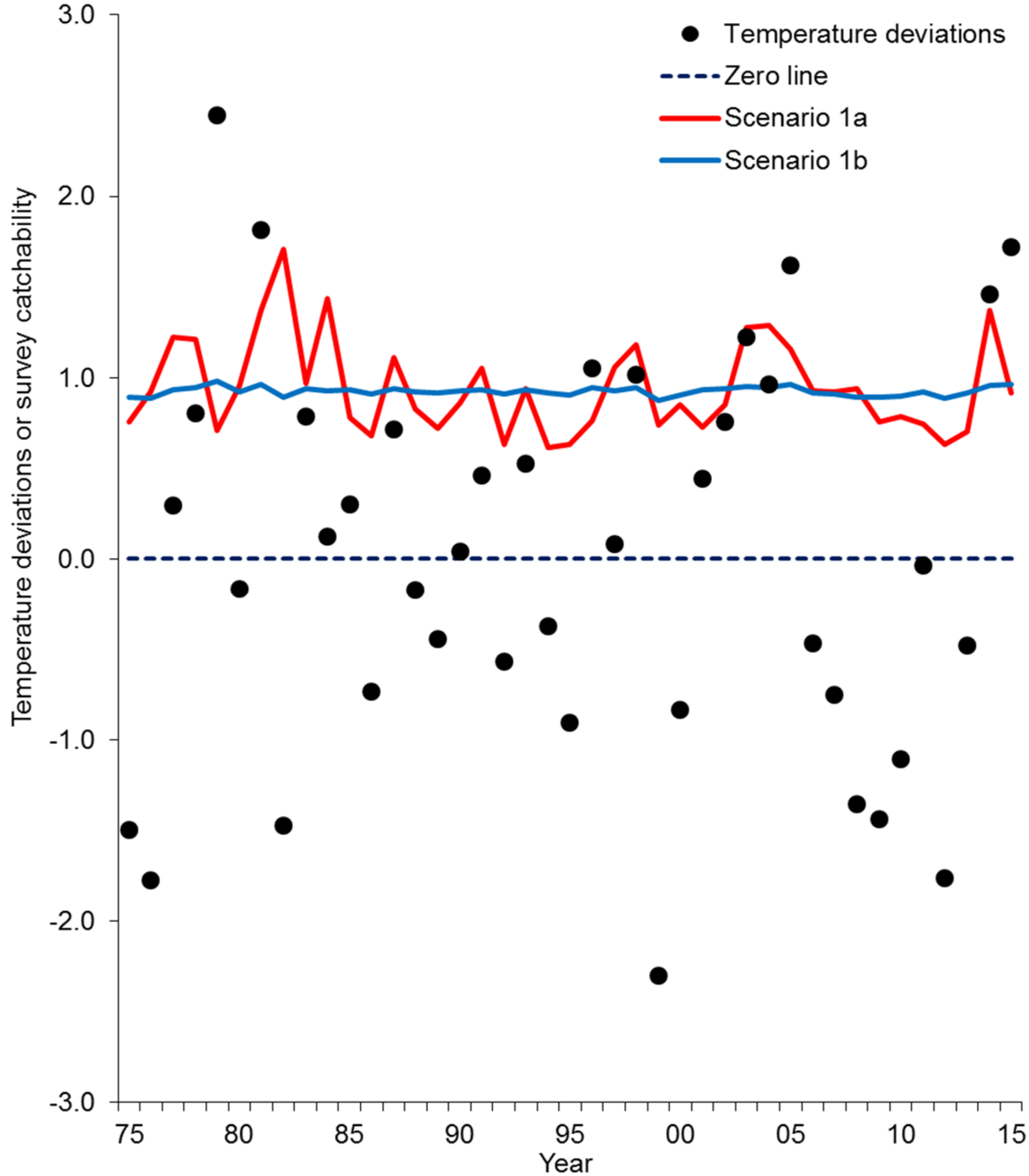


Figure 27b. Annual summer temperature deviations in Bristol Bay and annual estimated trawl survey catchabilities for scenarios 1a and 1b during 1975-2015.

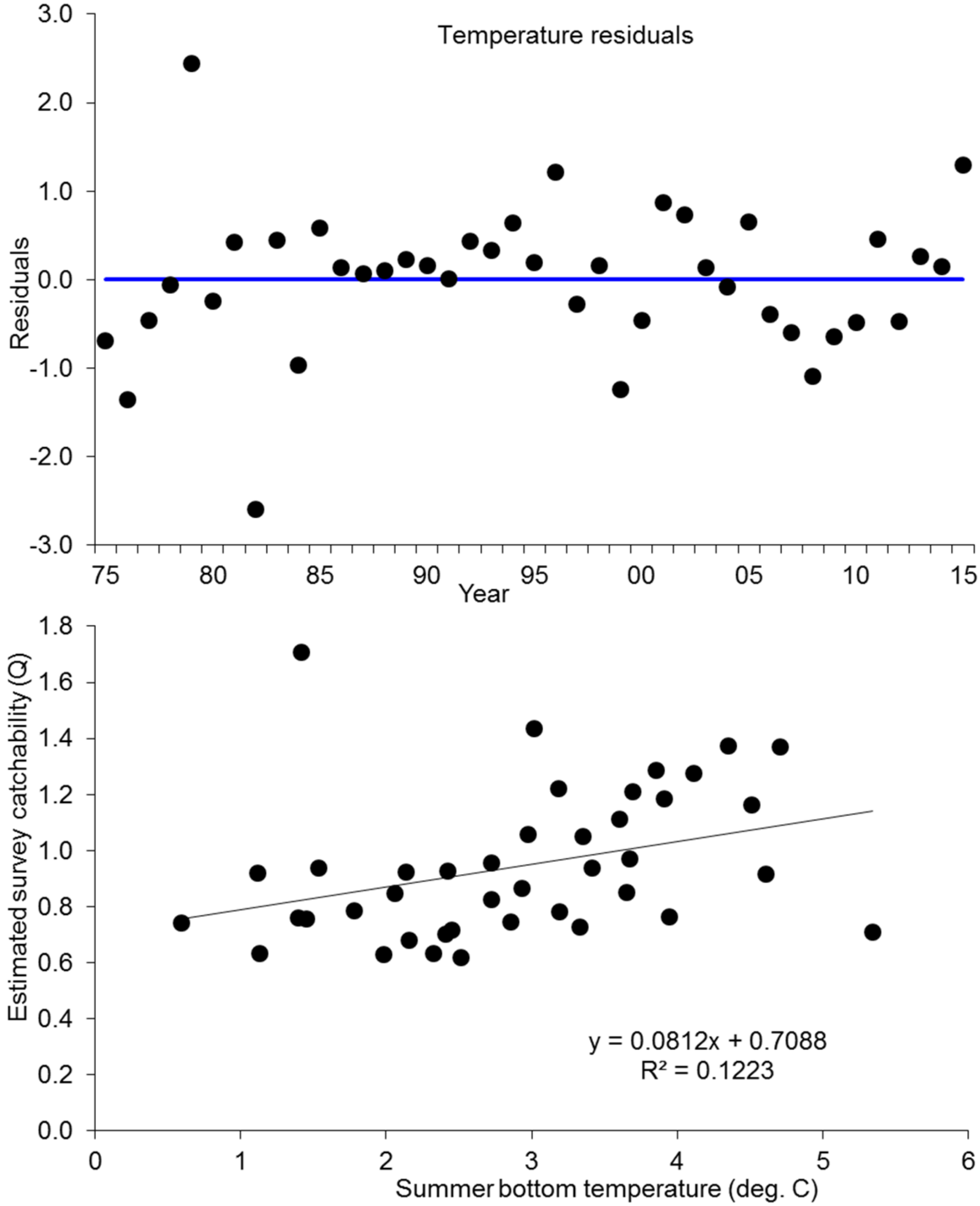


Figure 27c. Standardized temperature residuals during 1975-2015 (upper panel) and the relationship between annual estimated trawl survey catchabilities and summer bottom temperatures (lower panel) with an assumed σ_T of 0.3 for scenario 1a.

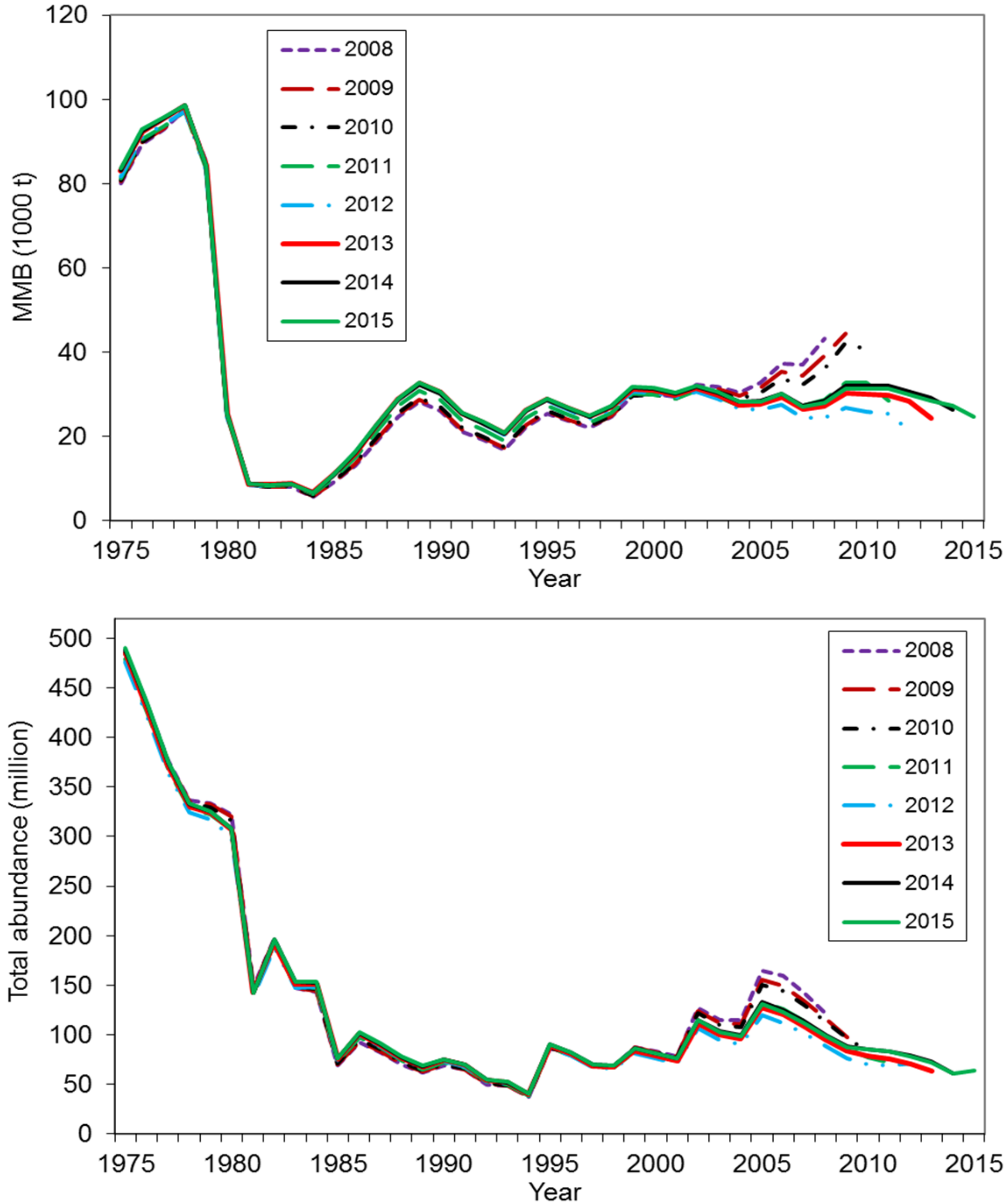
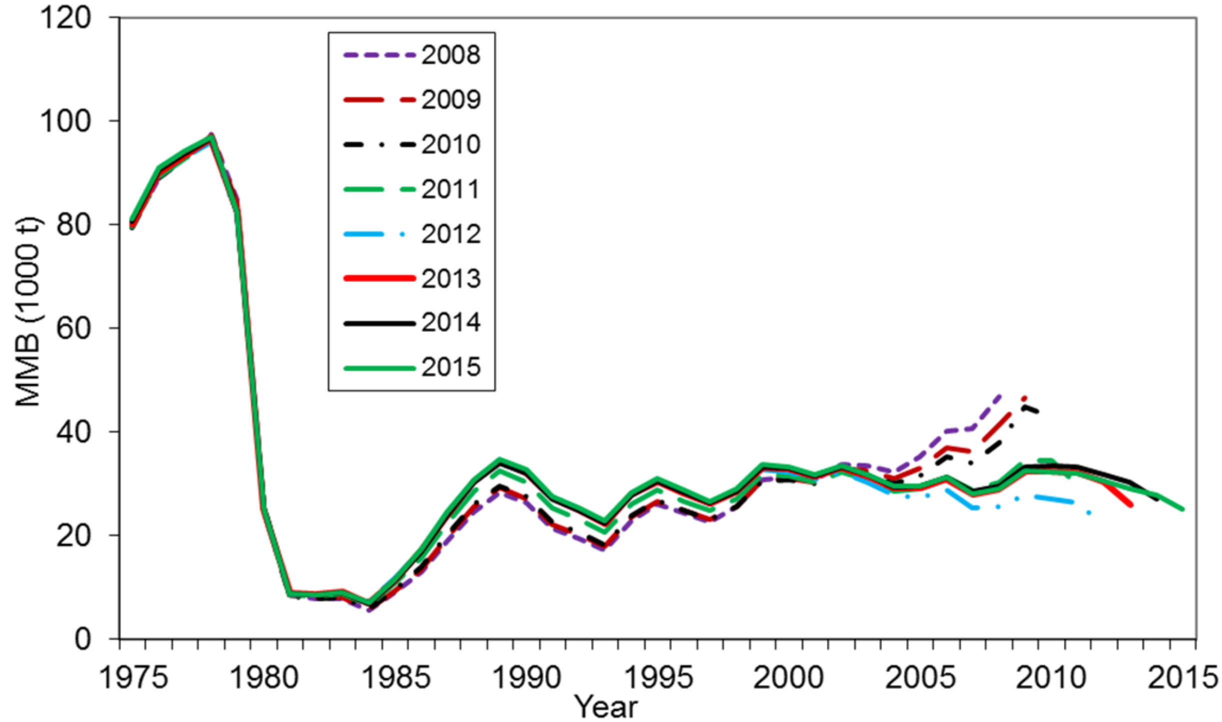


Figure 28a(1). Comparison of hindcast estimates of mature male biomass on Feb. 15 (top) and total abundance (bottom) of Bristol Bay red king crab from 1975 to 2015 made with terminal years 2008-2015 with scenario 1. These are results of the 2015 model. Legend shows the terminal year. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.



