BRISTOL BAY RED KING CRAB STOCK ASSESSMENT IN FALL 2018

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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 2017/18 was approximately 6.8 million lbs (3,094 t), below the catch in 2016/17 (8.5 million lbs). The magnitude of bycatch from groundfish trawl and fixed gear 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 three times more abundant in 2009 than in 1985 and mature males being about two 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 1984-2018, only in 1984, 1986, 1995, 1999, 2002 and 2005 were estimated recruitments above the historical average for 1976-2018. Estimated recruitment was extremely low during the last ten years.
5. Management performance:

Status and catch specifications (1,000 t) (scenario 18.0):

Year	MSST	Biomass (MMB)	TAC	Retained Catch	Total Catch	OFL	ABC
2014/15	13.03[A]	27.25[A]	4.49	4.54	5.41	6.82	6.14
2015/16	12.89[B]	27.68[B]	4.52	4.61	5.31	6.73	6.06
2016/17	12.53[C]	25.81[C]	3.84	3.92	4.35	6.64	5.97
2017/18	12.77[D]	24.53[D]	2.99	3.09	3.48	5.60	5.04
2018/19		20.62[D]				5.21	4.69

The stock was above MSST in 2017/18 and hence was not overfished. Overfishing did not occur.

Status and catch specifications (million lbs):

Year	MSST	Biomass (MMB)	TAC	Retained Catch	Total Catch	OFL	ABC
2014/15	28.7[A]	60.1[A]	9.99	10.01	11.92	15.04	13.53
2015/16	28.4[B]	61.0[B]	9.97	10.17	11.71	14.84	13.36
2016/17	27.6[C]	56.9[C]	8.47	8.65	9.59	14.63	13.17
2017/18	28.2[D]	54.1[D]	6.60	6.82	7.67	12.35	11.11
2018/19		45.5[D]				11.48	10.33

Notes:

A – Calculated from the assessment reviewed by the Crab Plan Team in September 2015
B – Calculated from the assessment reviewed by the Crab Plan Team in September 2016
C – Calculated from the assessment reviewed by the Crab Plan Team in September 2017
D – Calculated from the assessment reviewed by the Crab Plan Team in September 2018

6. Basis for the OFL: All table values are in 1000 t (Scenario 18.0):

Year	Tier	BMSY	Current MMB	B/BMSY (MMB)	FOFL	Years to define BMSY	Natural Mortality
2014/15	3b	25.7	24.7	0.96	0.28	1984-2014	0.18
2015/16	3b	26.1	24.7	0.95	0.27	1984-2015	0.18
2016/17	3b	25.8	24.0	0.93	0.27	1984-2016	0.18
2017/18	3b	25.1	21.3	0.85	0.24	1984-2017	0.18
2018/19	3b	25.5	20.6	0.81	0.24	1984-2017	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
2014/15	3b	56.7	54.4	0.96	0.28	1984-2014	0.18
2015/16	3b	57.5	54.4	0.95	0.27	1984-2015	0.18
2016/17	3b	56.8	52.9	0.93	0.27	1984-2016	0.18
2017/18	3b	55.2	47.0	0.85	0.24	1984-2017	0.18
2018/19	3b	56.3	45.5	0.81	0.24	1984-2017	0.18

A. Summary of Major Changes

1. Change to management of the fishery: None.

2. Changes to the input data:

a. Updated summer trawl survey data and directed pot fisheries catch and bycatch data through 2018.

b. Updated groundfish fisheries bycatch data during 2013-2017.

3. Changes to the assessment methodology:

a. Correcting two coding errors that result in overweighting small size length composition data of NMFS surveys and underweighting BSFRF survey biomass. These two errors were discovered recently by Dr. Andre Punt while working on GMACS. Combinations of these two errors make the model fit the NMFS survey data a little better and fit the BSFRF data a little worse. Comparison of the model results with the errors and without the errors are showed in survey biomass fits and absolute mature male biomass. The two errors do not affect past TACs and fishery.

b. Estimated recruitment in the terminal year is not used for estimating $B_{35\%}$. That is, the mean recruitment from 1984-2017 is used for estimating $B_{35\%}$.

c. For the directed pot fishery, the model fits total observer male biomass and length compositions, instead of discarded male biomass and length compositions. Observers will not separate retained and discarded legal males in the directed pot fishery from now on.

d. Analyses of terminal year of recruitment and dynamic B_0 (see Appendix C).

e. Six model scenarios are compared in this report (See Section E.3.a for details):

Scenario 2b: the scenario 2b in the SAFE report in September 2017 with correction of the two errors mentioned in (a) above. This scenario assumes that BSFRF survey capture probabilities are 1.0 for all length groups. Under this assumption, NMFS survey selectivities are the products of crab availabilities (equal to BSFRF survey selectivities) and NMFS survey capture probabilities. A survey capture probability for a length group is simply defined as the proportion of the crab in the length group within the area-swept that is caught by the survey net. Also, groundfish fisheries bycatch is separated into trawl fisheries and fixed gear fisheries.

Scenario 2b-old: the scenario 2b in the SAFE report in September 2017 without two error corrections. The purpose to include this scenario is to compare it with scenario 2b to examine the impacts of the two errors on the results.

Scenario 18.0: renamed from scenario 2bn1 in May 2018 with some changes based on the requests of CPT and SSC and the same as scenario 2b except with differences: (1) the total observer male biomass and total observer male length composition data in the directed pot fishery are used to replace discarded male biomass and discarded male length composition data, (2) total male selectivity and retained proportions in the directed pot fishery are used to replace retained selectivity and discarded male selectivity, and (3) due to high grading problems in some years since rationalization, two logistic curves are estimated for retained proportions: one before rationalization (before 2005) and another after 2004.

Scenario 18.0a: the same as scenario 18.0 except with equal annual effective sample sizes of male and female length compositions. Annual effective sample sizes with scenario 18.0 may be different between male and female length composition data.

Scenario 18.0b: renamed from scenario 2bn2 in May 2018 with some changes based on the requests of CPT and SSC and the same as scenario 18.0 except that only one logistic curve is estimated for all years for retained proportions and annual retention adjusted factors are estimated to modify retained proportions for years after 2004.

Scenario 18.0c: the same as scenario 18.0 except with the differences of total male selectivity and retained proportions in the directed pot fishery: (1) one logistic curve for total male selectivity is estimated with annual deviations of length at 50% selectivity parameter ($L_{50}^{dir,tot}$) and (2) another logistic curve is estimated for all years for retained proportions and for years after 2004 with annual deviations of length at 50% retained proportion parameter (L_{50}^{ret}). Similar to scenario 18.0b, after 2004, annual deviations are used to deal with annual high gradings

4. Changes to assessment results:

The population biomass estimates in 2018 are lower than those in 2017. Among the six scenarios, model estimated relative survey biomasses are very similar. The absolute mature male biomass estimates are higher for scenarios 18.0, 18.0a, 18.0b and 18.0c than for scenarios 2b and 2b-old during recent years. The model fits to BSFRF survey biomass are similar among six scenarios. The absolute mature male biomass estimates between scenarios 2b and 2b-old are very close: average relative error of -1.6% and average absolute relative error of 7.5%, and during the period covering the BSFRF survey data (2006-2017), relative errors ranging from -10.4% to 6.4%. Because of overweighting NMFS survey small length composition data and underweighting BSFRF survey biomass, scenario 2b-old fits the NMFS survey data better than other scenarios. We recommend scenario 18.0 or scenario 18.0a for overfishing definition for September 2018 because the results are hardly different among scenarios 18.0, 18.0a, 18.0b and 18.0c and these two scenarios have the least number of estimated parameters. Scenario 2b will be discontinued next year due to changes in data collection.

The recruitment breakpoint analysis (Appendix B) estimates 1986 as the breakpoint brood year, or 1992 recruitment year in May 2017. Terminal year recruitment analysis suggests the estimated recruitment in the last terminal year should not be used for estimating $B_{35\%}$.

B. Responses to SSC and CPT Comments

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

CPT and SSC Comments (from January and February 2018)
Conduct a dynamic B0 analysis and a retrospective analysis of terminal years of recruitment for the CPT meeting of May 2018.

Response: These two analyses are presented in this draft report (see retrospective results and Appendix C).

CPT comments (from January 2018)

"The CPT requested for the May 2018 meeting that assessment authors evaluate the impacts associated with discontinuing the collecting of information on legal retention status by crab observers. In addition, authors were encouraged to evaluate alternative discard calculations and/or suggest alternative methods for the determination of legal male retention status. It was also suggested that stock assessment authors outline for the CPT how legal not retained information is used or addressed in stock assessments."

Response: Four approaches (scenarios 18.0, 18.0a, 18.0b, and 18.0c) to deal with this issue are presented in this draft report.

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

Response to CPT Comments (from September 2017):

"Look at the weighting again for this assessment: it is still based on multiplicative lambda's."

Response: Corresponding CV values are provided for the lambda values in this SAFE report.

"The difficulties achieving convergence need to be explored: they are unexpected and concerning."

Response: Yes, it is a concern. At the September 2017 CPT meeting, Jack Turnock mentioned that he had similar problems with the snow crab model. This could be parameter confounding or initial value problems.

“Jittering initial parameter values was not used in this assessment, but may be useful in evaluating convergence issues.”

Response: Agreed. We used jittering before and may use it in the future.

“The tensions in the assessment data leading to estimates of NMFS survey Q at 1 need to be identified and approaches to deal with them need to be developed.”

Response: Correcting the error of underweighting BSFRF survey biomass help reducing estimated Q values somewhat. There may be several causes to explain this: (1) M and Q are confounded, (2) the sharp decline of abundance in the early 1980s may make estimated Q higher, and (3) few small crab were caught in the survey during the most recent 10 or more years, causing small estimated survey logistic curve values for the small size classes; for a given length, the overall selectivity value (combined catchability and logistic curve value) is Q times logistic curve value, not just Q.

In May 2018, we did several runs to explore Q values: (1) for scenario 2b, estimated Qs are 0.97, 0.95, and 0.93 with base M of 0.18, 0.22 and 0.3; (2) starting the model in 1985 for scenario 2b, resulting in scenario 2b85, Q is estimated as 0.91, which fits the BSFRF survey biomass very well (see the results for scenario 2b85 in this draft SAFE report); (3) starting the model in 1985 for scenario 2c with a fixed M of 0.18, resulting in scenario 2c85, Q is estimated as 0.92. These runs were with the error of underweighting BSFRF survey biomass. After correcting the error, estimated Q values would be smaller than the values here; for example, estimated Q value is 0.91 with scenario 2b in this report.

“The assessment document needs to be updated to reflect changes in the 2016 BSFRF estimate in the main section of text, not just in the Executive Summary.”

Response: This was done in 2017 SAFE report.

“Provide an explanation of why Equation A4 (catch in the directed fishery) is correct (or correct it if it is wrong).”

Response: The equation A4 (below) is correct. It is a simple equation under the assumption of pulse fishing. Total abundance is reduced by natural mortality to the mid-point of the directed pot fishing and then total fishing mortality is applied to the remaining abundance to get catch. For females, it is female bycatch. For males, the retained catch and bycatch are then separated by their selectivity proportions. The Tanner crab fishery and groundfish fisheries are assumed to be pulse fishing and occur after the directed fishery.

$$G^{s}_{l,t} = (N^{s}_{l,t} + O^{s}_{l,t})e^{-y_t M^{s}_{t}}(1 - e^{-F^{s}_{l,t}})$$

Response to CPT Comments (from May 2018):

“1) fitting the total catch estimated from at-sea observer data and total retained catch without incorporating the “subtraction” method for estimating legal discards,”

Response: Done for scenarios 18.0, 18.0a, 18.0b and 18.0c.

"2) incorporating time varying fishery selectivity and annual retained proportions,"

Response: Scenarios 18.0, 18.0b and 18.0c address this.

"3) the recruitment in terminal year should not be used for estimating B35% (i.e., mean recruitment is estimated from recruitments from 1984 to endyear – 1)."

Response: Done for all scenarios.

Response to SSC Comments specific to this assessment (from October 2017):

"The SSC reiterates its request from June 2017 for the BBRKC author and CPT to objectively define the terminal year of recruitment to include in reference point calculations in this and other crab assessments, and again requests that the author use the breakpoint analysis applied for Tanner crab to BBRKC to evaluate whether there was a detectable break in production in 2006. The SSC looks forward to the outcomes of a more comprehensive discussion on this topic at the January 2018 CPT meeting."

Response: Analysis of terminal year of recruitment is included in this draft SAFE report. Based on the results, we recommend not including the recruitment in the most recent year. Breakpoint analysis was done in May 2017, which includes brood years only up to 2005. We will repeat the breakpoint analysis in May 2019 to detect brood year 2006 when we get one more data point.

"This assessment uses the number of lengths measured as a starting point for input sample sizes. The SSC recommends following the approach of other crab and groundfish stocks in using the number of stations or pots sampled as a better proxy for statistical sample size given the frequently very high correlation among individuals within a single sample."

Response: Right now for crab stocks, only the Aleutian Islands golden king crab model does not use the number of lengths measured as a starting point for input sample sizes. The golden king crab model uses only directed fishery length composition data, so it is easy for the model to use boat-days for a starting point for effective sample sizes. The Bristol Bay red king crab model includes length composition data from the trawl survey, directed pot fishery, Tanner crab fishery bycatch, groundfish trawl bycatch, and groundfish fixed gear bycatch. It is difficult to find measurement units of sample sizes that are comparable. The number of survey hauls will be almost constant over time, which is difficult to compare with number of pots, or boat-days, or trips. Snow and Tanner crab models have the same problem. Hopefully we can learn from the groundfish stock model approaches and find a better way to deal with sample sizes in the future.

"More research on catchability is needed, including review of existing camera work from BSFRF surveys that may shed light on crab behavior in response to trawl gear. The SSC provided some

comments on new research using modifications of the BSFRF Model under the subsection "Crab Bycatch" earlier in this report."

Response: We agree with these suggestions for needed research. Analysis of camera work from BSFRF surveys will be helpful, especially on the herding effects of BSFRF surveys.

"The CPT suggested that large catches that drove the stock down in the early 1980s could drive the fits, resulting in an estimate of q near 1.0. On this basis, other evaluation of q could include investigating the effect of the period of historical decline (perhaps by down-weighting it) on more recent estimates of catchability, or fitting a research model fit to BBRKC with only data after the stock collapse in the early 1980s."

"The SSC noted that historical modelling was conducted using relatively simple catch-survey analysis (Collie and Kruse 1998; Can. Spec. Publ. Fish. Aquat. Sci. 125: 73-83). This might provide another tool for exploring why current estimates of catchability are so close to 1.0."

Response: There may be several causes to explain Q value close to or higher than 1.0: (1) M and Q are confounded, (2) the sharp decline of abundance in the early 1980s may make estimated Q higher and (3) few small crab were caught in the survey during the most recent 10 or more years, causing small estimated survey logistic curve values for the small size classes; for a given length, the overall selectivity value (combined catchability and logistic curve value) is Q times logistic curve value, not just Q.

We did several runs to explore Q values in May 2018: (1) for scenario 2b, estimated Qs are 0.97, 0.95, and 0.93 with base M of 0.18, 0.22 and 0.3; (2) starting the model in 1985 for scenario 2b, resulting in scenario 2b85, Q is estimated as 0.91, which fits the BSFRF survey biomass very well (see the results for scenario 2b85 in this draft SAFE report); (3) starting the model in 1985 for scenario 2c with a fixed M of 0.18, resulting in scenario 2c85, Q is estimated as 0.92. After correcting the error that underweights BSFRF survey biomass, estimated Q values would be smaller than the values here; for example, estimated Q value is 0.91 with scenario 2b in this report.

The catch-survey analysis (Collie and Kruse 1998; Can. Spec. Publ. Fish. Aquat. Sci. 125: 73-83) is a simple way to explore Q and M relationships. With similar M values as our model, Q is estimated to be 0.95 by Collie and Kruse (1998); however, with a constant M of 0.36, Q is estimated to be 1.01.

"The SSC is also looking forward to continued development of the Gmacs model for BBRKC during 2018."

Response: We are looking forward to the day of moving over to GMACS too.

Response to SSC Comments specific to this assessment (from June 2018):

"to not use the subtraction method moving forward."

Response: Agree and no subtraction method from now on.

"The SSC also requests that the authors investigate whether groundfish discard information is available for fixed gear prior to 2010. In addition, the document uses inconsistent terminology for pot gear and fixed gear (particularly on figure and table headings), as well as groundfish gear versus crab gear, and the associated mortality rates. The SSC requests that the authors check the document for consistent use of these terms."

Response: We did some preliminary search on groundfish bycatch data and found that the data from 1991 to 2009 have been added to the NMFS database. During these years, fixed gear bycatch is an average of 22.6% of total groundfish bycatch. Due to time constraint, we will not separate groundfish bycatch into trawl and fixed gear bycatch before 2009 for this CPT meeting (September 2018) and will sort out these data and use them in the CPT meeting in May 2019.

We went through our SAFE report to check for consistent use of gear terms and corrected them as necessary.

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, eastern Bering Sea, and the Gulf of Alaska.

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

The NMFS and BSFRF trawl survey data were updated to include the 2018 survey data.

Catch and biomass data were updated to 2017/18. Groundfish fisheries bycatch data during 2013-2017 were updated.

Data types and ranges are illustrated in Figure 2.

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 2017. 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 July 1 to June 30; 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 3. 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 1). 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 4). 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 1975-2017 were provided by NMFS.

Abundance estimates by sex, carapace length, and shell condition were derived from survey data using an area-swept approach (Figures 5a and 5b). 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 since 2015 discards all "hot spot" tows. We used the new area-swept estimates provided by NMFS in 2018.

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, 2006-2012, and 2017. 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. BSFRF also conducted a side-by-side survey concurrent with the NMFS trawl survey during 2013-2016 in Bristol Bay. In May 2017, survey biomass and size composition estimates from 2016 BSFRF side-by-side trawl survey data were updated. Total survey biomass decreased from 87,725.1 t initially estimated in September 2016 to 77,815.7 t in the final estimate in May 2017, about 11.3% reduction. The initial estimate mistakenly included the tows conducted in the recruitment study.

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 2018.

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. Francis' approaches for re-weighting the effective sample sizes for size composition data are detailed in Appendix C.

a-f. See appendix A.

g. Critical assumptions of the model:

  i. The base natural mortality is constant over sex, 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) 1982-2018, 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, growth-per-molt increments as a function of length were estimated for three periods (1975-1982, 1983-1993, and 1994-2018) 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 for some scenarios. *Q* is assumed to be constant over time and is estimated in the model.

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 (scenarios):

2b: Scenario 2b is the same as scenario 2b in the SAFE draft report in September 2017 with correction of the two errors that result in overweighting small size length composition data of NMFS surveys and underweighting BSFRF survey biomass. This scenario assumes that BSFRF survey capture probabilities are 1.0 for all length groups. Under this assumption, NMFS survey selectivities are the products of crab availabilities (equal to BSFRF survey selectivities) and NMFS survey capture probabilities. A survey capture probability for a length group is simply defined as the proportion of the crab in the length group within the area-swept that is caught by the survey net. Also, groundfish fisheries bycatch is separated into trawl fisheries and fixed gear fisheries.

Scenario 2b includes:

(1) Base *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. Additional mortalities are estimated in the model.

(2) Including BSFRF survey data during 2007-2008 and 2013-2016. The BSFRF survey is treated as an independent survey, and no assumption is made about the capture probabilities of the BSFRF survey. In effect, survey selectivities for both surveys are estimated separately in the model.

(3) NMFS survey catchability is estimated in the model and is assumed to be constant over time. BSFRF survey catchability is assumed to be 1.0.

(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. Stage-1 effective sample sizes are estimated as min(0.5*n1, N) for trawl surveys and min(0.1* n1, N) for catch and bycatch, where n1 is an observed sample size for a sex, 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 groundfish fisheries. There is a justification for enforcing a maximum limit to effective sample sizes because the number of length measurements is large (Fournier at al. 1998). 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:

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

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 NMFS survey retow data (during cold years) for females.

(7) Estimating initial year length compositions.

For scenario 2b, survey abundances $\hat{N}^b_{s,y,l}$ (BSFRF survey) and $\hat{N}^n_{s,y,l}$ (NMFS survey) by sex *s* and in year *y* and length group *l* are computed as follows:

$$\begin{aligned} \hat{N}^b_{s,y,l} &= N_{s,y,l}\, s^b_{s,l}, \\ \hat{N}^n_{s,y,l} &= N_{s,y,l}\, s^n_{s,l}, \end{aligned} \qquad (2)$$

where $s^b_{s,l}$ and $s^n_{s,l}$ are survey selectivities for BSFRF and NMFS surveys by sex *s* and in length group *l*, respectively, and $N_{s,y,l}$ is the population abundance by sex *s* and in year y and length group *l*. BSFRF survey selectivities are computed as

$$s^b_{s,l} = \frac{1}{1 + e^{-\beta^b_s\,(l - L^b_{50,s})}}, \qquad (3)$$

where *β* and L_{50} are parameters. 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*, *L50* for females and *L50* for males) were estimated in the model for each survey. The BSFRF survey catchability is assumed to be 1.0.

Scenario 2b assumes that the BSFRF survey capture probabilities are 1.0 for all length groups. Under this assumption, NMFS survey selectivities are the products of crab availabilities (equal to BSFRF survey selectivities) and NMFS survey capture probabilities (*p*):

$$s^n_{s,l} = p_{s,l}\, s^b_{s,l}. \qquad (4)$$

Therefore, the model estimates NMFS survey capture probabilities and BSFRF survey selectivities and computes NMFS survey selectivities from these estimates. NMFS survey capture probabilities are computed as

$$p_{s,l} = \frac{Q}{1+e^{-\beta_s \ (l-L_{50,s})}}, \tag{5}$$

where β and *L50* are parameters and similar to the survey selectivities, only three parameters (β, *L50* for females and *L50* for males) were estimated in the model for each sex. Q is the NMFS survey catchability and is estimated in the model with or without a prior from the double-bag experiment, depending on scenarios.

Since fishing times for both Tanner crab fishery and groundfish fishery are assumed to occur the same time, the fraction separation of fishing mortality rates for both fisheries is used to divide the total fishing mortality rate to individual fisheries, that is, $F_i/F_{tot}*(1-\exp(-F_{tot}))$ for fishery i, and the sum of $F_i = F_{tot}$.

2b-old: the scenario 2b in the SAFE report in September 2017 without two error corrections. The purpose to include this scenario is to compare it with scenario 2b to examine the impacts of the two errors on the results.

18.0: renamed from scenario 2bn1 in May 2018 with some changes based on the requests of CPT and SSC and the same as scenario 2b except with differences: (1) the total observer male biomass and total observer male length composition data in the directed pot fishery are used to replace discarded male biomass and discarded male length composition data, (2) total male selectivity and retained proportions in the directed pot fishery are used to replace retained selectivity and discarded male selectivity, and (3) due to high grading problems in some years since rationalization, two logistic curves are estimated for retained proportions: one before rationalization (before 2005) and another after 2004.

18.0a: the same as scenario 18.0 except with equal annual effective sample sizes of male and female length compositions. Annual effective sample sizes with scenario 18.0 may be different between male and female length composition data. To maintain the same level of effective sample sizes with scenario 18.0, stage-1 effective sample sizes for scenario 18.0a are estimated as min[0.25*n, N] for trawl surveys and min(0.05* n, N) for catch and bycatch, where n is the sum of observed sample sizes for two sexes, 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 groundfish fisheries.

18.0b: renamed from scenario 2bn2 in May 2018 with some changes based on the requests of CPT and SSC and the same as scenario 18.0 except that only one logistic curve is estimated for all years for retained proportions and to deal with annual high gradings, annual adjusted factor parameter, x_t, is estimated for each year after 2004 and a logit transformation is used to make sure the adjusted factor, u_t, be <1.0:

$$u_t = \frac{e^{x_t}}{1+e^{x_t}} \tag{6}$$

Annual retained proportions after 2004 are estimated as:

$$S^{ret}_{l,t} = u_t \, S^{ret}_{l} \tag{7}$$

To avoid overfitting the data, a negative likelihood value is computed as:

$$\sum_t (u_t - 1.0)^2/(2\sigma^2) \tag{8}$$

where σ is the standard deviation of u_t and is assumed to be 0.1. The model results hardly change with either 0.1 or 0.2.

18.0c: the same as scenario 18.0 except with the differences of total male selectivity and retained proportions in the directed pot fishery: (1) one logistic curve for total male selectivity is estimated with annual deviations of length at 50% selectivity parameter ($devL_{50,t}^{dir,tot}$) and (2) another logistic curve is estimated for all years for retained proportions and for years after 2004 with annual deviations of length at 50% retained proportion parameter ($devL_{50,t}^{ret}$). Similar to scenario 18.0b, after 2004, annual deviations are used to deal with annual high gradings.

To avoid overfitting the data, a negative likelihood value is computed as:

$$0.1[first\ difference(devL_{50,t}^{dir,tot})]^2 + 0.1[first\ difference(devL_{50,t}^{ret})]^2 \tag{9}$$

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.

j. Jittering: the Stock Synthesis Approach is used to do jittering to find the optimum:

The *Jitter* factor of 0.1 is multiplied by a random normal deviation *rdev*=*N*(0,1), to a transformed parameter value based upon the predefined parameter:

$$temp = 0.5\ rdev\ Jitter\ \ln\left(\frac{P_{\max} - P_{\min} + 0.0000002}{P_{val} - P_{\min} + 0.0000001} - 1\right), \tag{6}$$

with the final jittered starting parameter value backtransformed as:

$$P_{new} = P_{\min} + \frac{P_{\max} - P_{\min}}{1.0 + \exp(-2.0\ temp)}, \tag{7}$$

where P_{max} and P_{min} are upper and lower bounds of parameters and P_{val} is the estimated parameter value before the jittering. Due to time constraints, the jittering approach is not used in this report.

4. Results

a. Effective sample sizes and weighting factors. Effective sample sizes and weighting factors.

i. For scenario 18.0, effective sample sizes are illustrated in Figures 6 and 7.

ii. CVs are assumed to be 0.03 for retained catch biomass, and 0.07 for all bycatch biomasses, 0.53 for recruitment variation, and 0.23 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 for all scenarios.

b. Tables of estimates.

  i. Parameter estimates for scenarios 18.0 and 18.0a are summarized in Tables 3-5.

  ii. Abundance and biomass time series are provided in Table 6 for scenarios 18.0 and 18.0a.

  iii. Recruitment time series for scenarios 18.0 and 18.0a 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 groundfish fisheries 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 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 18.0, 18.0a, and 18.0c.

One of the most important results is estimated trawl survey selectivity (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. 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 all scenarios, estimated molting probabilities during 1975-2018 (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 among the six scenarios and fit the survey data quite well. The absolute mature male biomass estimates are higher for scenarios 18.0, 18.0a, 18.0b and 18.0c than for scenarios 2b and 2b-old in recent years. The model fits to BSFRF survey biomass are similar among six scenarios. The absolute mature male biomass estimates between scenarios 2b and 2b-old are very close: average relative error of -1.6% and average absolute relative error of 7.5%, and during the period covering the BSFRF survey data (2006-2017), relative errors ranging from -10.4% to 6.4%. Because of overweighting NMFS survey small length composition data and underweighting BSFRF survey biomass, scenario 2b-old fits the NMFS survey data better than other scenarios. The two errors with scenario 2b-old do not affect past TACs and fishery.

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 and 2018 (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 all scenarios have a similar trend 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 18.0 and 18.0a.

iv. Estimated fishing mortality rates are plotted against mature male biomass in Figure 13 for scenarios 18.0 and 18.0a.

The average of estimated male recruits from 1984 to 2017 (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 1998-1999, 2005-2009 for scenarios 18.0 and 18.0a but below the $F_{35\%}$ limits in the other post-1995 years.

For scenario 18.0, estimated full pot fishing mortalities ranged from 0.00 to 2.41 during 1975-2017. Estimated values were greater than 0.40 during 1975-1982, 1984-1987, 1990-1991, 1993, 1998 and 2007-2008 (Table 5, Figure 13). For scenario 18.0a, estimated full pot fishing mortalities ranged from 0.00 to 2.36 during 1975-2017, with estimated values over 0.40 during 1975-1982, 1984-1987, 1990-1991, 1993, 1998, and 2007-2008 (Figure 13). Estimated fishing mortalities for pot female and groundfish fisheries bycatches were generally less than 0.06.

v. Estimated mature male biomass and recruitment are plotted to illustrate their relationships with scenario 18.0 (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 14b).

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). Egg clutch fullness during the last three years is relatively low.

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 (six scenarios) fit the fishery biomass data well and the survey biomass reasonably well (Figures 10 and 16). Because the model estimates annual fishing mortality for directed pot male catch, undirected pot male bycatch, pot female bycatch, trawl and fixed gear 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 total pot males well with different approaches (Figure 21).

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 18.0 and 18.0a (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.

e. Retrospective and historic analyses.

Two kinds of retrospective analyses were conducted for this report: (1) the 2018 model (scenario 18.0) hindcast results and (2) historical results. The 2018 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 2018 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 2018 model includes sequentially excluding one-year of data. The model with scenario 18.0 performed reasonably well during 2011-2017 with a lower terminal year estimates of mature male biomass in 2011-2013 and higher estimates in 2014-2016 (Figures 27-28).

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 2018 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 2018 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).

Ratios of estimated retrospective recruitments to terminal estimates in 2018 as a function of number of years estimated in the model show converging to 1.0 as the number of years increase (Figure 28). Standard deviations of the ratios drop sharply from one year estimated in the model to two years (Figure 28), showing great uncertainty of recruitment estimates for terminal years. Based on these results, we suggest not using recruitment estimates in a terminal year for overfishing/overfished determination.

f. Uncertainty and sensitivity analyses

i. Estimated standard deviations of parameters are summarized in Table 5 for scenarios 18.0 and 18.0a. 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 18.0 and 18.0a using the mcmc approach; estimated *Q*s are less than 1.0. Probabilities for mature male biomass and OFL in 2018 are illustrated in Figure 31 for scenarios 18.0 and 18.0a using the mcmc approach. 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 2018), six scenarios are compared. Model estimated relative survey biomasses are very similar among the scenarios. The absolute mature male biomass estimates are higher for scenarios 18.0, 18.0a, 18.0b and 18.0c than for scenarios 2b and 2b-old during recent years. The model fits to BSFRF survey biomass are similar among six scenarios. The absolute mature male biomass estimates between scenarios 2b and 2b-old are very close: average relative error of -1.6% and average absolute relative error of 7.5%, and during the period covering the BSFRF survey data (2006-2017), relative errors ranging from -10.4% to

6.4%. Because of overweighting NMFS survey small length composition data and underweighting BSFRF survey biomass, scenario 2b-old fits the NMFS survey data better than other scenarios. The two errors with scenario 2b-old do not affect past TACs and fishery. We recommend scenario 18.0 or scenario 18.0a for overfishing definition for September 2018 because the results are hardly different among scenarios 18.0, 18.0a, 18.0b and 18.0c and these two scenarios have the least number of estimated parameters. Scenario 2b will be discontinued next year due to changes in data collection.

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

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

c) $\frac{B}{B^*} \le \beta$ $\qquad$ 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 is not related to pot fishing mortality, average trawl bycatch fishing mortality during 2008 to 2017 is used for the per recruit analysis as well as for projections in the next section. Pot female bycatch fishing mortality is set equal to pot male fishing mortality times 0.02, an intermediate level during 1990-2017. 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 2016-2017 are used to represent current trends for per recruit analysis and projections. Average molting probabilities during 2008-2017 are used for per recruit analysis and projections.

Average recruitments during three periods are used to estimate $B_{35\%}$: 1976-2017, 1984-2017, and 1991-2017 (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 1984-2018 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/B_{MSY} or B/B_{MSY}-proxy equals or declines below β, then the stock productivity is severely depleted and the fishery is closed.

The estimated probability distribution of MMB in 2018 is illustrated in Figure 30. Based SSC suggestion in 2011, ABC = 0.9*OFL is used to estimate ABC.

Status and catch specifications (1,000 t) (scenario 18.0):

Year	**MSST**	**Biomass (MMB)**	**TAC**	**Retained Catch**	**Total Catch**	**OFL**	**ABC**
2014/15	13.03^{A}	27.25^{A}	4.49	4.54	5.41	6.82	6.14
2015/16	12.89^{B}	27.68^{B}	4.52	4.61	5.31	6.73	6.06
2016/17	12.53^{C}	25.81^{C}	3.84	3.92	4.35	6.64	5.97
2017/18	12.77^{D}	24.53^{D}	2.99	3.09	3.48	5.60	5.04
2018/19		20.62^{D}				5.21	4.69

The stock was above MSST in 2017/18 and hence was not overfished. Overfishing did not occur.

Status and catch specifications (million lbs):

Year	MSST	Biomass (MMB)	TAC	Retained Catch	Total Catch	OFL	ABC
2014/15	28.7^A	60.1^A	9.99	10.01	11.92	15.04	13.53
2015/16	28.4^B	61.0^B	9.97	10.17	11.71	14.84	13.36
2016/17	27.6^C	56.9^C	8.47	8.65	9.59	14.63	13.17
2017/18	28.2^D	54.1^D	6.60	6.82	7.67	12.35	11.11
2018/19		45.5^D				11.48	10.33

Notes:

A – Calculated from the assessment reviewed by the Crab Plan Team in September 2015
B – Calculated from the assessment reviewed by the Crab Plan Team in September 2016
C – Calculated from the assessment reviewed by the Crab Plan Team in September 2017
D – Calculated from the assessment reviewed by the Crab Plan Team in September 2018

4. Based on the $B_{35\%}$ estimated from the average male recruitment during 1984-2017, the biological reference points and OFL are illustrated in Table 4.

5. Based on the 10% buffer rule used last year, ABC = 0.9*OFL (Table 4). 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 is a random selection from estimated recruitments during 1984-2018. Besides recruitment, the other major uncertainty for the projections is estimated abundance in 2018. The 2018 abundance is 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 are 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 is replicated 1,000 times and projections made over 10 years beginning in 2018 (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 tracked during 2012-2018 surveys. This single 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 also inconsistent with the 2015-2018 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.

J. Acknowledgements

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Table 1a. Bristol Bay red king crab annual catch and bycatch mortality biomass (t) from July 1 to June 30. A handling mortality rate of 20% for the directed pot, 25% for the Tanner fishery, 80% for trawl and 50% or fixed gear was assumed to estimate bycatch mortality biomass.

Year	Retained Catch				Pot Bycatch		Trawl Bycat.	Fixed Bycat.	Tanner Fishery Bycat.	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	94.8	5.8	1.6	8348.1
2010	6728.5	33.0	0	6761.5	797.5	122.6	83.3	2.4	0.0	7767.3
2011	3553.3	53.8	0	3607.1	395.0	24.0	56.3	10.9	0.0	4093.2
2012	3560.6	61.1	0	3621.7	205.2	12.3	34.2	18.4	0.0	3891.9
2013	3901.1	89.9	0	3991.0	310.6	99.8	66.8	55.5	28.5	4552.1
2014	4530.0	8.6	0	4538.6	584.7	86.2	34.7	118.8	42.0	5405.0
2015	4522.3	91.4	0	4613.7	266.1	222.9	46.3	77.3	84.2	5310.6
2016	3840.4	83.4	0	3923.9	237.4	87.1	71.0	29.3	0.0	4348.6
2017	2994.1	99.6	0	3093.7	225.2	53.3	97.4	11.0	0.0	3480.6

Table 1b. 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		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	
2015					1.527	31	
2016					1.281	38	
2017					0.997	20	

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

Year	Trawl Survey		Retained Catch	Pot Bycatch		Trawl & Fixed Gear Bycatch		Tanner Fishery Bycatch	
	Males	Females		Males	Females	Males	Females	Males	Females
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	1,431	848		
2010	705	1,633	20,137	36,654	6,868	612	837		
2011	525	994	10,706	20,629	1,920	563	1,068		
2012	580	707	8,956	7,206	561	1,507	1,751		
2013	633	560	10,197	13,828	6,048	4,806	4,198	218	596
2014	1,106	1,255	9,618	13,040	1,950	2,027	2,602	256	381
2015	600	677	11,746	8,037	5,889	1,267	3,753	726	2163
2016	374	803	10,811	9,497	4,216	1,977	3,035		
2017	470	558	9,867	12,511	3,725	1,001	1,145		
2018	384	420							

Table 3. Number of parameters and the list of likelihood components for the model (Scenarios 2b,18.0, 18.0a, 18.0b, and 18.0c).

Parameter counts	**Sce. 2b**	**Sce. 18.0 & 18.0a**	**Sce. 18.0b**	**Sce. 18.0c**
Fixed growth parameters	9	9	9	9
Fixed recruitment parameters	2	2	2	2
Fixed length-weight relationship parameters	6	6	6	6
Fixed mortality parameters	4	4	4	4
Fixed survey catchability parameter	1	1	1	1
Fixed high grading parameters	13	0	0	0
Total number of fixed parameters	35	22	22	22
Free survey catchability parameter	1	1	1	1
Free growth parameters	6	6	6	6
Initial abundance (1975)	1	1	1	1
Recruitment-distribution parameters	2	2	2	2
Mean recruitment parameters	1	1	1	1
Male recruitment deviations	43	43	43	43
Female recruitment deviations	43	43	43	43
Natural and fishing mortality parameters	4	4	4	4
Pot male fishing mortality deviations	44	44	44	44
Bycatch mortality from the Tanner crab fishery	11	11	11	11
Pot female bycatch fishing mortality deviations	29	29	29	29
Trawl bycatch fishing mortality deviations	43	43	43	43
Fixed gear bycatch fishing mortality deviations	10	10	10	10
Initial (1975) length compositions	35	35	35	35
BSFRF survey extra CV	1	1	1	1
Free selectivity parameters	24	25	37	81
Total number of free parameters	298	299	311	355
Total number of fixed and free parameters	333	321	333	377

Table 4. Negative log likelihood components for scenarios 2b, 18.0, 18.0a, 18.0b, and 18.0c and some management quantities.

Scenario

Negative log likelihood	18.0	18.0a	18.0b	18.0c	2b	18.0-18.0b	18.0-18.0c	18.0-2b	18.0b-18.0c
R-variation	65.0	64.7	65.6	65.8	65.6	-0.54	-0.77	-0.55	-0.23
Length-like-retained	-1109.7	-1109.7	-1104.3	-1124.5	-1102.6	-5.43	14.77	-7.15	20.20
Length-like-tot/dis male	-1273.8	-1274.2	-1274.9	-1296.9	-1133.1	1.11	23.07	-140.71	21.96
Length-like-discfemale	-859.4	-859.4	-854.9	-854.7	-845.0	-4.49	-4.70	-14.41	-0.22
Length-like-survey	-5096.2	-5097.4	-5096.7	-5098.4	-5070.7	0.54	2.23	-25.48	1.69
Length-like-disctrawl	-3918.1	-3935.9	-3922.1	-3926.5	-3913.2	3.98	8.37	-4.89	4.39
Length-like-discfix	-880.6	-887.4	-881.2	-879.6	-878.2	0.63	-1.01	-2.34	-1.63
Length-like-discTanner	-480.5	-491.8	-480.4	-480.4	-477.4	-0.18	-0.10	-3.13	0.07
Length-like-bsfrfsurvey	-649.7	-650.7	-649.8	-650.2	-644.9	0.15	0.52	-4.76	0.37
Catchbio_retained	16.7	16.7	14.6	9.2	27.5	2.11	7.55	-10.83	5.44
Catchbio_tot/discmale	58.2	58.4	48.1	21.7	135.8	10.11	36.44	-77.67	26.33
Catchbio-discfemale	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
Catchbio-disctrawl	0.0	0.0	0.0	0.0	0.0	0.00	0.00	-0.01	0.00
Catchbio-discfix	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
Catchbio-discTanner	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
Biomass-trawl survey	115.3	115.9	115.2	116.9	112.4	0.10	-1.59	2.84	-1.69
Biomass-bsfrfsurvey	-10.8	-10.9	-10.9	-11.1	-10.0	0.18	0.38	-0.81	0.20
Q-trawl survey	0.7	0.7	0.6	0.9	0.2	0.07	-0.20	0.48	-0.26
Others	18.1	18.1	22.1	19.6	18.0	-4.03	-1.45	0.13	2.58
Total	-14005	-14043	-14009	-14088	-13715	4.30	83.50	-289.30	79.20
Free parameters	299	299	311	368	298	-12	-69	1	-57
B35%(t)	25540	25479	25514	25920	24910	26.30	-380.10	630.40	-406.40
F35%	0.31	0.31	0.32	0.30	0.30	-0.01	0.01	0.01	0.02
MMB2018(t)	20617	20804	20581	20940	19820	35.60	-323.70	797.00	-359.30
OFL2018	5207	5336	5137	5236	4789	69.88	-28.77	417.78	-98.65
ABC2018(t)	4686	4803	4623	4712	4310	62.89	-25.89	376.00	-88.78
Fofl2018	0.244	0.247	0.251	0.236	0.232	-0.01	0.01	0.01	0.02
Q	0.925	0.925	0.923	0.929	0.911	0.00	0.00	0.01	-0.01

Table 5(18.0). Summary of estimated model parameter values and standard deviations and limits for scenario 18.0 for Bristol Bay red king crab. All values are on a log scale. Male recruit in year *t* is exp($mean+males_t$), and female recruit in year *t* is exp($mean+males_t+females_t$).

Year	Recruits				F for Directed Pot Fishery				F for Trawl	
	Females	SD	Males	SD	Males	SD	Females	SD	Estimate	SD
Mean	15.965	0.034	15.965	0.034	-1.570	0.042	0.012	0.001	-4.484	0.078
Limits↑	13,18		13,18		-3.0,0.0		.001,0.1		-8.5,-1.0	
Limits↓	-15,15		-15,15		-10,2.43		-6.0,3.5		-10,10	
1975					0.780	0.135				
1976	0.083	0.597	0.480	0.393	0.737	0.096			0.165	0.128
1977	0.550	0.438	0.510	0.260	0.656	0.075			0.629	0.118
1978	0.519	0.396	0.765	0.217	0.805	0.062			0.663	0.112
1979	0.746	0.297	1.135	0.199	1.093	0.056			0.821	0.110
1980	0.248	0.306	1.609	0.174	2.005	0.056			1.610	0.110
1981	0.012	0.370	0.992	0.243	2.425	0.013			1.295	0.110
1982	0.012	0.155	2.335	0.109	0.780	0.089			2.481	0.114
1983	0.041	0.238	1.436	0.139	-9.995	0.029			2.120	0.111
1984	0.655	0.177	1.065	0.123	0.885	0.090			3.219	0.114
1985	-0.268	0.428	-0.304	0.208	0.927	0.098			1.998	0.114
1986	0.742	0.177	0.334	0.124	1.237	0.077			0.988	0.113
1987	-0.039	0.392	-0.422	0.183	0.826	0.068			0.578	0.111
1988	-0.065	0.448	-0.932	0.212	-0.069	0.056			1.388	0.106
1989	-0.094	0.341	-0.580	0.166	0.060	0.050			-0.030	0.105
1990	0.307	0.183	0.073	0.118	0.753	0.045	1.988	0.089	0.396	0.105
1991	0.138	0.239	-0.239	0.137	0.749	0.047	-0.618	0.089	0.768	0.106
1992	-0.536	0.478	-1.243	0.234	0.174	0.052	2.141	0.091	0.838	0.107
1993	-0.192	0.287	-0.513	0.151	0.920	0.059	1.920	0.095	1.315	0.111
1994	-0.113	0.478	-1.227	0.242	-4.201	0.056	1.254	0.122	-0.500	0.107
1995	0.053	0.095	1.164	0.072	-4.622	0.046	1.408	0.123	0.058	0.105
1996	-0.999	0.455	-0.604	0.245	-0.076	0.045	-3.702	0.140	-0.574	0.105
1997	-0.894	0.453	-0.887	0.234	0.017	0.047	-0.389	0.088	-0.954	0.105
1998	-0.577	0.327	-0.104	0.151	0.823	0.052	1.495	0.088	-0.067	0.106
1999	0.065	0.158	0.625	0.100	0.421	0.049	-2.778	0.095	0.083	0.105
2000	-0.126	0.366	-0.307	0.193	-0.178	0.047	1.133	0.084	-0.778	0.105
2001	0.116	0.368	-0.352	0.205	-0.232	0.046	0.817	0.084	-0.387	0.104
2002	0.419	0.132	0.906	0.096	-0.110	0.046	-1.972	0.089	-0.505	0.104
2003	-0.415	0.472	-0.410	0.242	0.354	0.044	1.122	0.083	-0.390	0.104
2004	-0.248	0.387	-0.141	0.197	0.336	0.045	0.328	0.084	-0.760	0.104
2005	0.076	0.160	0.874	0.095	0.636	0.048	0.820	0.085	-0.457	0.104
2006	-0.189	0.289	0.237	0.138	0.411	0.047	-1.404	0.085	-0.782	0.104
2007	-0.492	0.334	-0.096	0.151	0.698	0.047	-0.272	0.084	-0.594	0.104
2008	-0.059	0.372	-0.693	0.201	0.820	0.051	-0.517	0.086	-0.417	0.104
2009	0.366	0.304	-0.491	0.181	0.555	0.051	-0.695	0.086	-0.983	0.105
2010	0.390	0.227	0.092	0.122	0.355	0.050	-0.225	0.086	-1.178	0.105
2011	0.368	0.286	-0.252	0.157	-0.350	0.049	-1.117	0.087	-1.672	0.106
2012	-0.032	0.354	-0.511	0.169	-0.417	0.049	-1.775	0.089	-2.222	0.108
2013	-0.325	0.342	-0.596	0.159	-0.285	0.051	0.253	0.085	-1.560	0.107
2014	-0.224	0.446	-1.233	0.220	-0.072	0.053	-0.277	0.087	-2.185	0.110
2015	0.132	0.333	-0.900	0.203	-0.059	0.058	0.852	0.089	-1.863	0.111
2016	0.120	0.314	-0.585	0.205	-0.183	0.064	0.317	0.092	-1.406	0.112
2017	-0.174	0.452	-0.892	0.261	-0.383	0.069	-0.106	0.095	-1.149	0.114
2018	-0.095	0.421	-0.120	0.295						

Table 5(18.0) (continued). Summary of estimated model parameter values and standard deviations and limits for scenario 18.0 for Bristol Bay red king crab. 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	0.512	0.031	0.184, 1.0	68	1.015	0.421	-5, 5
Mf80-84	0.815	0.041	0.276, 1.5	73	0.662	0.602	-5, 5
Mf76-79,85-93	0.088	0.012	0.0, 0.108	78	0.465	0.456	-5, 5
log_betal, females	0.552	0.133	-0.67, 1.32	83	0.688	0.299	-5, 5
log_betal, males	-0.146	0.240	-0.67, 1.32	88	0.554	0.277	-5, 5
log_betar, females	-0.396	0.219	-1.14, 0.5	93	0.439	0.275	-5, 5
log_betar, males	-0.574	0.167	-1.14, 0.5	98	0.454	0.260	-5, 5
Bsfrf_CV	0.088	0.055	0.00, 0.40	103	0.322	0.275	-5, 5
moltp_slope, 75-78	0.110	0.018	0.01, 0.259	108	0.404	0.259	-5, 5
moltp_slope, 79-18	0.093	0.006	0.01, 0.259	113	0.457	0.253	-5, 5
log_moltp_L50, 75-78	4.954	0.013	4.445, 5.52	118	0.239	0.293	-5, 5
log_moltp_L50, 79-18	4.940	0.005	4.445, 5.52	123	0.243	0.287	-5, 5
log_N75	19.919	0.052	15.0, 22.0	128	0.097	0.315	-5, 5
log_avg_L50_tot	4.767	0.011	4.38, 5.45	133	0.239	0.266	-5, 5
tot_fish_slope	0.101	0.006	0.05, 0.57	138	0.034	0.199	-5, 5
Log_ret_L50, 75-04	4.921	0.002	4.6, 5.1	143	-0.228	0.195	-5, 5
Ret_fish_slope, 75-04	0.496	0.034	0.05, 0.87	148	-0.408	0.201	-5, 5
Log_ret_L50, 05-18	4.930	0.003	4.6, 5.1	153	-0.777	0.228	-5, 5
Ret_fish_slope, 05-18	0.494	0.065	0.05, 0.7	158	-1.307	0.287	-5, 5
pot disc.fema., slope	0.085	0.014	0.05, 0.43	163	-1.355	0.290	-5, 5
log_pot disc.fema., L50	4.556	0.040	4.20, 4.666	68	1.686	0.391	-5, 5
trawl disc slope	0.057	0.003	0.01, 0.20	73	1.461	0.431	-5, 5
log_trawl disc L50	5.195	0.077	4.50, 5.40	78	1.367	0.363	-5, 5
log_srv_L50, m, bsfrf	4.345	0.039	3.359, 5.48	83	1.165	0.331	-5, 5
srv_slope, f, bsfrf	0.041	0.009	0.01, 0.134	88	1.108	0.279	-5, 5
log_srv_L50, f, bsfrf	4.491	0.061	3.471, 5.539	93	0.716	0.311	-5, 5
log_srv_L50, m, 75-81	4.349	0.027	3.551, 5.864	98	0.350	0.372	-5, 5
srv_slope, f, 75-81	0.102	0.013	0.01, 0.303	103	0.131	0.411	-5, 5
log_srv_L50, f, 75-81	4.434	0.026	3.709, 4.80	108	-0.024	0.413	-5, 5
log_srv_L50, m, 82-18	4.092	0.283	3.709, 5.10	113	-0.217	0.443	-5, 5
srv_slope, f, 82-18	0.073	0.021	0.01, 0.43	118	-0.805	0.657	-5, 5
log_srv_L50, f, 82-18	4.170	0.083	3.709, 4.90	123	-0.992	0.732	-5, 5
TC_slope, females	0.344	0.103	0.02, 0.40	128	-1.296	0.871	-5, 5
log_TC_L50, females	4.530	0.014	4.24, 4.90	133	-2.346	1.906	-5, 5
TC_slope, males	0.211	0.079	0.05, 0.90	138	-2.640	2.281	-5, 5
log_TC_L50, males	4.569	0.022	4.25, 5.14	143	NA	NA	
Q	0.925	0.022	0.59, 1.2	Fixed gear bycatch parameters:			
log_TC_F, males, 91	-3.949	0.092	-10.0, 1.00	log_avg_f	-8.146	0.079	-8.5, -0.5
log_TC_F, males, 92	-5.915	0.094	-10.0, 1.00	fmortf_09	-1.276	0.112	-10, 10
log_TC_F, males, 93	-6.613	0.099	-10.0, 1.00	fmortf_10	-2.157	0.132	-10, 10
log_TC_F, males, 13	-8.314	0.093	-10.0, 1.00	fmortf_11	-0.643	0.104	-10, 10
log_TC_F, males, 14	-7.460	0.091	-10.0, 1.00	fmortf_12	-0.117	0.101	-10, 10
log_TC_F, males, 15	-7.049	0.093	-10.0, 1.00	fmortf_13	0.991	0.097	-10, 10
log_TC_F, females, 91	-2.897	0.098	-10.0, 1.00	fmortf_14	1.788	0.097	-10, 10
log_TC_F, females, 92	-4.540	0.101	-10.0, 1.00	fmortf_15	1.413	0.098	-10, 10
log_TC_F, females, 93	-6.441	0.104	-10.0, 1.00	fmortf_16	0.504	0.100	-10, 10
log_TC_F, females, 13	-7.761	0.092	-10.0, 1.00	fmortf_17	-0.503	0.106	-10, 10
log_TC_F, females, 14	-7.624	0.092	-10.0, 1.00	Fix_slo	0.093	0.020	0, 0.2
log_TC_F, females, 15	-6.602	0.090	-10.0, 1.00	log_l50	4.656	0.035	4.5, 5.4

Table 5(18.0a). Summary of estimated model parameter values and standard deviations and limits for scenario 18.0a for Bristol Bay red king crab. All values are on a log scale. Male recruit in year t is exp($mean+males_t$), and female recruit in year t is exp($mean+males_t+females_t$).

Year	Recruits				F for Directed Pot Fishery				F for Trawl	
	Females	SD	Males	SD	Males	SD	Females	SD	Estimate	SD
Mean	15.968	0.034	15.968	0.034	-1.570	0.042	0.012	0.001	-4.465	0.079
Limits↑	13,18		13,18		-3.0,0.0		.001,0.1		-8.5,-1.0	
Limits↓	-15,15		-15,15		-15,2.43		-6.0,3.5		-10,10	
1975					0.779	0.135				
1976	0.094	0.593	0.483	0.390	0.738	0.096			0.166	0.129
1977	0.554	0.434	0.508	0.260	0.657	0.075			0.629	0.118
1978	0.520	0.392	0.764	0.217	0.806	0.062			0.662	0.112
1979	0.744	0.296	1.133	0.199	1.094	0.056			0.820	0.110
1980	0.245	0.304	1.608	0.173	2.006	0.056			1.611	0.110
1981	0.019	0.367	0.990	0.242	2.425	0.013			1.296	0.110
1982	0.007	0.154	2.332	0.108	0.780	0.089			2.482	0.114
1983	0.045	0.236	1.433	0.139	-9.995	0.030			2.121	0.111
1984	0.638	0.177	1.056	0.123	0.885	0.090			3.221	0.114
1985	-0.270	0.425	-0.314	0.208	0.929	0.098			2.004	0.114
1986	0.725	0.175	0.324	0.124	1.238	0.077			0.995	0.113
1987	-0.027	0.386	-0.434	0.183	0.828	0.068			0.585	0.111
1988	-0.067	0.446	-0.941	0.212	-0.065	0.056			1.394	0.106
1989	-0.112	0.337	-0.566	0.162	0.065	0.050			-0.026	0.105
1990	0.325	0.180	0.069	0.117	0.761	0.045	1.980	0.089	0.402	0.105
1991	0.068	0.243	-0.226	0.135	0.760	0.047	-0.628	0.089	0.777	0.106
1992	-0.540	0.475	-1.250	0.235	0.188	0.052	2.127	0.090	0.847	0.107
1993	-0.213	0.282	-0.508	0.151	0.935	0.060	1.906	0.095	1.328	0.111
1994	-0.162	0.463	-1.212	0.244	-4.190	0.056	1.244	0.122	-0.492	0.108
1995	0.061	0.093	1.157	0.072	-4.616	0.047	1.409	0.123	0.062	0.105
1996	-0.998	0.454	-0.605	0.245	-0.073	0.045	-3.701	0.140	-0.574	0.105
1997	-0.876	0.452	-0.887	0.234	0.019	0.047	-0.392	0.088	-0.956	0.105
1998	-0.545	0.324	-0.104	0.150	0.824	0.052	1.491	0.088	-0.066	0.106
1999	0.082	0.157	0.623	0.100	0.422	0.049	-2.782	0.095	0.085	0.105
2000	-0.108	0.364	-0.307	0.193	-0.176	0.047	1.126	0.084	-0.777	0.105
2001	0.091	0.373	-0.354	0.206	-0.230	0.046	0.807	0.084	-0.388	0.104
2002	0.392	0.132	0.905	0.096	-0.109	0.046	-1.978	0.090	-0.507	0.104
2003	-0.370	0.466	-0.402	0.240	0.355	0.044	1.117	0.083	-0.391	0.104
2004	-0.253	0.388	-0.140	0.197	0.337	0.045	0.324	0.084	-0.761	0.104
2005	0.076	0.159	0.876	0.095	0.636	0.048	0.819	0.085	-0.459	0.104
2006	-0.219	0.291	0.239	0.137	0.410	0.047	-1.404	0.085	-0.784	0.104
2007	-0.489	0.330	-0.097	0.150	0.696	0.047	-0.271	0.084	-0.596	0.104
2008	-0.052	0.370	-0.704	0.201	0.815	0.051	-0.514	0.086	-0.419	0.104
2009	0.365	0.303	-0.488	0.179	0.548	0.051	-0.690	0.086	-0.985	0.105
2010	0.377	0.227	0.109	0.120	0.347	0.050	-0.217	0.086	-1.182	0.105
2011	0.315	0.293	-0.241	0.154	-0.358	0.049	-1.108	0.087	-1.677	0.106
2012	0.010	0.342	-0.509	0.168	-0.424	0.049	-1.766	0.089	-2.229	0.108
2013	-0.323	0.339	-0.596	0.159	-0.293	0.050	0.262	0.085	-1.569	0.107
2014	-0.204	0.442	-1.239	0.219	-0.082	0.053	-0.266	0.087	-2.194	0.110
2015	0.183	0.326	-0.898	0.199	-0.072	0.058	0.866	0.089	-1.874	0.111
2016	0.160	0.308	-0.581	0.200	-0.198	0.063	0.332	0.092	-1.419	0.112
2017	-0.179	0.452	-0.888	0.261	-0.399	0.068	-0.092	0.095	-1.163	0.114
2018	-0.087	0.420	-0.119	0.293						

Table 5(18.0a) (continued). Summary of estimated model parameter values and standard deviations and limits for scenario 18.0a for Bristol Bay red king crab. 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	0.512	0.031	0.184, 1.0	68	1.016	0.420	-5, 5
Mf80-84	0.811	0.041	0.276, 1.5	73	0.662	0.600	-5, 5
Mf76-79,85-93	0.087	0.012	0.0, 0.108	78	0.467	0.454	-5, 5
log_betal, females	0.542	0.129	-0.67, 1.32	83	0.688	0.298	-5, 5
log_betal, males	-0.154	0.239	-0.67, 1.32	88	0.553	0.277	-5, 5
log_betar, females	-0.430	0.216	-1.14, 0.5	93	0.439	0.275	-5, 5
log_betar, males	-0.575	0.166	-1.14, 0.5	98	0.454	0.260	-5, 5
Bsfrf_CV	0.084	0.054	0.00, 0.40	103	0.323	0.275	-5, 5
moltp_slope, 75-78	0.110	0.018	0.01, 0.259	108	0.405	0.259	-5, 5
moltp_slope, 79-18	0.093	0.006	0.01, 0.259	113	0.459	0.253	-5, 5
log_moltp_L50, 75-78	4.954	0.013	4.445, 5.52	118	0.241	0.293	-5, 5
log_moltp_L50, 79-18	4.940	0.005	4.445, 5.52	123	0.244	0.287	-5, 5
log_N75	19.918	0.052	15.0, 22.0	128	0.098	0.315	-5, 5
log_avg_L50_tot	4.767	0.011	4.38, 5.45	133	0.239	0.265	-5, 5
tot_fish_slope	0.101	0.006	0.05, 0.57	138	0.035	0.199	-5, 5
Log_ret_L50, 75-04	4.921	0.002	4.6, 5.1	143	-0.227	0.194	-5, 5
Ret_fish_slope, 75-04	0.496	0.034	0.05, 0.87	148	-0.408	0.201	-5, 5
Log_ret_L50, 05-18	4.930	0.003	4.6, 5.1	153	-0.777	0.228	-5, 5
Ret_fish_slope, 05-18	0.495	0.065	0.05, 0.7	158	-1.307	0.287	-5, 5
pot disc.fema., slope	0.091	0.015	0.05, 0.43	163	-1.355	0.290	-5, 5
log_pot disc.fema., L50	4.551	0.037	4.20, 4.666	68	1.678	0.395	-5, 5
trawl disc slope	0.056	0.003	0.01, 0.20	73	1.456	0.434	-5, 5
log_trawl disc L50	5.222	0.091	4.50, 5.40	78	1.365	0.364	-5, 5
log_srv_L50, m, bsfrf	4.340	0.040	3.359, 5.48	83	1.163	0.332	-5, 5
srv_slope, f, bsfrf	0.041	0.009	0.01, 0.134	88	1.108	0.279	-5, 5
log_srv_L50, f, bsfrf	4.484	0.063	3.471, 5.539	93	0.716	0.310	-5, 5
log_srv_L50, m, 75-81	4.348	0.027	3.551, 5.864	98	0.351	0.371	-5, 5
srv_slope, f, 75-81	0.103	0.013	0.01, 0.303	103	0.132	0.410	-5, 5
log_srv_L50, f, 75-81	4.434	0.026	3.709, 4.80	108	-0.022	0.411	-5, 5
log_srv_L50, m, 82-18	4.127	0.251	3.709, 5.10	113	-0.218	0.442	-5, 5
srv_slope, f, 82-18	0.071	0.020	0.01, 0.43	118	-0.804	0.656	-5, 5
log_srv_L50, f, 82-18	4.180	0.082	3.709, 4.90	123	-0.993	0.733	-5, 5
TC_slope, females	0.338	0.104	0.02, 0.40	128	-1.296	0.872	-5, 5
log_TC_L50, females	4.531	0.014	4.24, 4.90	133	-2.348	1.913	-5, 5
TC_slope, males	0.213	0.068	0.05, 0.90	138	-2.638	2.278	-5, 5
log_TC_L50, males	4.566	0.020	4.25, 5.14	143	NA	NA	
Q	0.925	0.022	0.59, 1.2	Fixed gear bycatch parameters:			
log_TC_F, males, 91	-3.942	0.092	-10.0, 1.00	log_avg_f	-8.134	0.081	-8.5, -0.5
log_TC_F, males, 92	-5.909	0.093	-10.0, 1.00	fmortf_09	-1.270	0.112	-10, 10
log_TC_F, males, 93	-6.609	0.099	-10.0, 1.00	fmortf_10	-2.154	0.132	-10, 10
log_TC_F, males, 13	-8.325	0.093	-10.0, 1.00	fmortf_11	-0.642	0.104	-10, 10
log_TC_F, males, 14	-7.472	0.091	-10.0, 1.00	fmortf_12	-0.117	0.101	-10, 10
log_TC_F, males, 15	-7.062	0.093	-10.0, 1.00	fmortf_13	0.992	0.097	-10, 10
log_TC_F, females, 91	-2.889	0.097	-10.0, 1.00	fmortf_14	1.787	0.097	-10, 10
log_TC_F, females, 92	-4.534	0.100	-10.0, 1.00	fmortf_15	1.411	0.098	-10, 10
log_TC_F, females, 93	-6.433	0.103	-10.0, 1.00	fmortf_16	0.501	0.100	-10, 10
log_TC_F, females, 13	-7.756	0.091	-10.0, 1.00	fmortf_17	-0.508	0.106	-10, 10
log_TC_F, females, 14	-7.620	0.091	-10.0, 1.00	Fix_slo	0.087	0.019	0, 0.2
log_TC_F, females, 15	-6.599	0.090	-10.0, 1.00	log_l50	4.664	0.037	4.5, 5.4

Table 6(18.0). Annual abundance estimates (million 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 18.0) from 1975-2018. 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	59.461	29.052	86.150	9.149	65.001		257.439	202.731
1976	69.210	36.783	101.903	8.271	96.044	28.949	293.778	331.868
1977	73.151	42.454	110.539	6.673	119.542	39.074	300.230	375.661
1978	75.042	45.067	110.395	4.916	115.822	49.458	287.312	349.545
1979	65.294	44.165	88.041	3.227	102.734	83.039	261.876	167.627
1980	45.133	33.828	22.711	0.918	97.168	97.908	229.005	249.322
1981	13.075	7.488	5.410	0.493	47.113	46.566	96.719	132.669
1982	6.026	2.068	5.642	0.555	23.308	178.326	52.657	143.740
1983	6.060	2.181	7.055	0.556	17.542	73.647	48.574	49.320
1984	6.266	2.600	5.546	0.530	17.861	72.873	47.194	155.311
1985	8.271	2.212	10.872	0.804	15.248	11.178	36.671	34.535
1986	13.073	5.016	16.350	1.146	20.472	37.168	47.084	48.158
1987	15.160	7.094	21.244	1.316	24.238	11.041	52.113	70.263
1988	15.270	8.803	25.685	1.367	27.765	6.549	54.405	55.372
1989	16.240	10.078	28.168	1.306	25.148	9.181	56.177	55.941
1990	15.880	10.703	24.389	1.230	21.306	21.804	55.689	60.321
1991	12.368	8.982	19.048	1.167	19.953	14.519	49.800	85.055
1992	9.754	6.863	17.660	1.127	20.405	3.926	44.268	37.687
1993	10.430	6.361	15.167	1.140	18.764	9.382	43.009	53.703
1994	10.022	5.735	20.294	1.205	15.795	4.764	37.973	32.335
1995	10.720	7.497	23.272	1.208	15.474	56.490	45.109	38.396
1996	11.078	8.246	21.747	1.172	21.860	6.420	53.672	44.649
1997	10.560	7.534	20.442	1.173	29.903	4.984	58.720	85.277
1998	15.797	7.340	23.438	1.362	28.126	12.082	62.542	85.176
1999	17.137	9.311	27.610	1.555	24.944	33.140	62.591	65.604
2000	14.909	10.518	27.973	1.563	27.168	11.887	64.845	68.102
2001	14.485	10.228	28.106	1.525	30.874	12.809	68.492	53.188
2002	16.902	10.171	31.302	1.529	30.884	53.541	74.265	69.786
2003	17.802	11.483	30.815	1.525	37.502	9.457	80.089	116.794
2004	16.238	11.164	28.596	1.477	44.803	13.280	82.045	131.910
2005	18.419	10.455	29.410	1.472	42.654	42.769	85.104	107.341
2006	18.368	11.190	30.894	1.503	43.847	19.881	87.019	95.676
2007	17.107	11.493	27.277	1.476	47.858	12.560	90.249	104.841
2008	18.456	10.253	27.749	1.567	46.175	8.342	88.979	114.430
2009	19.219	10.832	30.704	1.693	42.055	12.834	85.559	91.673
2010	18.134	11.780	30.922	1.706	38.997	23.310	83.293	81.642
2011	15.849	11.494	31.319	1.666	39.408	16.318	81.125	67.053
2012	14.756	11.139	30.493	1.615	41.333	10.140	81.403	61.248
2013	15.082	10.572	30.458	1.603	40.560	8.151	80.608	62.410
2014	15.264	10.572	29.854	1.635	37.335	4.499	77.862	114.103
2015	14.301	10.345	28.221	1.672	33.313	7.476	73.217	64.240
2016	12.992	9.698	26.491	1.704	29.720	10.177	68.049	61.231
2017	11.452	8.968	24.529	1.705	27.862	6.477	63.528	52.922
2018	10.315	8.123	20.617	1.385	26.366	14.547	60.436	28.932

Table 6(18.0a). Annual abundance estimates (million 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 18.0a) from 1975-2018. 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	59.480	29.058	86.181	9.146	65.006		257.619	202.731
1976	69.257	36.777	101.950	8.268	95.921	29.262	293.907	331.868
1977	73.181	42.456	110.550	6.672	119.395	39.150	300.394	375.661
1978	75.065	45.057	110.380	4.917	115.754	49.524	287.515	349.545
1979	65.334	44.154	88.037	3.226	102.775	82.878	262.099	167.627
1980	45.164	33.829	22.701	0.917	97.215	97.773	229.229	249.322
1981	13.080	7.490	5.420	0.493	47.276	46.752	96.976	132.669
1982	6.027	2.069	5.647	0.554	23.482	177.879	52.667	143.740
1983	6.059	2.181	7.056	0.554	17.579	73.717	48.556	49.320
1984	6.259	2.599	5.540	0.528	17.958	71.531	47.055	155.311
1985	8.264	2.209	10.860	0.800	15.211	11.080	36.548	34.535
1986	13.057	5.013	16.324	1.140	20.342	36.453	46.853	48.158
1987	15.114	7.084	21.171	1.309	23.936	10.996	51.802	70.263
1988	15.196	8.773	25.556	1.358	27.405	6.494	54.044	55.372
1989	16.139	10.027	27.980	1.294	24.856	9.248	55.797	55.941
1990	15.760	10.631	24.149	1.216	21.087	21.983	55.328	60.321
1991	12.250	8.895	18.790	1.153	19.827	14.215	49.459	85.055
1992	9.668	6.774	17.431	1.116	20.308	3.902	43.964	37.687
1993	10.367	6.290	14.977	1.134	18.602	9.360	42.756	53.703
1994	9.990	5.680	20.163	1.201	15.635	4.737	37.773	32.335
1995	10.710	7.468	23.195	1.205	15.302	56.446	44.923	38.396
1996	11.081	8.234	21.711	1.169	21.648	6.430	53.507	44.649
1997	10.572	7.534	20.438	1.171	29.816	5.019	58.576	85.277
1998	15.784	7.344	23.411	1.362	28.063	12.246	62.426	85.176
1999	17.106	9.303	27.554	1.555	24.933	33.439	62.517	65.604
2000	14.880	10.500	27.914	1.563	27.267	12.009	64.837	68.102
2001	14.465	10.207	28.056	1.525	31.135	12.649	68.538	53.188
2002	16.892	10.155	31.269	1.529	31.116	52.714	74.263	69.786
2003	17.798	11.476	30.795	1.526	37.359	9.731	80.050	116.794
2004	16.234	11.162	28.585	1.477	44.473	13.282	81.990	131.910
2005	18.425	10.453	29.415	1.473	42.383	42.963	85.064	107.341
2006	18.393	11.197	30.935	1.504	43.616	19.697	87.005	95.676
2007	17.144	11.513	27.348	1.477	47.674	12.595	90.272	104.841
2008	18.520	10.283	27.874	1.567	45.952	8.296	89.036	114.430
2009	19.307	10.884	30.885	1.691	41.857	12.886	85.651	91.673
2010	18.223	11.851	31.128	1.704	38.827	23.574	83.425	81.642
2011	15.920	11.568	31.511	1.663	39.285	16.020	81.281	67.053
2012	14.821	11.201	30.677	1.612	41.171	10.393	81.601	61.248
2013	15.193	10.630	30.706	1.602	40.353	8.170	80.857	62.410
2014	15.417	10.660	30.184	1.634	37.228	4.526	78.166	114.103
2015	14.457	10.463	28.586	1.671	33.255	7.715	73.570	64.240
2016	13.133	9.821	26.852	1.701	29.741	10.465	68.451	61.231
2017	11.572	9.083	24.864	1.701	28.033	6.497	63.970	52.922
2018	10.420	8.224	20.804	1.378	26.629	14.641	60.900	28.932

Table 7(18.0). 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 2018-2027. Parameter estimates with scenario 18.0 are used for the projection.