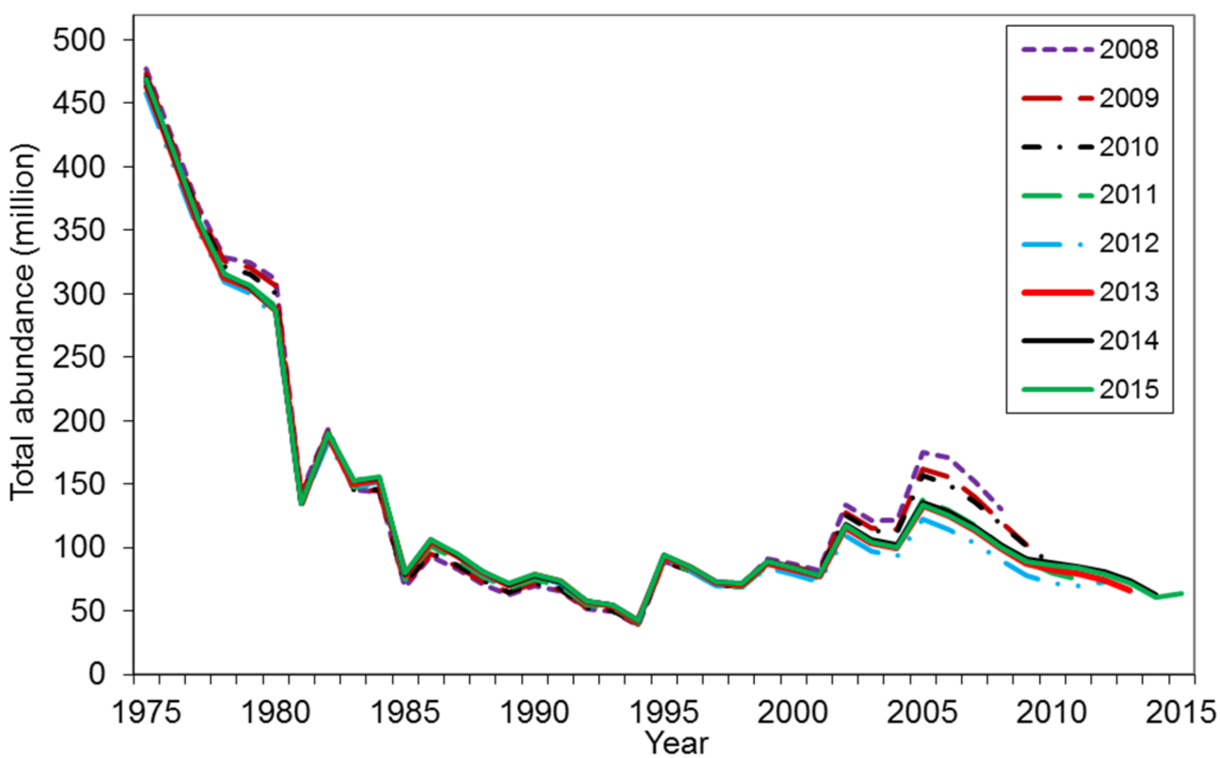


Figure 28a(1a). Comparison of hindcast estimates of mature male biomass on Feb. 15 (top) and total abundance (bottom) of Bristol Bay red king crab from 1975 to 2015 made with terminal years 2008-2015 with scenario 1a. These are results of the 2015 model. Legend shows the terminal year. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

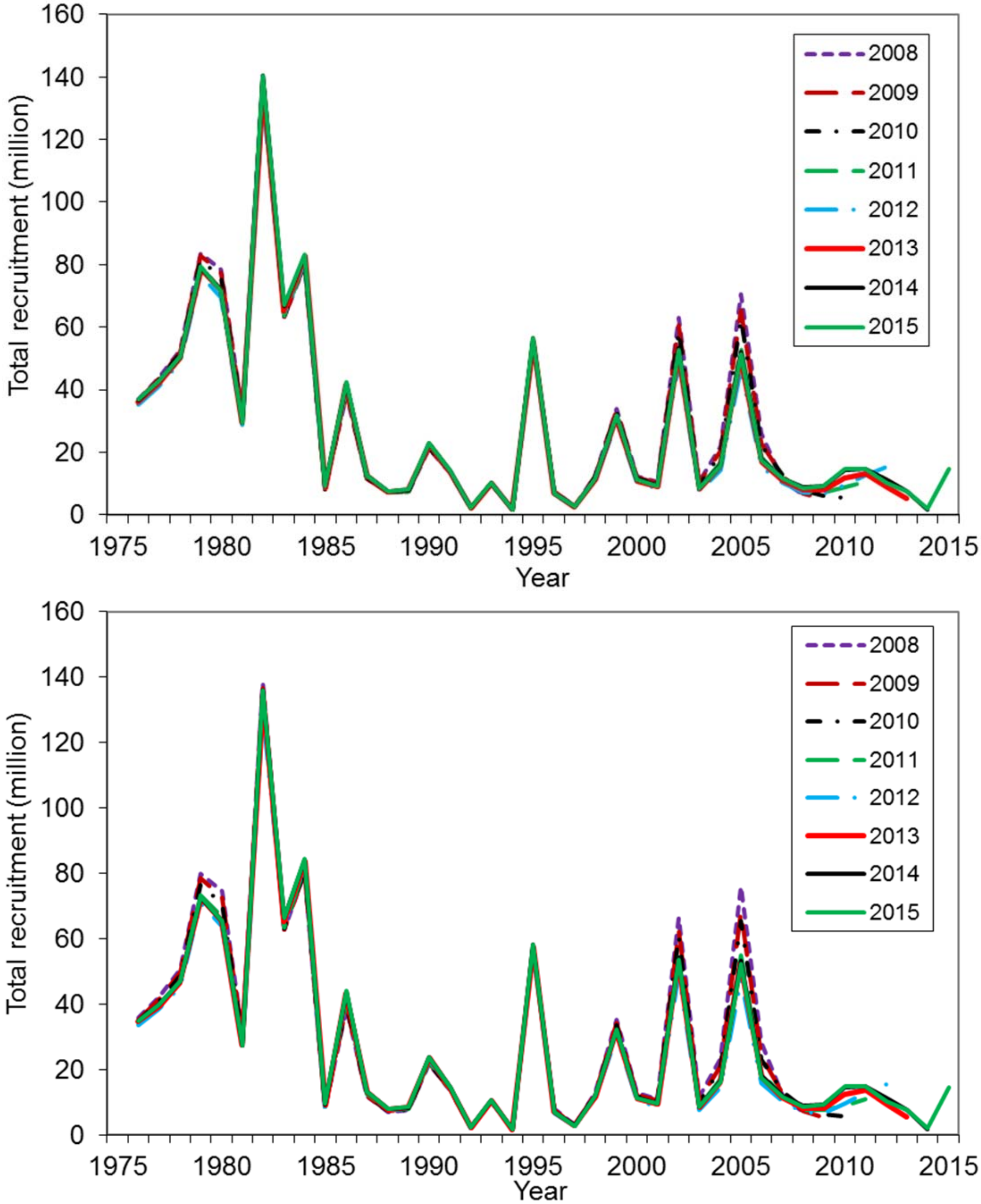
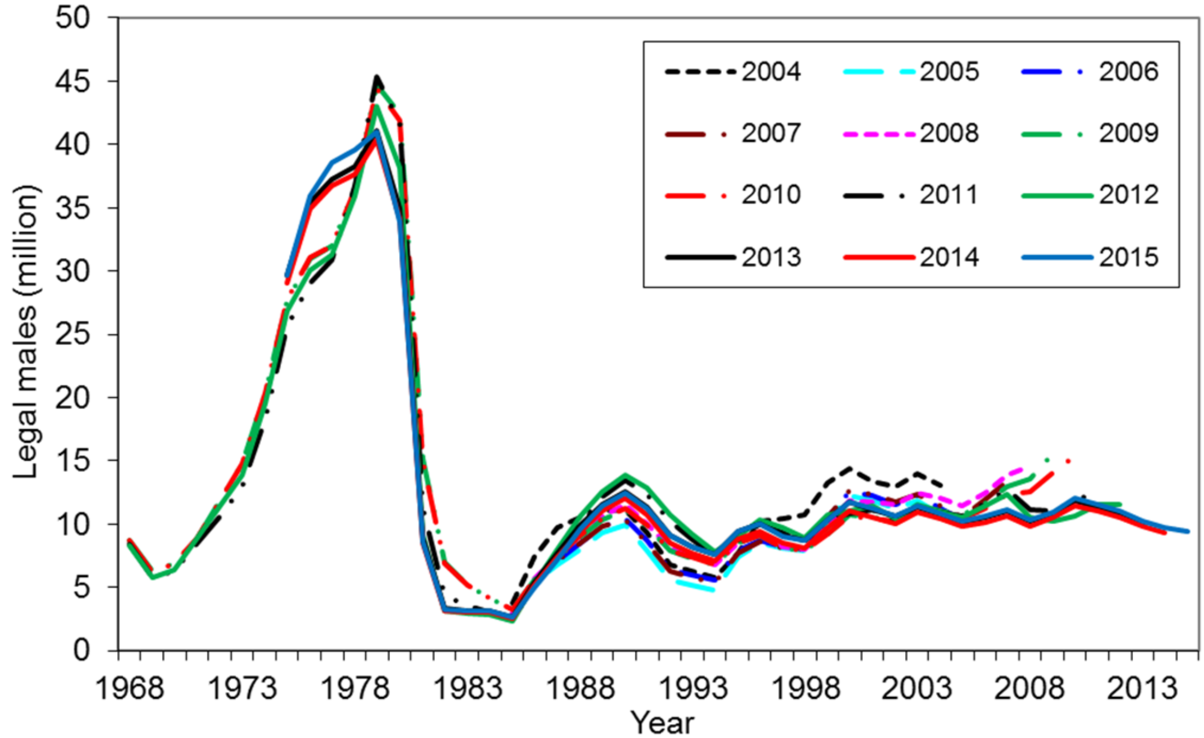


Figure 28b(1 & 1a). Comparison of hindcast estimates of total recruitment for scenario 1 (upper panel) and scenario 1a (lower panel) of Bristol Bay red king crab from 1976 to 2015 made with terminal years 2008-2015. These are results of the 2015 model. Legend shows the terminal year. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.



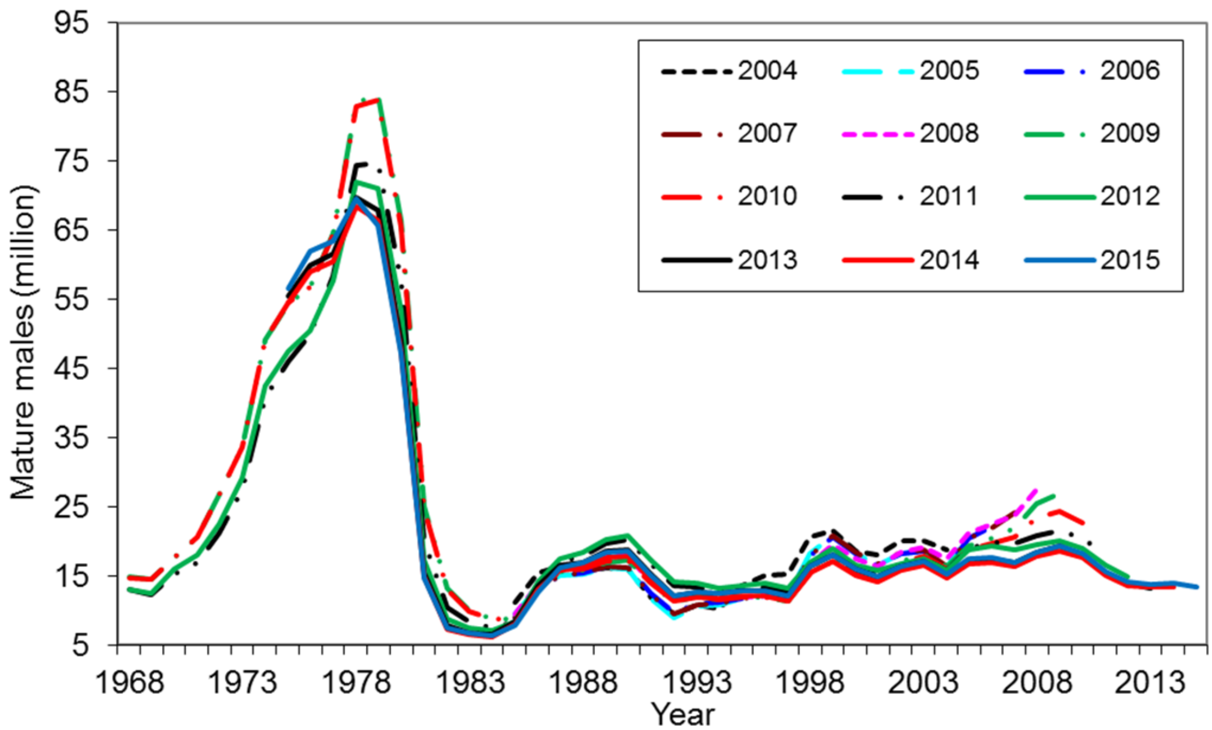


Figure 29. Comparison of estimates of legal male abundance (top) and mature males (bottom) of Bristol Bay red king crab from 1968 to 2015 made with terminal years 2004-2015 with the base scenarios. Scenario 1 is used for 2014 and 2015. These are results of historical assessments. Legend shows the year in which the assessment was conducted. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

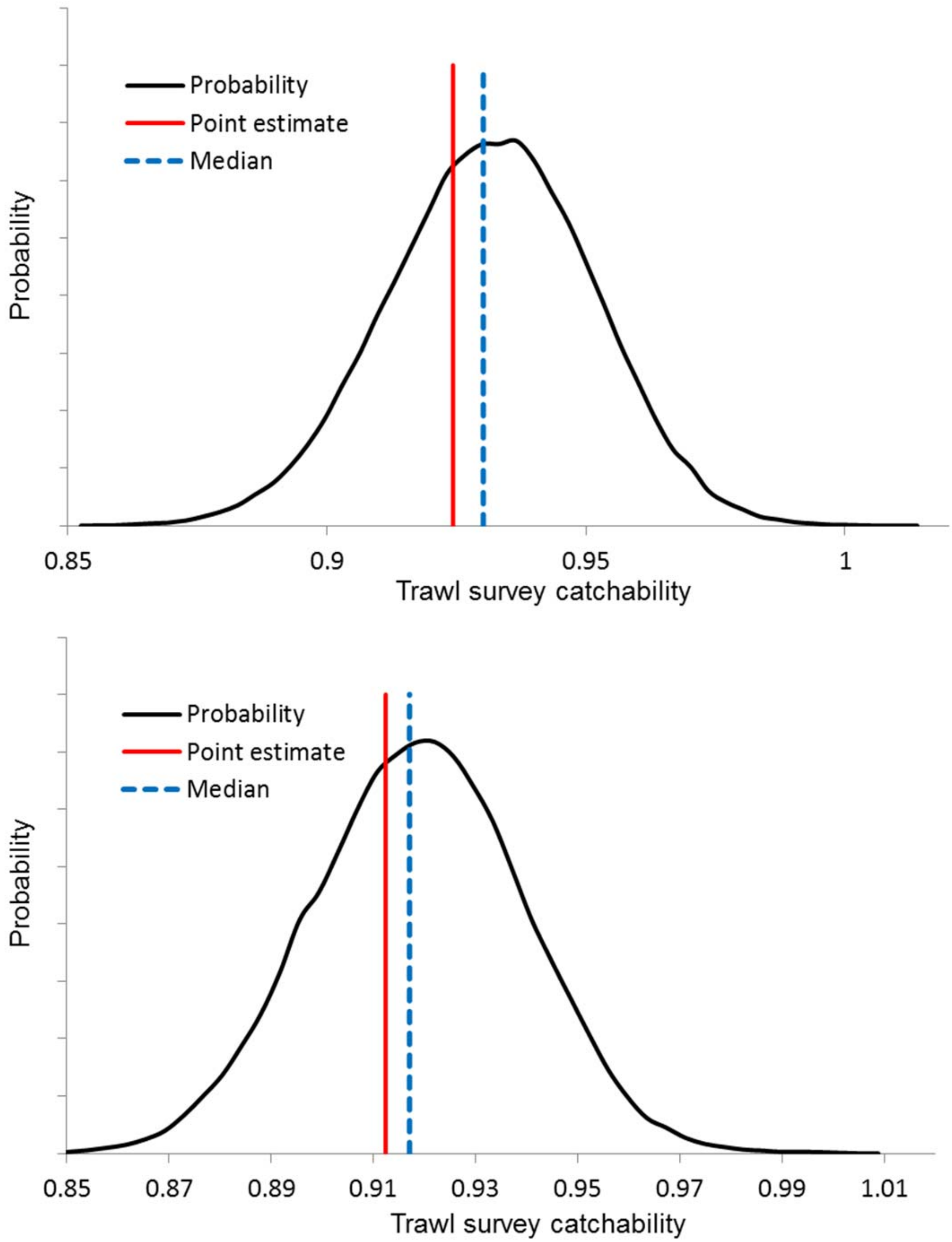


Figure 30(1&1a). Probability distributions of estimated trawl survey catchability (*Q*) under scenarios 1 (upper panel) and 1a (lower panel) with the mcmc approach. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

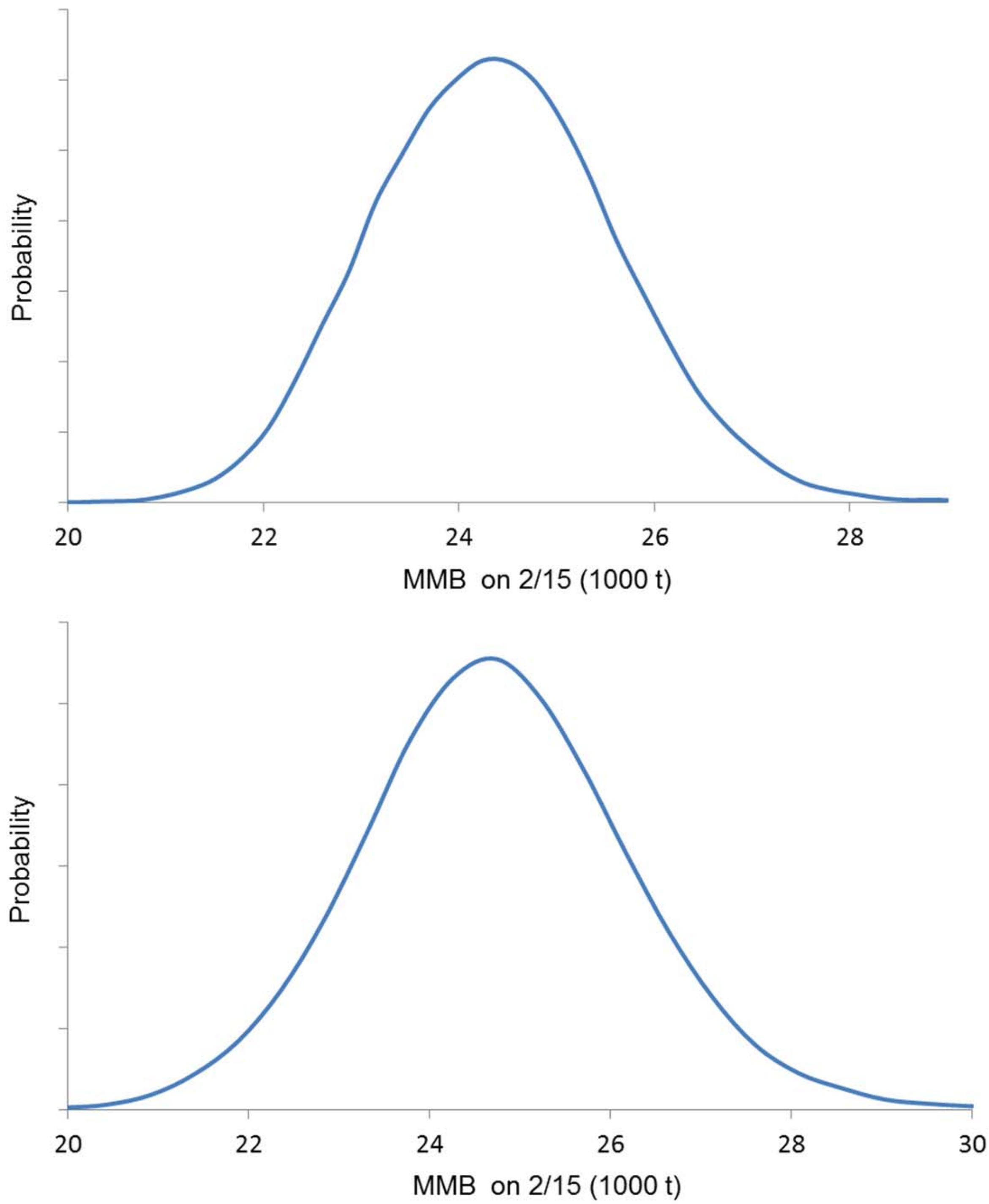


Figure 31a(1&1a). Probability distributions of estimated mature male biomass on Feb. 15, 2015 with $F_{35\%}$ under scenarios 1 (upper panel) and 1a (lower panel) with the mcmc approach. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

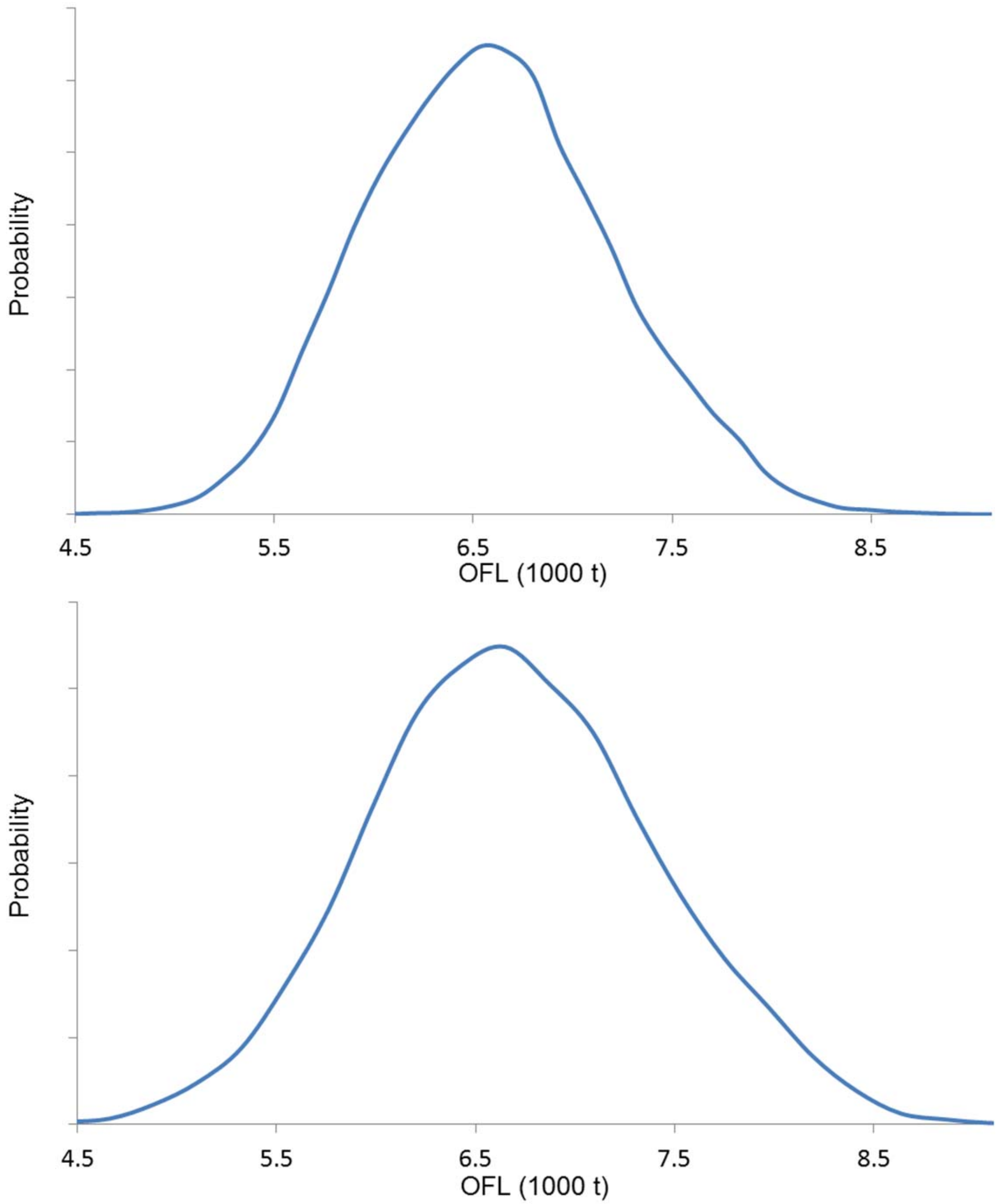


Figure 31b(1&1a). Probability distributions of the 2015 estimated OFL with scenarios 1 (upper panel) and 1a (lower panel) with the mcmc approach. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

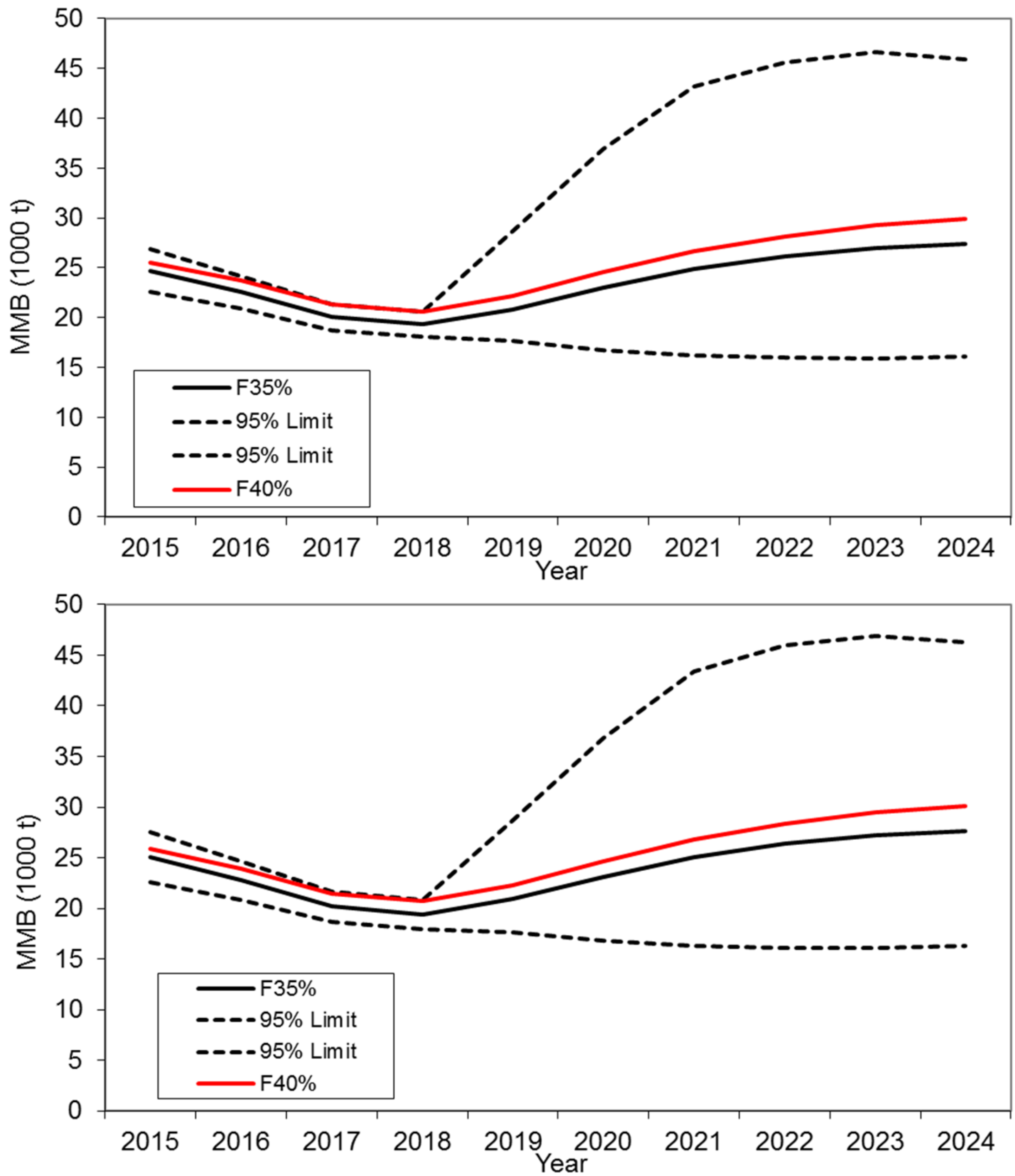
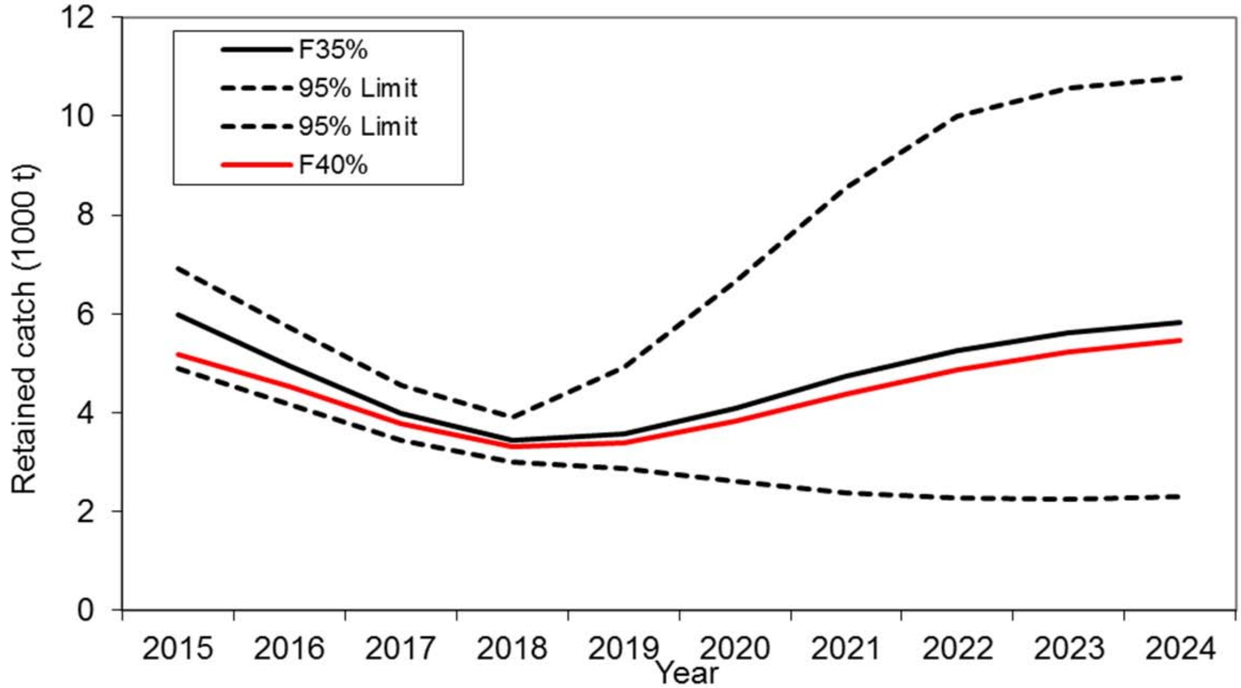


Figure 32(1&1a). Projected mature male biomass on Feb. 15 with $F_{40\%}$ and $F_{35\%}$ harvest strategy during 2015-2024. Input parameter estimates are based on scenarios 1 (upper panel) and 1a (lower panel). Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively, and the confidence limits are for the $F_{35\%}$ harvest strategy.