No Directed Fishery

Year	MMB	95% LCI	95% UCI	Catch	95% LCI	95% UCI
2018	25.347	20.810	29.632	0.000	0.000	0.000
2019	26.515	21.768	30.997	0.000	0.000	0.000
2020	27.673	22.719	32.351	0.000	0.000	0.000
2021	30.070	24.722	35.429	0.000	0.000	0.000
2022	34.151	27.308	45.596	0.000	0.000	0.000
2023	38.829	29.136	59.221	0.000	0.000	0.000
2024	43.524	31.093	67.482	0.000	0.000	0.000
2025	47.937	32.665	75.040	0.000	0.000	0.000
2026	51.887	34.423	81.460	0.000	0.000	0.000
2027	55.497	35.681	87.154	0.000	0.000	0.000
			$F_{40\%}$			
2018	21.373	18.091	24.357	4.119	2.819	5.466
2019	19.729	17.018	22.143	3.290	2.367	4.204
2020	18.821	16.413	20.945	2.860	2.121	3.573
2021	19.417	16.990	21.634	2.815	2.128	3.513
2022	21.507	17.878	31.030	3.141	2.332	4.137
2023	23.850	18.105	39.611	3.650	2.476	5.713
2024	25.874	17.967	42.028	4.217	2.519	7.492
2025	27.432	18.200	46.223	4.702	2.542	8.167
2026	28.509	18.636	49.131	5.075	2.619	8.880
2027	29.372	18.630	50.436	5.328	2.684	9.478
			$F_{35\%}$			
2018	20.692	17.601	23.485	4.824	3.326	6.367
2019	18.748	16.279	20.932	3.660	2.669	4.629
2020	17.709	15.547	19.606	3.089	2.326	3.818
2021	18.223	16.037	20.225	3.004	2.301	3.708
2022	20.185	16.854	29.140	3.366	2.503	4.673
2023	22.316	16.996	37.107	3.951	2.650	6.494
2024	24.058	16.799	39.108	4.591	2.661	8.439
2025	25.321	16.937	42.935	5.105	2.694	9.036
2026	26.134	17.370	44.698	5.473	2.753	9.809
2027	26.778	17.315	45.949	5.704	2.799	10.426

Table 7(18.0a). 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 2018-2027. Parameter estimates with scenario 18.0a are used for the projection.

Year	MMB	95% LCI	95% UCI	Catch	95% LCI	95% UCI
No Directed Fishery						
2018	25.653	21.105	29.949	0.000	0.000	0.000
2019	26.802	22.050	31.290	0.000	0.000	0.000
2020	27.944	22.989	32.623	0.000	0.000	0.000
2021	30.326	24.984	35.681	0.000	0.000	0.000
2022	34.390	27.555	45.820	0.000	0.000	0.000
2023	39.049	29.367	59.326	0.000	0.000	0.000
2024	43.726	31.292	67.578	0.000	0.000	0.000
2025	48.122	32.932	75.147	0.000	0.000	0.000
2026	52.058	34.550	81.402	0.000	0.000	0.000
2027	55.656	35.820	87.205	0.000	0.000	0.000
$F_{40\%}$						
2018	21.576	18.301	24.552	4.228	2.908	5.595
2019	19.863	17.168	22.262	3.354	2.425	4.273
2020	18.916	16.528	21.024	2.902	2.162	3.616
2021	19.487	17.082	21.684	2.848	2.162	3.544
2022	21.559	17.956	31.048	3.167	2.361	4.148
2023	23.888	18.157	39.692	3.671	2.500	5.717
2024	25.903	18.001	42.041	4.234	2.539	7.511
2025	27.455	18.219	46.191	4.716	2.560	8.175
2026	28.530	18.688	49.074	5.088	2.639	8.879
2027	29.390	18.632	50.407	5.340	2.696	9.484
$F_{35\%}$						
2018	20.879	17.798	23.664	4.949	3.429	6.513
2019	18.865	16.413	21.034	3.727	2.731	4.701
2020	17.790	15.647	19.671	3.132	2.368	3.860
2021	18.282	16.116	20.266	3.036	2.335	3.737
2022	20.227	16.912	29.121	3.392	2.529	4.684
2023	22.345	17.038	37.146	3.972	2.667	6.507
2024	24.078	16.805	39.112	4.608	2.680	8.459
2025	25.335	16.946	42.972	5.120	2.709	9.051
2026	26.146	17.369	44.638	5.486	2.780	9.823
2027	26.788	17.309	45.966	5.716	2.805	10.418

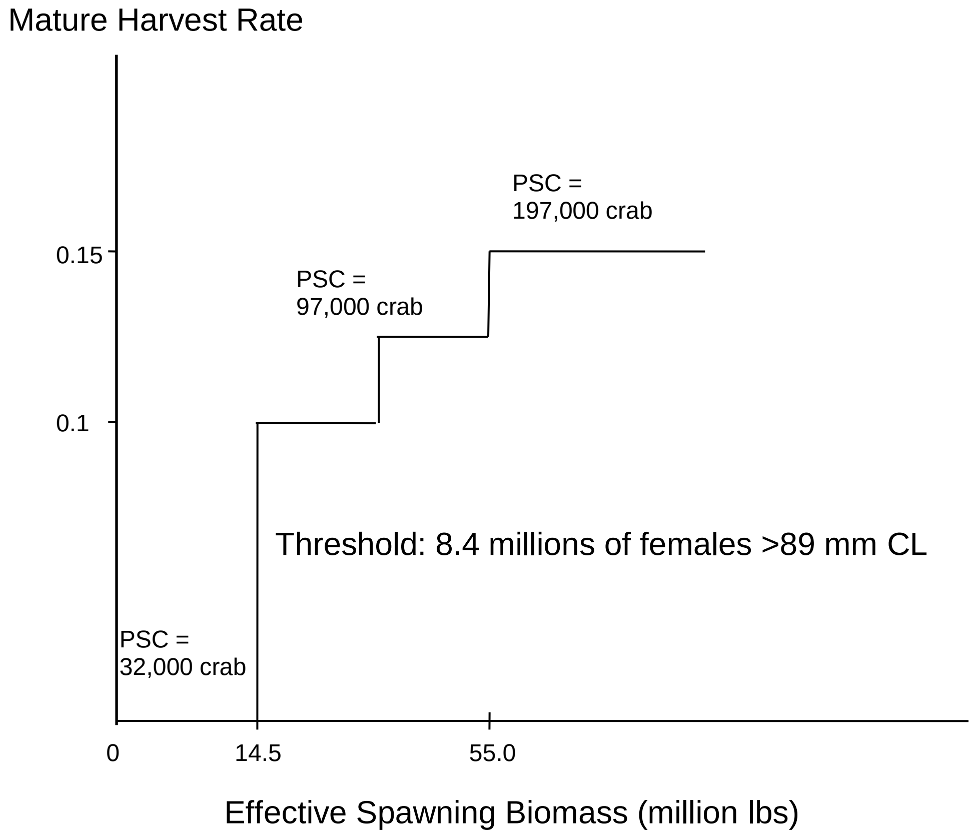


Figure 1. Current harvest rate strategy (line) for the Bristol Bay red king crab fishery and annual prohibited species catch (PSC) limits (numbers of crab) of Bristol Bay red king crab in the groundfish fisheries in zone 1 in the eastern Bering Sea. Harvest rates are based on current-year estimates of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

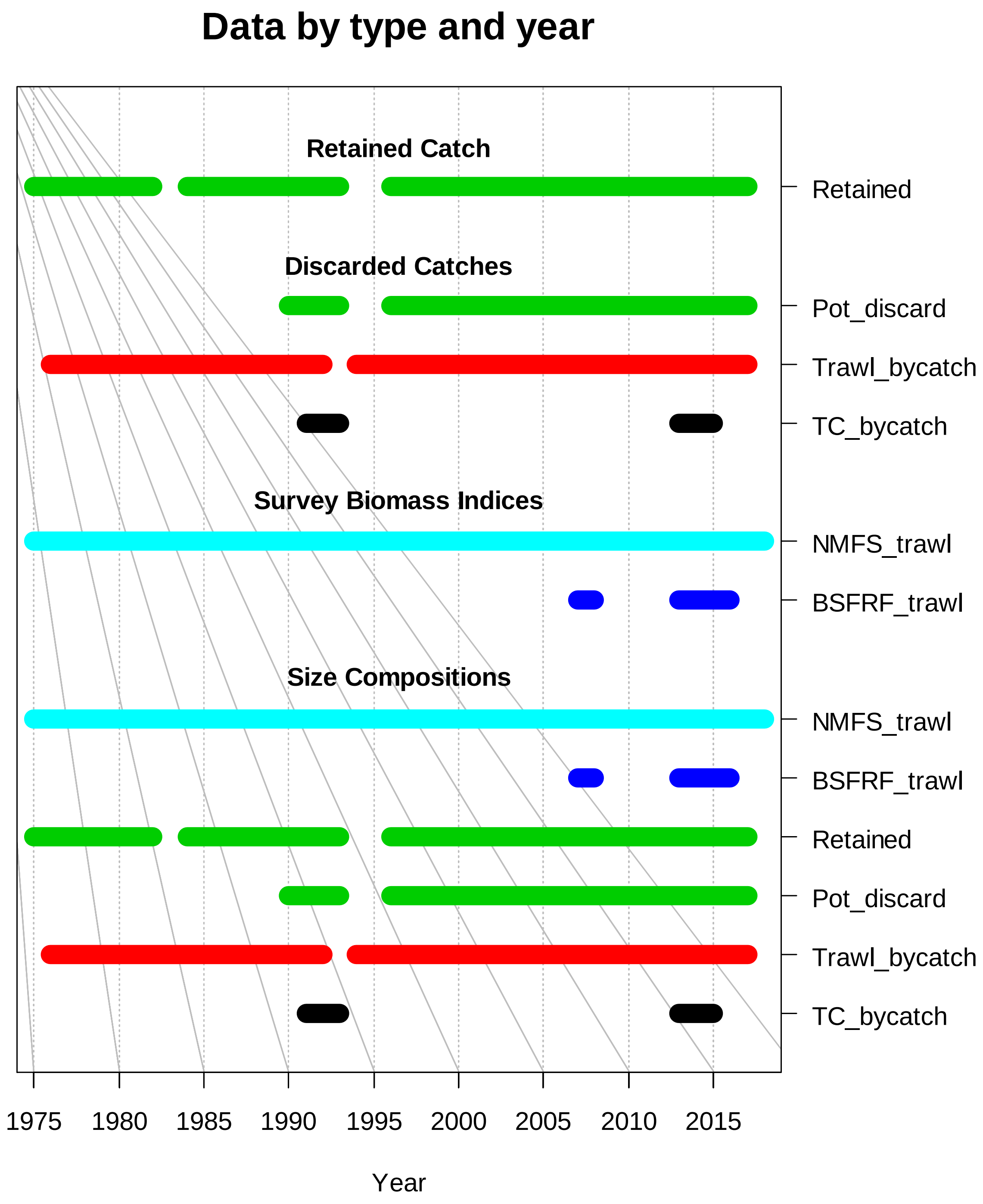


Figure 2. Data types and ranges used for the stock assessment.

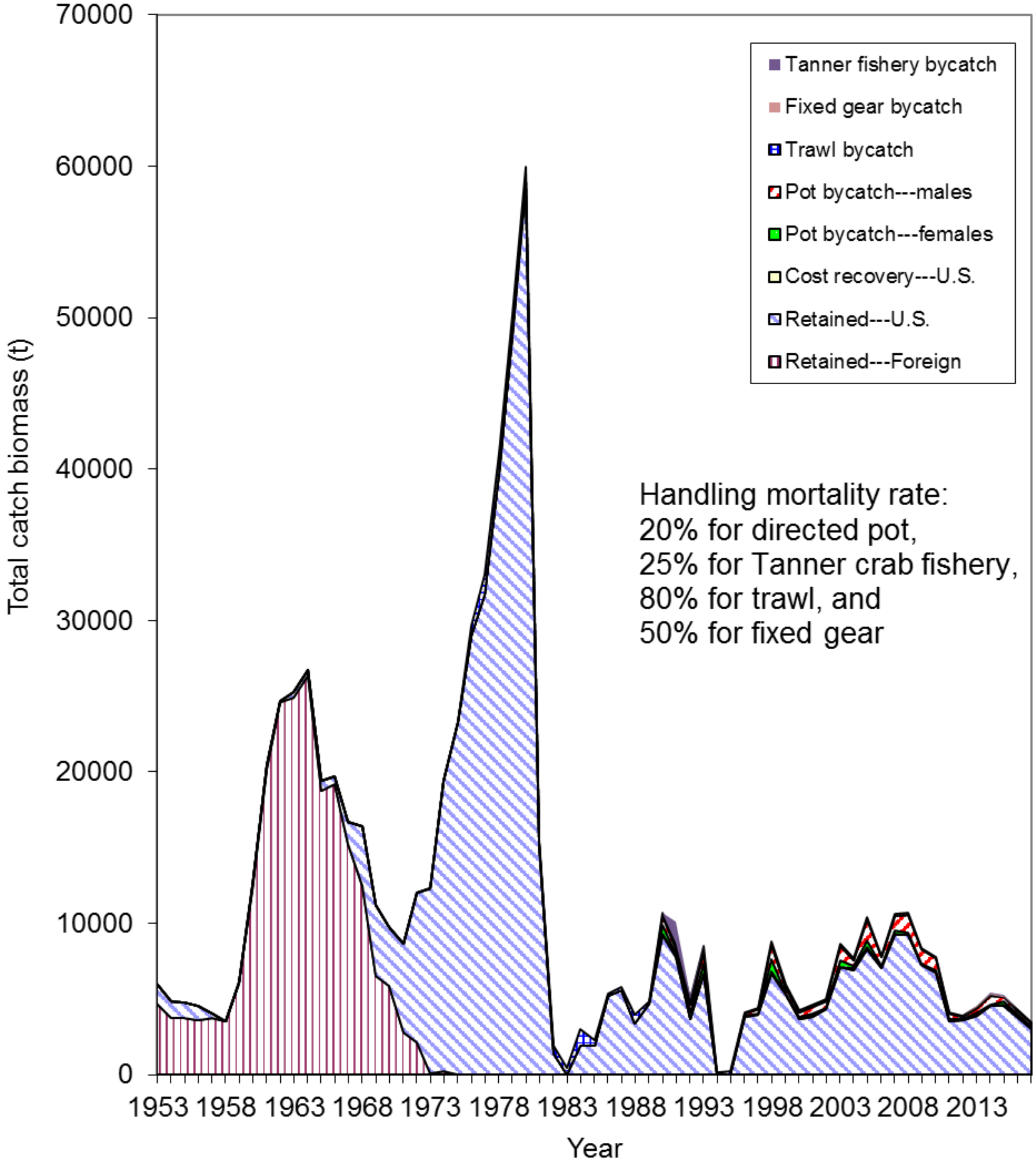


Figure 3. Retained catch biomass and bycatch mortality biomass (t) for Bristol Bay red king crab from 1953 to 2017. Handling mortality rates were assumed to be 0.2 for the directed pot fishery, 0.25 for the Tanner crab fishery, 0.8 for the trawl fisheries, and 50% for the fixed gear fisheries.

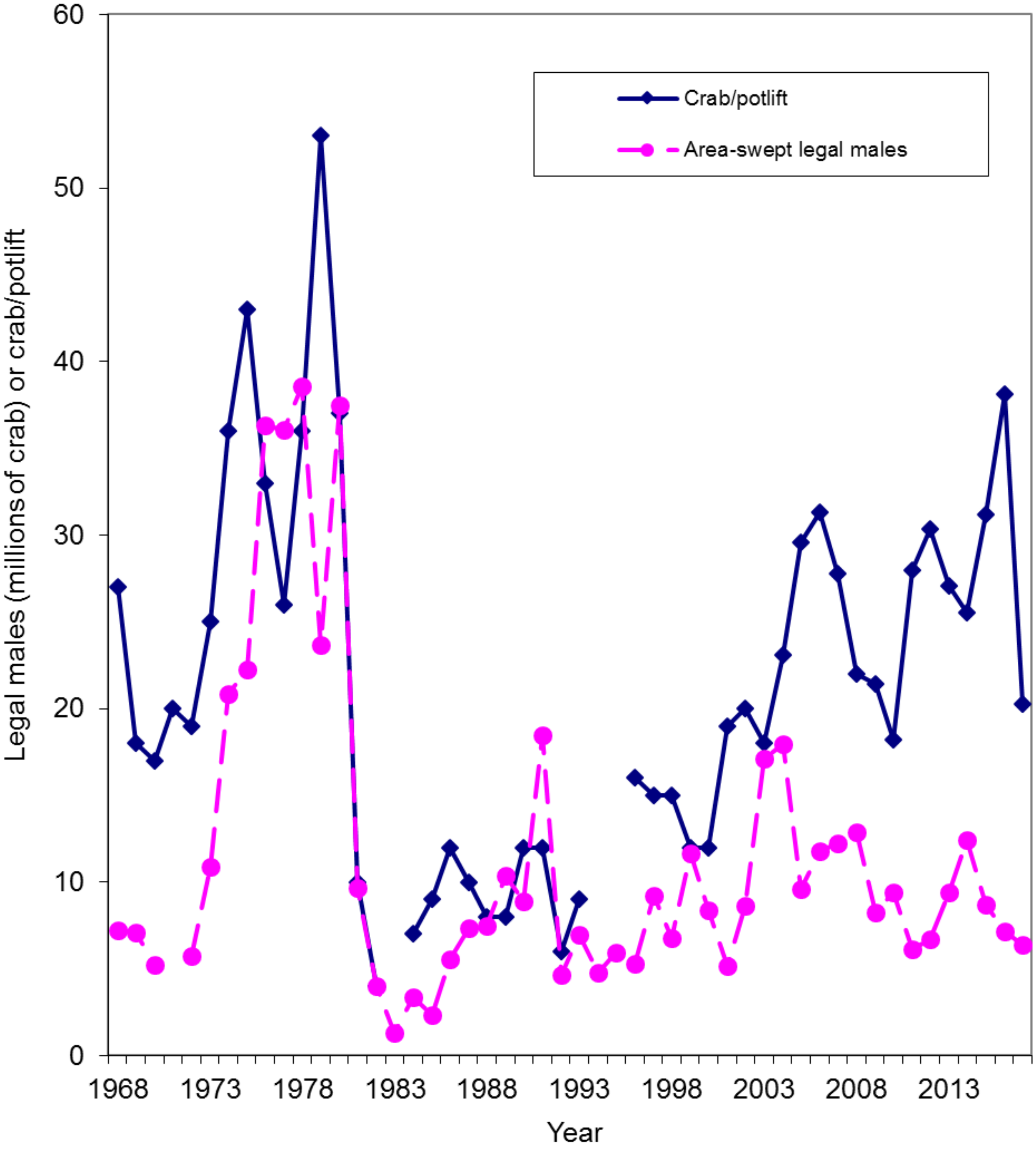


Figure 4. Comparison of survey legal male abundances and catches per unit effort for Bristol Bay red king crab from 1968 to 2017.

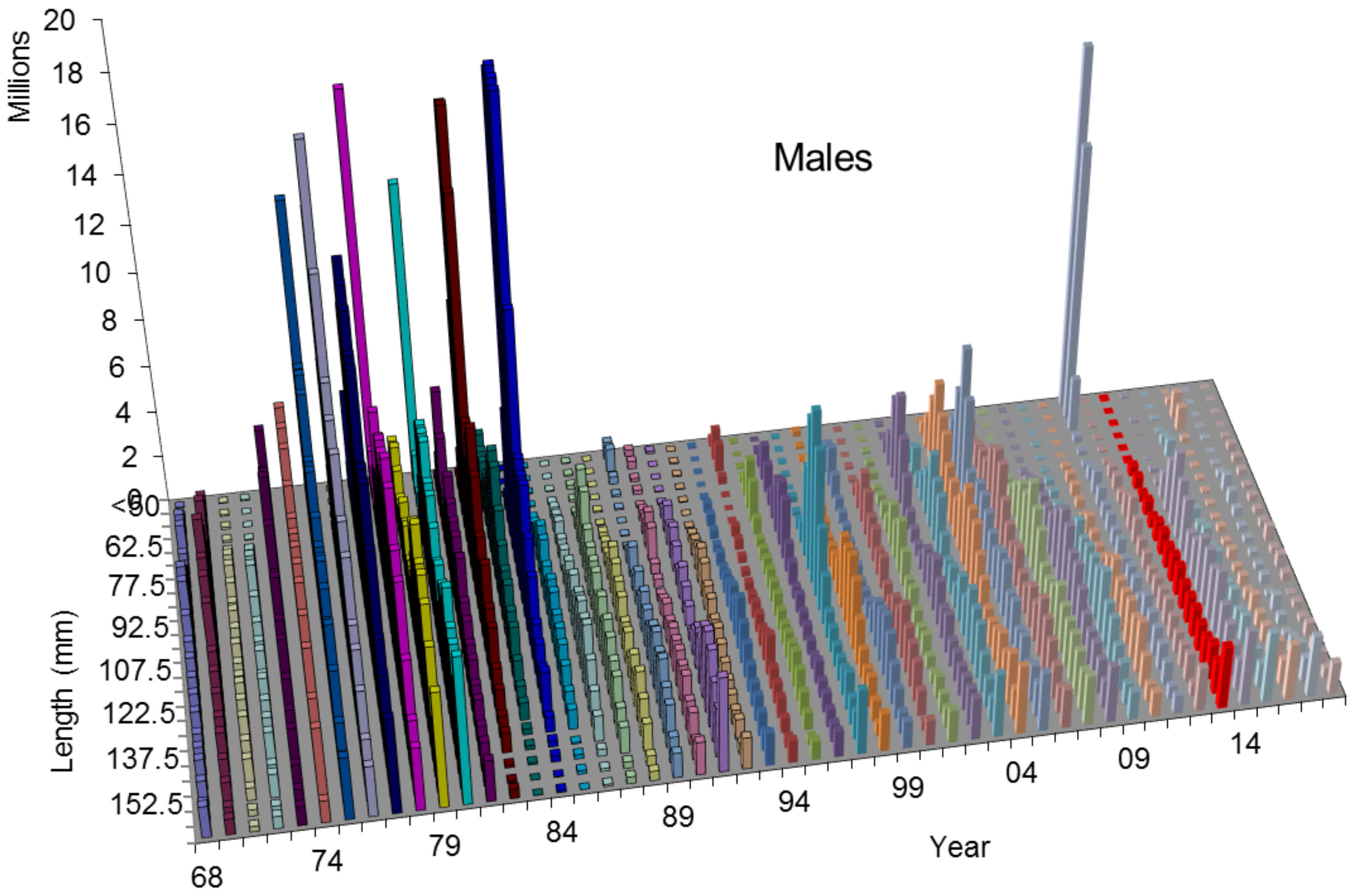


Figure 5a. Survey abundances by 5-mm carapace length bin for male Bristol Bay red king crab from 1968 to 2018.

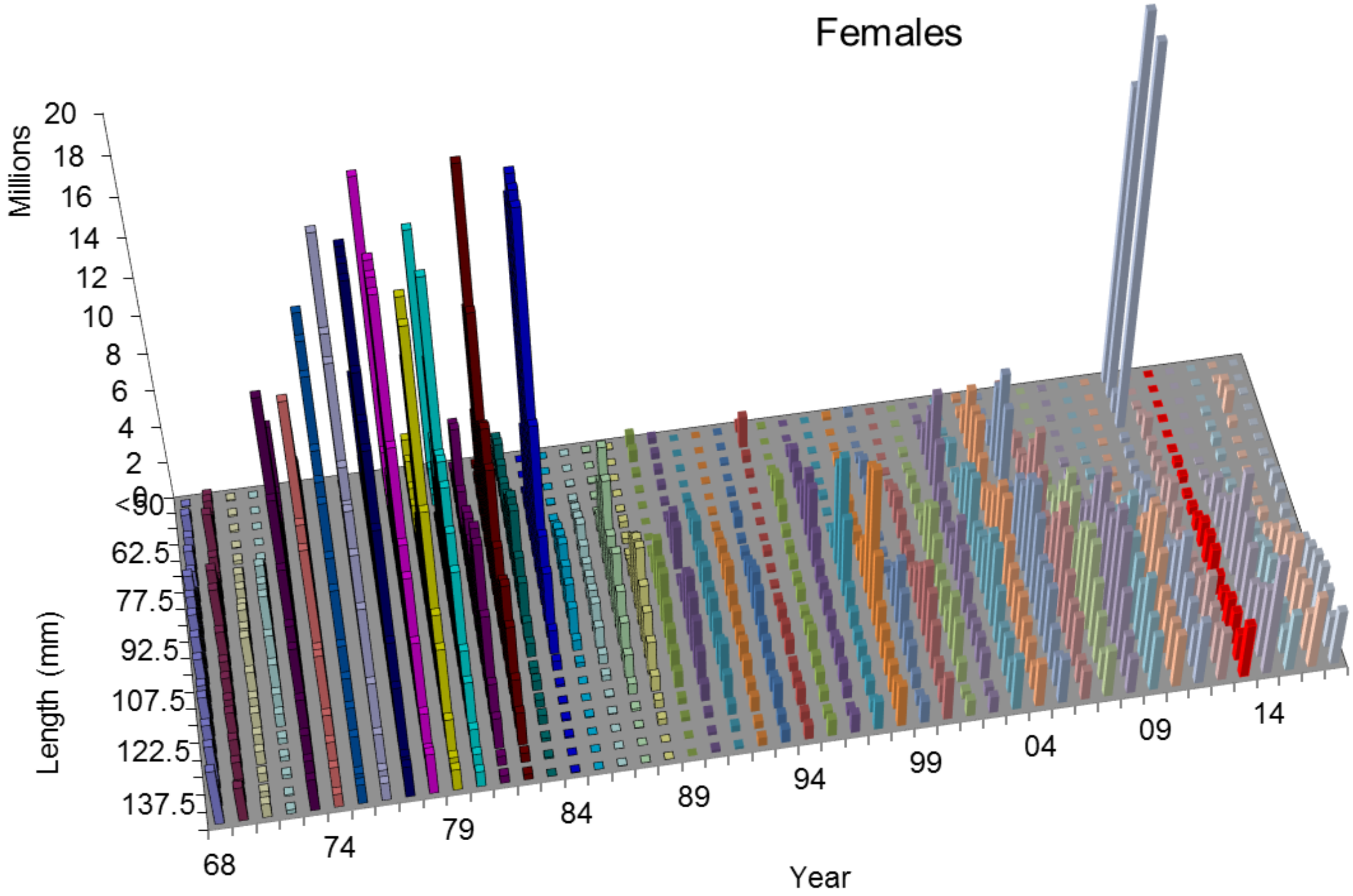


Figure 5b. Survey abundances by 5 mm carapace length bin for female Bristol Bay red king crab from 1968 to 2018.