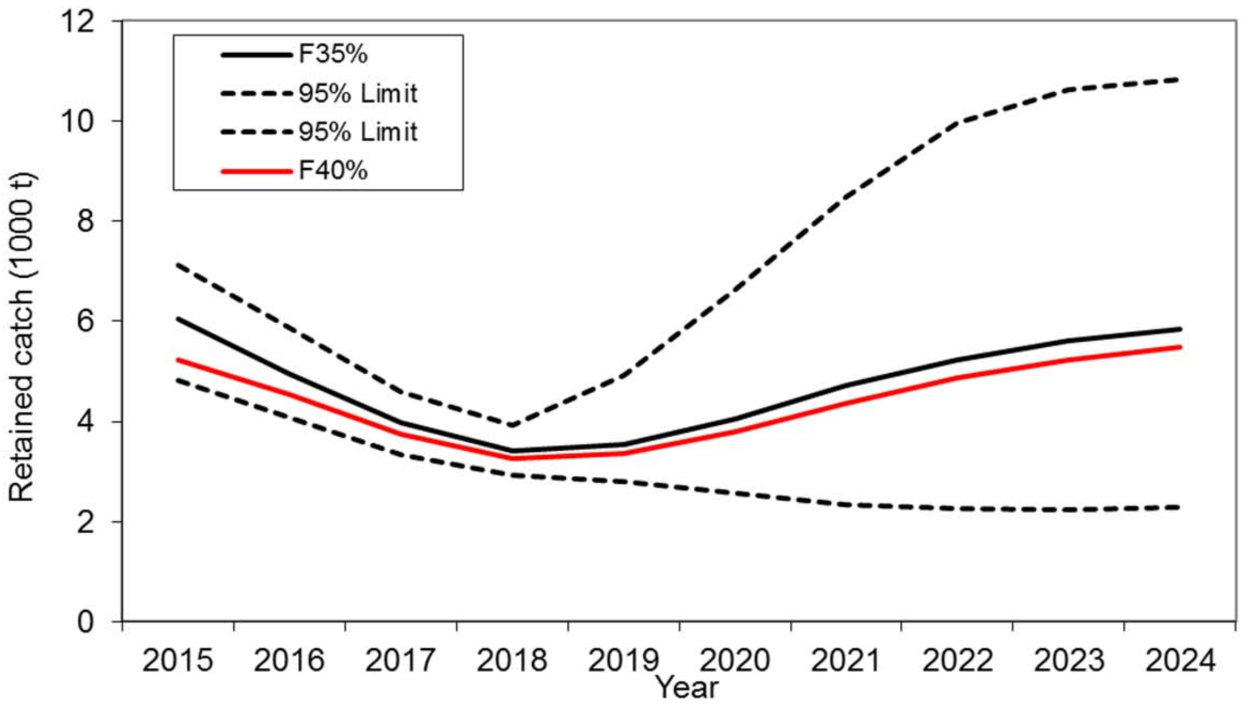


Figure 33(1&1a). Projected retained catch biomass with $F_{40\%}$ and $F_{35\%}$ harvest strategy during 2015-2124. Input parameter estimates are based on scenarios 1 (upper panel) and 1a (lower panel). Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively, and the confidence limits are for the $F_{35\%}$ harvest strategy.

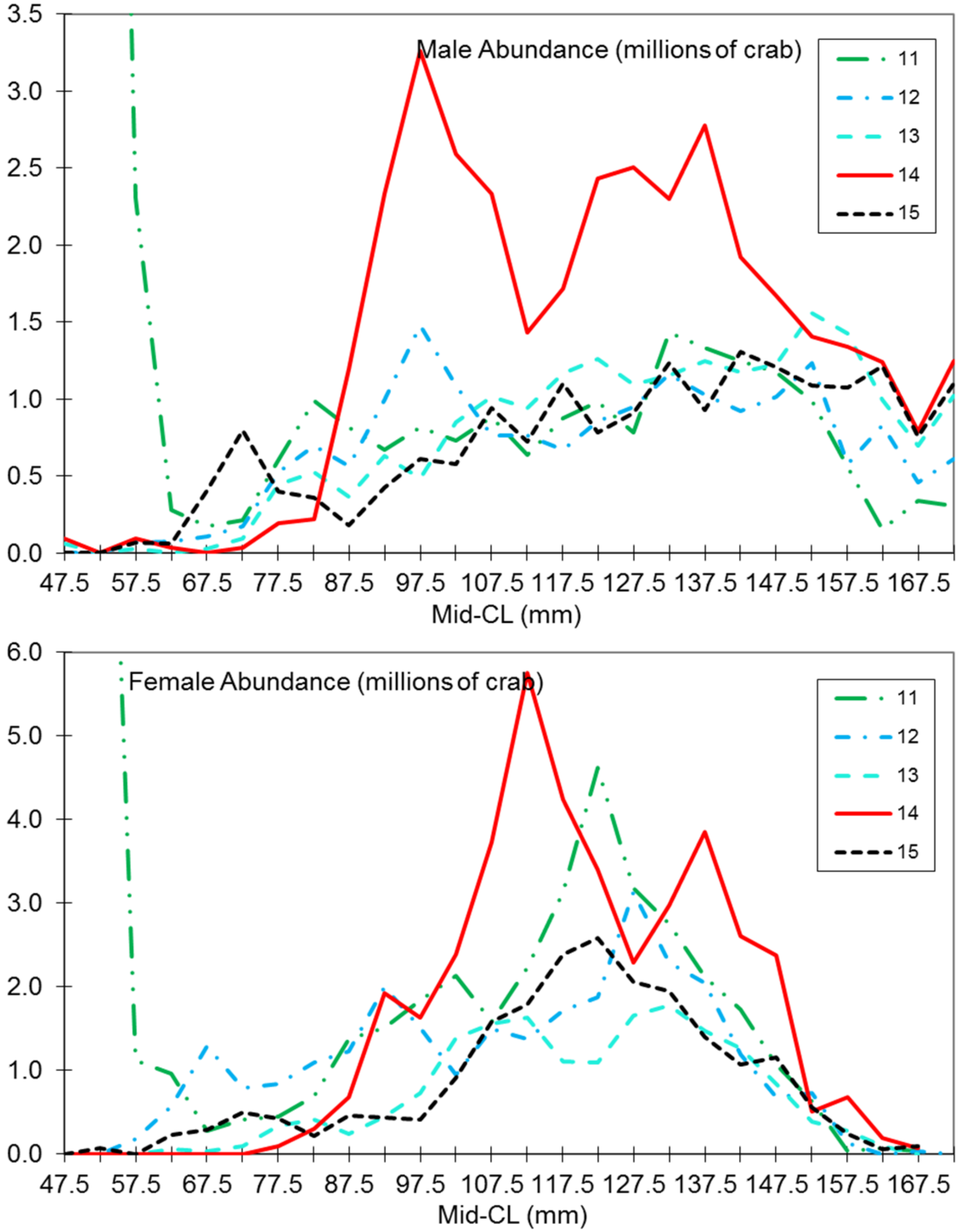


Figure 34. Length frequency distributions of male (top panel) and female (bottom panel) red king crab in Bristol Bay from NMFS trawl surveys during 2011-2015. For purposes of these graphs, abundance estimates are based on area-swept methods.

Appendix A. Description of the Bristol Bay Red King Crab Model

a. Model Description

i. Population model

The original LBA model was described in detail by Zheng et al. (1995a, 1995b) and Zheng and Kruse (2002). Crab abundances by carapace length and shell condition in any one year are modeled to result from abundances in the previous year minus catch and handling and natural mortalities, plus recruitment, and additions to or losses from each length class due to growth:

$$N^s_{l,t+1} = \sum_{l'=1}^{l} \{P^s_{l',l,t}[(N^s_{l',t} + O^s_{l',t})e^{-M^s_t} - (C^s_{l',t} + D^s_{l',t})e^{(y_t-1)M^s_t} - T^s_{l',t}\, e^{(j_t-1)M^s_t}]m^s_{l',t}\} + R^s_{t+1}U^s_l$$
$$O^s_{l,t+1} = [(N^s_{l,t} + O^s_{l,t})e^{-M^s_t} - (C^s_{l,t} + D^s_{l,t})e^{(y_t-1)M^s_t} - T^s_{l,t}\, e^{(j_t-1)M^s_t}](1 - m^s_{l,t}) \quad \text{(A1)}$$

where $N^s_{l,t}$ is the number of new shell crab of sex *s* in length-class *l* at the start of year *t*, $O^s_{l,t}$ the number of old shell crab of sex *s* in length-class *l* at the start of year *t*, $P^s_{l',l,s}$ the proportion during year *t* of an animals of sex *s* in length-class *l'* which grow into length-class *l* given that they moulted, M^s_t the rate of natural mortality on animals of sex *s* during year *t*, $m^s_{l,t}$ the probability that an animal of sex *s* in length-class *l* will moult during year *t*, R^s_{t+1} the recruitment [to the model] of animals of sex *s* during year *t*, U^s_l the proportion of recruits of sex *s* which recruit to length-class *l*, $C^s_{l,t}$ the retained catch (in numbers) of animals of sex *s* in length-class *l* during year *t*, $D^s_{l,t}$ the discarded catch of animals of sex *s* in length-class *l* during year *t* in the directed fishery and the trawl fishery, $T^s_{l,t}$ the discarded catch of animals of sex *s* in length-class *l* during year *t* in the Tanner crab fishery, y_t the time in years between survey and the directed pot and groundfish trawl fisheries during year *t*, and j_t the time in years between survey and the Tanner fishery during year *t*.

The minimum carapace length for both males and females is set at 65 mm, and crab abundance is modeled with a length-class interval of 5 mm. The last length class includes all crab ≥160-mm CL for males and ≥140-mm CL for females. Thus, length classes/groups are 20 for males and 16 for females. Since females moult annually (Powell 1967), females have only the first part of the equation (A1).

The growth increment is assumed to be gamma distributed with mean which depends linearly on pre-moult length, i.e.:

$$P^s_{l,l',t} = \int_{L_l-\Delta L/2}^{L_l+\Delta L/2} \frac{x^{\alpha^s_{L_{l'},t}} e^{x/\beta^s}}{(\beta^s)^{\alpha^s_{L_{l'},t}}\,\Gamma(\alpha^s_{L_{l'},t})} dx \qquad \alpha^s_{L_l,t}\beta^s = a^s_t + b^s_t L_l \qquad \text{(A2)}$$

where L_l is the mid-point of length-class l, ΔL the width of each size-class (5 mm carapace length), a_t^s, b_t^s the parameters of the length–growth increment relationship for sex s and year t, and β^s the parameter determining the variance of the growth increment. Growth is time-invariant for males, and specified for three time-blocks for females (1968-82; 1983-93; 1994-2014) based on changes to the size at maturity for females. The probability of moulting as a function of length for males is given by an inverse logistic function, i.e.:

$$m_l = \frac{1}{1 + e^{\tilde{\beta}(L_l - L_{50})}} \qquad \text{(A3)}$$

where $\tilde{\beta}, L_{50}$ are the parameters which determine the relationship between length and the probability of moulting.

Recruitment is defined as recruitment to the model and survey gear rather than recruitment to the fishery. Recruitment is separated into a time-dependent variable, R_{t+1}^s, and size-dependent variables, U_l^s, representing the proportion of recruits belonging to each length class. R_{t+1}^s is assumed to consist of crab at the recruiting age with different lengths and thus represents year class strength for year t. The proportion of recruits by length-class, U_l^s, is described using a gamma distribution with parameters α_l^s and β_l^s. Because of different growth rates, recruitment is estimated separately for males and females under a constraint of approximately equal sex ratios of recruitment over time.

The above population models are for scenarios 1, 1a and 1b. For scenario 2, immature and mature females are modeled separately. Defining N^i as immature females and N^m as mature females, the female abundances by carapace length and mature status for scenario 2 are:

$$N_{l,t+1}^i = \sum_{l'=1}^{l} \{P_{l',l,t}^i (N_{l',t}^i e^{-M_t^{fem}} - D_{l',t}^i e^{(y_t-1)M_t^{fem}} - T_{l',t}^i \, e^{(j_t-1)M_t^{fem}})(1 - o_{l',t})\} + R_{t+1}^{fem} U_l^{fem}$$

$$\begin{aligned} N_{l,t+1}^m = & \sum_{l'=1}^{l} [P_{l',l,t}^m (N_{l',t}^m e^{-M_t^{fem}} - D_{l',t}^m e^{(y_t-1)M_t^{fem}} - T_{l',t}^m \, e^{(j_t-1)M_t^{fem}})] \\ & + \sum_{l'=1}^{l} [P_{l',l,t}^i (N_{l',t}^i e^{-M_t^{fem}} - D_{l',t}^i e^{(y_t-1)M_t^{fem}} - T_{l',t}^i \, e^{(j_t-1)M_t^{fem}}) o_{l',t}] \end{aligned} \qquad \text{(A4)}$$

where superscripts i stands for immature females, m for mature females and *fem* for females, and $o_{l,t}$ is the mature probability in length-class l in year t. Equations A1-A3 apply to scenario 2 except for the growth increments for mature females. Although the linear relationship is used for mature female growth increments, due to lack of data, the linear equation is used to estimate growth increments starting at 90 mm CL and estimated growth increments per molt for mature females <90 mm CL are assumed as the same as that of 90 mm CL.

Mature probability, $o_{l,t}$, is a logistic function of length with two parameters like equation A3. A random walk approach is used to model the annual changes of sizes at the 50% maturity for females ($L_{50,t}$) for scenario 2:

$$L_{50,t+1} = L_{50,t} \, e^{\delta_t} \qquad \text{(A5)}$$

where δ_t are independent, normally distributed random variables with a mean of zero. This allows us to model the changes in maturity probability over time under a constraint condition.

ii. Catches and Fisheries Selectivities

Before 1990, no observed bycatch data were available in the directed pot fishery; the crab that were discarded and died in those years were estimated as the product of handling mortality rate, legal harvest rates, and mean length-specific selectivities. It is difficult to estimate bycatch from the Tanner crab fishery before 1991. A reasonable index to estimate bycatch fishing mortalities is potlifts of the Tanner crab fishery within the distribution area of Bristol Bay red king crab. Thus, bycatch fishing mortalities from the Tanner crab fishery before 1991 were estimated to be proportional to the smoothing average of potlifts east of 163° W. The smoothing average is equal to $(P_{t-2}+2P_{t-1}+3P_t)/6$ for the potlifts in year t. The smoothing process not only smoothes the annual number of potlifts, it also indexes the effects of lost pots during the previous years.

The catch (by sex) in numbers by the directed fishery and the groundfish trawl fishery is:

$$G^s_{l,t} = (N^s_{l,t} + O^s_{l,t})e^{-y_t M^s_t}(1 - e^{-F^s_{l,t}}) \tag{A6}$$

where $F^s_{l,t}$ is the fishing mortality rate during year t on animals of sex s in length-class l due to the directed fishery and the groundfish trawl fishery:

$$F^s_{l,t} = \begin{cases} S^{\text{dir,land}}_l F^{\text{dir}}_t + (S^{\text{dir,disc,mal}}_l + h_t \phi S^{\text{dir,land}}_{l,t})F^{\text{disc,mal}}_t + S^{\text{trawl}}_l F^{\text{trawl}}_t & \text{if } s = \text{mal} \\ S^{\text{dir,disc,fem}}_l F^{\text{disc,fem}}_t + S^{\text{trawl}}_l F^{\text{trawl}}_t & \text{if } s = \text{fem} \end{cases} \tag{A7}$$

where $S^{\text{dir,land}}_l$ is the selectivity pattern for the landings by the directed fishery, $S^{\text{dir,disc},s}_l$ the selectivity pattern for the discards in the directed fishery by sex, S^{trawl}_l the selectivity pattern for the bycatch in the groundfish trawl fishery, F^{dir}_t the fully-selected fishing mortality during year t (on males), $F^{\text{disc},s}_t$ the fully-selected fishing mortality on animals of sex s during year t related to discards in the directed fishery, F^{trawl}_t the fully-selected fishing mortality due to the groundfish trawl fishery, ϕ the handling mortality (the proportion of animals which die due to being returned to the water following capture), and h_t the rate of high-grading during year t , i.e. discards of animals which can be legally-retained by the directed pot fishery (non-zero only for 2005-2014).

There are no landings of females in a male-only fishery, while the landings C of males in the directed fishery and discards D of males in the directed and groundfish fisheries are:

$$\begin{aligned} C^{\text{mal}}_{l,t} &= (N^{\text{mal}}_{l,t} + O^{\text{mal}}_{l,t})e^{-y_t M^{\text{mal}}_t}(1 - e^{-S^{\text{dir,land}}_l F^{\text{dir}}_t}) \\ D^{\text{mal}}_{l,t} &= G^{\text{mal}}_{l,t} - C^{\text{mal}}_{l,t} \end{aligned} \tag{A8}$$

The catch (by sex) in numbers by the Tanner crab fishery in length-class l during year t is given by:

$$T_{l,t}^{s} = (N_{l,t}^{s} + O_{l,t}^{s})e^{-j_t M_t^s} e^{-F_{l,t}^{s}} (1 - e^{-\tilde{F}_{l,t}^{s}}) \tag{A9}$$

where $\tilde{F}_{l,t}^{s}$ is the fishing mortality rate during year t on animals of sex s in length-class l due to the Tanner crab fishery:

$$\tilde{F}_{l,t}^{s} = S_l^{\text{Tanner},s} F_t^{\text{Tanner},s} \tag{A10}$$

where $S_l^{\text{Tanner},s}$ is the selectivity pattern for the discards in the Tanner crab fishery by sex, and, $F_t^{\text{Tanner},s}$ the fully-selected fishing mortality during year t on animals of sex s during year t due to this fishery.

For scenario 2, discarded female bycatch in numbers is separated into immature and mature bycatches. The female bycatches in the directed and trawl fisheries in length-class l and during year t, $D_{l,t}^{i}$ and $D_{l,t}^{m}$, and $T_{l,t}^{i}$ and $T_{l,t}^{m}$, are:

$$\begin{aligned} D_{l,t}^{i} &= N_{l,t}^{i} e^{-y_t M_t^{fem}} (1 - e^{-F_{l,t}^{fem}}) \\ D_{l,t}^{m} &= N_{l,t}^{m} e^{-y_t M_t^{fem}} (1 - e^{-F_{l,t}^{fem}}) \end{aligned} \tag{A11}$$

The bycatches (by maturity) in numbers by the Tanner crab fishery in length-class l during year t for scenario 2 are given by:

$$\begin{aligned} T_{l,t}^{i} &= N_{l,t}^{i} e^{-j_t M_t^{fem}} e^{-F_{l,t}^{fem}} (1 - e^{-\tilde{F}_{l,t}^{fem}}) \\ T_{l,t}^{m} &= N_{l,t}^{m} e^{-j_t M_t^{fem}} e^{-F_{l,t}^{fem}} (1 - e^{-\tilde{F}_{l,t}^{fem}}) \end{aligned} \tag{A12}$$

Retained selectivity, $S^{\text{dir,land}}$, selectivity for females in the directed fishery, $S^{\text{dir,disc,fem}}$, selectivity for males and females in the groundfish trawl trawl, S^{trawl}, and selectivity for males and females in the Tanner crab fishery, $S^{\text{Tanner},s}$, are all assumed to be logistic functions of length:

$$S_l^{type} = \frac{1}{1 + e^{-\beta^{type}(\iota - L_{50}^{type})}} \tag{A13}$$

Different sets of parameters (β, L_{50}) are estimated for retained males, female pot bycatch, male and female trawl bycatch, and discarded males and females from the Tanner crab fishery.

Male pot bycatch selectivity in the directed fishery is modeled by two linear functions:

$$\begin{aligned} s_l &= \varphi + \kappa\iota, \quad if\ \iota < 135\,\text{mm CL}, \\ s_l &= s_{l-1} + 5\gamma, \quad if\ \iota > 134\,\text{mm CL} \end{aligned} \tag{A14}$$

where φ, κ, γ are parameters.

iii. Trawl Survey Selectivities/Catchability

Trawl survey selectivities/catchability are estimated as

$$S_{l,t}^{s} = \frac{Q}{1 + e^{-\beta_t^s \ (t - L_{50,t}^s)}} \tag{A15}$$

with different sets of parameters (β, L_{50}) estimated for males and females as well as two different periods (1975-81 and 1982-15). Survey selectivity for the first length group (67.5 mm) was assumed to be the same for both males and females, so only three parameters (β, L_{50} for females and L_{50} for males) were estimated in the model for each of the four periods. Parameter Q was called the survey catchability that was estimated based on a trawl experiment by Weinberg et al. (2004; Figure A1). Q was assumed to be constant over time.

Assuming that the BSFRF survey caught all crab within the area-swept, the ratio between NMFS abundance and BSFRF abundance is a capture probability for the NMFS survey net. The Delta method was used to estimate the variance for the capture probability. A maximum likelihood method was used to estimate parameters for a logistic function as an estimated capture probability curve (Figure A1). For a given size, the estimated capture probability is smaller based on the BSFRF survey than from the trawl experiment, but the Q value is similar between the trawl experiment and the BSFRF surveys (Figure A1). Because many small-sized crab are likely in the shallow water areas that are not accessible for the trawl survey, NMFS trawl survey catchability/selectivity consists of capture probability and crab availability.

b. Software Used: AD Model Builder (Fournier et al. 2012).

c. Likelihood Components

A maximum likelihood approach was used to estimate parameters. For length compositions ($p_{l,t,s,sh}$), the likelihood functions are :

$$Rf = \prod_{l=1}^{L}\prod_{t=1}^{T}\prod_{s=1}^{2}\prod_{sh=1}^{2} \frac{\left\{\exp\left[-\frac{(p_{l,t,s,sh} - \hat{p}_{l,t,s,sh})^2}{2\sigma^2}\right] + 0.01\right\}}{\sqrt{2\pi\sigma^2}} \tag{A16}$$

$$\sigma^2 = \left[\hat{p}_{l,t,s,sh}(1 - \hat{p}_{l,t,s,sh}) + 0.1/L\right]/n$$

where L is the number of length groups, T the number of years, and n the effective sample size, which was estimated for trawl survey and pot retained catch and bycatch length composition data from the directed pot fishery, and was assumed to be 50 for groundfish trawl and Tanner crab fisheries bycatch length composition data.

The weighted negative log likelihood functions are:

$$Length\ compositions: \quad -\sum \ln(Rf_i)$$

$$Biomasses\ other\ than\ survey: \quad \lambda_j \sum \left[\ln(C_t / \hat{C}_t)^2\right]$$

$$NMFS\ survey\ biomass: \quad \sum \left[\ln(B_t / \hat{B}_t)^2 / (2\ln(CV_t^2 + 1))\right]$$

$$BSFRF\ mature\ males: \quad \sum [\ln(\ln(CV_t^2 + 1))^{0.5} + \ln(B_t / \hat{B}_t)^2 / (2\ln(CV_t^2 + 1))]$$

$$R\ variation: \quad \lambda_R \sum [\ln(R_t / \overline{R})^2]$$

$$R\ sex\ ratio: \quad \lambda_s [\ln(\overline{R}_M / \overline{R}_F)^2]$$

$$Trawl\ bycatch\ fishing\ mortalities: \lambda_t [\ln(F_{t,t} / \overline{F}_t)^2] \tag{A17}$$

$$Pot\ female\ bycatch\ fishing\ mortalities: \lambda_p [\ln(F_{t,f} / \overline{F}_f)^2]$$

$$Trawl\ survey\ catchability: (Q - \hat{Q})^2 / (2\sigma^2)$$

$$Scenario 2, each\ of\ six\ growth\ increment\ parameters: (a - \hat{a})^2 / (2\sigma^2)$$

$$Scenario 2, penalty\ for\ random\ walk\ at\ size\ of\ 50\%\ maturity: \lambda_m \delta^2$$

where R_t is the recruitment in year t, $\overline{R}$ the mean recruitment, $\overline{R}_M$ the mean male recruitment, $\overline{R}_F$ the mean female recruitment, $\overline{F}_t$ the mean trawl bycatch fishing mortality, $\overline{F}_f$ the mean pot female bycatch fishing mortality, Q summer trawl survey catchability, and σ the estimated standard deviation of Q (all scenarios) or each of six growth increment parameters for scenario 2.

For BSFRF total survey biomass, CV is the survey CV plus AV, where AV is additional CV and estimated in the model.

Weights λ_j are assumed to be 500 for retained catch biomass, and 100 for all bycatch biomasses, 2 for recruitment variation, 10 for recruitment sex ratio, 0.2 for pot female bycatch fishing mortality, 0.1 for trawl bycatch fishing mortality, and 200 for female maturity (scenario 2). These λ_j values represent prior assumptions about the accuracy of the observed catch biomass data and about the variances of these random variables.

d. Population State in Year 1.

The total abundance and proportions for the first year are estimated in the model.

e. Parameter estimation framework:

i. Parameters estimated independently

   Basic natural mortality, length-weight relationships, and mean growth increments per molt were estimated independently outside of the model. Mean length of recruits to the model depends on growth and was assumed to be 72.5 for both males and females. High grading parameters h_t were estimated to be 0.2785 in 2005, 0.0440 in 2006, 0.0197 in 2007, 0.0198 in 2008, 0.0337 in 2009, 0.0153 in 2010, 0.0113 in 2011, 0.0240 in 2012, 0.0632 in 2013, and 0.1605 in 2014, based on the proportions of discarded legal males to total caught legal males. Handling mortality rates were set to 0.2 for the directed pot fishery, 0.25 for the Tanner crab fishery, and 0.8 for the trawl fisheries.

(1). Natural Mortality

Based on an assumed maximum age of 25 years and the 1% rule (Zheng 2005), basic M was estimated to be 0.18 for both males and females. Natural mortality in a given year, M_t, equals to $M + Mm_t$ (for males) or $M + Mf_t$ (females). One value of Mm_t during 1980-1985 was estimated and two values of Mf_t during 1980-1984 and 1976-79, 1985-93 were estimated in the model for scenarios 1, 1a and 1b. For scenario 2, only one Mft during 1980-1984 was estimated.

(2). Length-weight Relationship

Length-weight relationships for males and females were as follows:

$$\begin{aligned} &\text{Immature Females:} && W = 0.000408\, L^{3.127956} \\ &\text{Ovigerous Females:} && W = 0.003593\, L^{2.666076} \\ &\text{Males:} && W = 0.0004031\, L^{3.141334} \end{aligned} \tag{A18}$$

where W is weight in grams, and L CL in mm.

(3). Growth Increment per Molt

A variety of data are available to estimate male mean growth increment per molt for Bristol Bay RKC. Tagging studies were conducted during the 1950s, 1960s and 1990s, and mean growth increment per molt data from these tagging studies in the 1950s and 1960s were analyzed by Weber and Miyahara (1962) and Balsiger (1974). Modal analyses were conducted for the data during 1957-1961 and the 1990s (Weber 1967; Loher et al. 2001). Mean growth increment per molt may be a function of body size and shell condition and vary over time (Balsiger 1974; McCaughran and Powell 1977); however, for simplicity, mean growth increment per molt was assumed to be only a function of body size in the models. Tagging data were used to estimate mean growth increment per molt as a function of pre-molt length for males (Figure A2). The results from modal analyses of 1957-1961 and the 1990s were used to estimate mean growth increment per molt for immature females during 1975-1993 and 1994-2015, respectively, and the data presented in Gray (1963) were used to estimate those for mature females for scenarios 1, 1a and 1b (Figure A2). To make a smooth transition of growth increment per molt from immature to mature females, weighted growth increment averages of 70% and 30% at 92.5 mm CL pre-molt length and 90% and 10% at 97.5 mm CL were used, respectively, for mature and immature females during 1983-1993. These percentages are roughly close to the composition of maturity. During 1975-1982, females matured at a smaller size, so the growth increment per molt as a function of length was shifted to smaller increments. Likewise, during 1994-2015, females matured at a slightly higher size, so the growth increment per molt was shifted to high increments for immature crab (Figure A2). Once mature, the growth increment per molt for male crab decreases slightly and annual molting probability decreases, whereas the growth increment for female crab decreases dramatically but annual molting probability remains constant at 1.0 (Powell

1967).

For females with scenario 2, some new immature female growth data from Kodiak red king crab are used to estimate initial parameter values of immature female growth increments per molt function (Figure A2(2)). Initial parameter values for three growth increments-per-molt functions are estimated using the growth increments per molt data: immature females, mature females, and males. Parameters for growth increments per molt are estimated inside the model with these initial estimates as a prior.

(4). Sizes at Maturity for Females

The NMFS collected female reproductive condition data during the summer trawl surveys. Mature females are separated from immature females by a presence of egg clutches or egg cases. Proportions of mature females at 5-mm length intervals were summarized and a logistic curve was fitted to the data each year to estimate sizes at 50% maturity. Sizes at 50% maturity are illustrated in Figure A3 with mean values for three different periods (1975-82, 1983-93, and 1994-2015).

(5). Sizes at Maturity for Males

Although size at sexual maturity for Bristol Bay red king crab males has been estimated (Paul et al. 1991), there are no data for estimating size of functional maturity collected in the natural environment. Sizes at functional maturity for Bristol Bay male RKC have been assumed to be 120 mm CL (Schmidt and Pengilly 1990). This is based on mating pair data collected off Kodiak Island (Figure A4). Sizes at maturity for Bristol Bay female RKC are about 90 mm CL, about 15 mm CL less than Kodiak female RKC (Pengilly et al. 2002). The size ratio of mature males to females is 1.3333 at sizes at maturity for Bristol Bay RKC, and since mature males grow at much larger increments than mature females, the mean size ratio of mature males to females is most likely larger than this ratio. Size ratios of the large majority of Kodiak mating pairs were less than 1.3333, and in some bays, only a small proportion of mating pairs had size ratios above 1.3333 (Figure A4).

In the laboratory, male RKC as small as 80 mm CL from Kodiak and SE Alaska can successfully mate with females (Paul and Paul 1990). But few males less than 100 mm CL were observed to mate with females in the wild. Based on the size ratios of males to females in the Kodiak mating pair data, setting 120 mm CL as a minimum size of functional maturity for Bristol Bay male RKC is proper in terms of managing the fishery.

(6). Potential Reasons for High Mortality during the Early 1980s

Bristol Bay red king crab abundance had declined sharply during the early 1980s. Many factors have been speculated for this decline: (i) completely wiped out by fishing: the directed pot fishery, the other directed pot fishery (Tanner crab fishery), and bottom trawling; and (ii) high fishing and natural mortality. With the survey abundance, harvest rates in 1980 and 1981 were among the highest, thus the directed fishing definitely had a big impact on the stock decline, especially legal and mature males. However, for the sharp decline during 1980-1884 for males, 3 out of 5 years had low mature harvest rates. During 1981-1984 for females, 3 out of 4 years had low mature harvest rates. Also pot catchability for females and immature males are generally much lower than for legal males, so the directed pot fishing alone cannot explain the sharp decline for all segments of the stock during the early 1980s.

Red king crab bycatch in the eastern Bering Sea Tanner crab fishery is another potential factor (Griffin et al. 1983). The main overlap between Tanner crab and Bristol Bay red king crab is east of 163° W. No absolute red king crab bycatch estimates are available until 1991. So there are insufficient data to fully evaluate the impact. Retained catch and potlifts from the eastern Bering Sea Tanner crab fishery are illustrated in Figure A5. The observed red king crab bycatch in the Tanner crab fishery during 1991-1993 and total potlifts east of 163° W during 1968 to 2005 were used to estimate the bycatch mortality in the current model. Because winter sea surface temperatures and air temperatures were warmer (which means a lower handling mortality rate) and there were fewer potlifts during the early 1980s than during the early 1990s, bycatch in the Tanner crab fishery is unlikely to have been a main factor for the sharp decline of Bristol Bay red king crab.

Several factors may have caused increases in natural mortality. Crab diseases in the early 1980s were documented by Sparks and Morado (1985), but inadequate data were collected to examine their effects on the stock. Stevens (1990) speculated that senescence may be a factor because many crab in the early 1980s were very old due to low temperatures in the 1960s and early 1970s. The biomass of the main crab predator, Pacific cod, increased about 10 times during the late 1970s and early 1980s. Yellowfin sole biomass also increased substantially during this period. Predation is primarily on juvenile and molting/softshell crab. But we lack stomach samples in shallow waters (juvenile habitat) and during the period when red king crab molt. Also cannibalism occurs during molting periods for red king crab. High crab abundance in the late 1970s and early 1980s may have increased the occurrence of cannibalism.