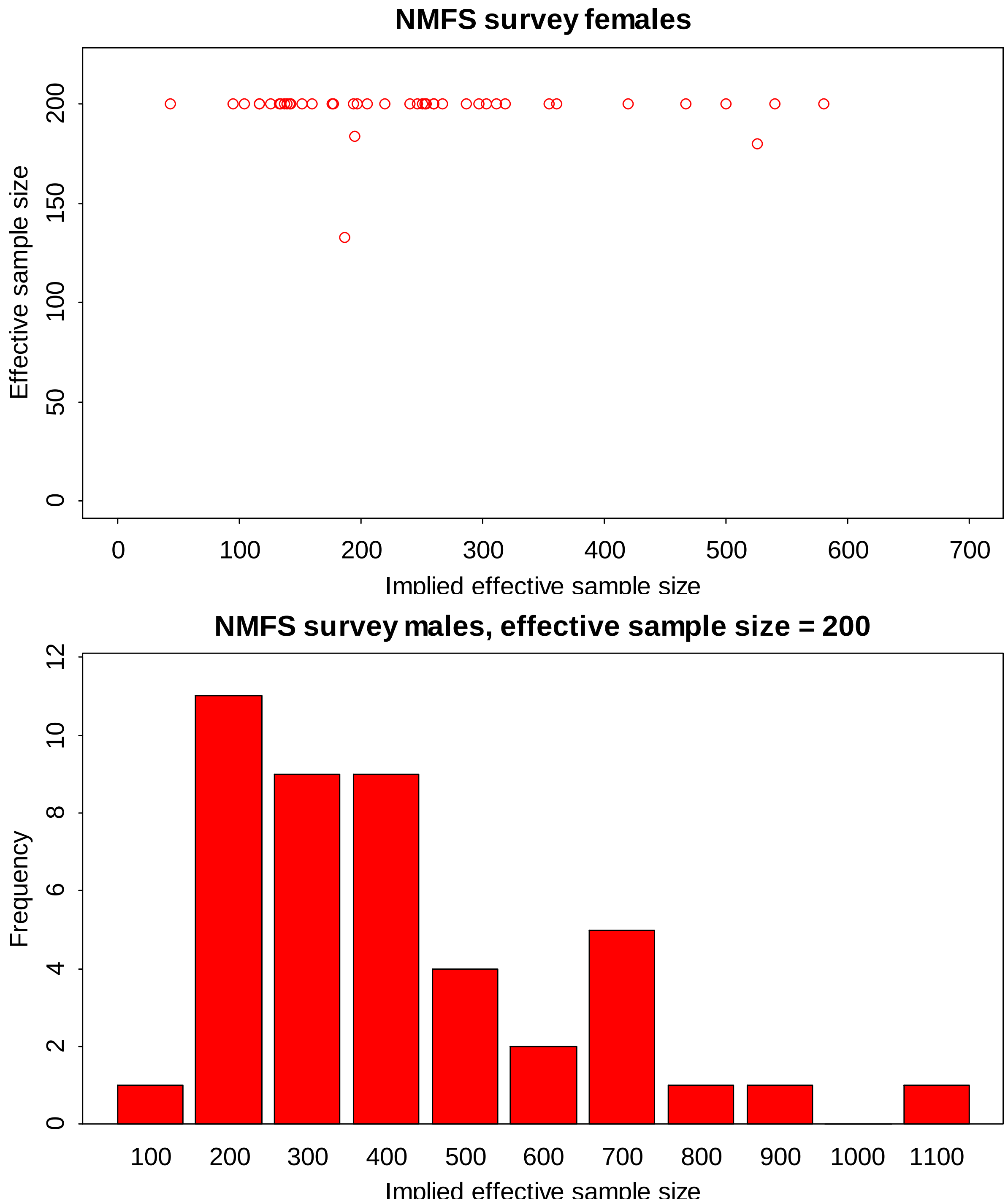
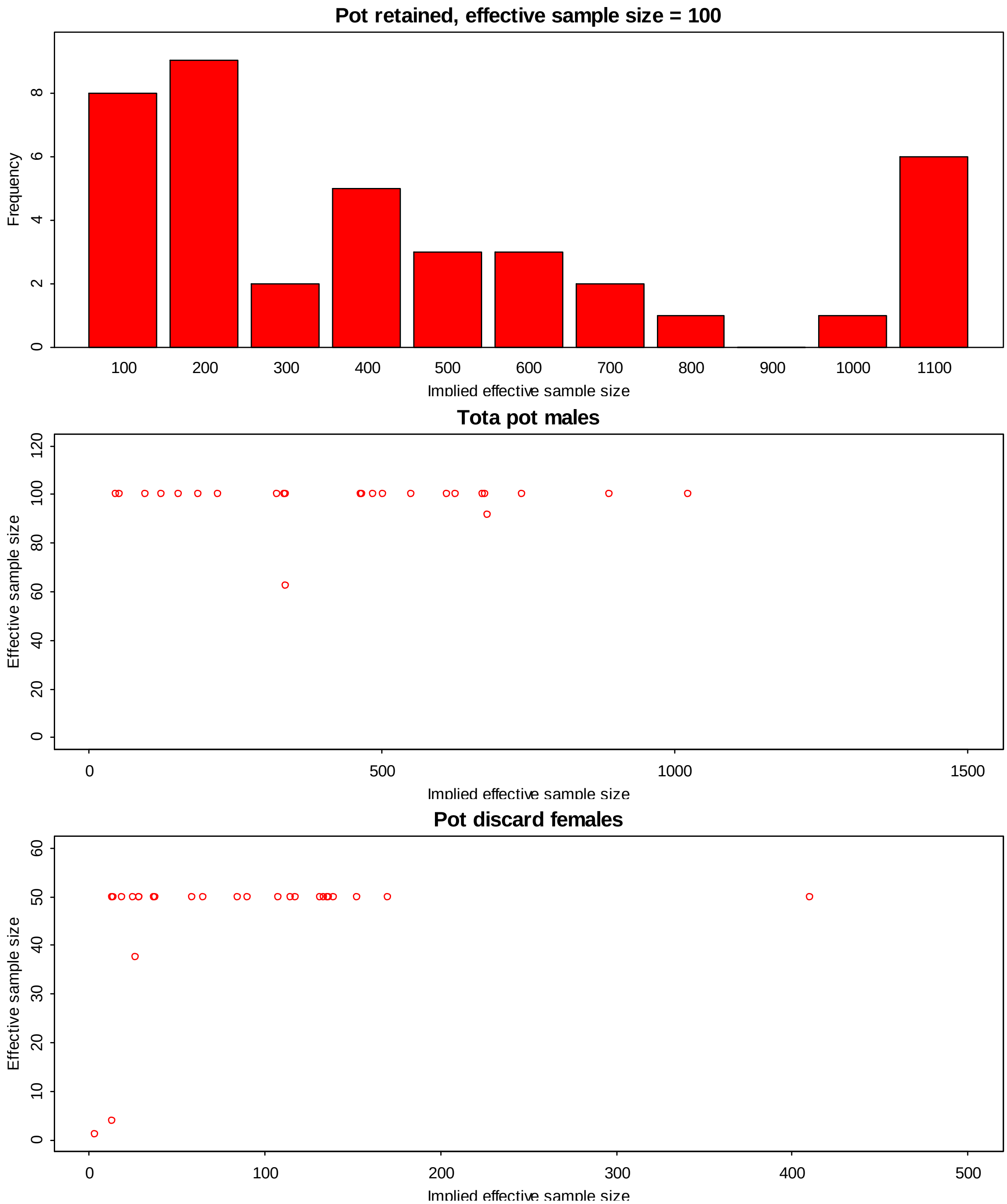


Figure 6. Relationship between implied effective sample sizes (section 3(a)(5)(i)) and effective sample sizes (see effective sample sizes for scenario 18.0) for length/sex composition data with scenario 18.0: trawl survey data.


Pot retained, effective sample size = 100

Tota pot males

Pot discard females

Figure 7. Relationship between implied effective sample sizes (section 3(a)(5)(i)) and effective sample sizes (see effective sample sizes for scenario 18.0) for length/sex composition data with scenario 18.0: directed pot fishery data.

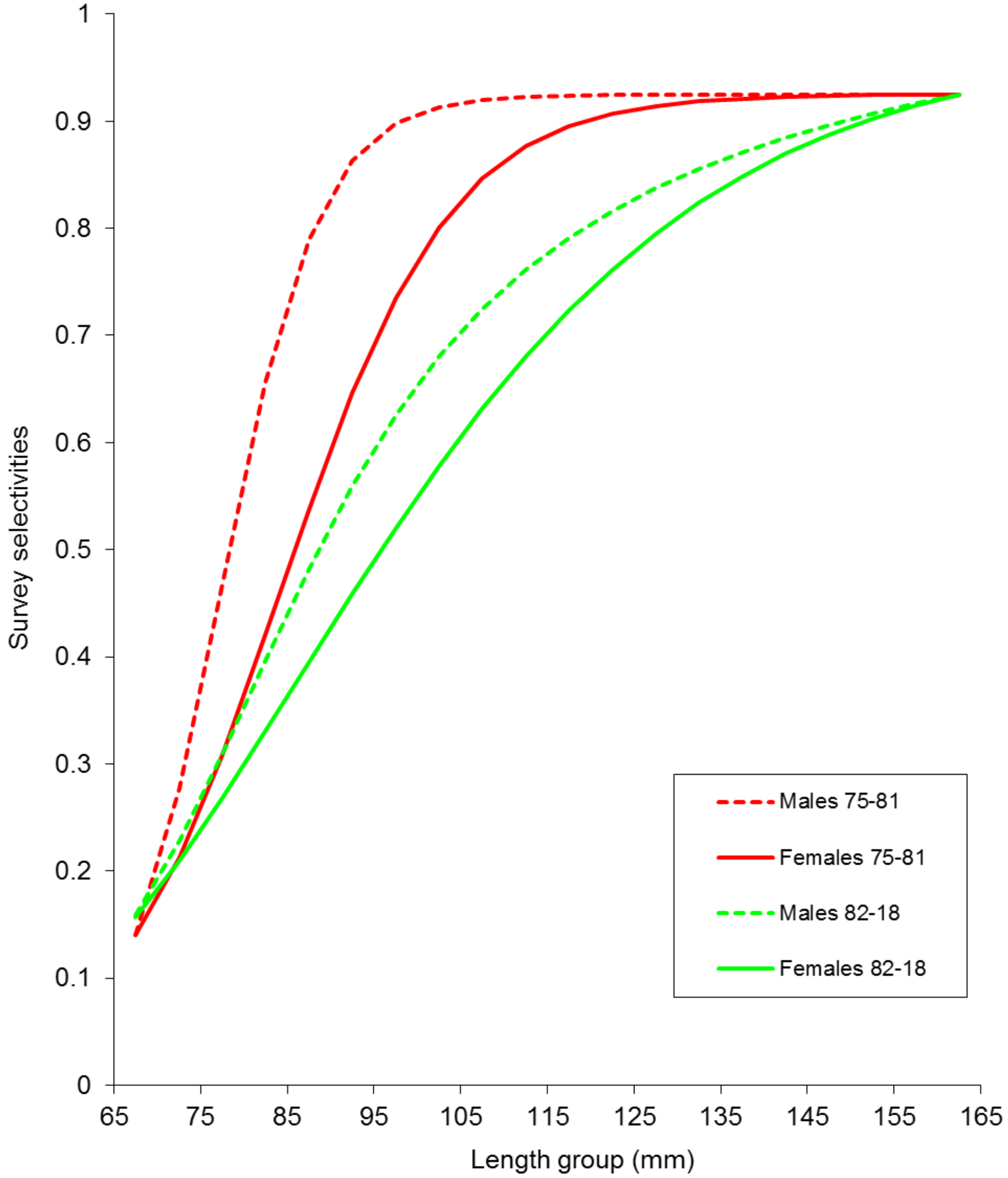


Figure 8a(18.0). Estimated trawl survey selectivities under scenario 18.0. Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively.

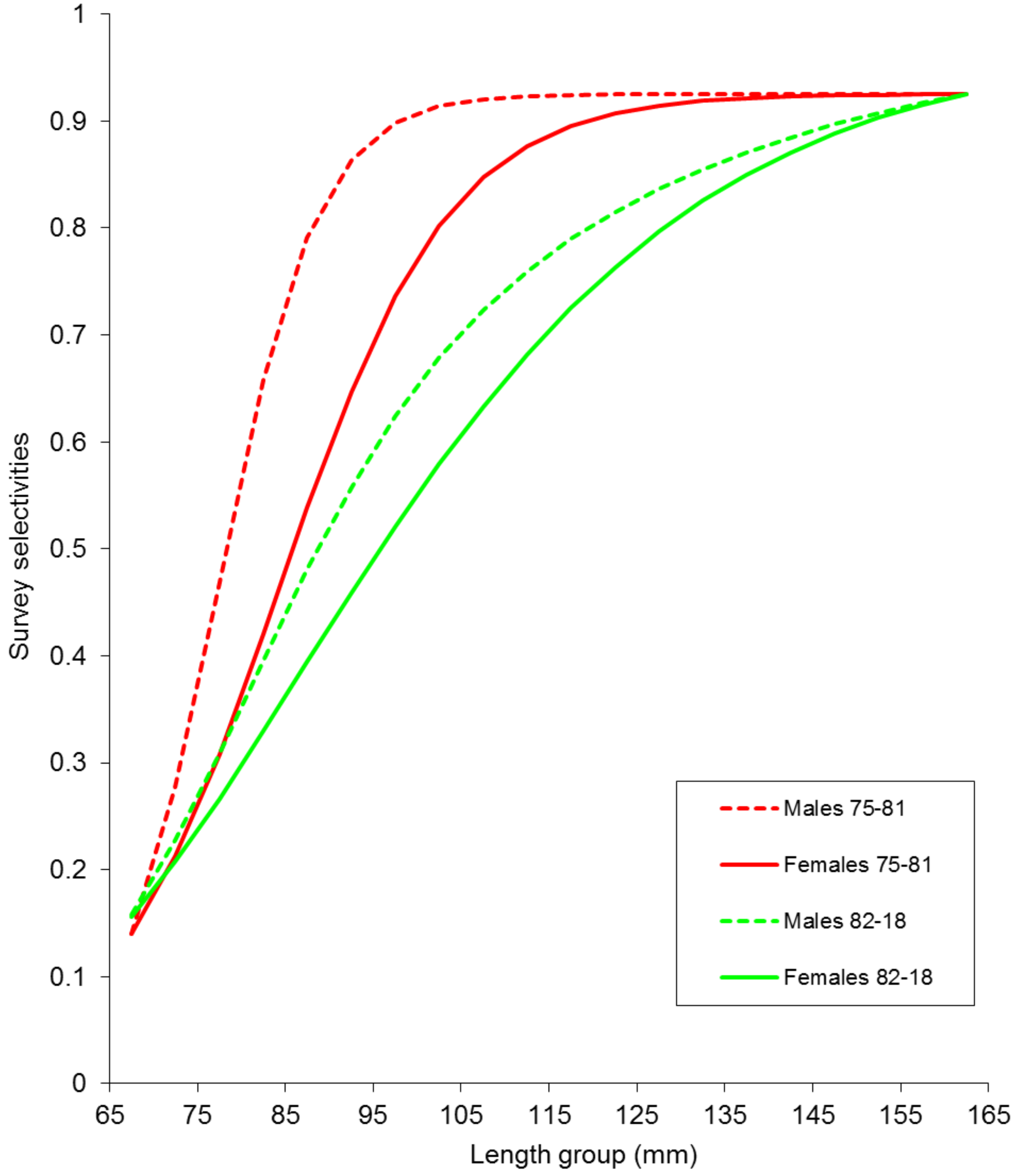


Figure 8a(18.0a). Estimated trawl survey selectivities under scenario 18.0a. Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively.

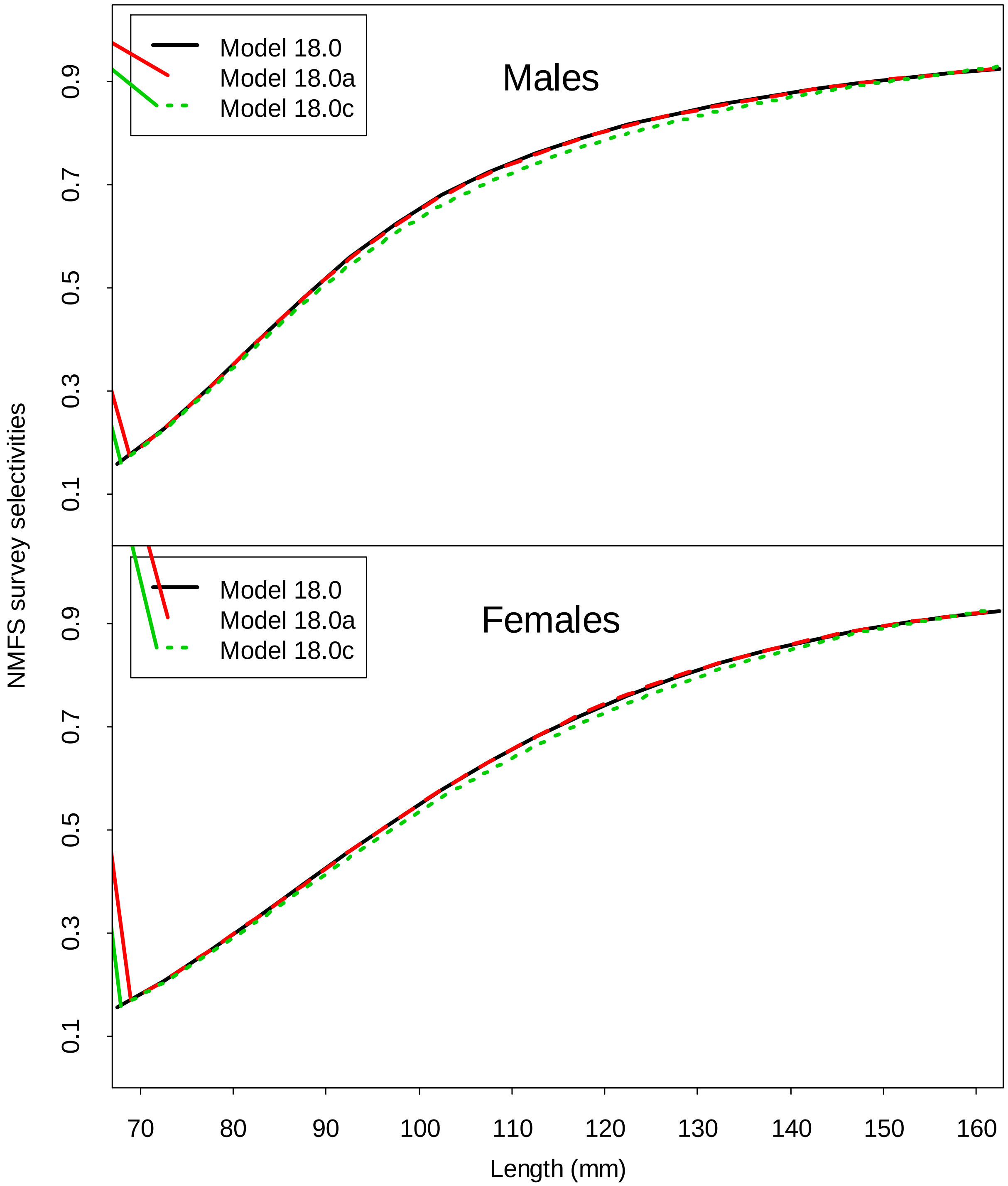


Figure 8b. Comparisons of estimated NMFS trawl survey selectivities for period 1982-2018 under scenarios 18.0, 18.0a, and 18.0c. Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively.

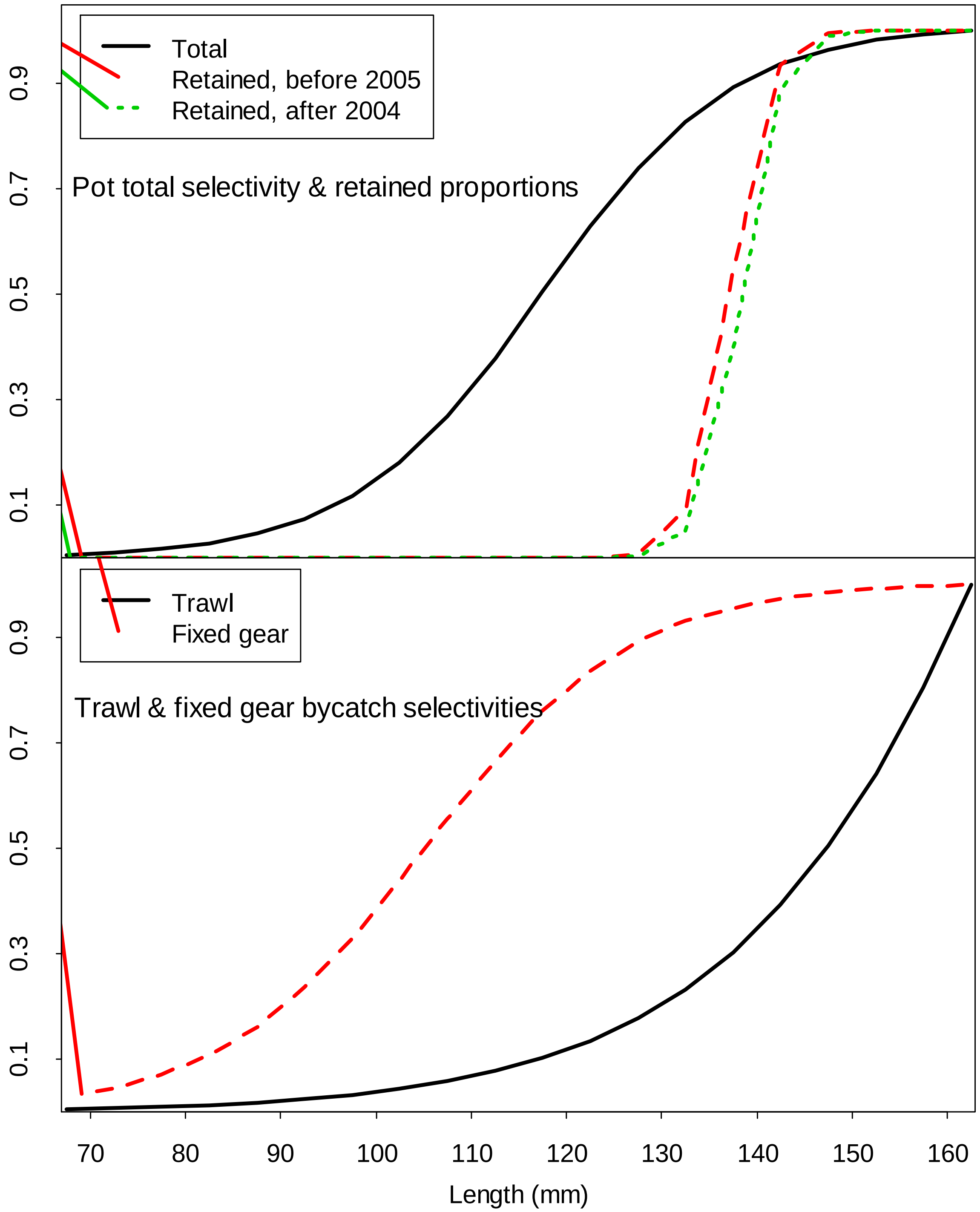


Figure 8c. Estimated pot fishery selectivities and groundfish trawl bycatch selectivities under scenario 18.0. Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively.

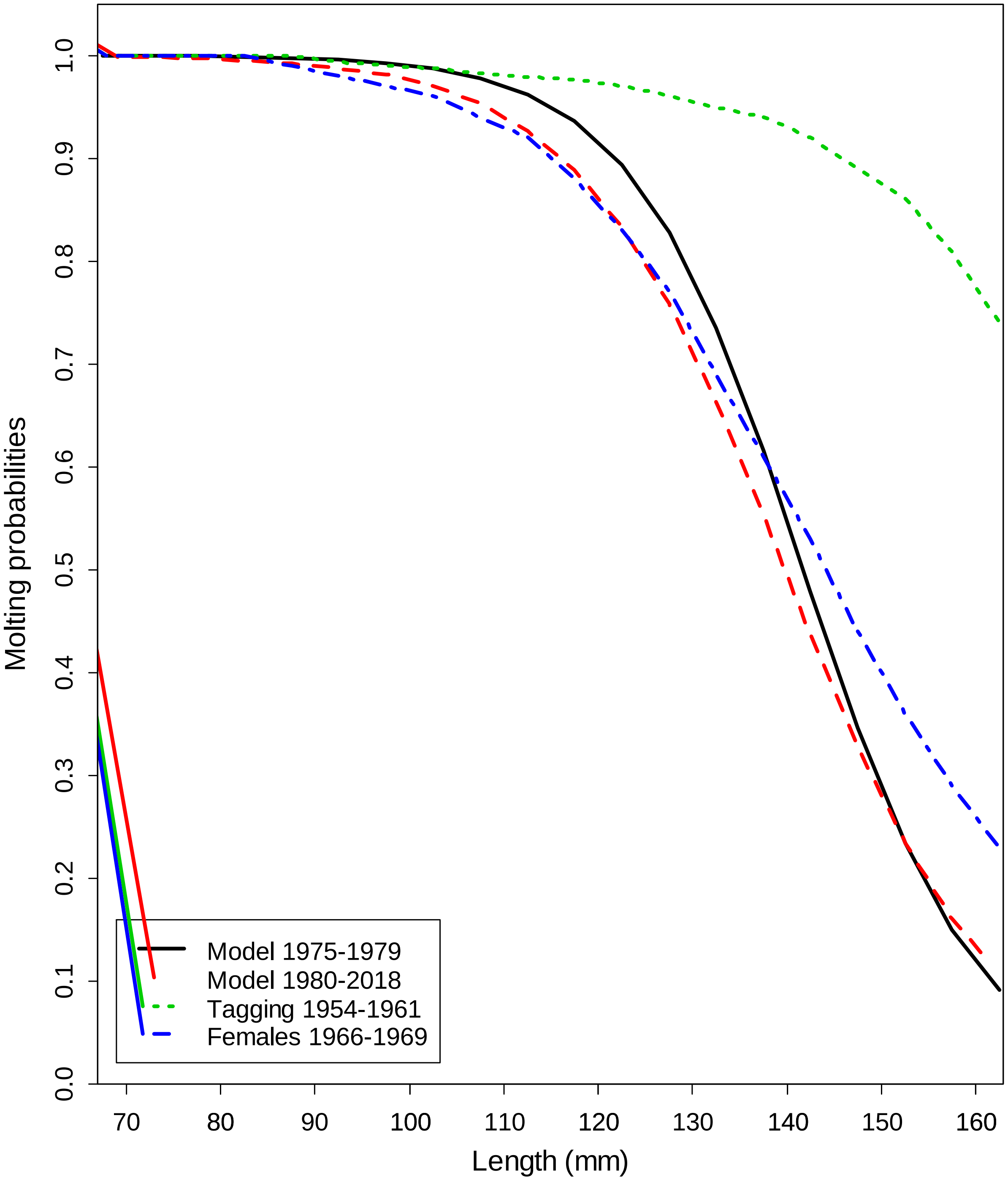


Figure 9(18.0). Comparison of estimated probabilities of molting of male red king crab in Bristol Bay for different periods. Molting probabilities for periods 1954-1961 and 1966-1969 were estimated by Balsiger (1974) from tagging data. Molting probabilities for 1975-2018 were estimated with a length-based model.

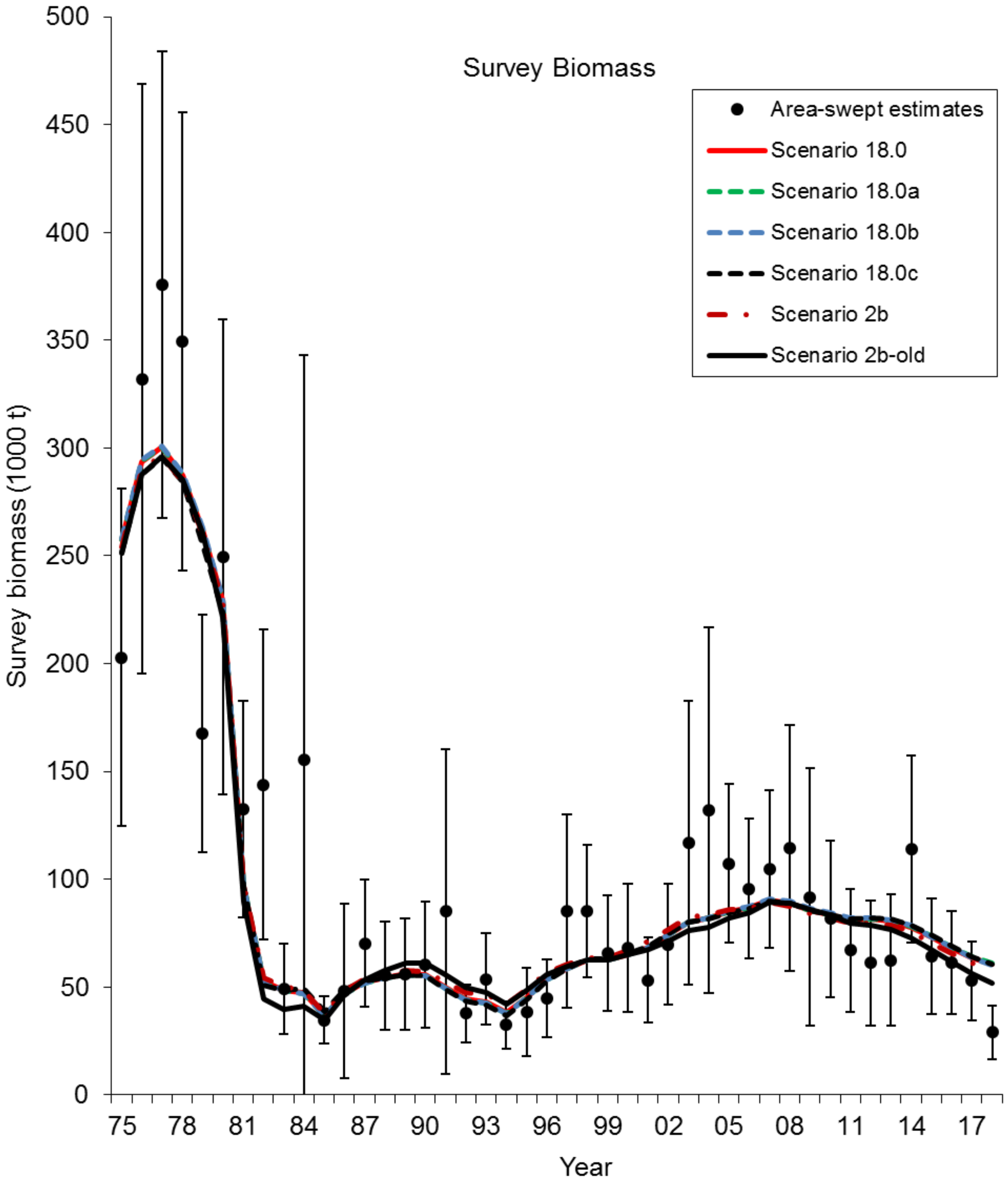


Figure 10a. Comparisons of area-swept estimates of total survey biomass and model prediction for model estimates in 2018 under scenarios 18.0, 18.0a, 8.0b, 18.0c, 2b and 2b-old. Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively. The error bars are plus and minus 2 standard deviations.

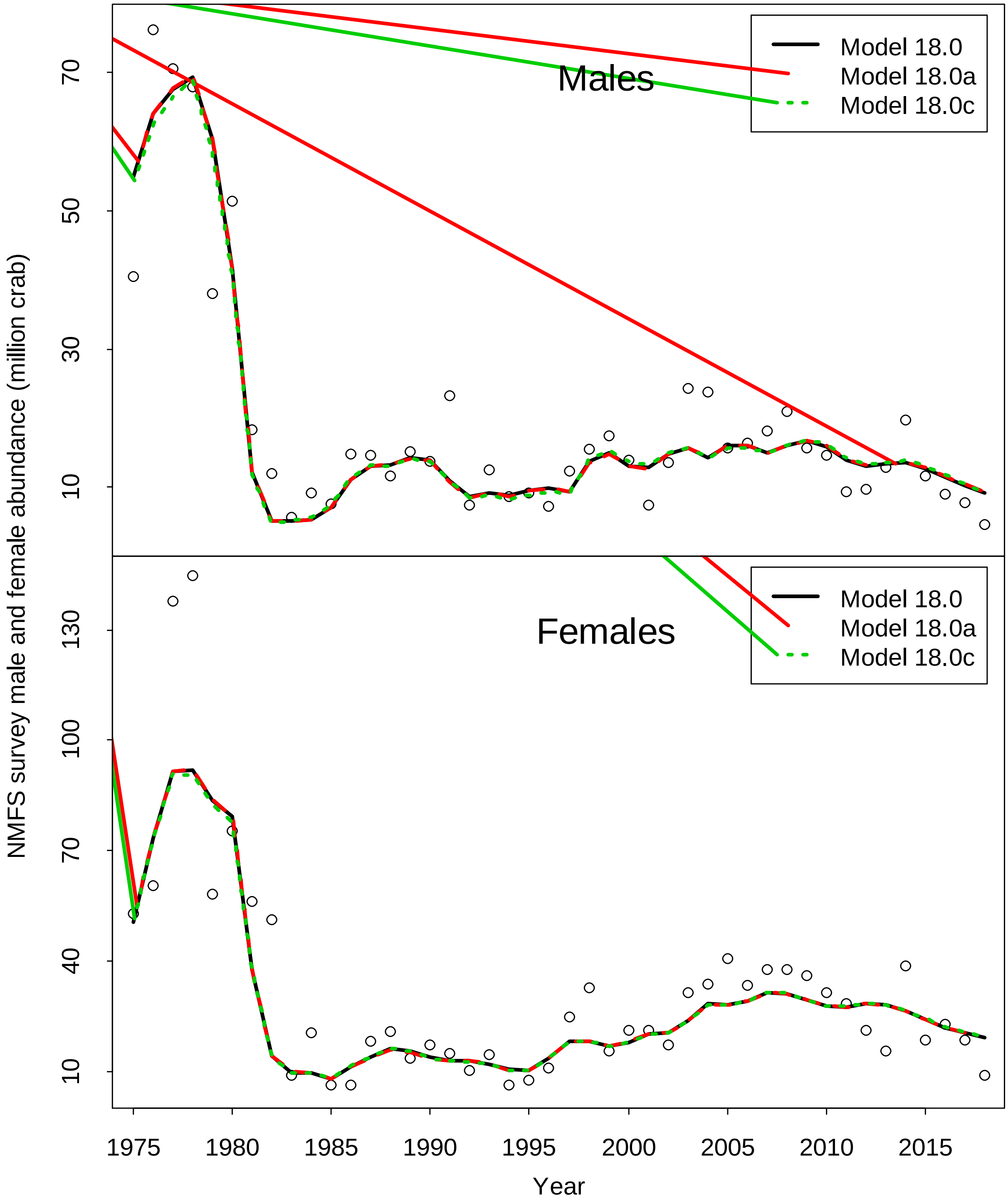


Figure 10b. Comparisons of area-swept estimates of male (>119 mm) and female (>89 mm) abundance and model prediction for model estimates in 2018 under scenarios 18.0, 18.0a, and 18.0c. Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively.