Overall, the likely causes for the sharp decline in the early 1980s are combinations of the above factors, such as pot fisheries on legal males, bycatch, and predation on females and juvenile and sublegal males, senescence for older crab, and disease for all crab. In our model, we estimated one mortality parameter for males and another for females during 1980-1984. We also estimated a mortality parameter for females during 1976-1979 and 1985-1993. These three mortality parameters are additional to the basic natural mortality of 0.18, all directed fishing mortality, and non-directed fishing mortality. These three mortality parameters could be attributed to natural mortality as well as undocumented non-directed fishing mortality. The model fit the data much better with these three parameters than without them.

ii. Parameters estimated conditionally

The following model parameters were estimated for male and female crab: total recruits for each year (year class strength R_t for t = 1976 to 2015), total abundance in the first year (1975), growth parameter β, and recruitment parameter β_r for males and females separately. Molting probability parameters β and L_{50} were also estimated for male crab. Estimated parameters also include β and L_{50} for retained selectivity, β and L_{50} for pot-discarded female selectivity, β and L_{50} for pot-discarded male and female selectivities from the eastern Bering Sea Tanner crab fishery, β and L_{50} for groundfish trawl discarded selectivity, φ, κ and γ for pot-discarded male selectivity, and β for trawl survey selectivity and L_{50} for trawl survey male and females separately. The NMFS survey catchabilities Q for some scenarios were also estimated. Three selectivity parameters are estimated for the survey data from the Bering Fisheries Research Foundation. Annual fishing mortalities were also estimated for the directed pot fishery for males (1975-2014), pot-discarded females from the directed fishery (1990-2014), pot-discarded males and females from the eastern Bering Sea Tanner crab fishery (1991-93, 2013-14), and groundfish trawl discarded males and females (1976-2014). Three additional mortality parameters for Mm_t and Mf_t were also estimated. Some estimated parameters were constrained in the model. For example, male and female recruitment estimates were forced to be close to each other for a given year.

f. Definition of model outputs.

i. Biomass: two population biomass measurements are used in this report: total survey biomass (crab >64 mm CL) and mature male biomass (males >119 mm CL). Mating time is assumed to Feb. 15.

ii. Recruitment: new number of males in the 1st seven length classes (65- 99 mm CL) and new number of females in the 1st five length classes (65-89 mm CL).

iii. Fishing mortality: full-selected instantaneous fishing mortality rate at the time of fishery.

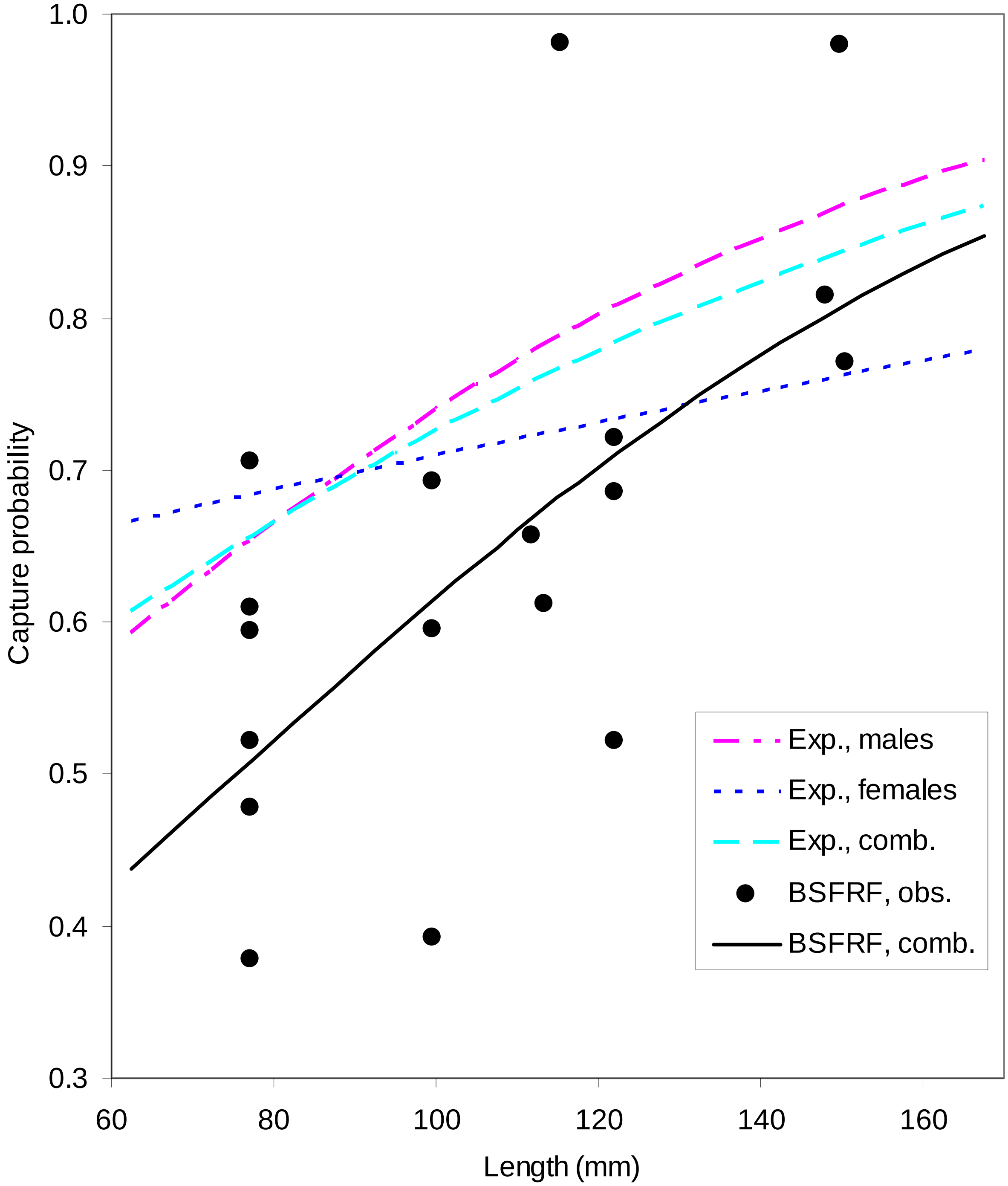
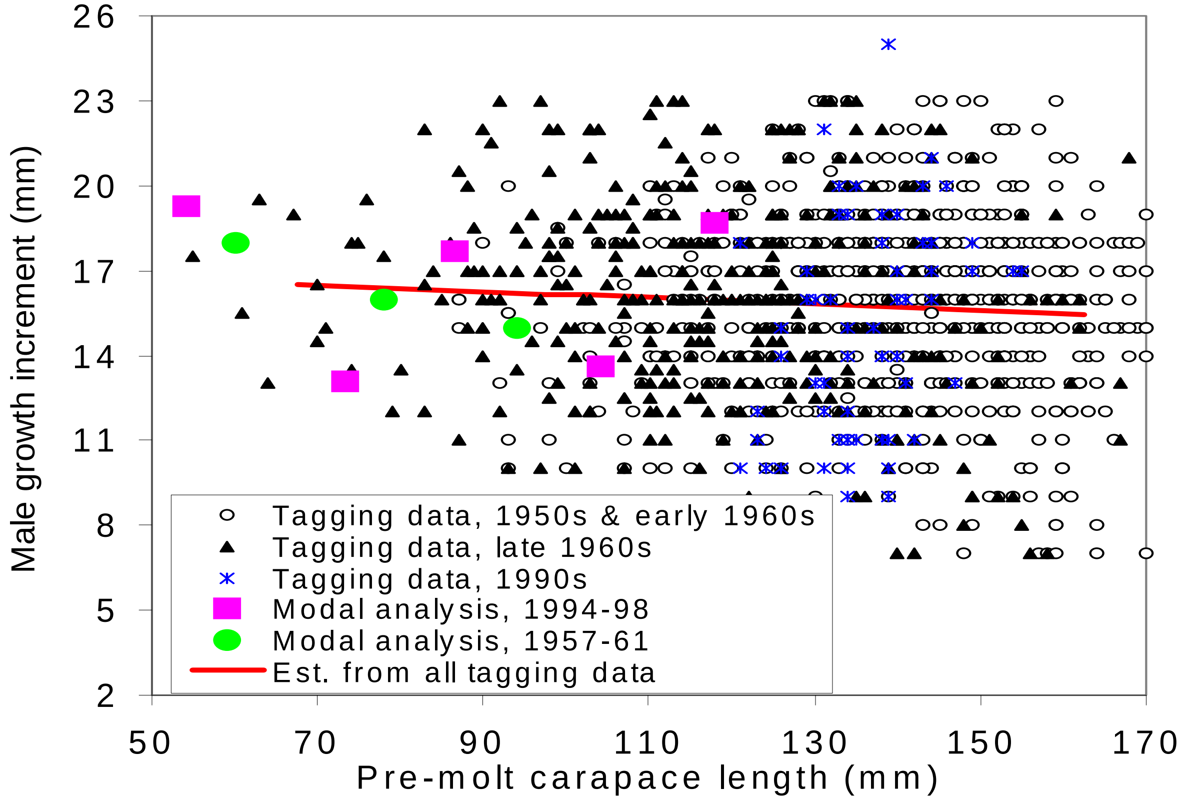


Figure A1. Estimated capture probabilities for NMFS Bristol Bay red king crab trawl surveys by Weinberg et al. (2004) and the Bering Sea Fisheries Research Foundation surveys.



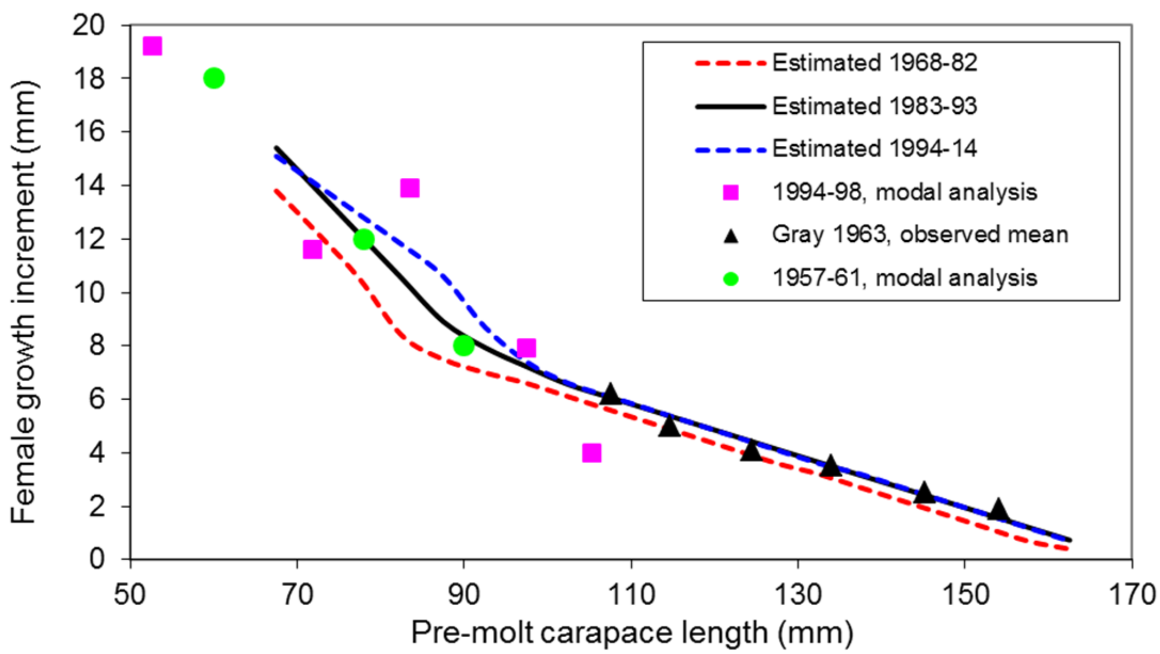


Figure A2. Mean growth increments per molt for Bristol Bay red king crab. Note: “tagging”---based on tagging data; “mode”---based on modal analysis. The female growth increments per molt are for scenarios 1, 1a and 1b.

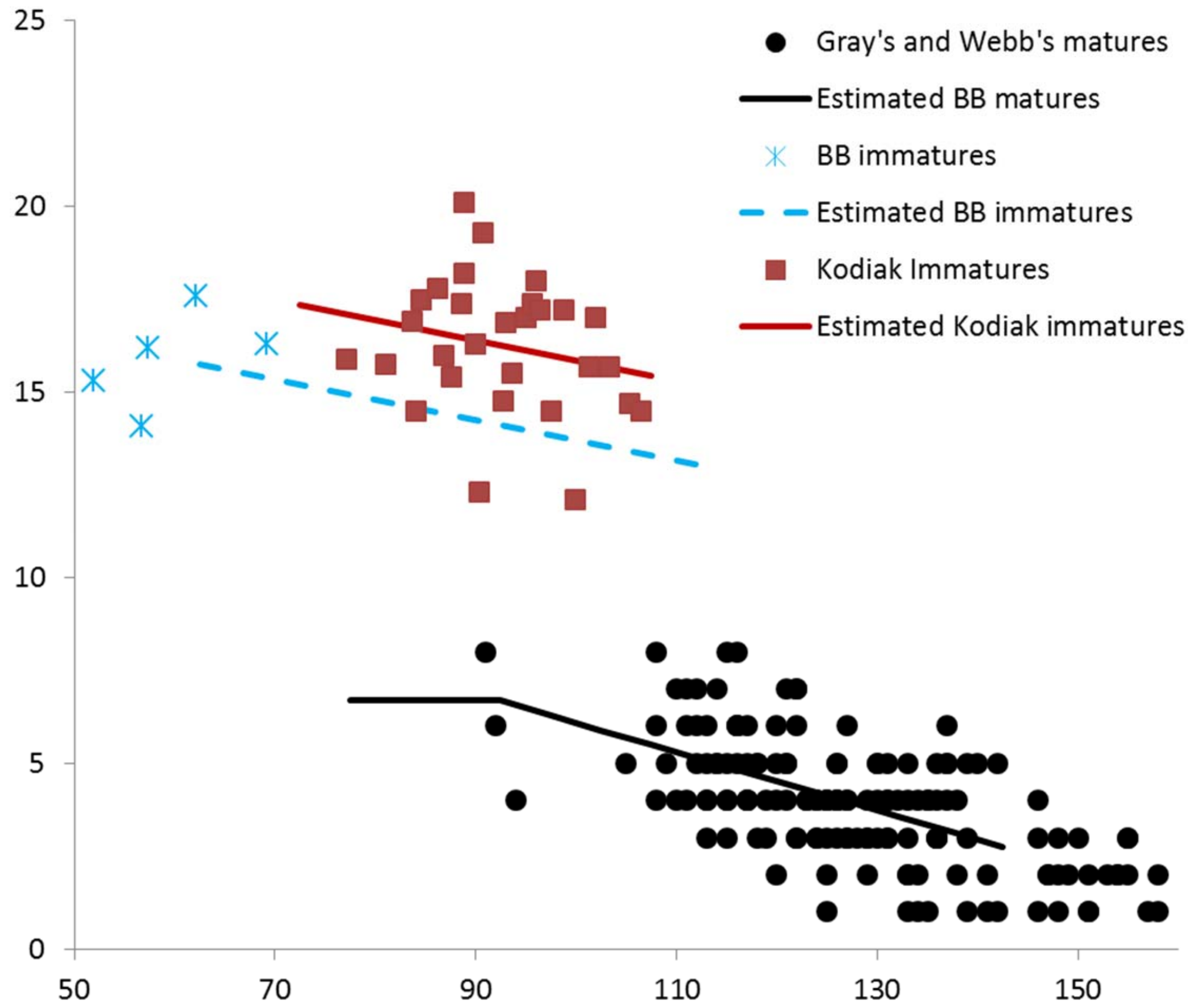


Figure A2(2). Mean growth increments per molt for female Bristol Bay red king crab for scenario 2. The slope parameter of the Bristol Bay immature female function is assumed to be the same as that of Kodiak red king crab; Estimated growth increments per molt for mature females <90 mm CL are assumed as the same as that of 90 mm CL.