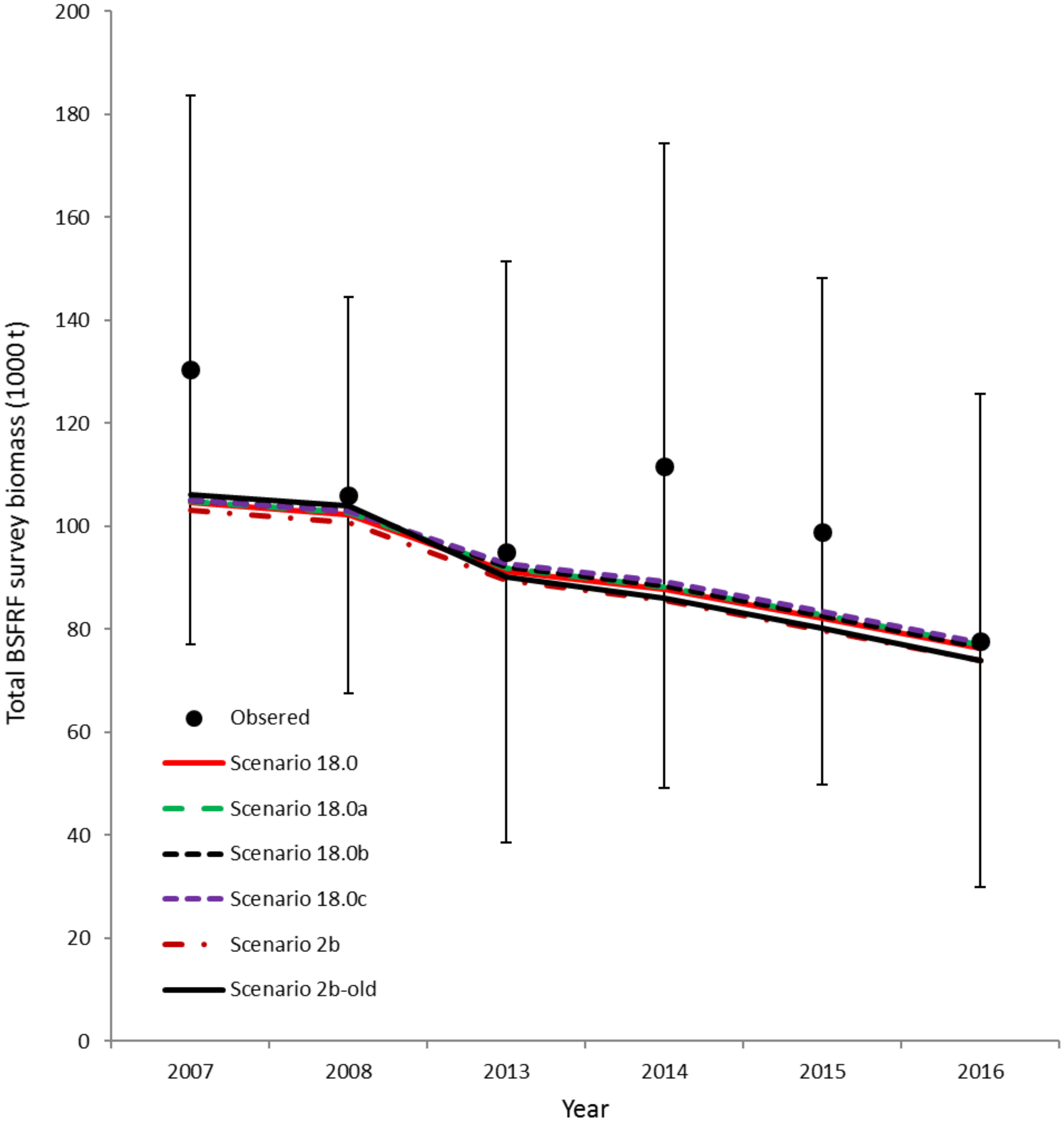


Figure 10c. Comparisons of total survey biomass estimates by the BSFRF survey and the model for model estimates in 2018 (scenarios 18.0, 18.0a, 8.0b, 18.0c, 2b and 2b-old). The error bars are plus and minus 2 standard deviations of scenario 18.0.

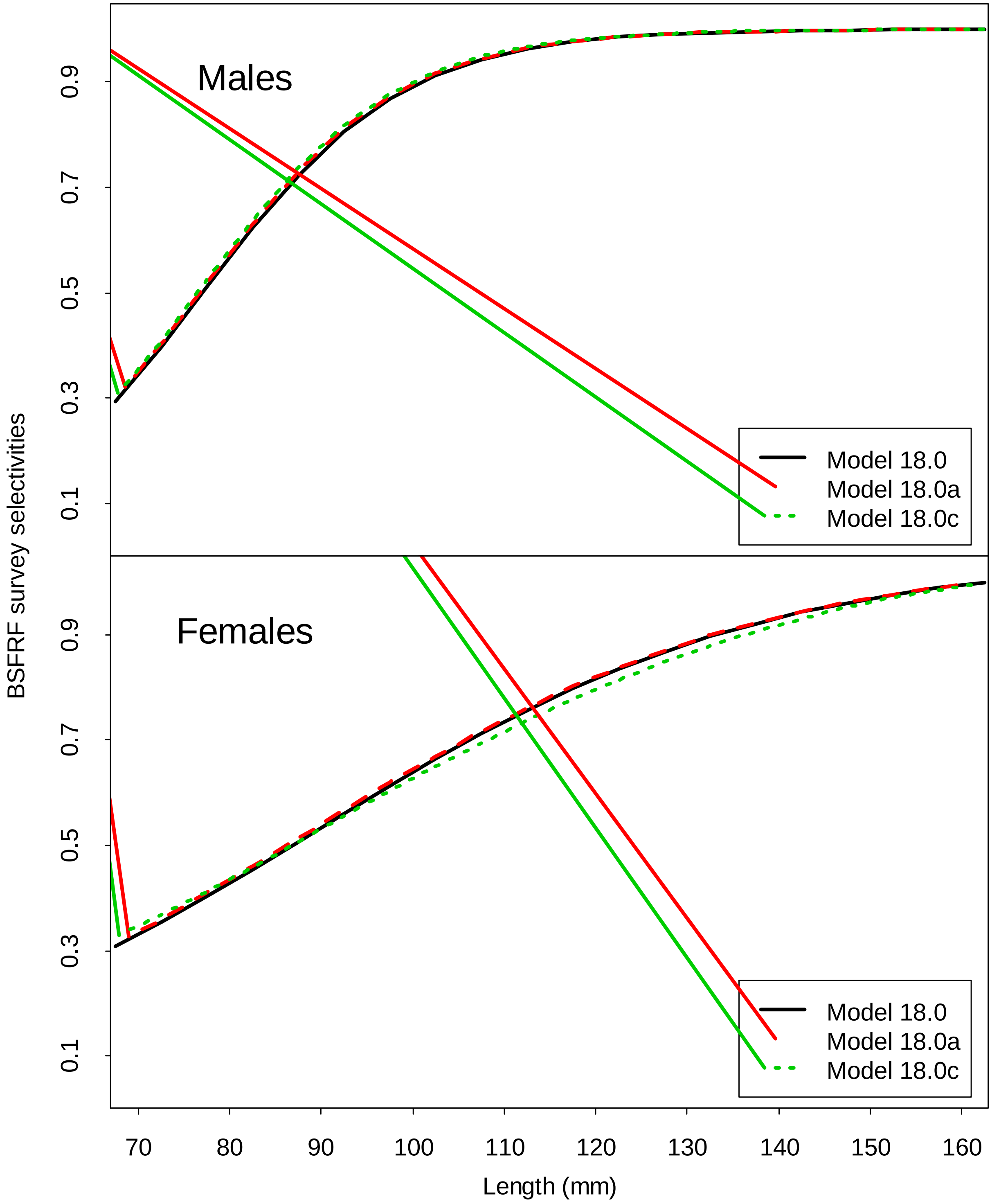


Figure 10d. Comparisons of estimated BSFRF survey selectivities with scenarios 18.0, 18.0a, and 18.0c. The catchability is assumed to be 1.0.

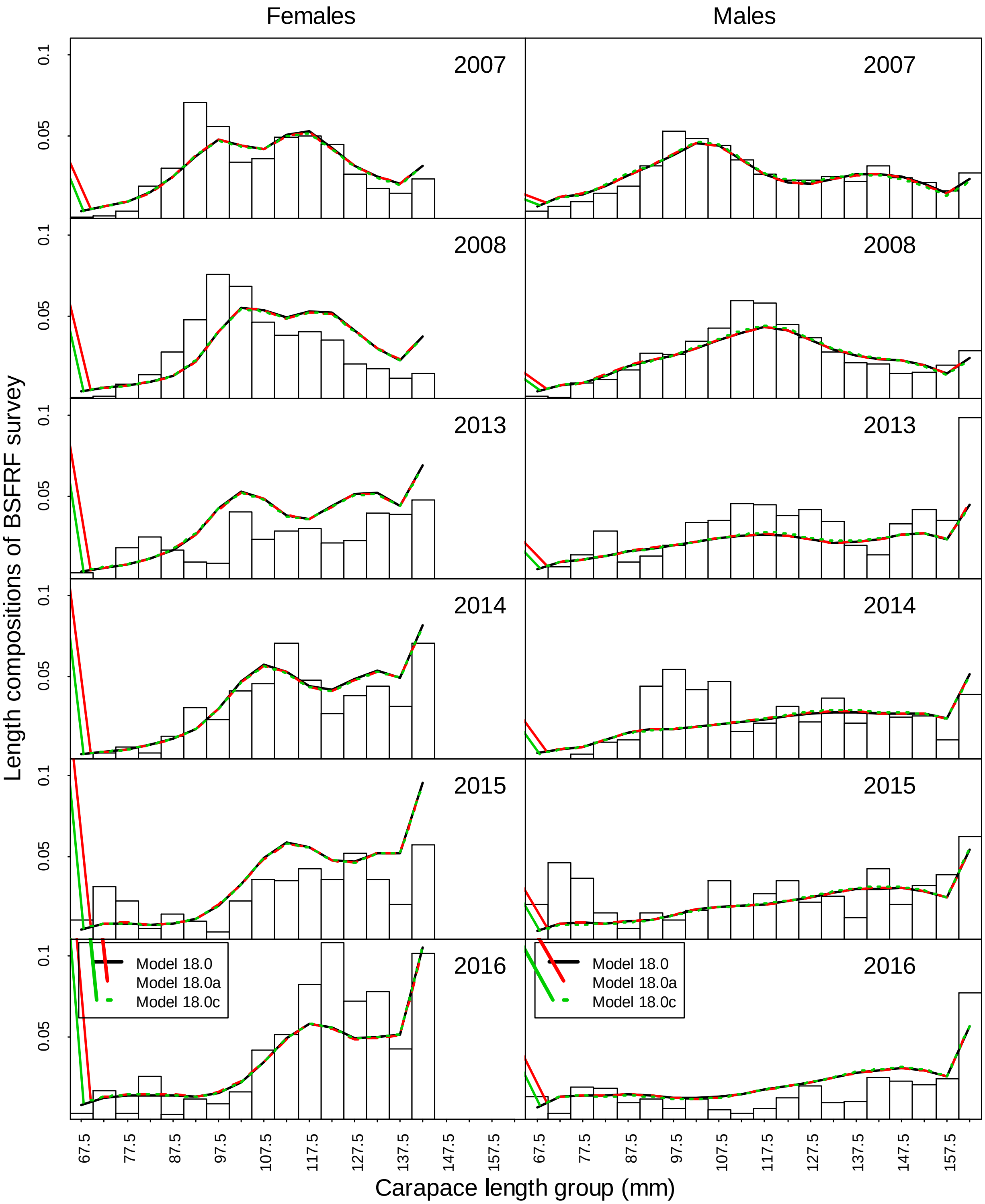


Figure 10e(18.0, 18.0a, & 18.0c). Comparisons of length compositions by the BSFRF survey and the model estimates during 2007-2008 and 2013-2016 with scenarios 18.0 (solid black), 18.0a (dashed red), and 18.0c (green lines).

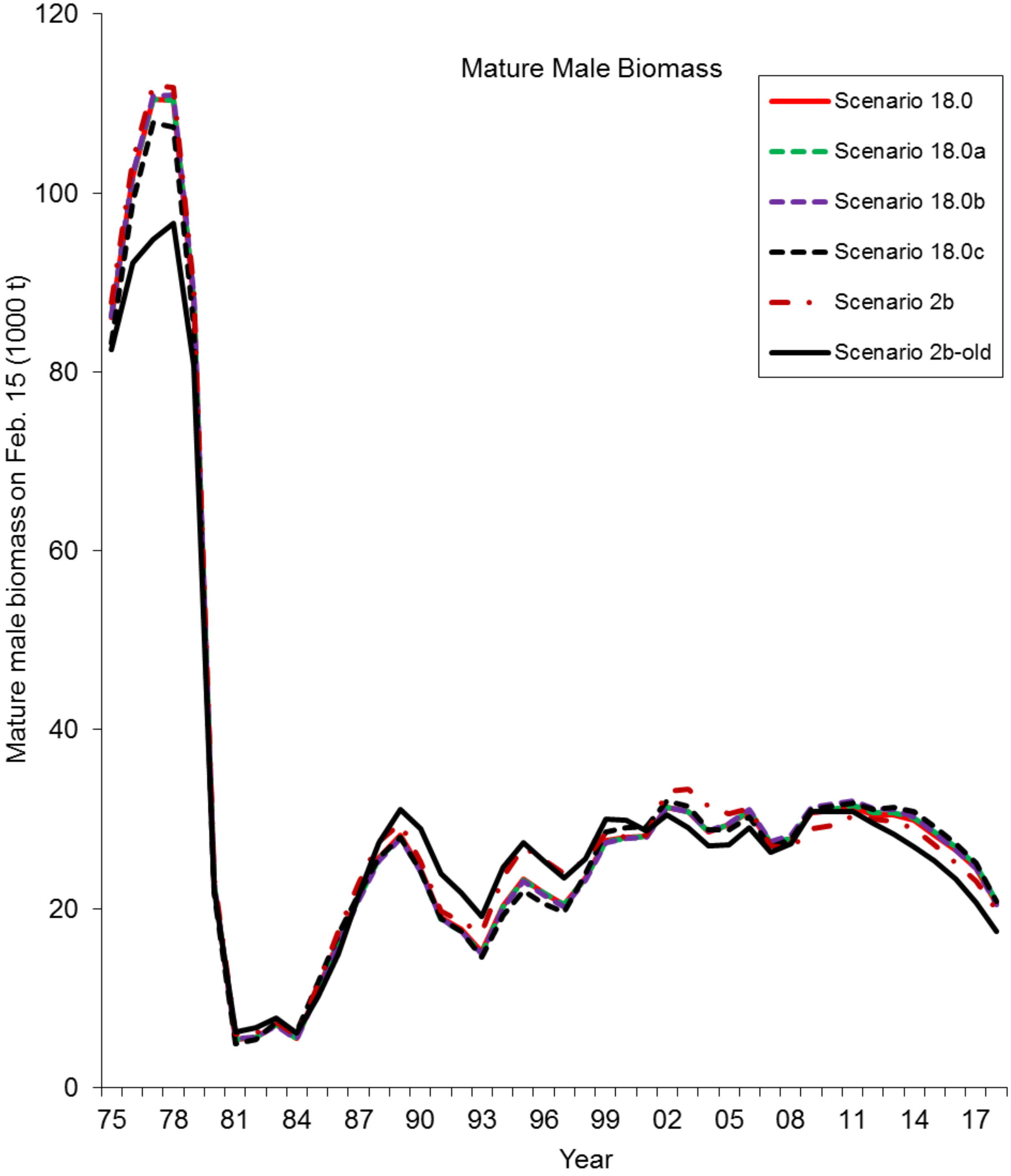


Figure 11. Estimated absolute mature male biomasses during 1975-2018 for scenarios 18.0, 18.0a, 18.0b, 18.0c, 2b, and 2b-old.

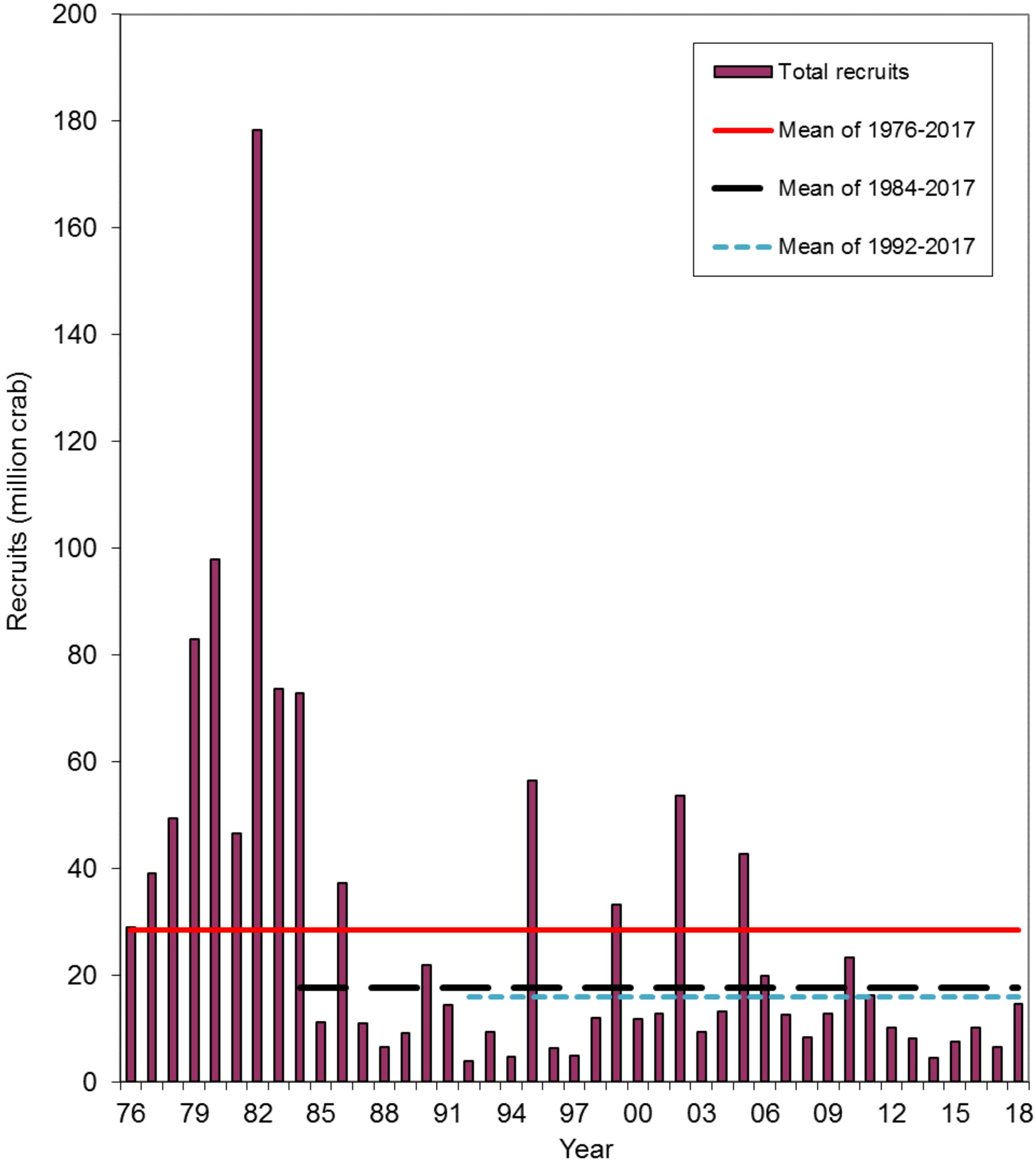


Figure 12(18.0). Estimated recruitment time series during 1976-2018 with scenario 18.0. Mean male recruits during 1984-2017 was used to estimate $B_{35\%}$.

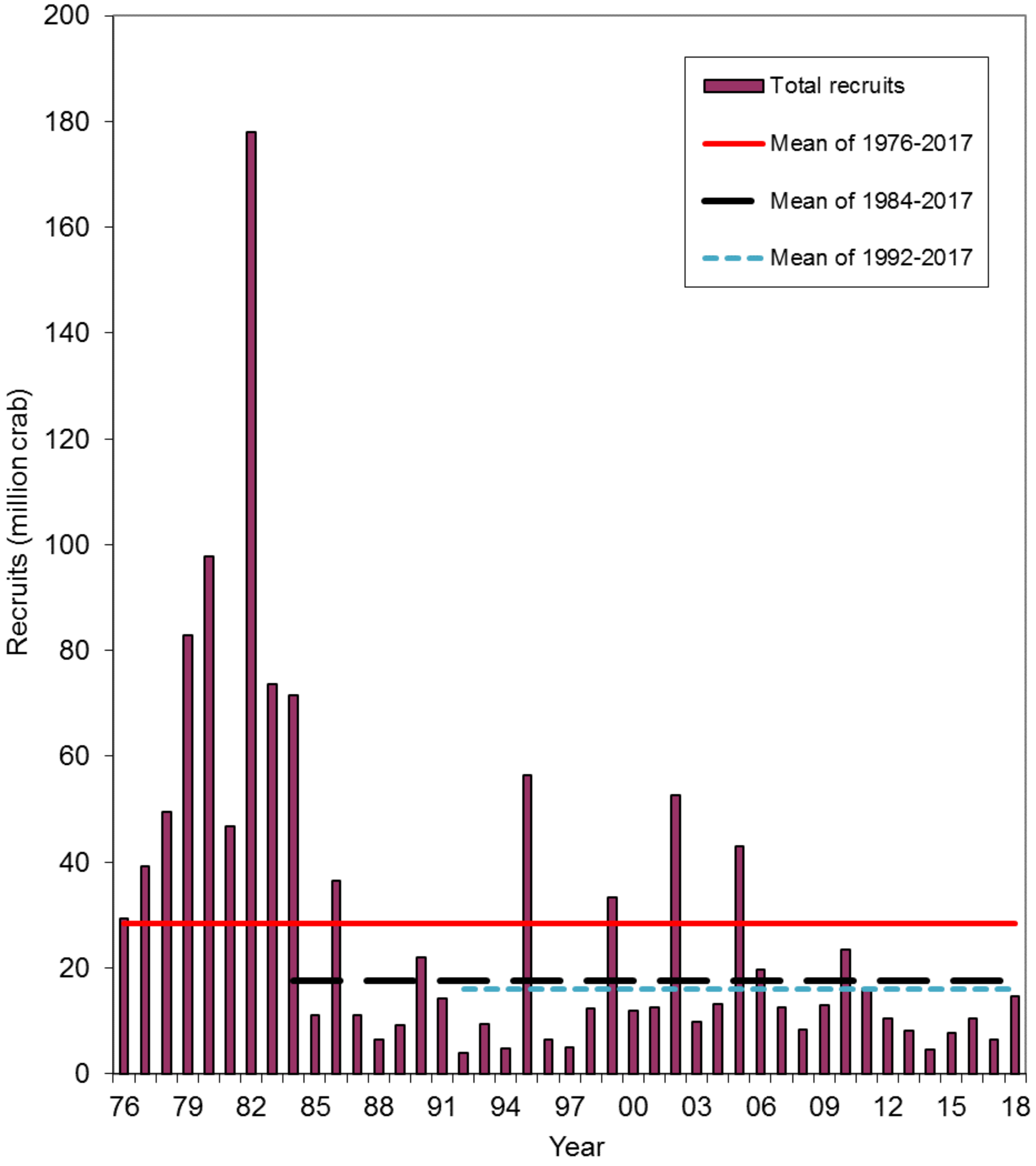


Figure 12(18.0a). Estimated recruitment time series during 1976-2018 with scenario 18.0a. Mean male recruits during 1984-2017 was used to estimate B35%.

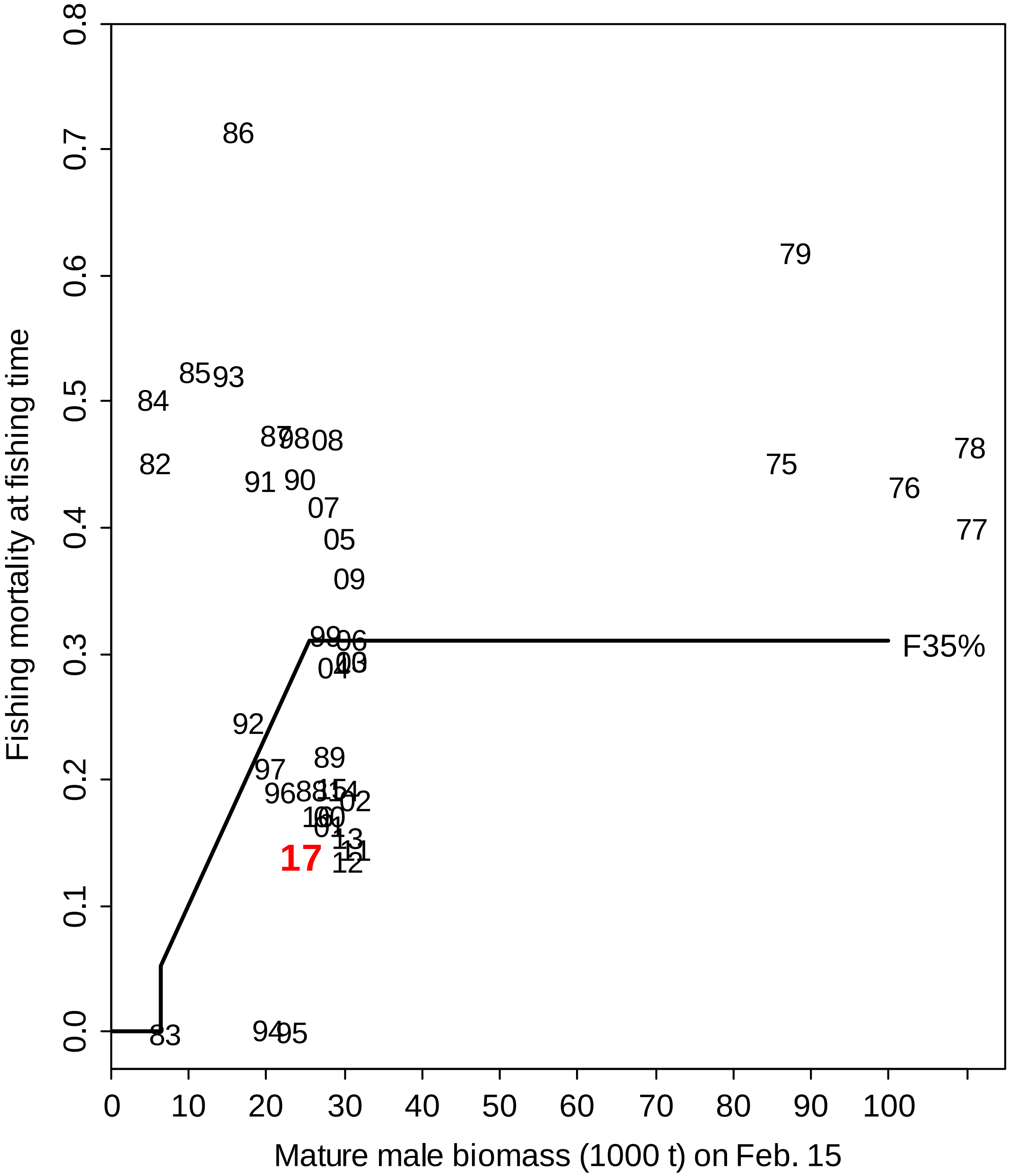


Figure 13(18.0). Relationships between full fishing mortalities for the directed pot fishery and mature male biomass on Feb. 15 during 1975-2018 under scenario 18.0. Average of recruitment from 1984 to 2017 was used to estimate B_{MSY}. Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively.

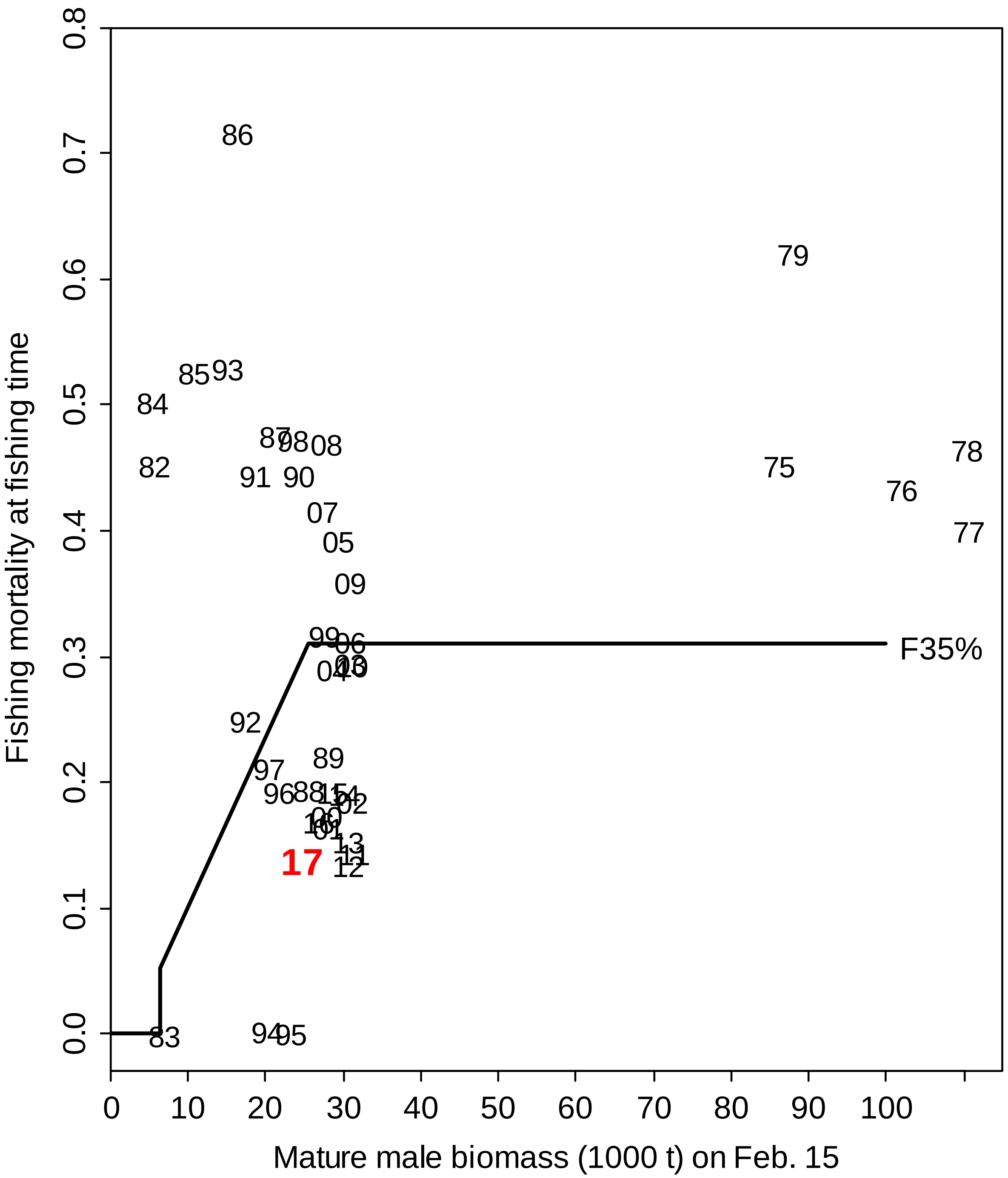


Figure 13(18.0a). Relationships between full fishing mortalities for the directed pot fishery and mature male biomass on Feb. 15 during 1975-2018 under scenario 18.0a. Average of recruitment from 1984 to 2017 was used to estimate BMSY. Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively.