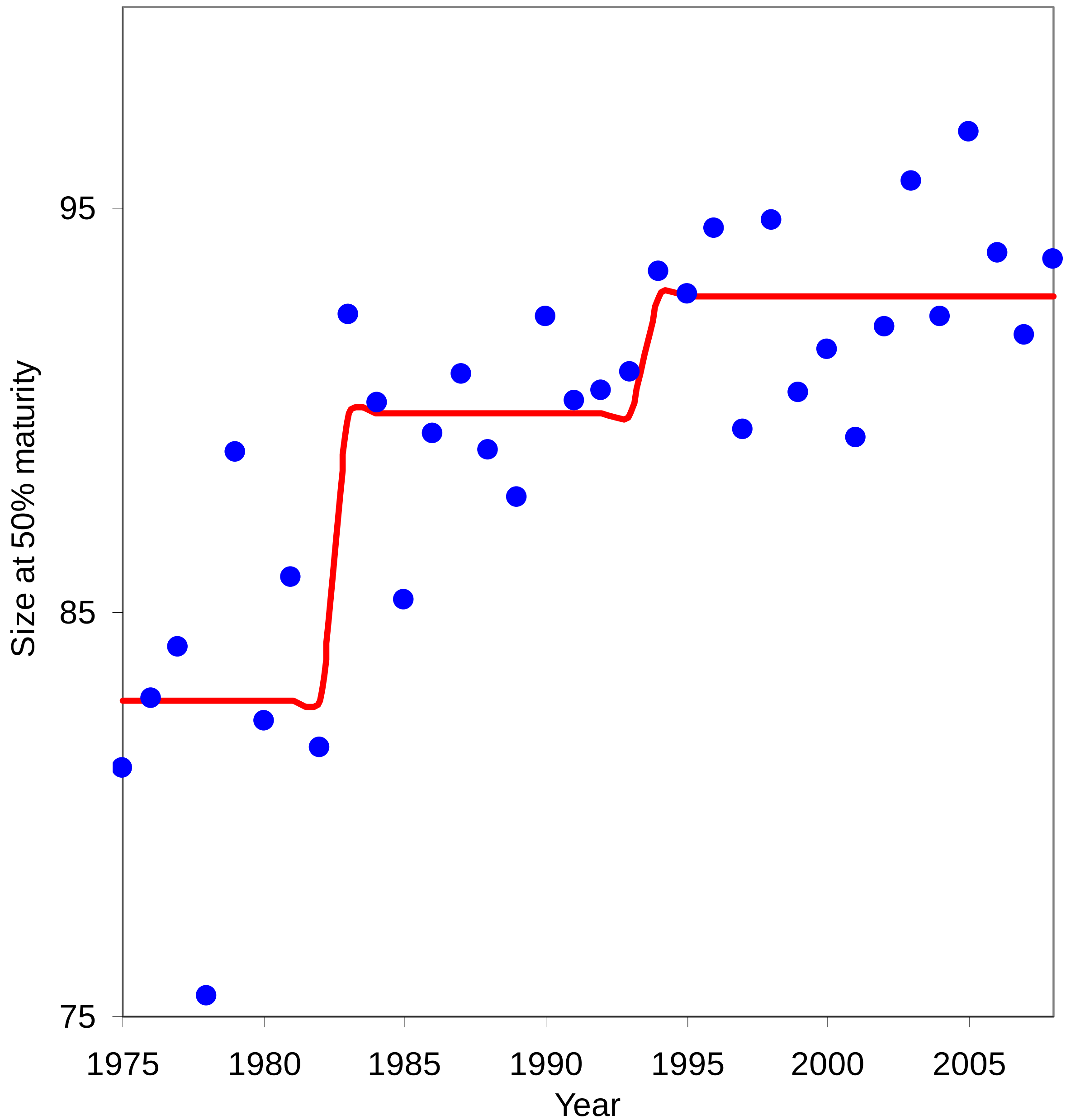


Figure A3. Estimated sizes at 50% maturity for Bristol Bay female red king crab from 1975 to 2008. Averages for three periods (1975-82, 1983-93, and 1994-08) are plotted with a line.

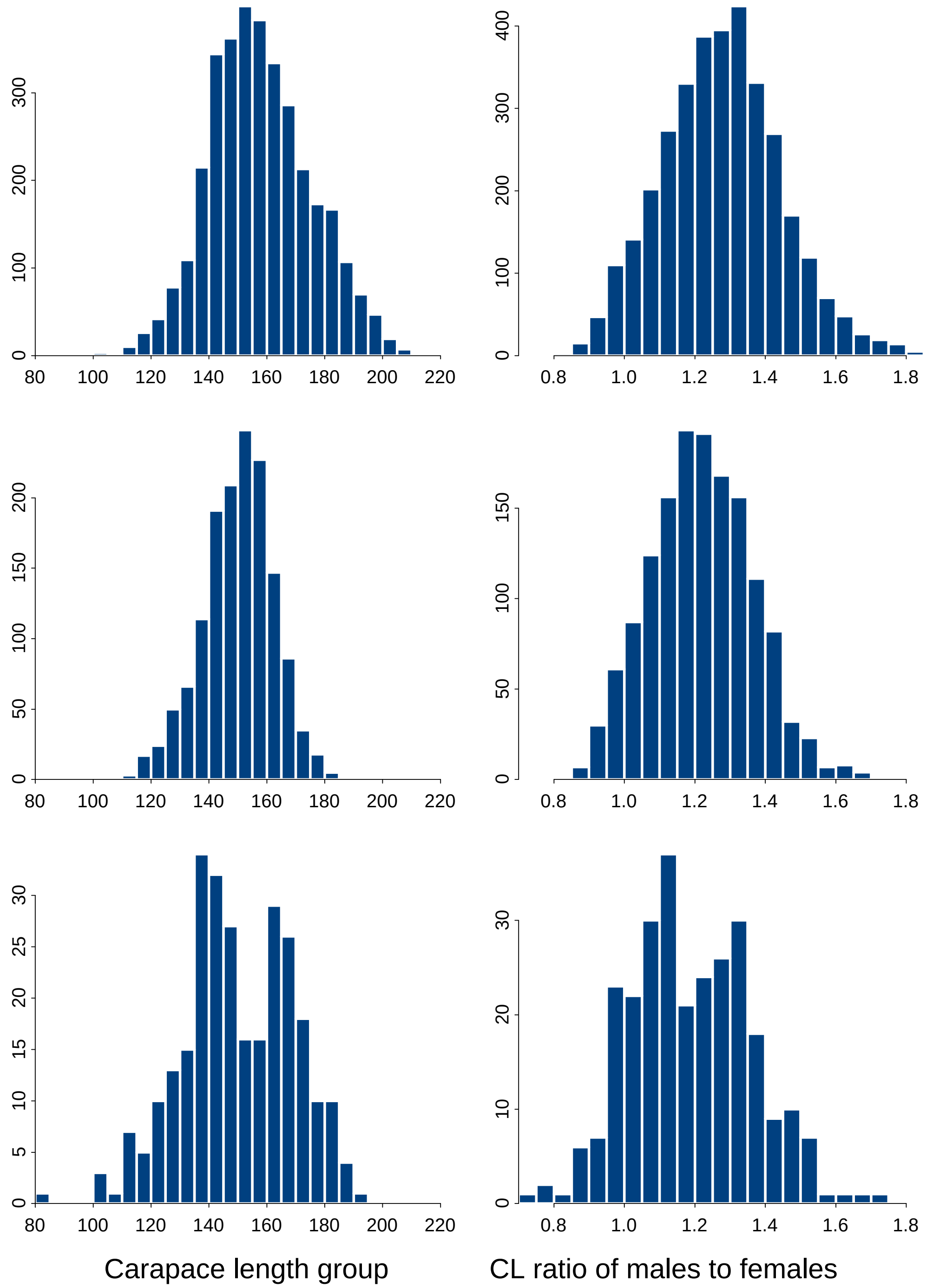
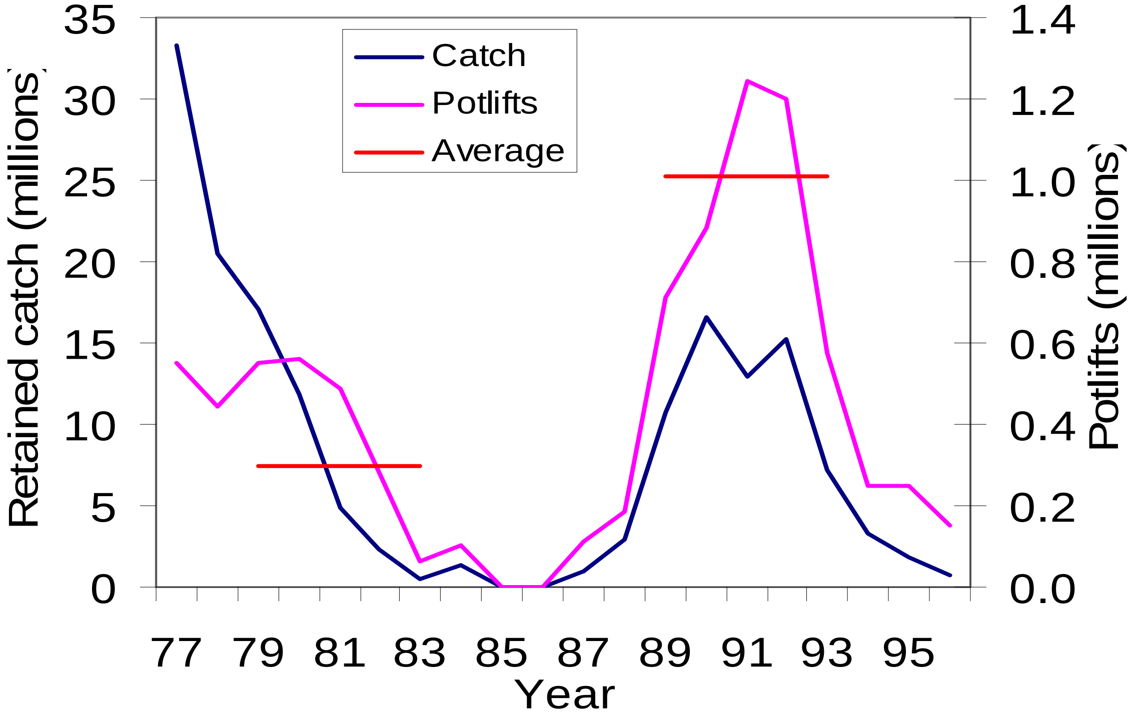


Figure A4. Histograms of carapace lengths (CL) and CL ratios of males to females for male shell ages ≤13 months of red king crab males in grasping pairs; Powell's Kodiak data. Upper plot: all locations and years pooled; middle plot: location 11; lower plot: locations 4 and 13. Sizes at maturity for Kodiak red king crab are about 15 mm larger than those for Bristol Bay red king crab. (Doug Pengilly, ADF&G, pers. comm.).