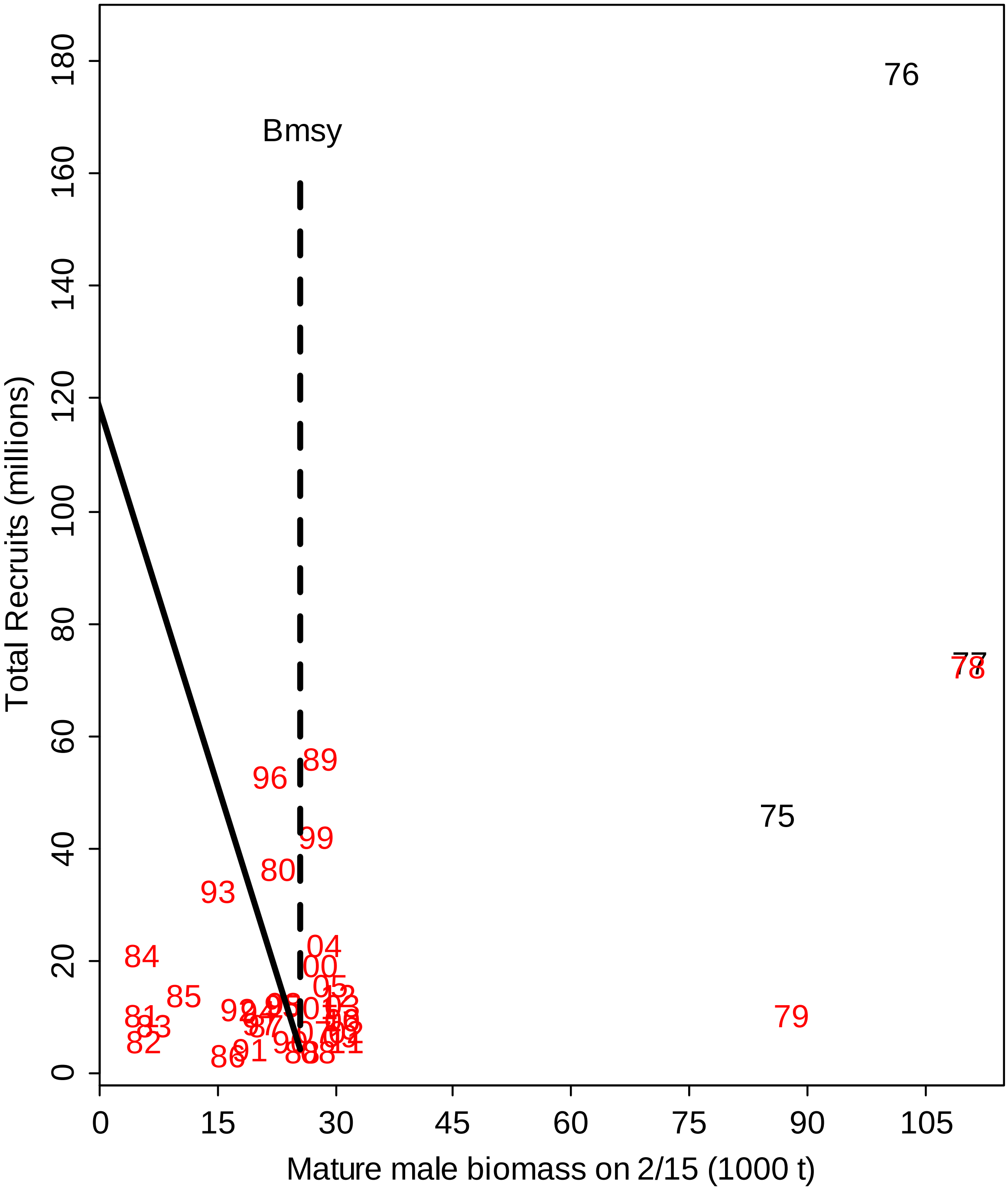


Figure 14a. Relationships between mature male biomass on Feb. 15 and total recruits at age 5 (i.e., 6-year time lag) for Bristol Bay red king crab with pot handling mortality rate of 0.2 under scenario 18.0. Numerical labels are years of mating, and the vertical dotted line is the estimated $B_{35\%}$ based on the mean recruitment level during 1984 to 2017.

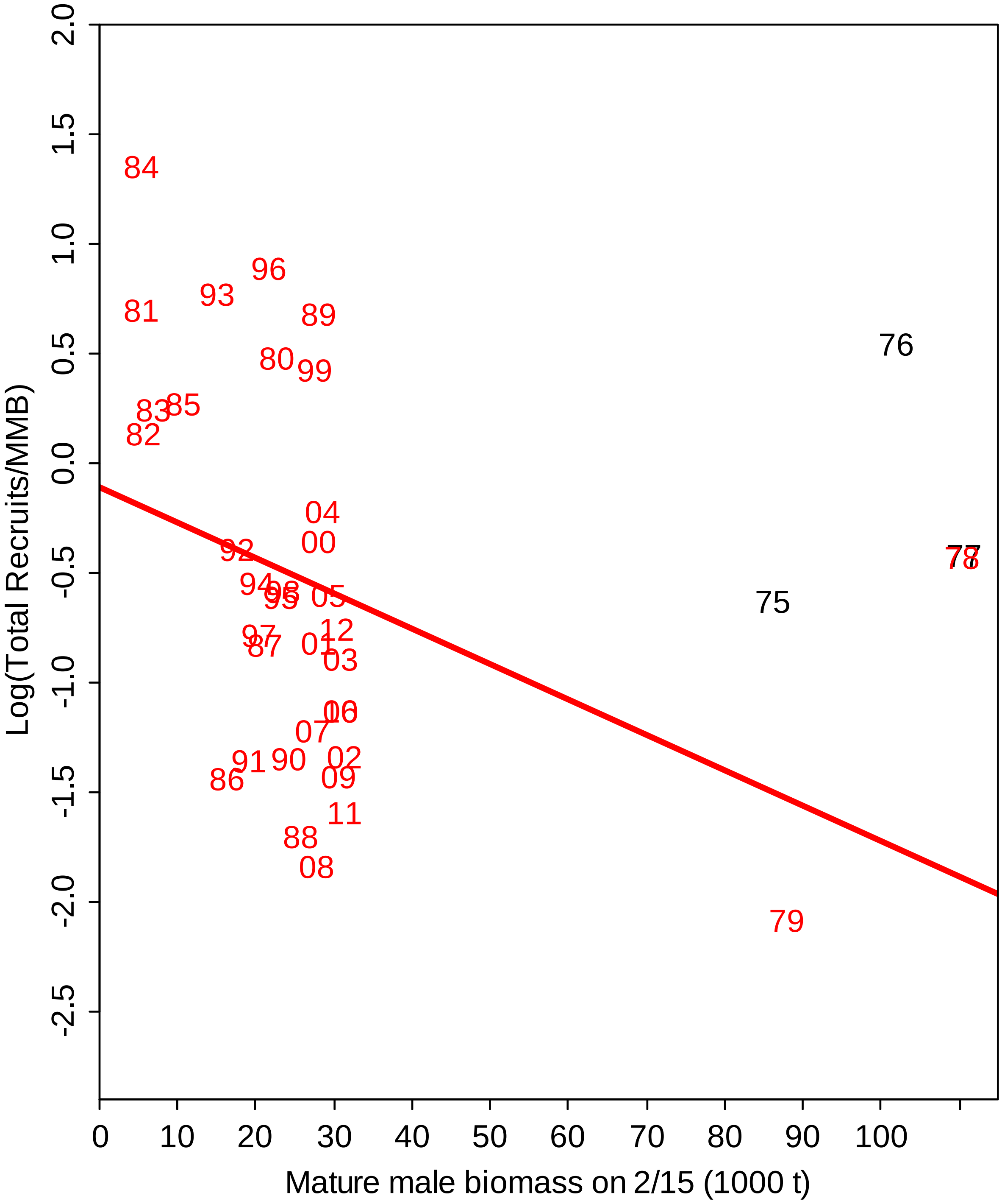


Figure 14b. Relationships between log recruitment per mature male biomass and mature male biomass on Feb. 15 for Bristol Bay red king crab with pot handling mortality rate of 0.2 under scenario 18.0. Numerical labels are years of mating, and the line is the regression line for data of 1978-2012.

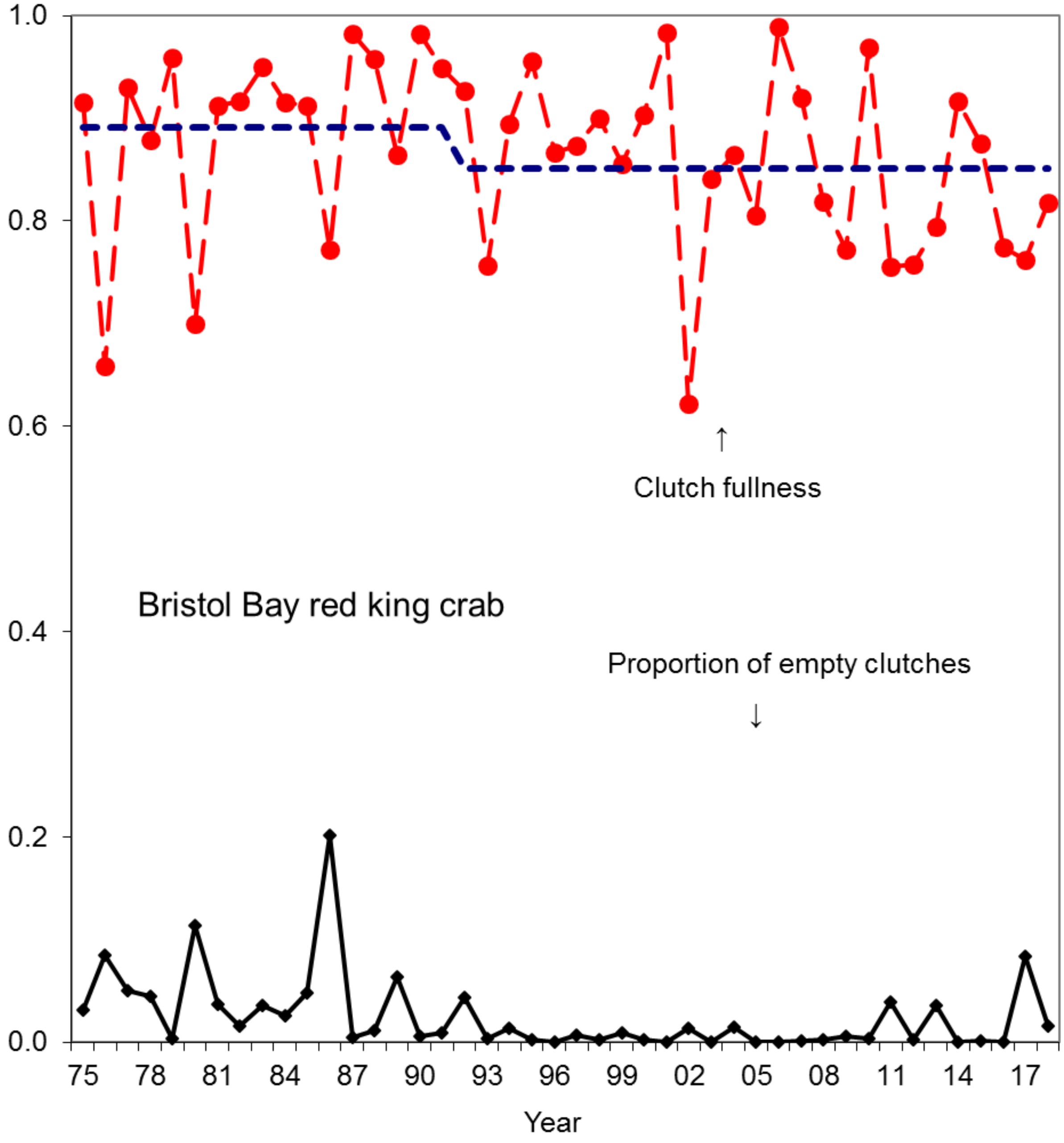


Figure 15. Average clutch fullness and proportion of empty clutches of newshell (shell conditions 1 and 2) mature female crab >89 mm CL from 1975 to 2018 from survey data. Oldshell females were excluded. The blue dashed line is the mean clutch fullness during two periods before 1992 and after 1991.

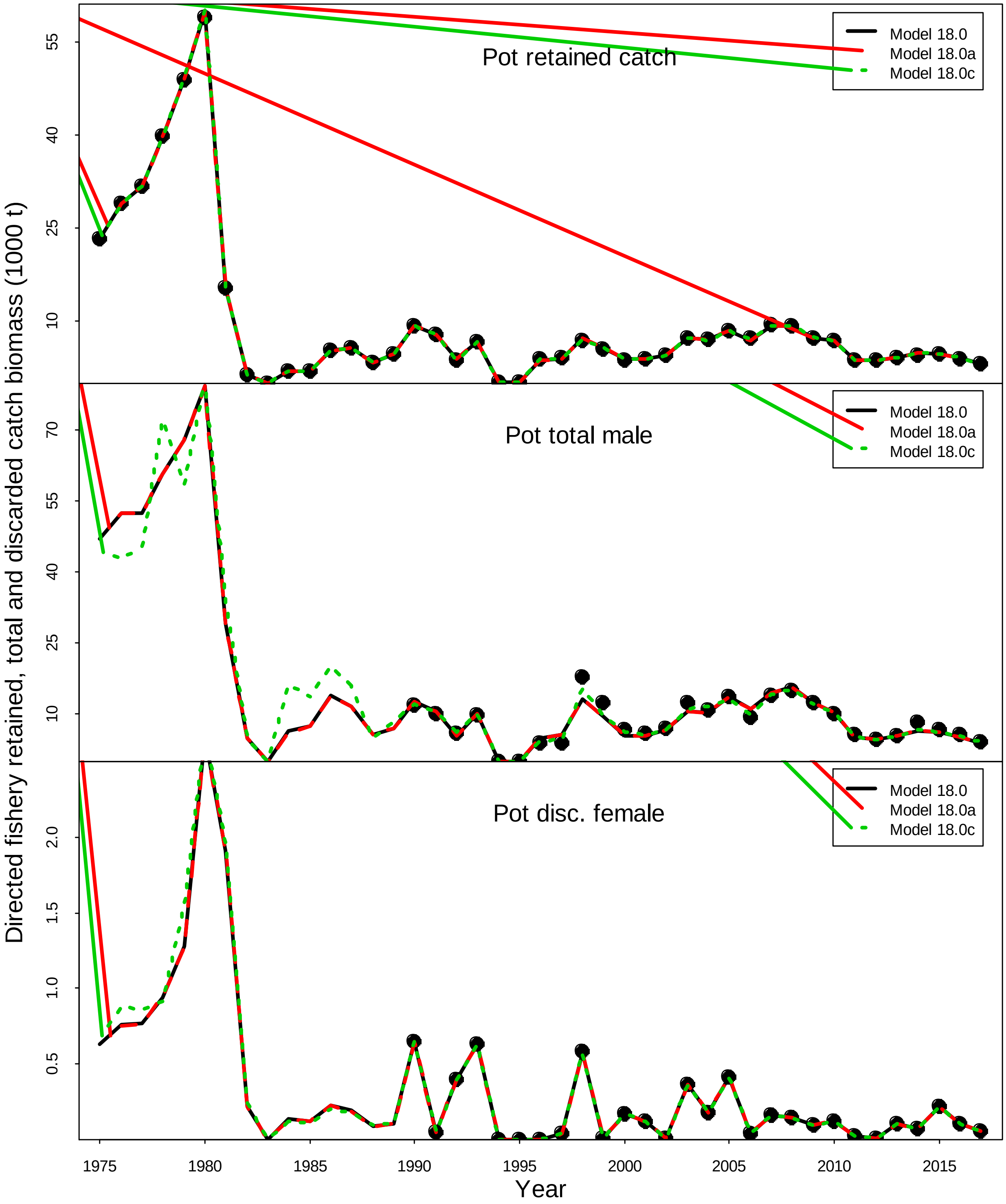


Figure 16a. Observed and predicted catch mortality biomass under scenarios 18.0(solid black), 18.0a (dashed red), and 18.0c (green lines). Mortality biomass is equal to caught biomass times a handling mortality rate.

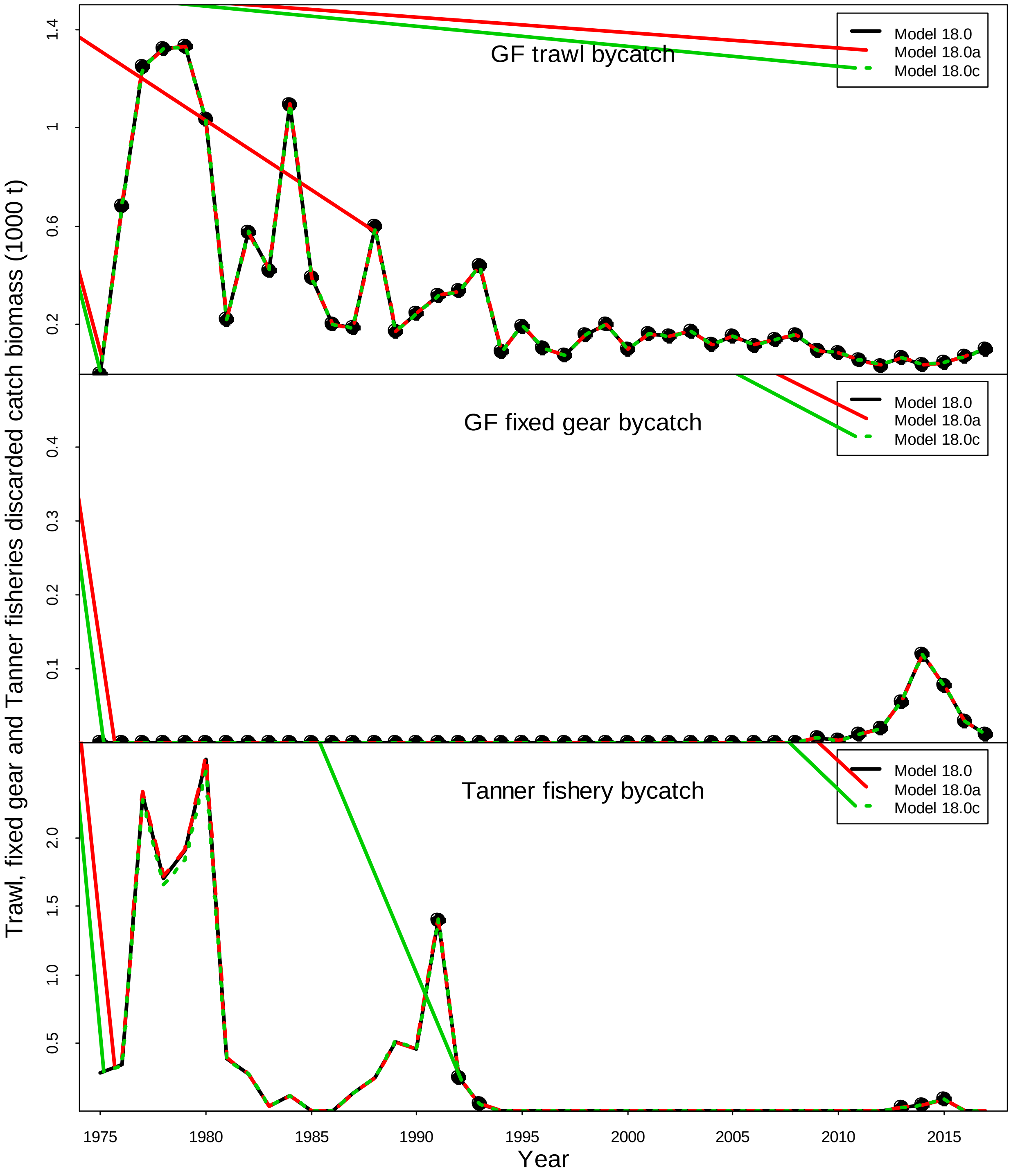


Figure 16b. Observed and predicted bycatch mortality biomass from groundfish fisheries and the Tanner crab fishery under scenarios 18.0(solid black), 18.0a (dashed red), and 18.0c (green lines). Mortality biomass is equal to caught biomass times a handling mortality rate. Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively. Trawl bycatch biomass was 0 before 1976.

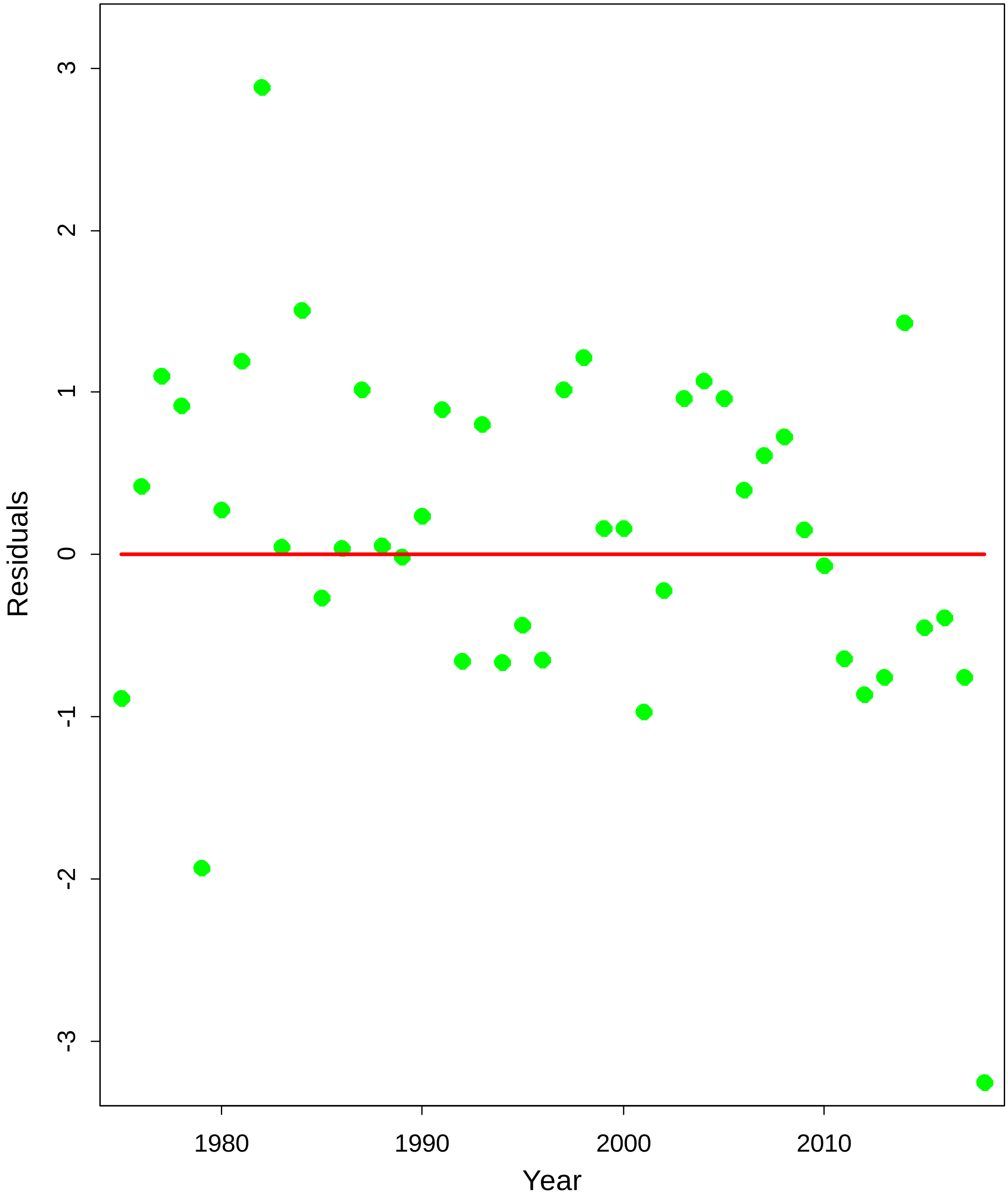


Figure 17(18.0). Standardized residuals of total survey biomass under scenario 18.0. Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively.

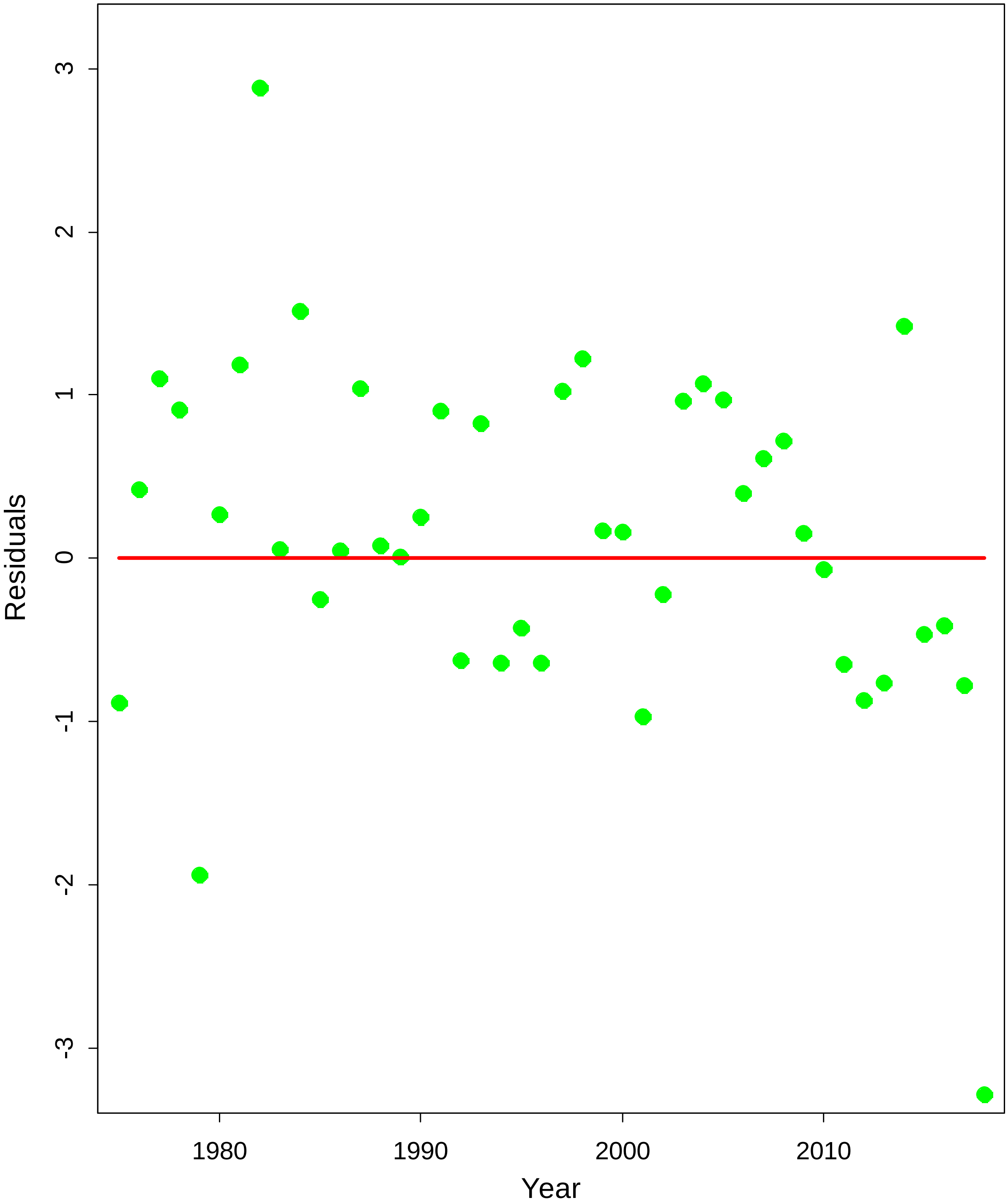


Figure 17(18.0a). Standardized residuals of total survey biomass under scenario 18.0a. Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively.

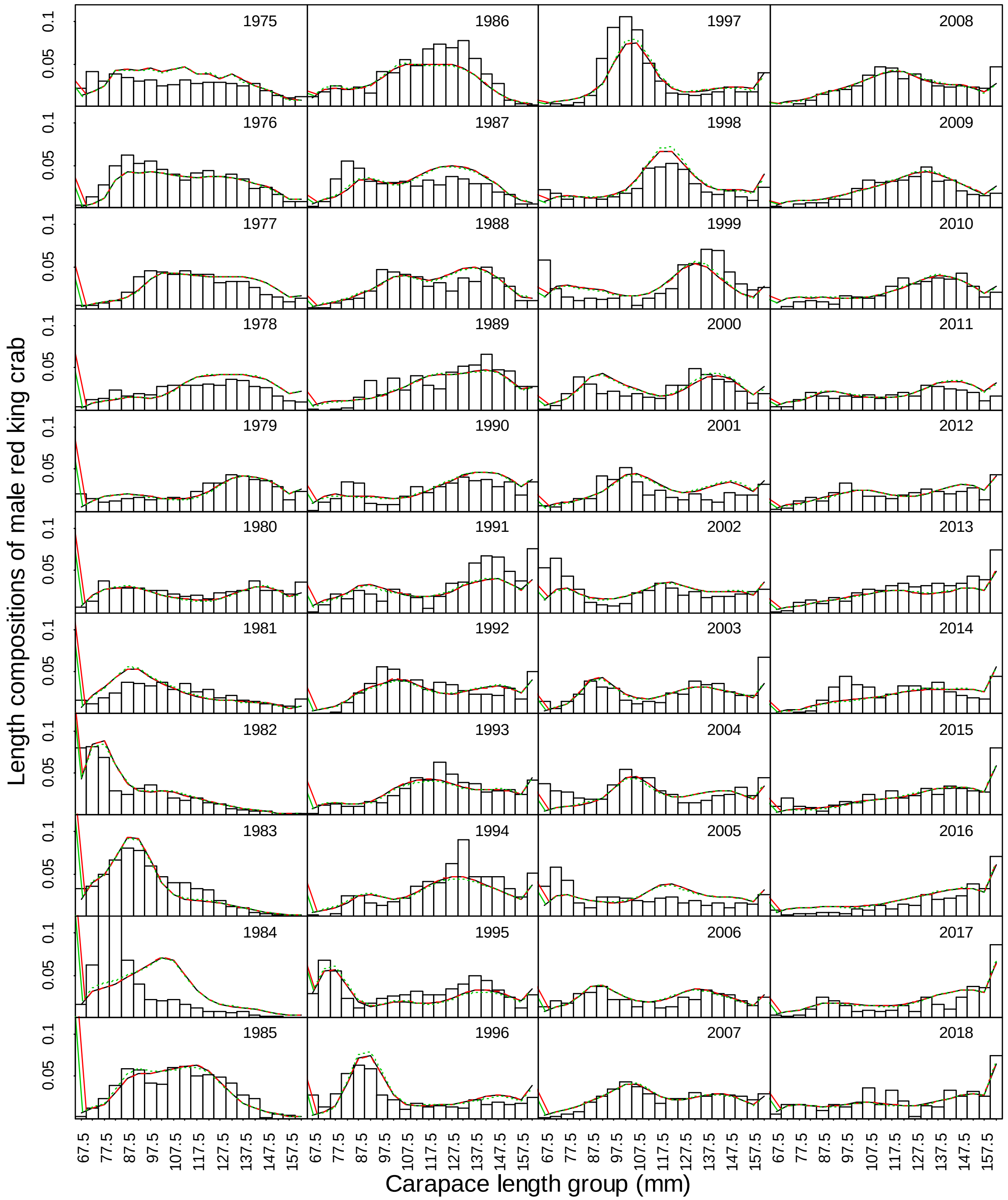


Figure 18(18.0, 18.0a & 18.0c). Comparison of area-swept and model estimated NMFS survey length frequencies of Bristol Bay male red king crab by year under scenarios 18.0(solid black), 18.0a (dashed red), and 18.0c (green lines). Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively.