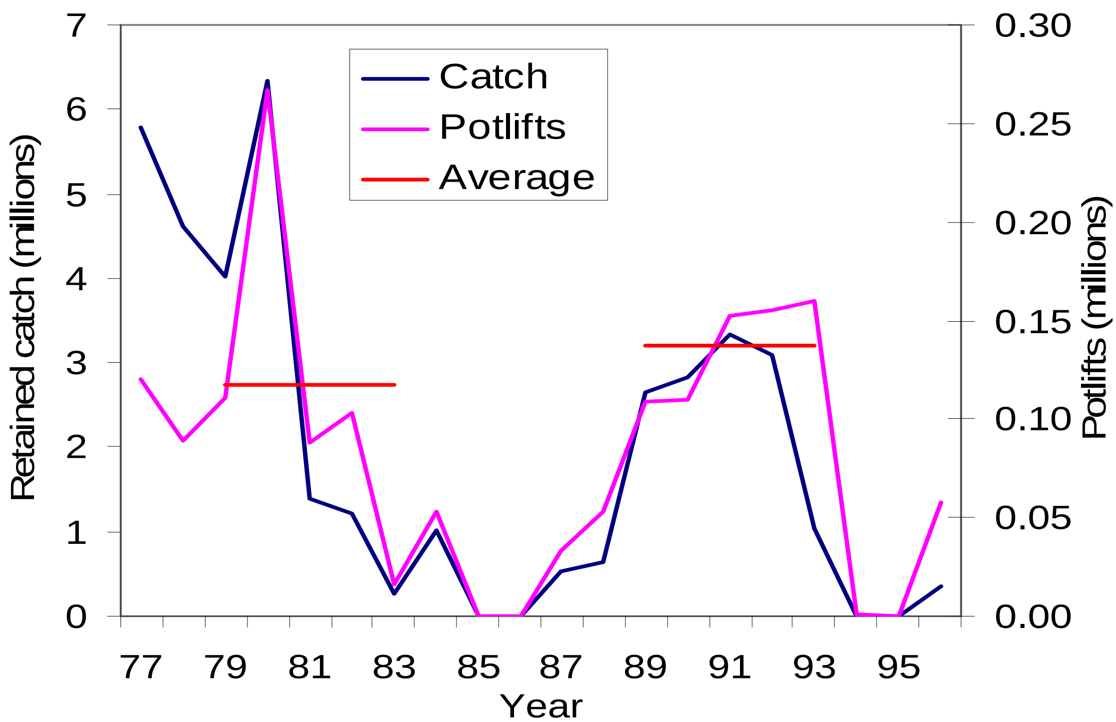
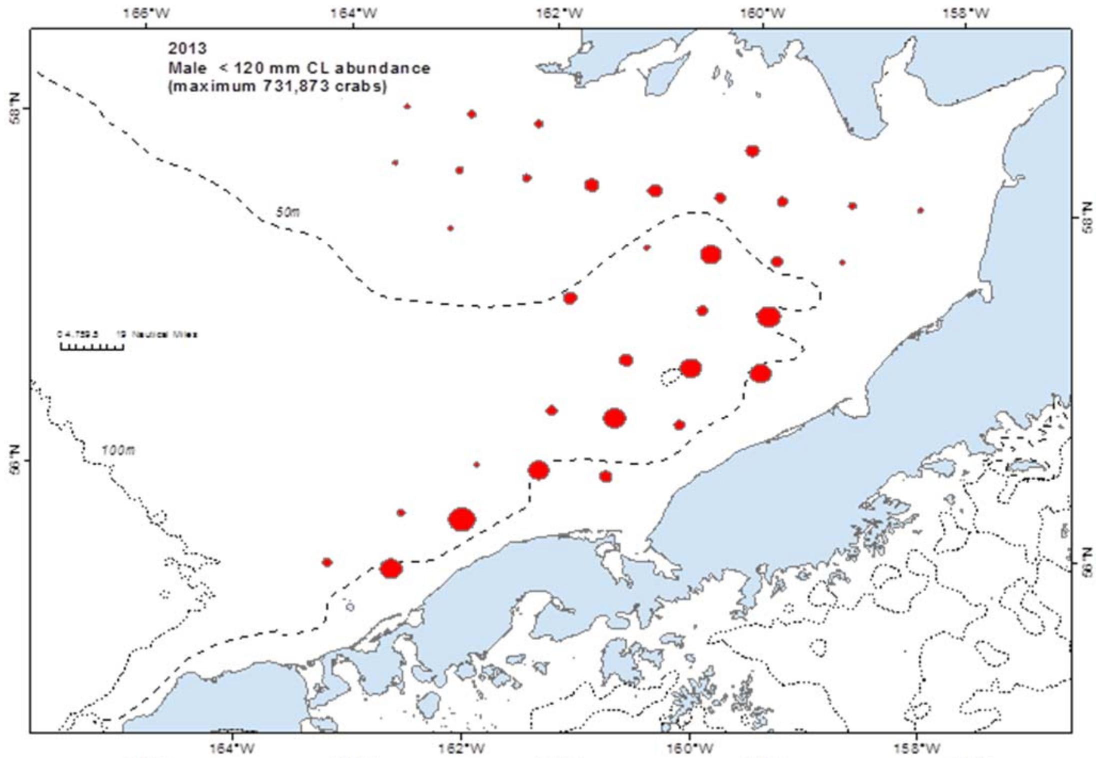
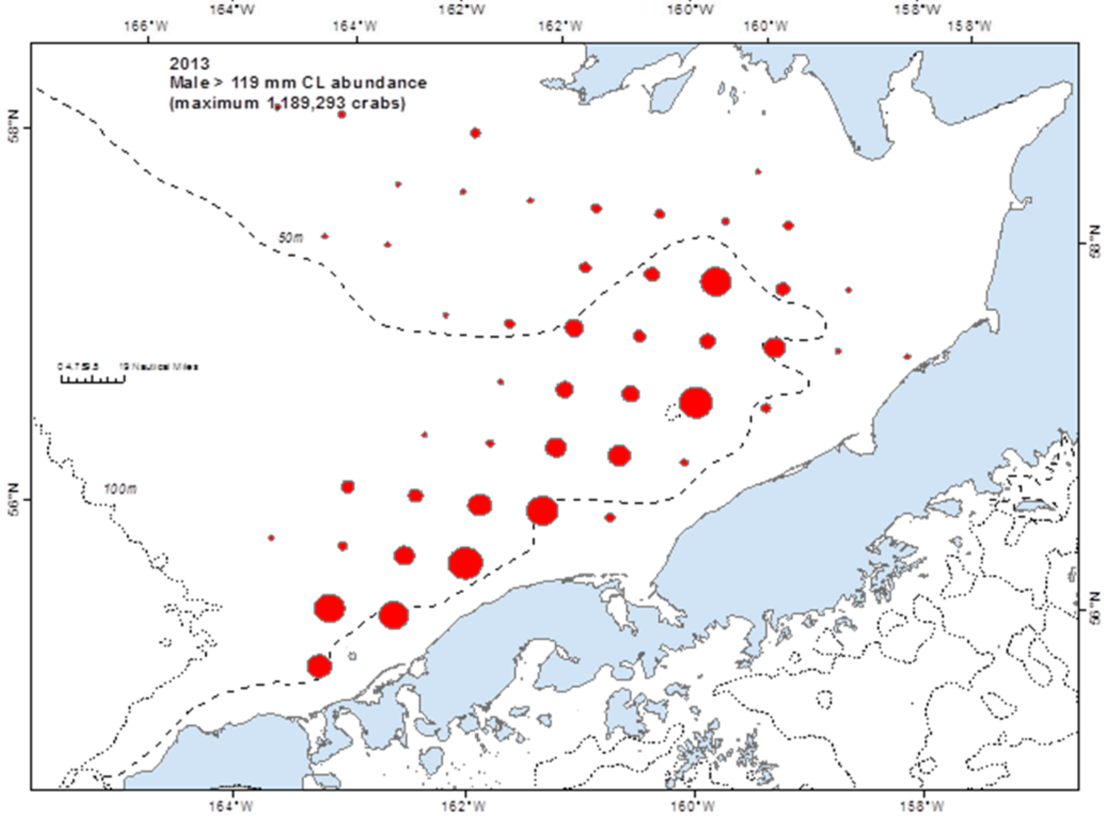
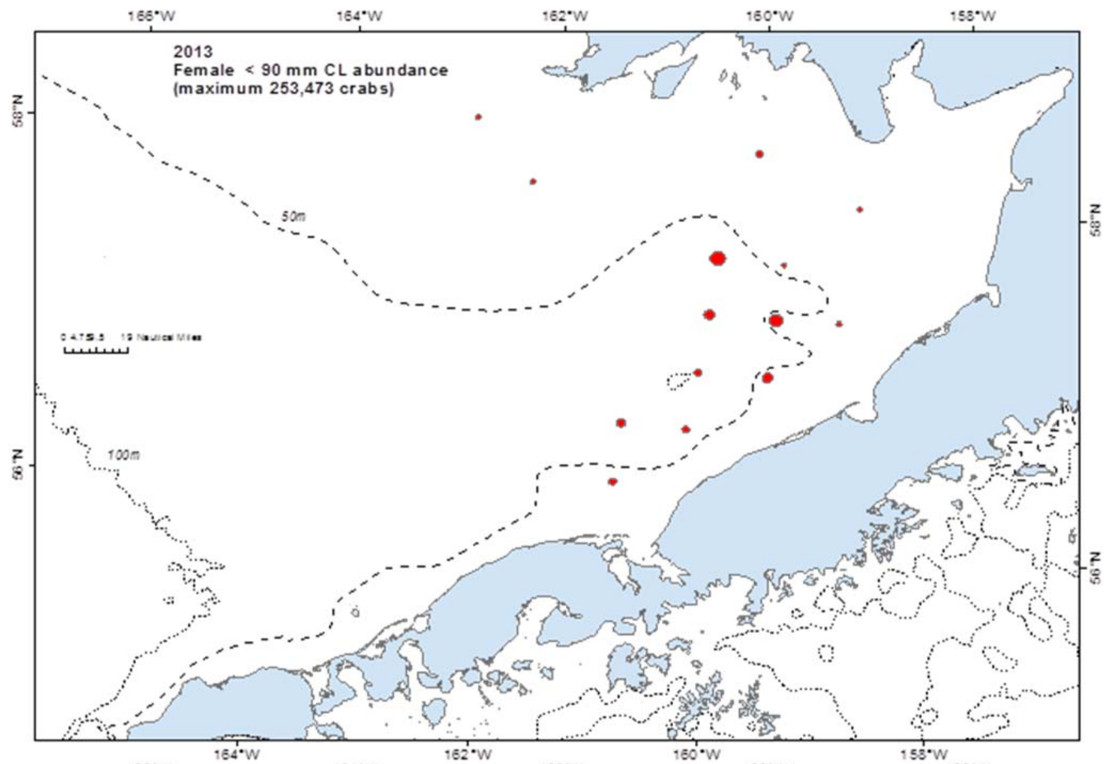


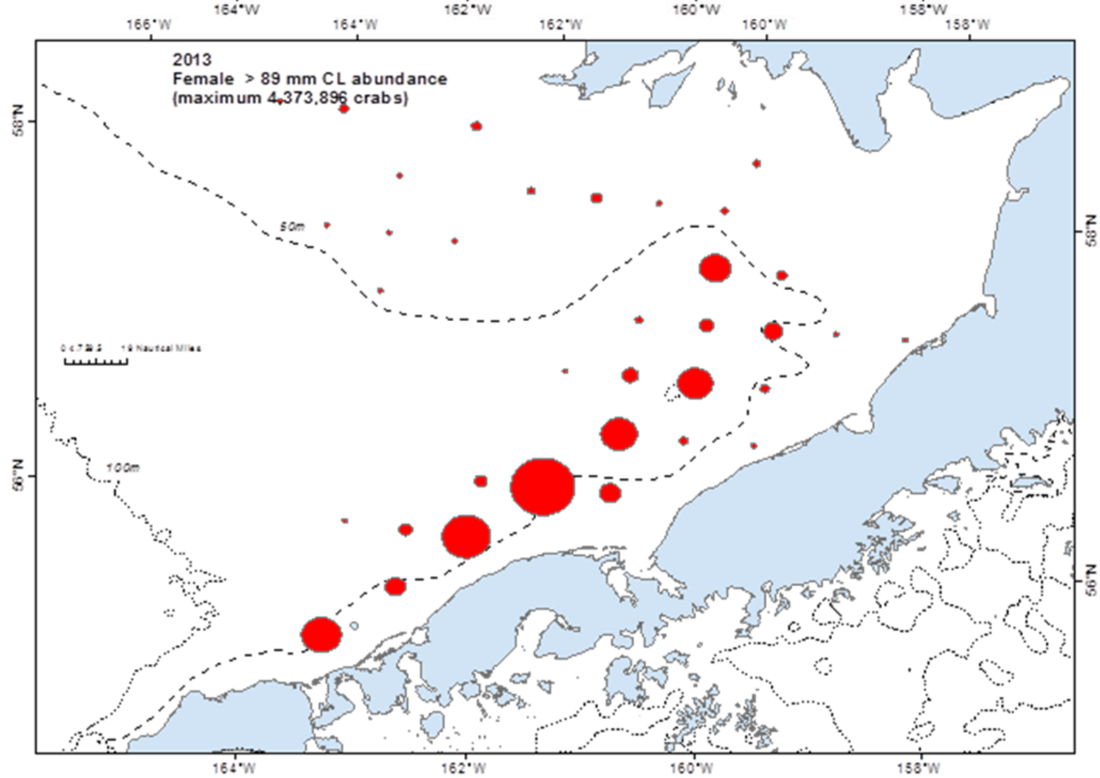
Figure A5. Retained catch and potlifts for total eastern Bering Sea Tanner crab fishery (upper plot) and the Tanner crab fishery east of 163° W (bottom).

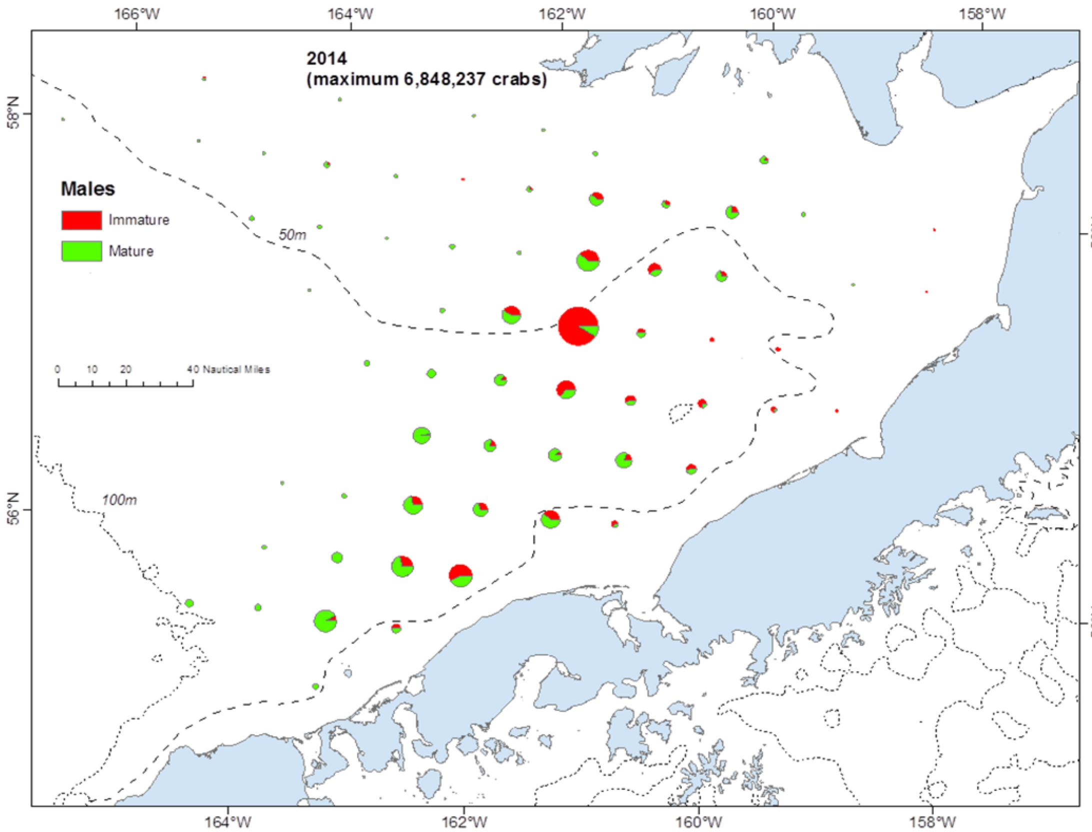
Appendix B. Spatial distributions of mature and juvenile male and female red king crab in Bristol Bay from 2013-2014 summer standard trawl surveys.

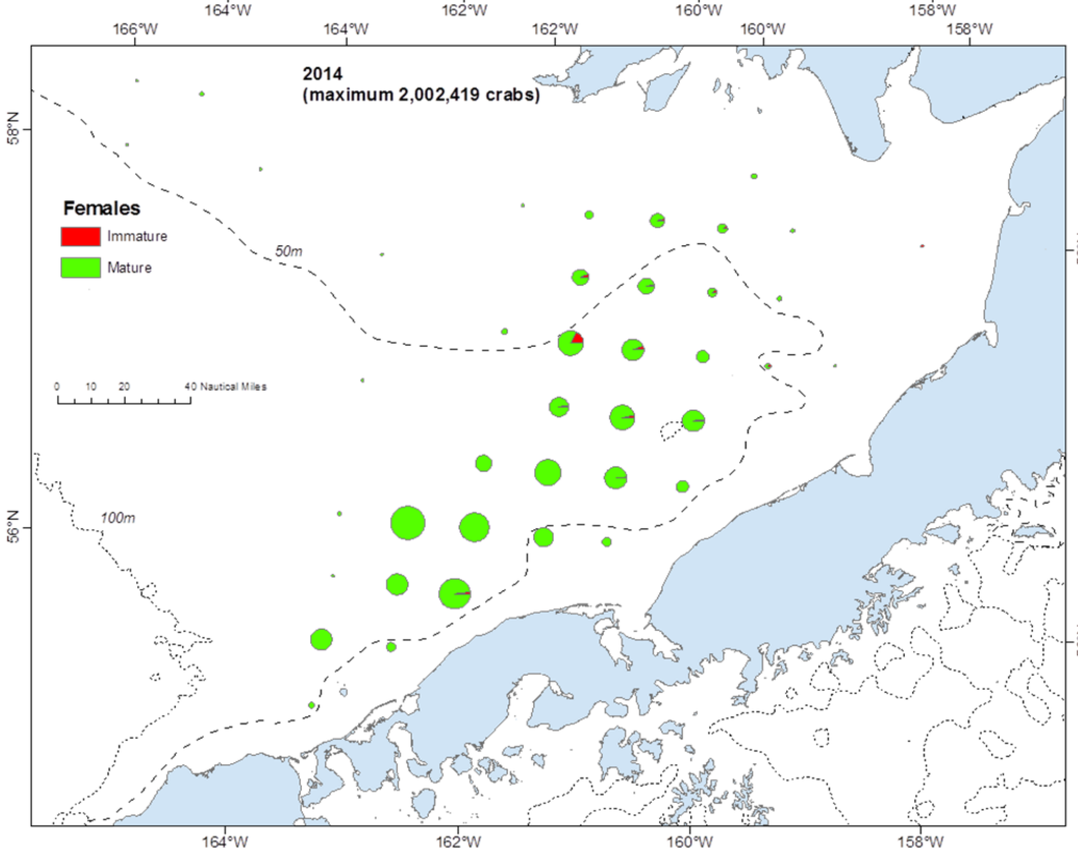





2013
Female < 90 mm CL abundance
(maximum 253,473 crabs)
166°W
164°W
162°W
160°W
158°W
58°N
56°N
50m
100m


2013
Female > 89 mm CL abundance
(maximum 4,373,896 crabs)
166°W
164°W
162°W
160°W
158°W
58°N
56°N
50m
100m


166°W
164°W
162°W
160°W
158°W
2014
(maximum 6,848,237 crabs)
Males
Immature
Mature
50m
100m
0 10 20 40 Nautical Miles
58°N
56°N


166°W
164°W
162°W
160°W
158°W
2014
(maximum 2,002,419 crabs)
Females
Immature
Mature
50m
100m
0 10 20 40 Nautical Miles
58°N
56°N