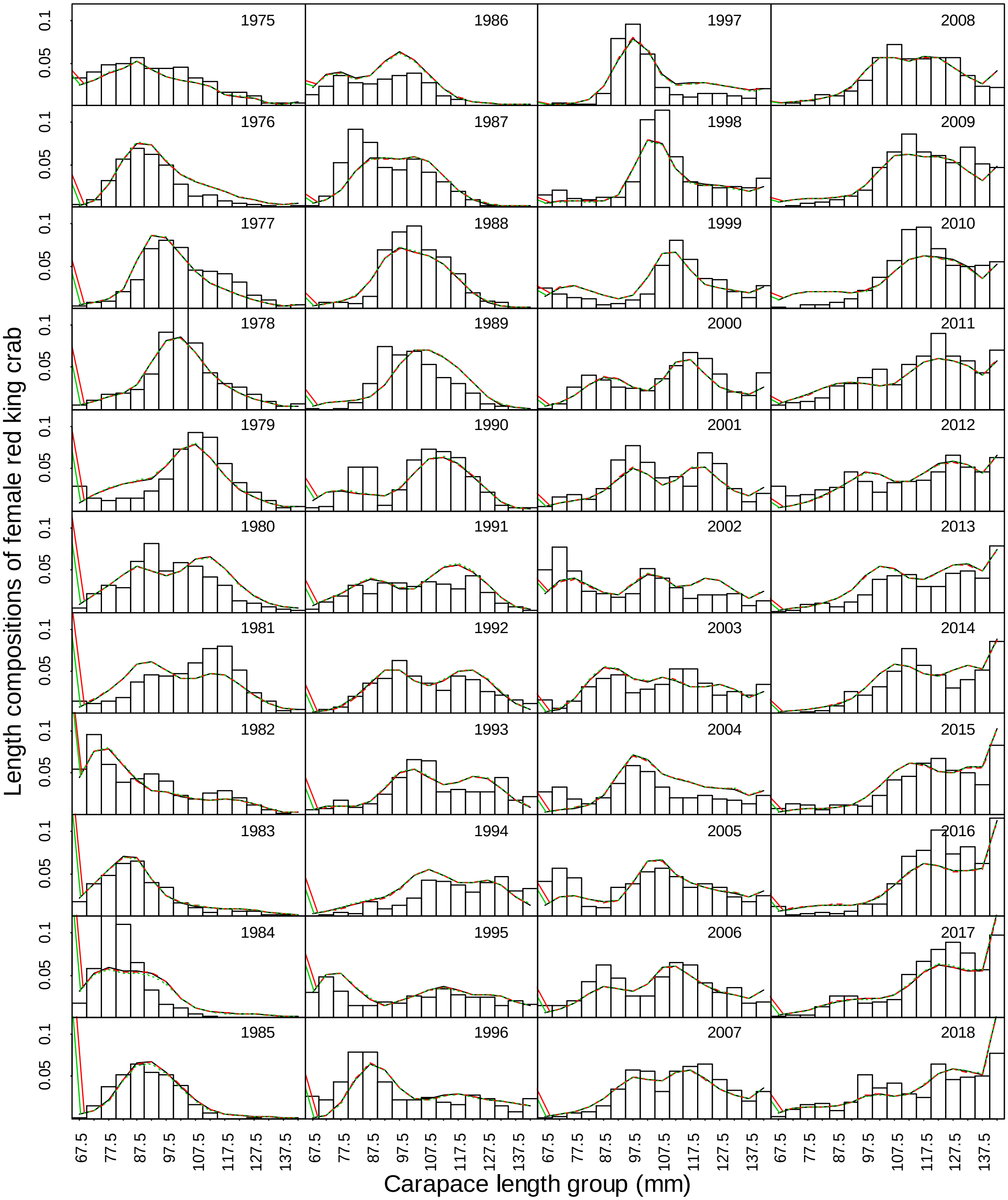


Figure 19(18.0, 18.0a & 18.0c). Comparison of area-swept and model estimated NMFS survey length frequencies of Bristol Bay female red king crab by year under scenarios 18.0(solid black), 18.0a (dashed red), and 18.0c (green lines). Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively.

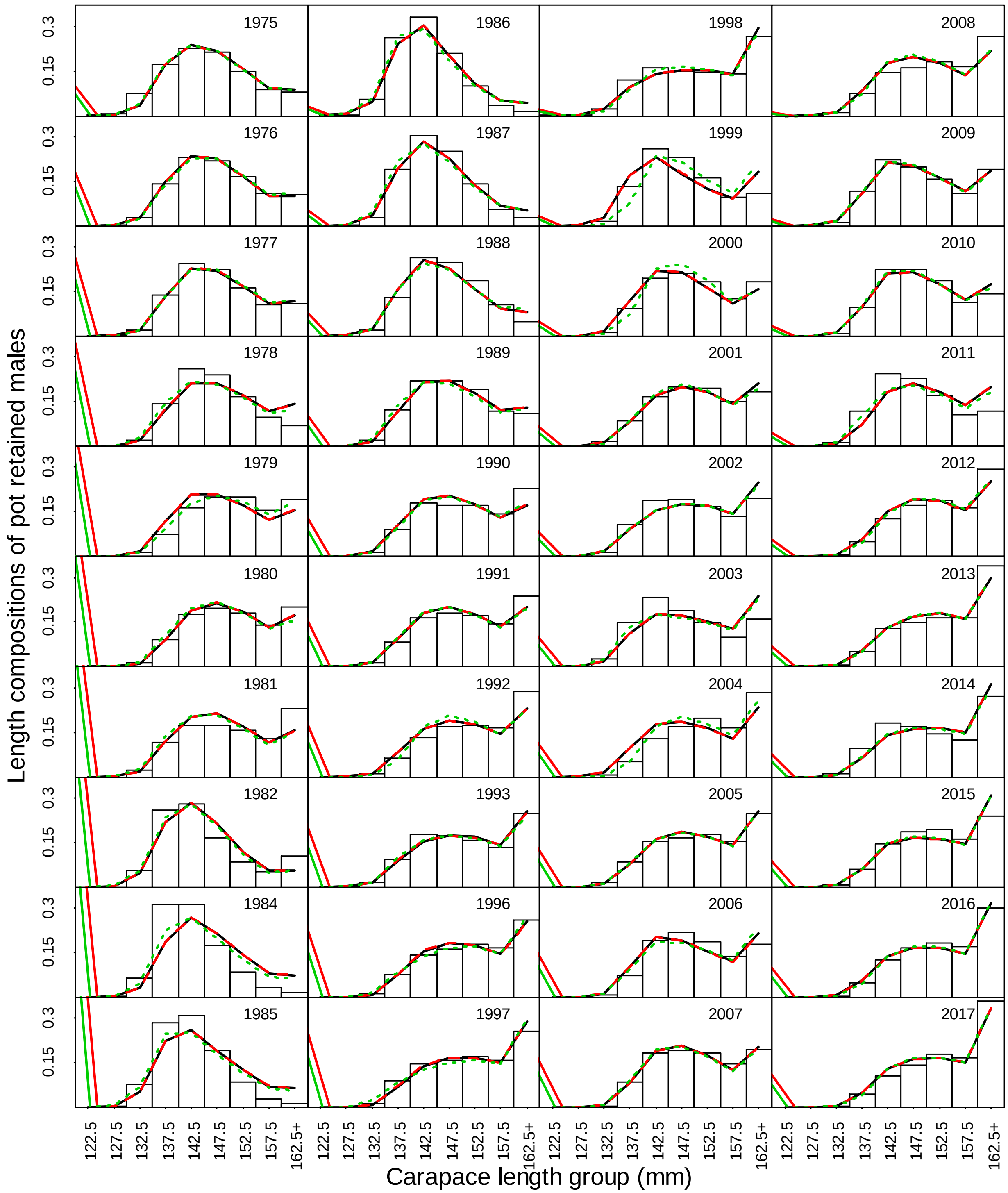


Figure 20(18.0, 18.0a & 18.0c). Comparison of observed and model estimated retained length frequencies of Bristol Bay male red king crab by year in the directed pot fishery under scenarios 18.0(solid black), 18.0a (dashed red), and 18.0c (green lines). Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively.

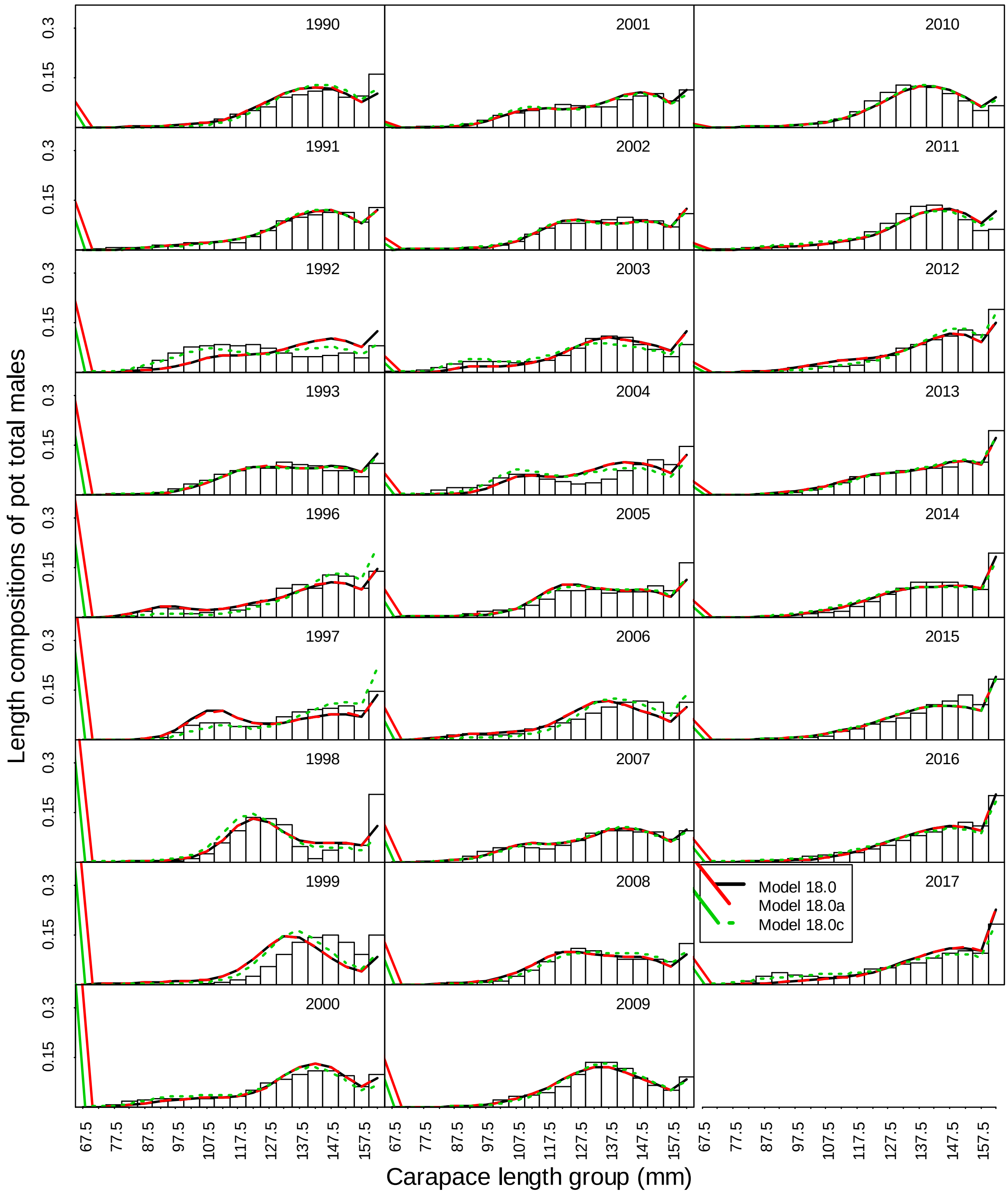


Figure 21(18.0, 18.0a & 18.0c). Comparison of observer and model estimated total observer length frequencies of Bristol Bay male red king crab by year in the directed pot fishery under scenarios 18.0(solid black), 18.0a (dashed red), and 18.0c (green lines). Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively.

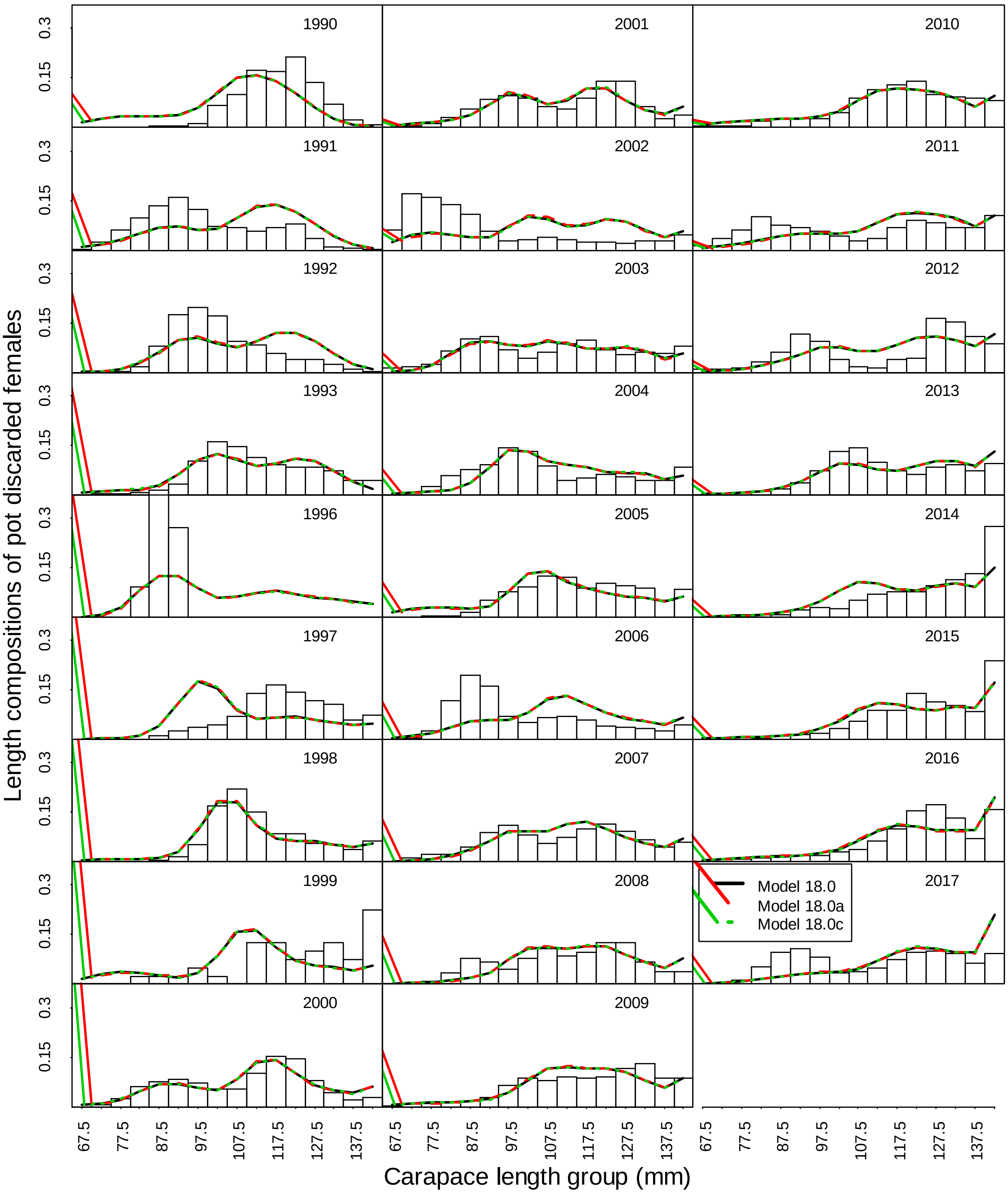


Figure 22(18.0, 18.0a & 18.0c). Comparison of observer and model estimated discarded length frequencies of Bristol Bay female red king crab by year in the directed pot fishery under scenarios 18.0(solid black), 18.0a (dashed red), and 18.0c (green lines). Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively.

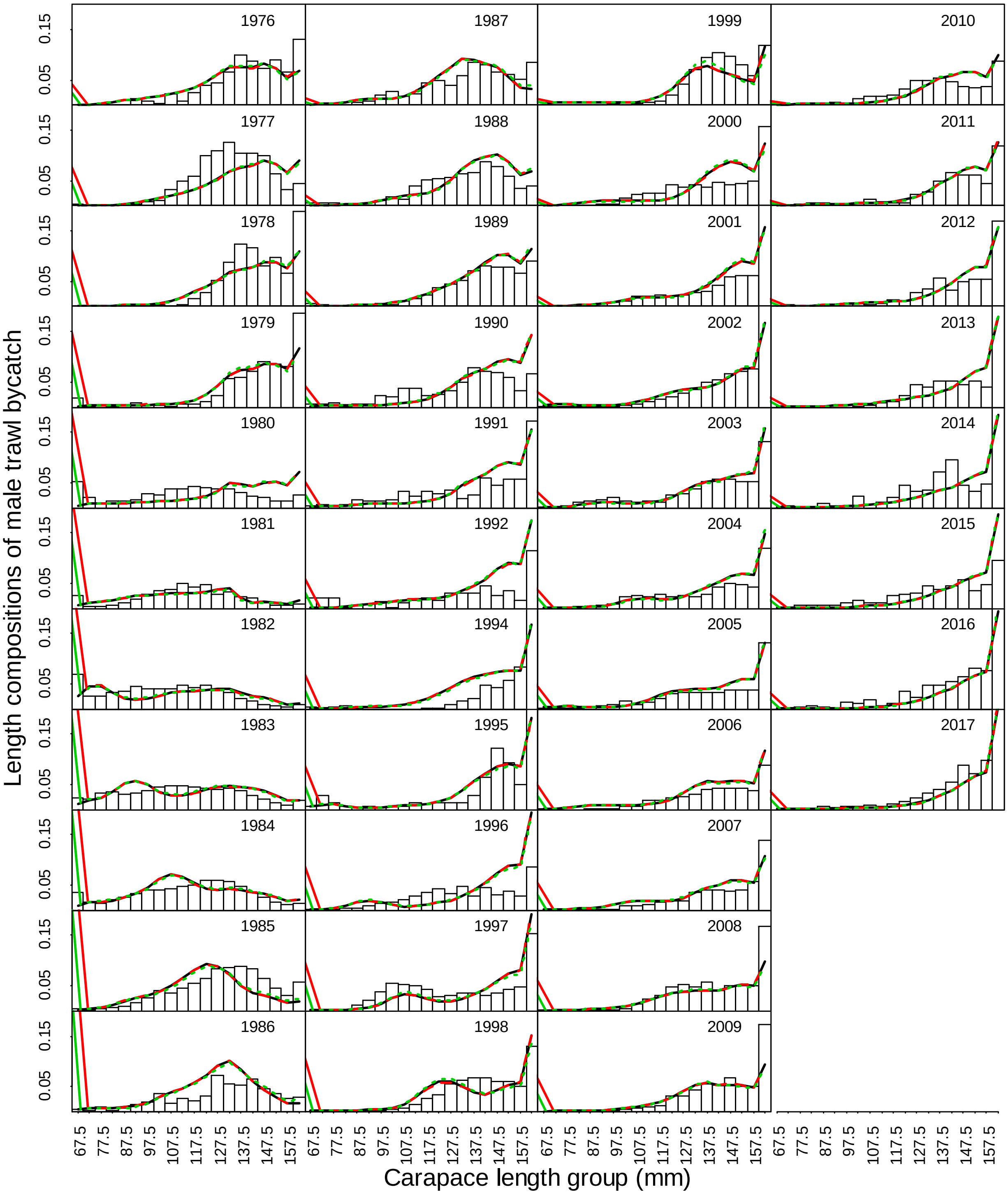


Figure 23(18.0, 18.0a & 18.0c). Comparison of observer and model estimated discarded length frequencies of Bristol Bay male red king crab by year in the groundfish trawl fisheries under scenarios 18.0(solid black), 18.0a (dashed red), and 18.0c (green lines). Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively.

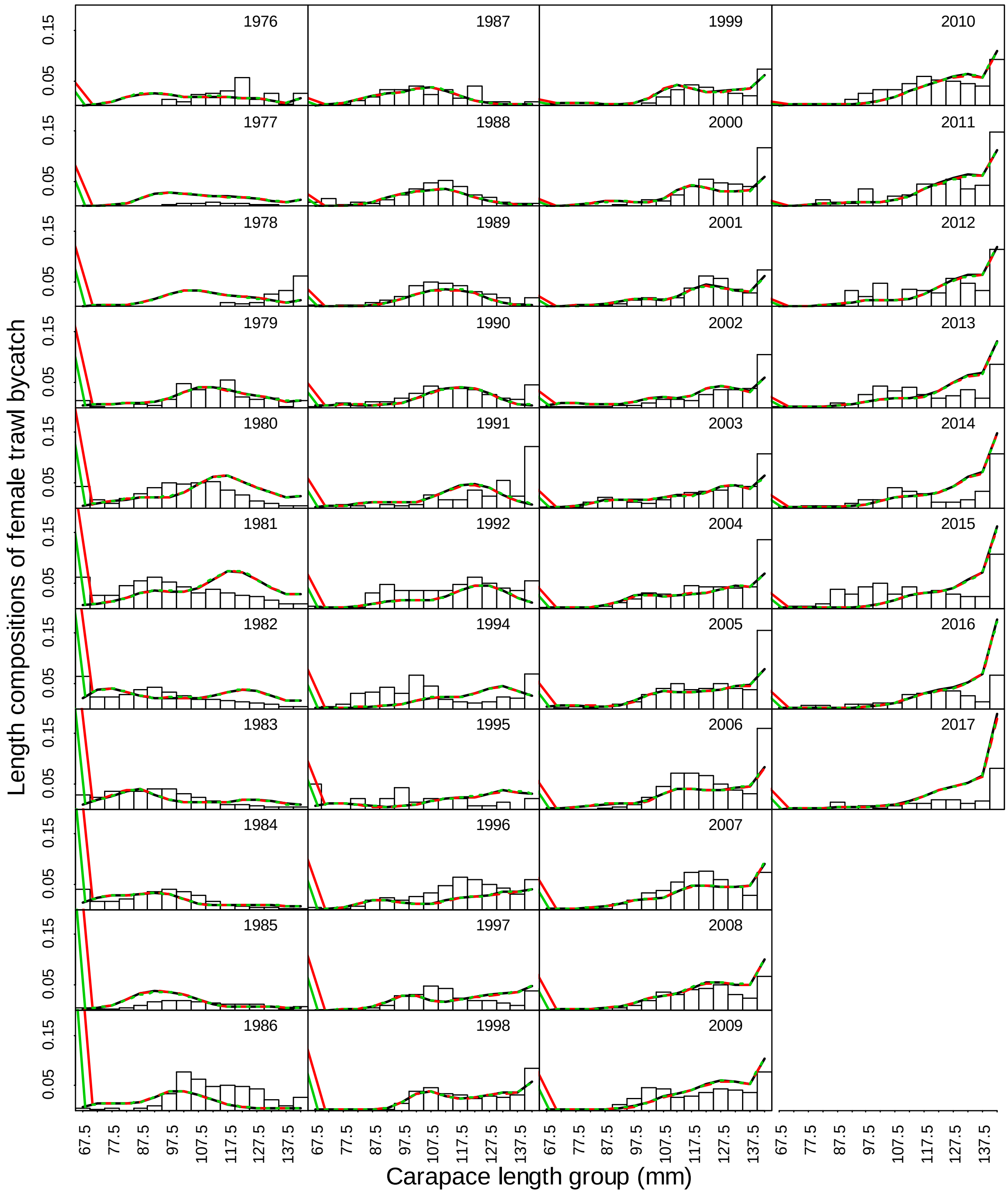


Figure 23(18.0, 18.0a & 18.0c). Comparison of observer and model estimated discarded length frequencies of Bristol Bay female red king crab by year in the groundfish trawl fisheries under scenarios 18.0(solid black), 18.0a (dashed red), and 18.0c (green lines). Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively.

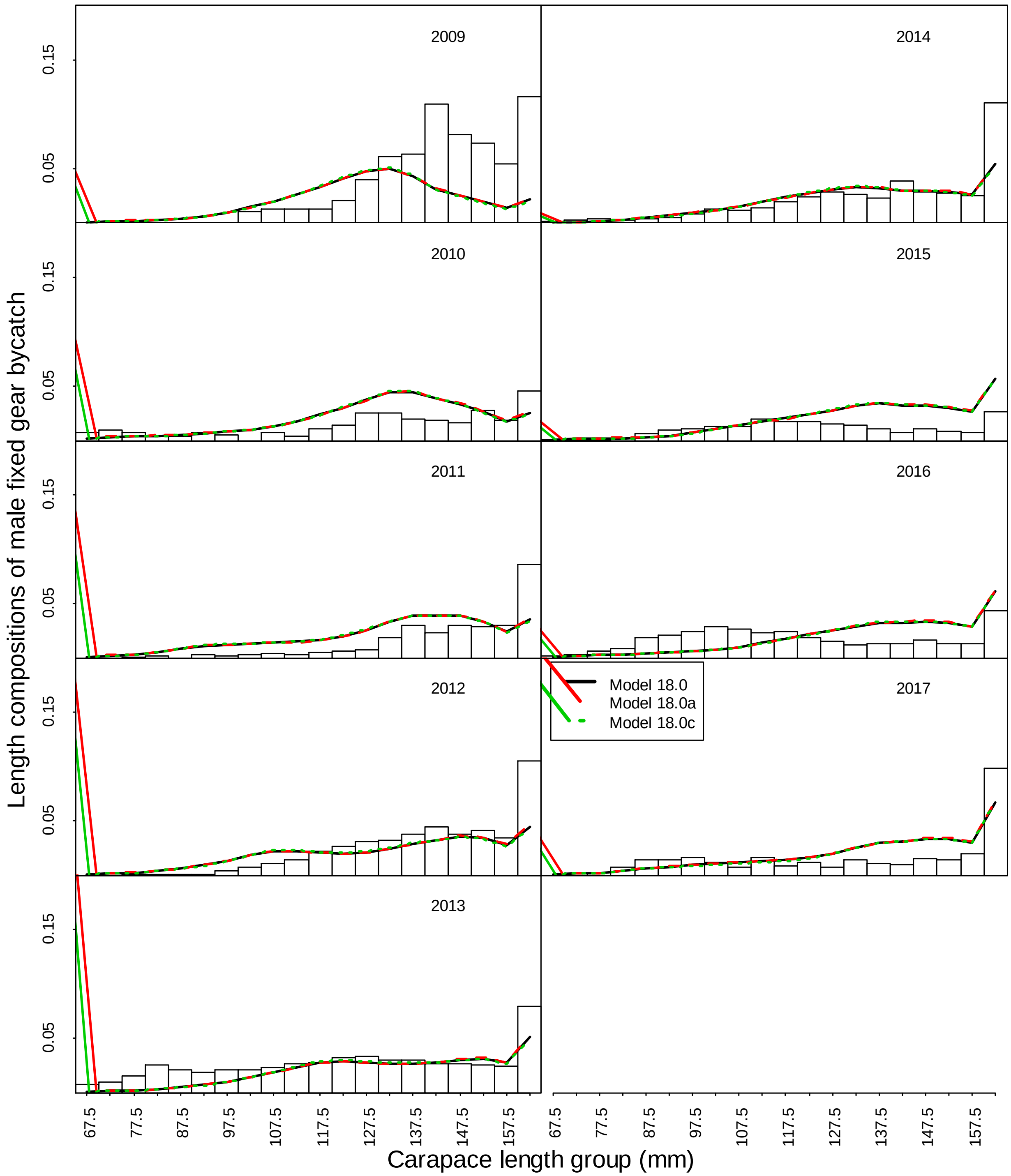


Figure 24(18.0, 18.0a & 18.0c). Comparison of observer and model estimated discarded length frequencies of Bristol Bay male red king crab by year in the groundfish fixed gear fisheries under scenarios 18.0(solid black), 18.0a (dashed red), and 18.0c (green lines). Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively.

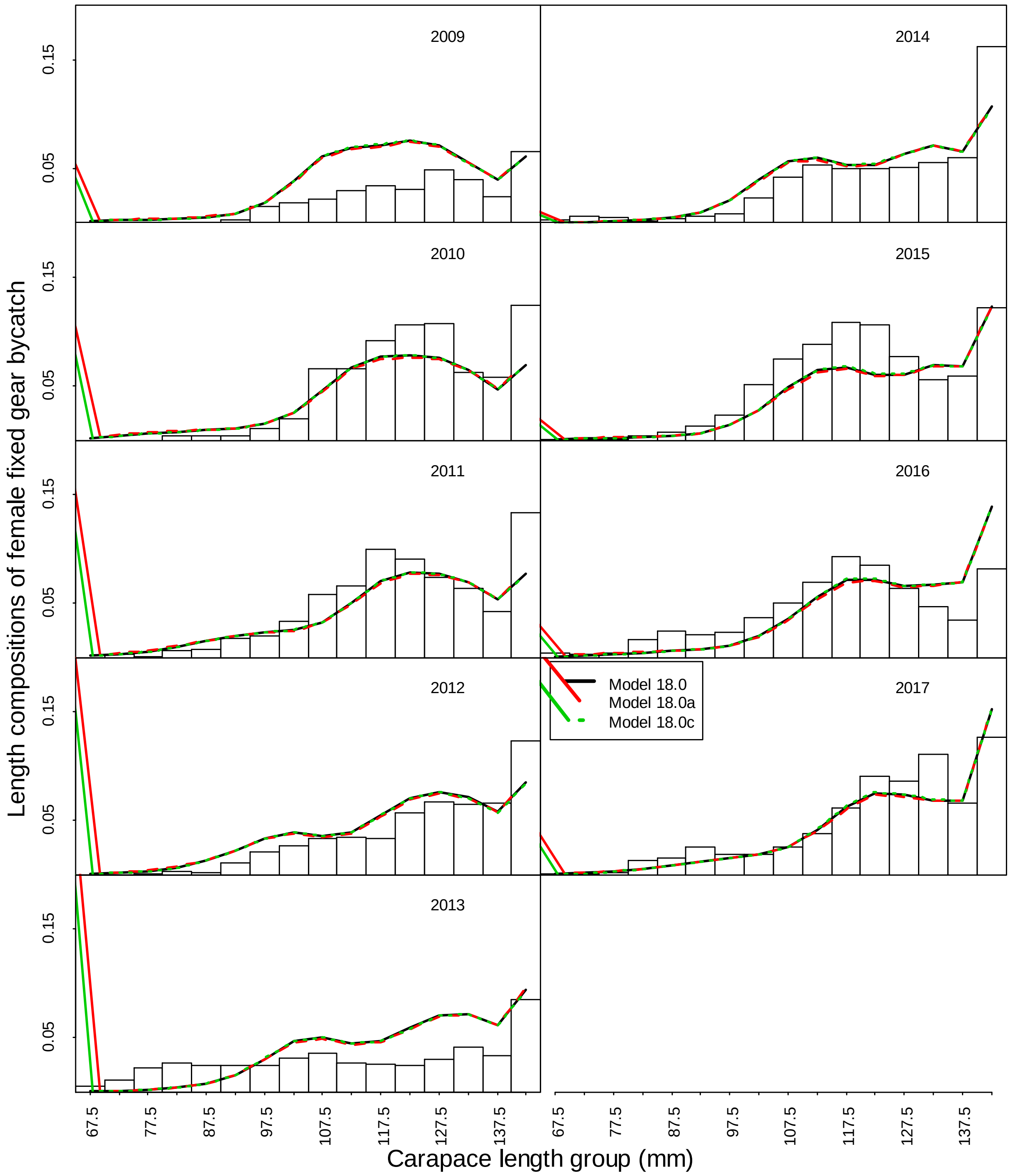


Figure 24(18.0, 18.0a & 18.0c). Comparison of observer and model estimated discarded length frequencies of Bristol Bay female red king crab by year in the groundfish fixed gear fisheries under scenarios 18.0 (solid black), 18.0a (dashed red), and 18.0c (green lines). Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively.

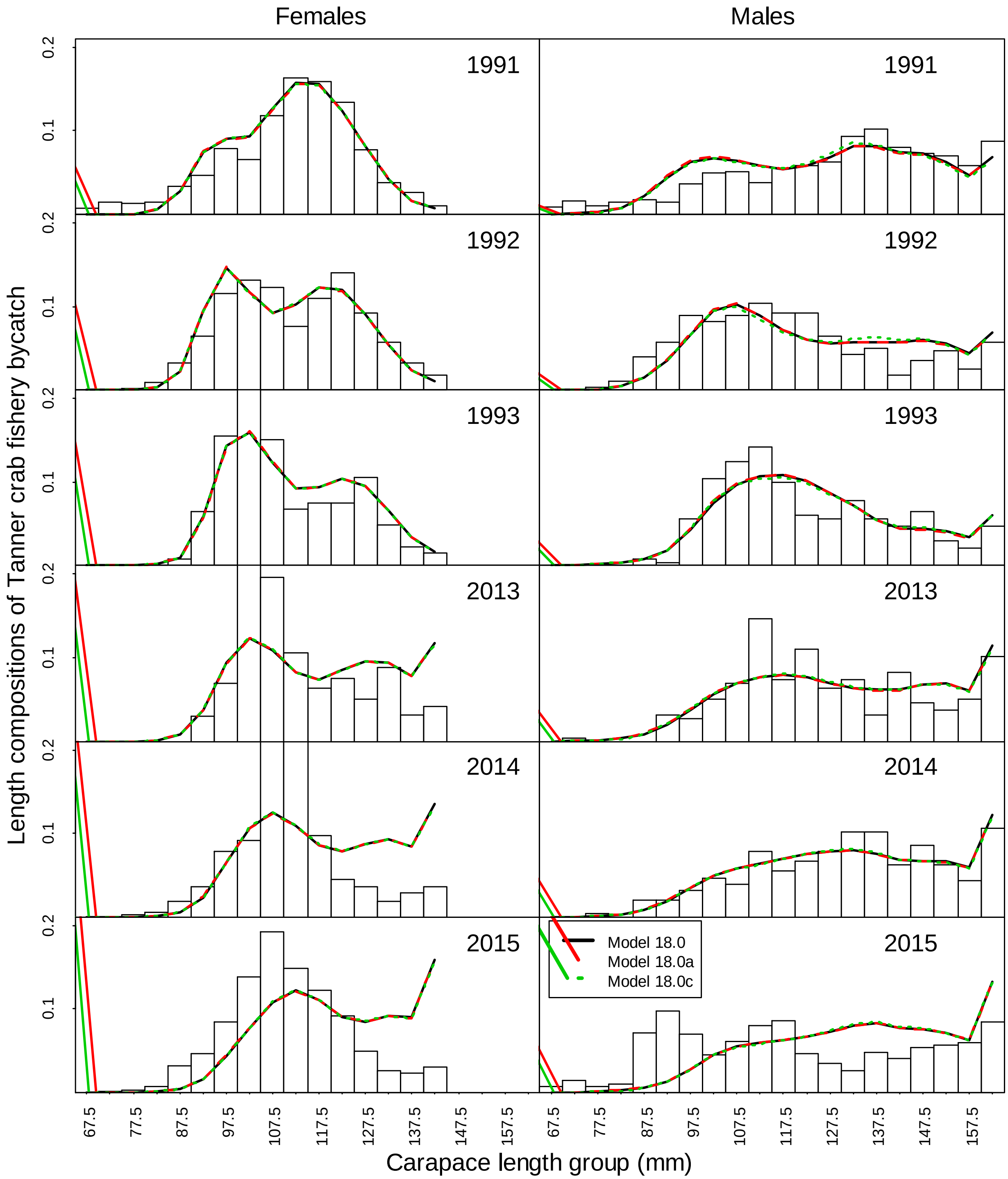


Figure 24(18.0, 18.0a & 18.0c). Comparison of observer and model estimated discarded length frequencies of Bristol Bay red king crab by year in the Tanner crab fishery under scenarios 18.0(solid black), 18.0a (dashed red), and 18.0c (green lines). Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively.

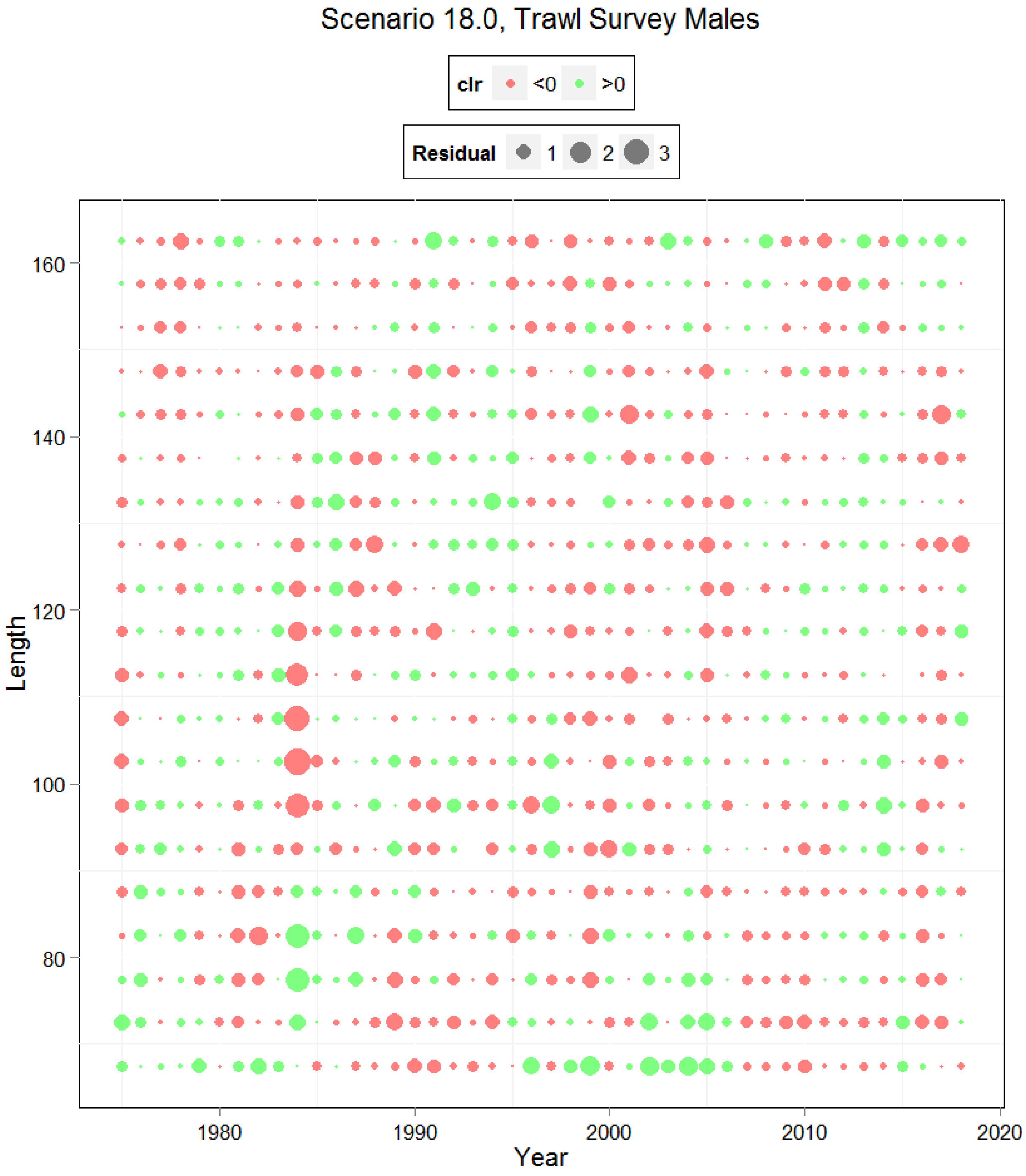


Figure 25(18.0). Standardized residuals of proportions of survey male red king crab by year and carapace length (mm) under scenario 18.0. Green circles are positive residuals, and red circles are negative residuals. Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively.

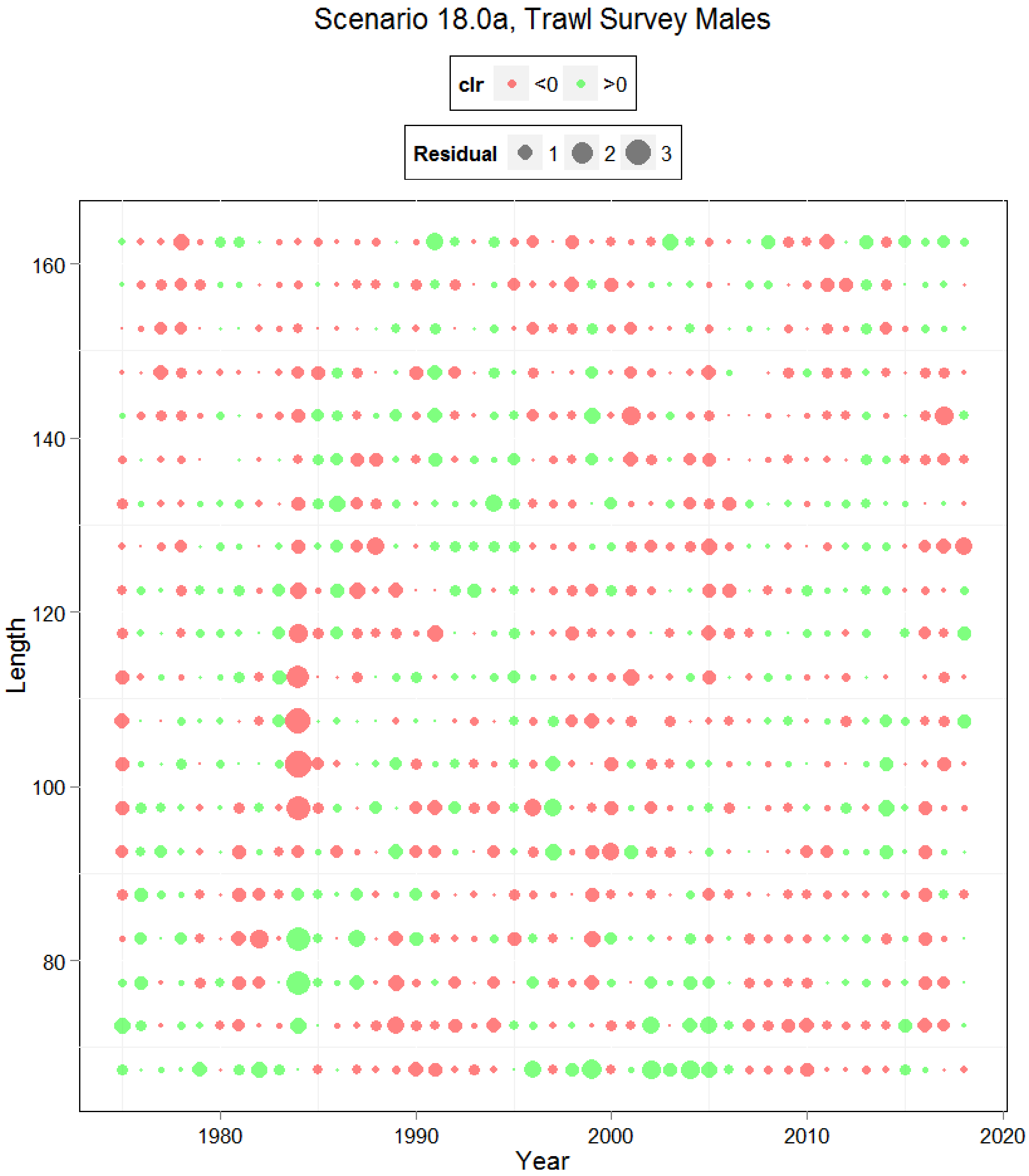


Figure 25(18.0a). Standardized residuals of proportions of survey male red king crab by year and carapace length (mm) under scenario 18.0a. Green circles are positive residuals, and red circles are negative residuals. Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively.

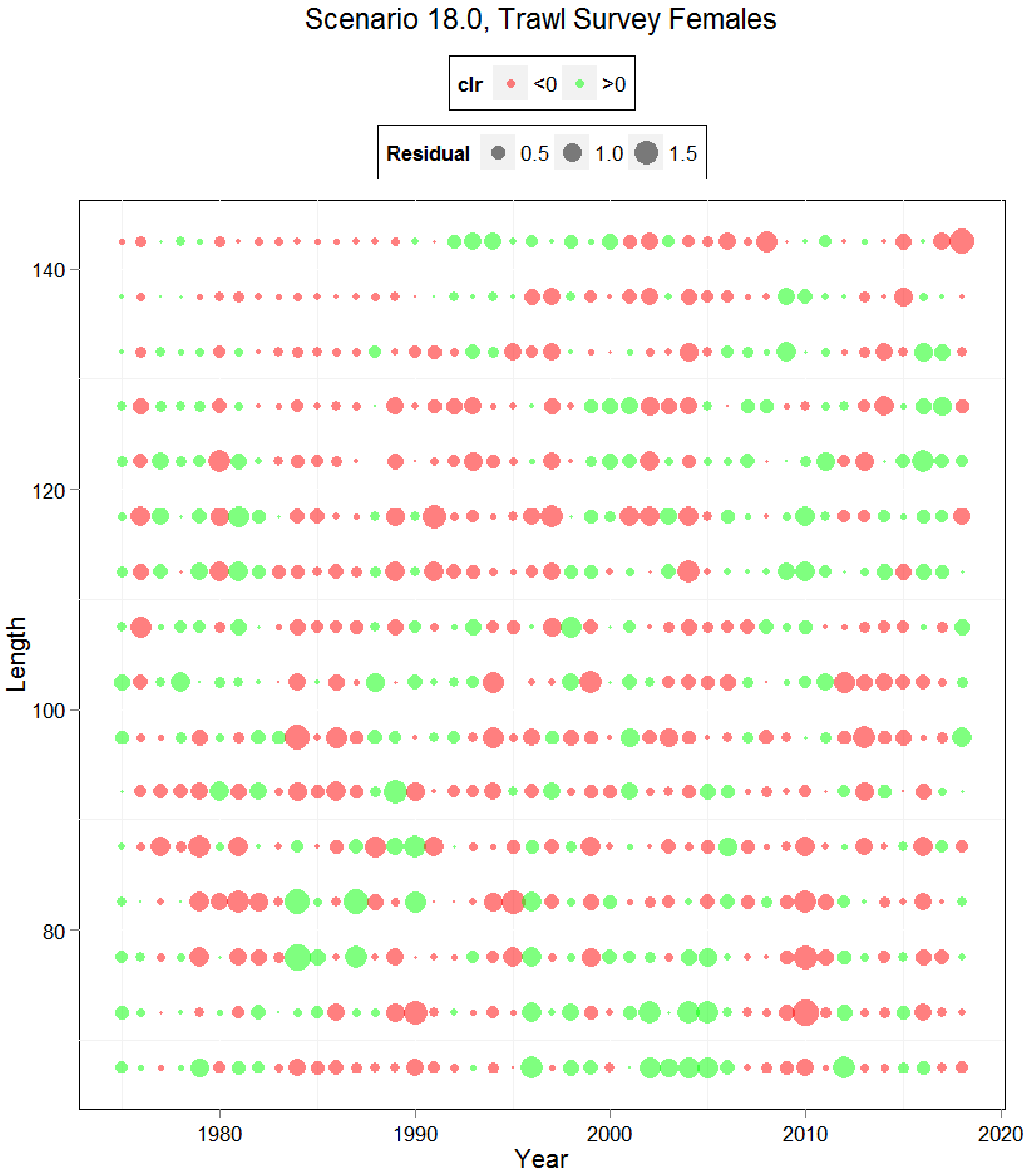


Figure 25(18.0). Standardized residuals of proportions of survey female red king crab by year and carapace length (mm) under scenario 18.0. Green circles are positive residuals, and red circles are negative residuals. Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively.

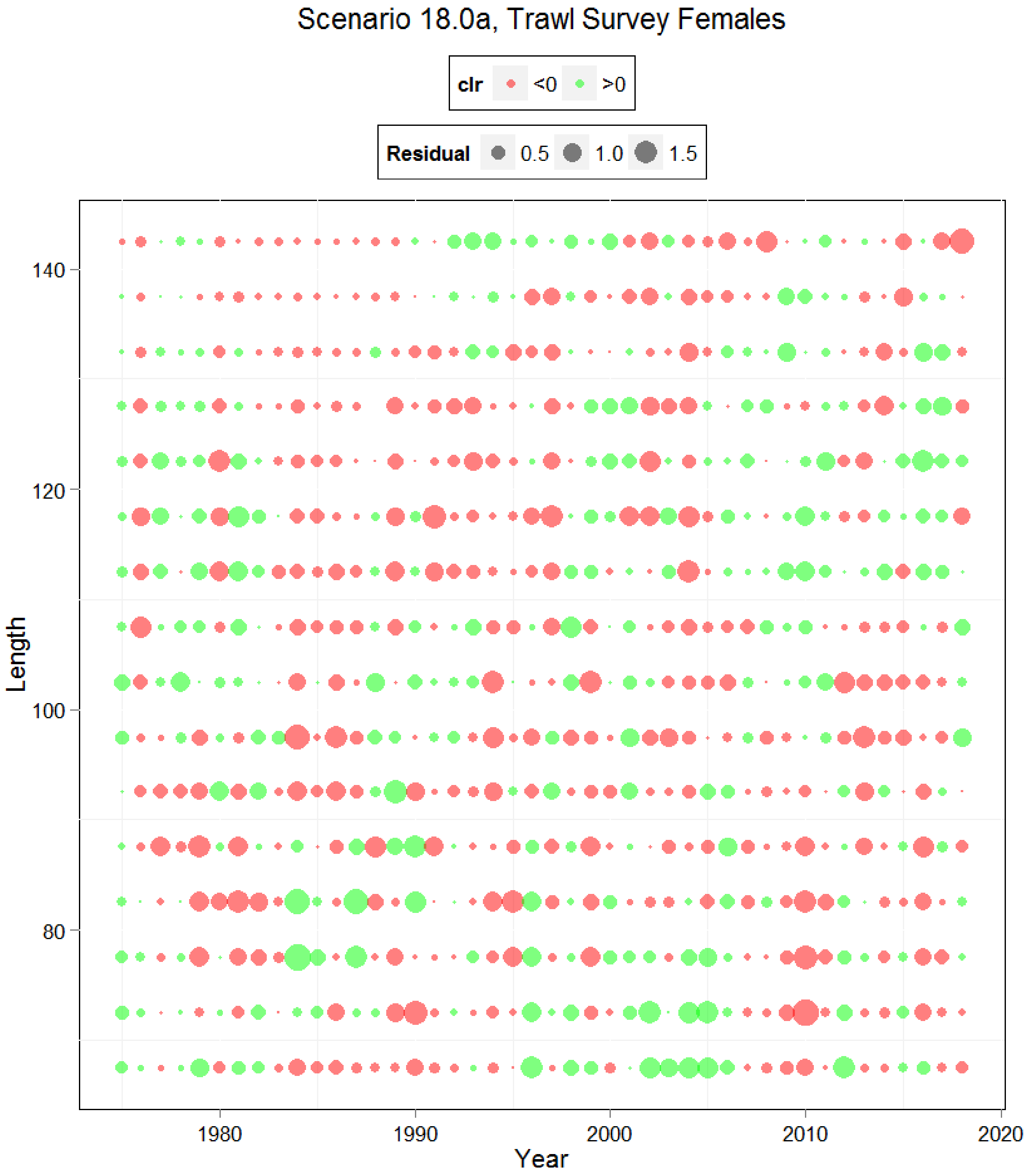


Figure 25(18.0a). Standardized residuals of proportions of survey female red king crab by year and carapace length (mm) under scenario 18.0a. Green circles are positive residuals, and red circles are negative residuals. Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively.

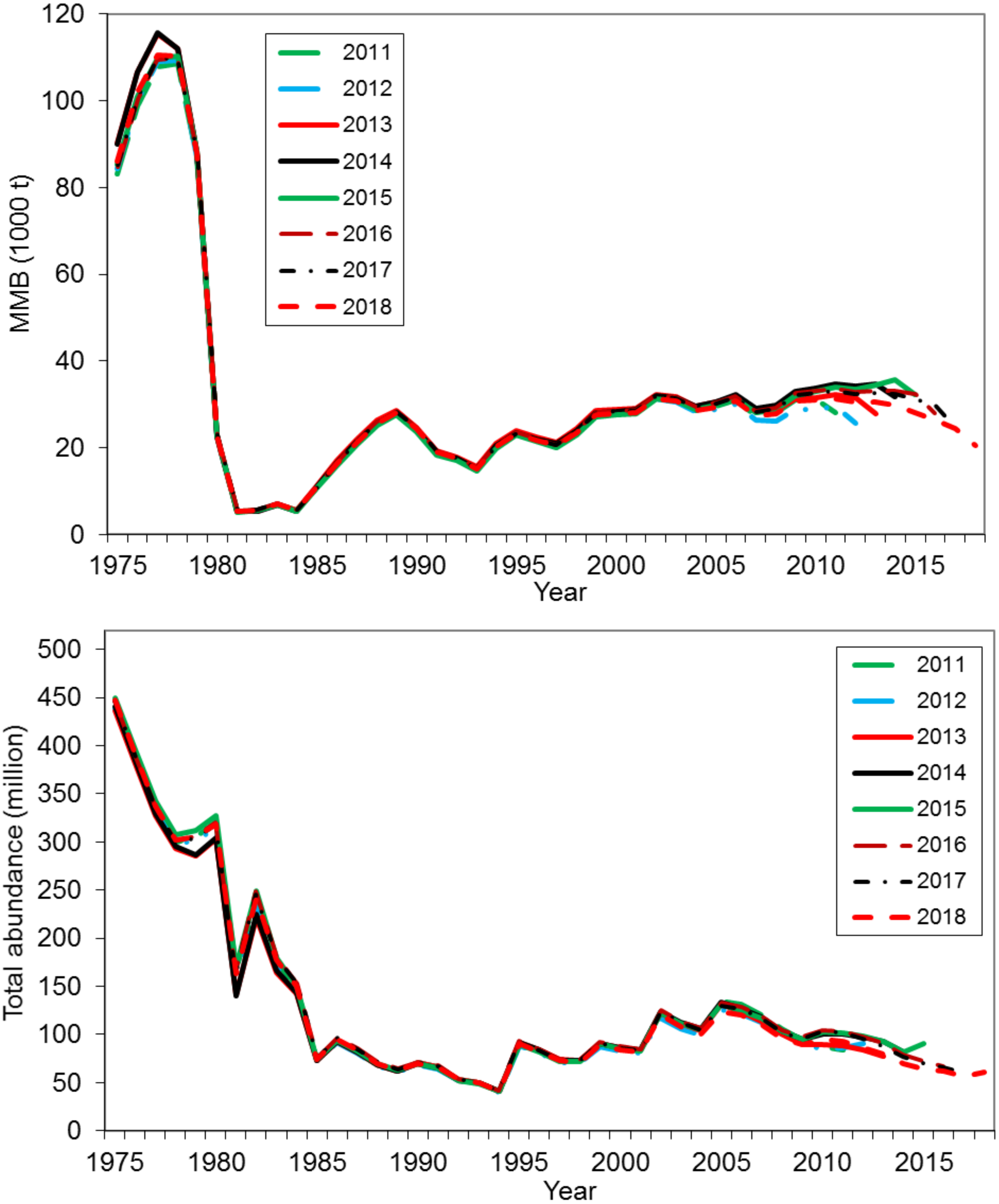


Figure 27. Comparison of hindcast estimates of mature male biomass on Feb. 15 (top) and total abundance (bottom) of Bristol Bay red king crab from 1975 to 2018 made with terminal years 2012-2018 with scenario 18.0. These are results of the 2018 model. Legend shows the terminal year. Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively.

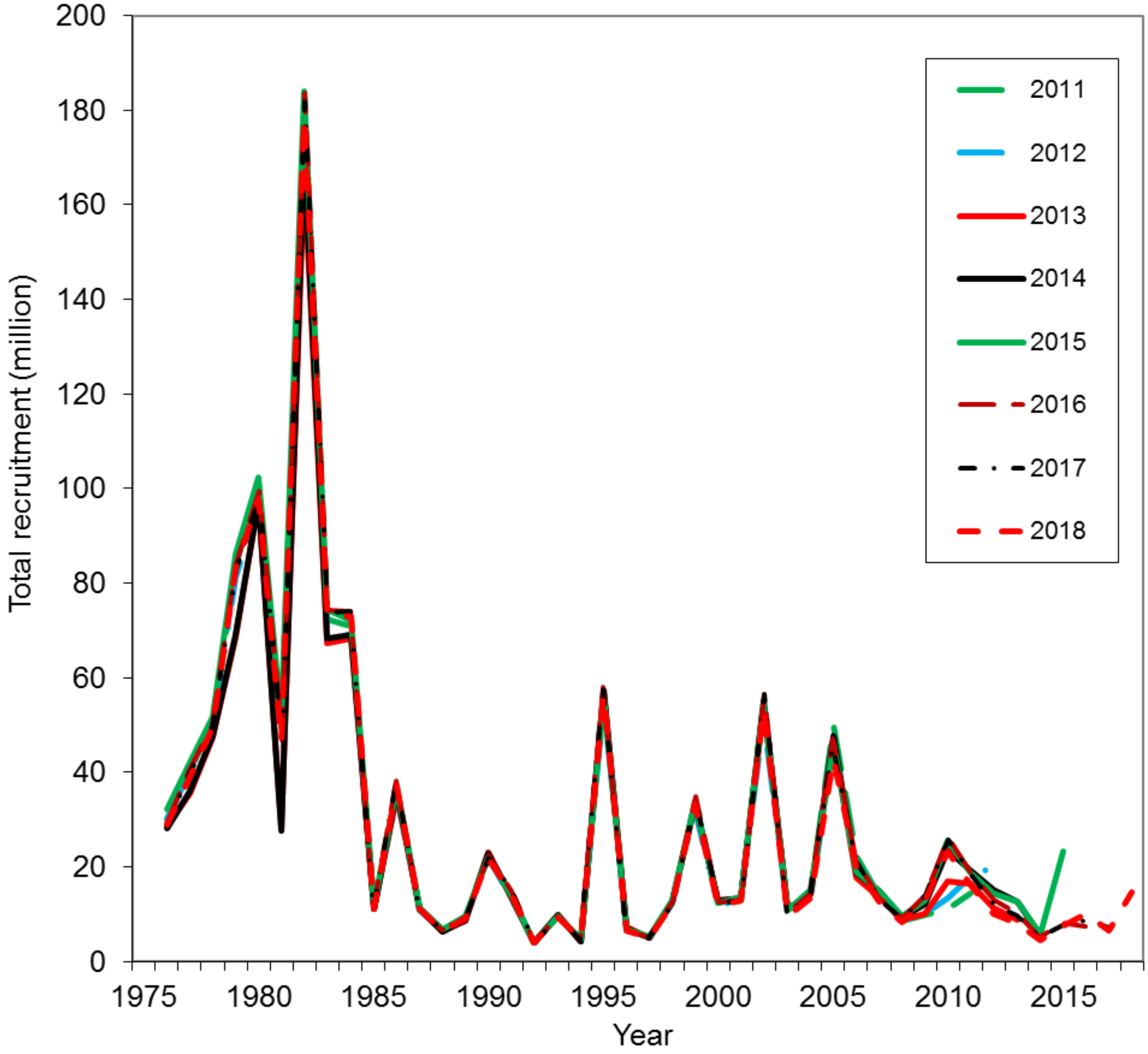


Figure 28a. Comparison of hindcast estimates of total recruitment for scenario 18.0 of Bristol Bay red king crab from 1976 to 2018 made with terminal years 2012-2018. These are results of the 2018 model. Legend shows the terminal year. Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively.

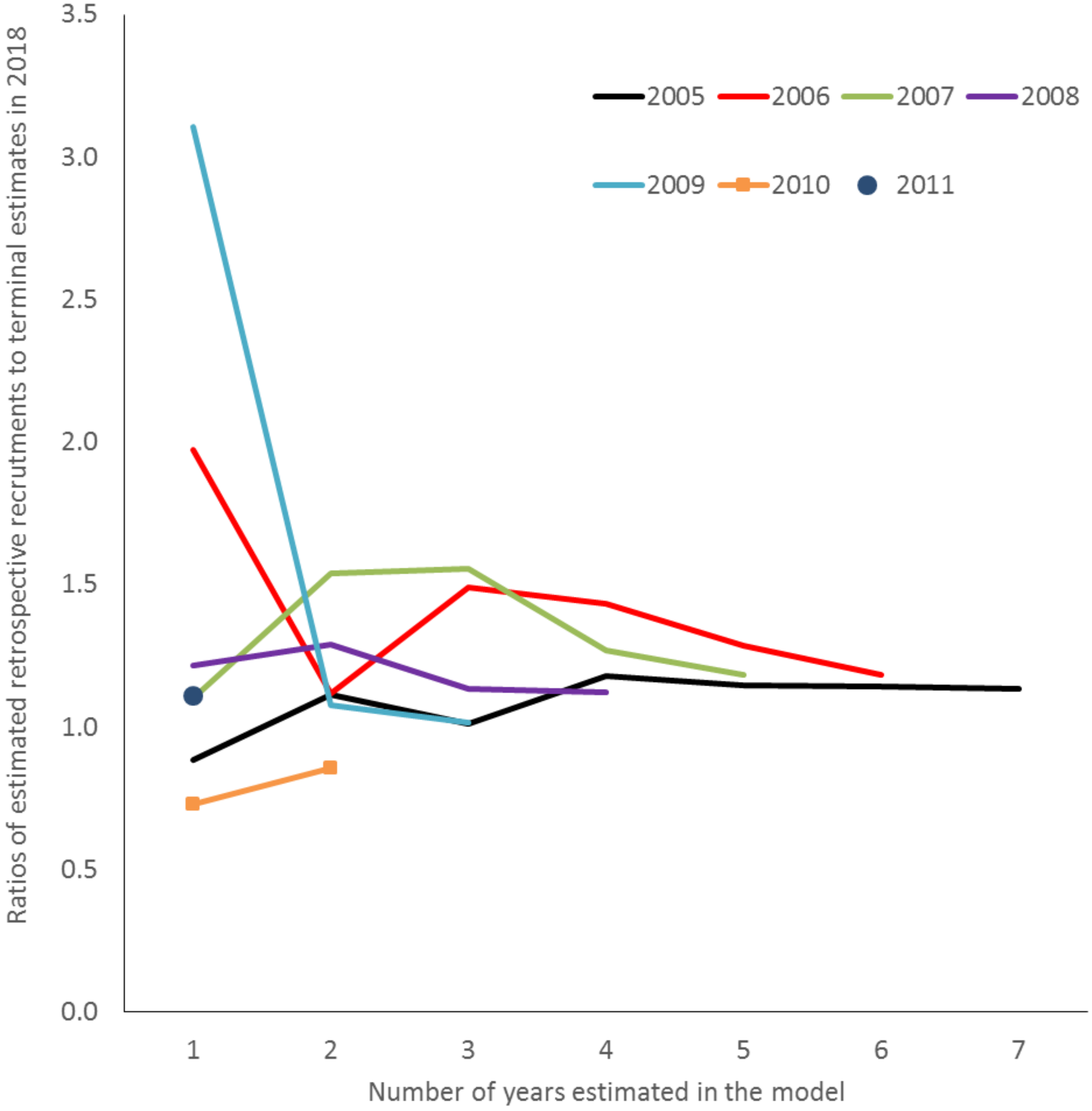


Figure 28b. Evaluation of Bristol Bay red king crab retrospective errors on recruitment estimates as a function of the number of years in the model for scenario 18.0.

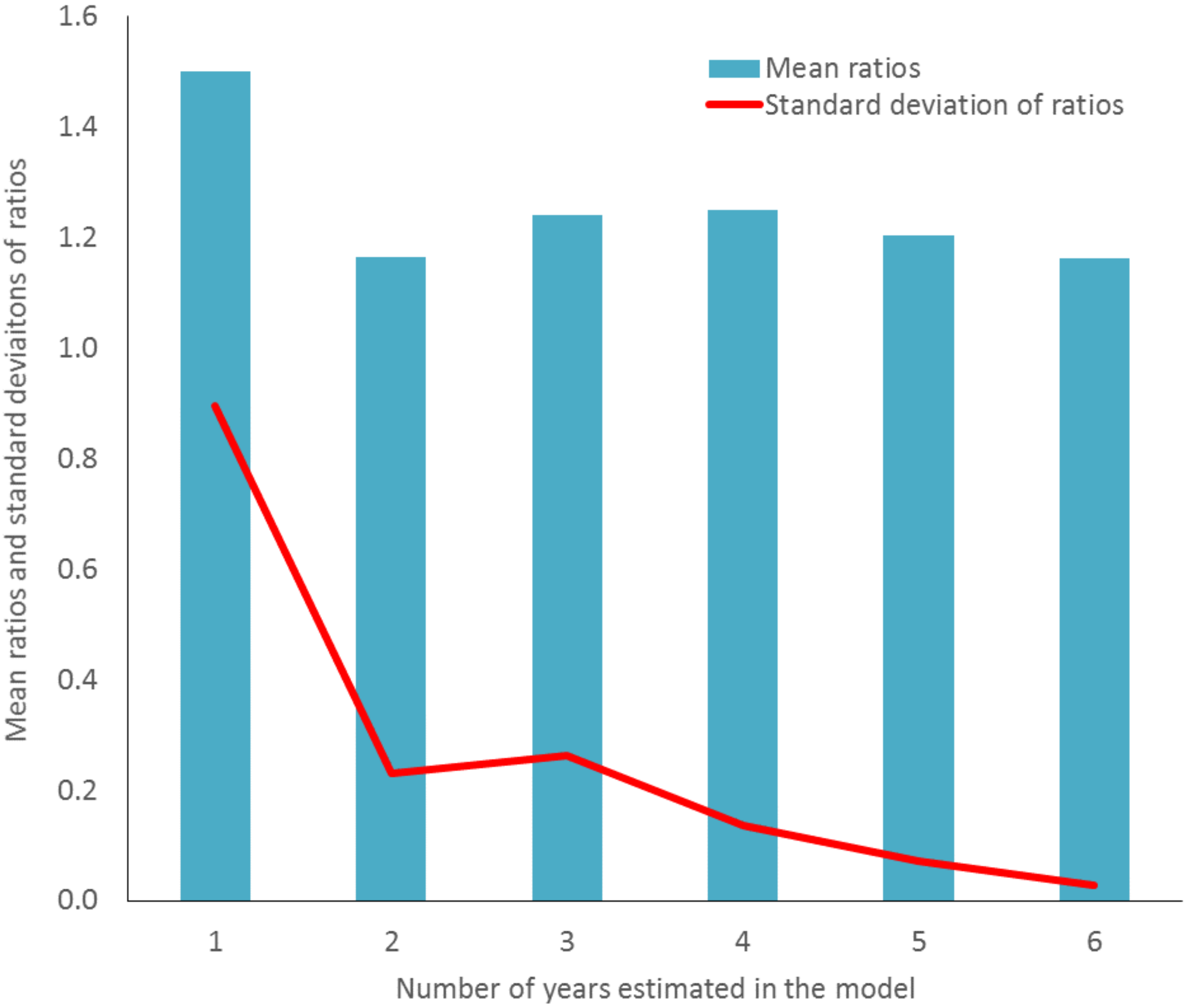


Figure 28c. Mean ratios of retrospective estimates of recruitments to those estimated in the most recent year (2018) and standard deviations of the ratios as a function of the number of years in the model for scenario 18.0.

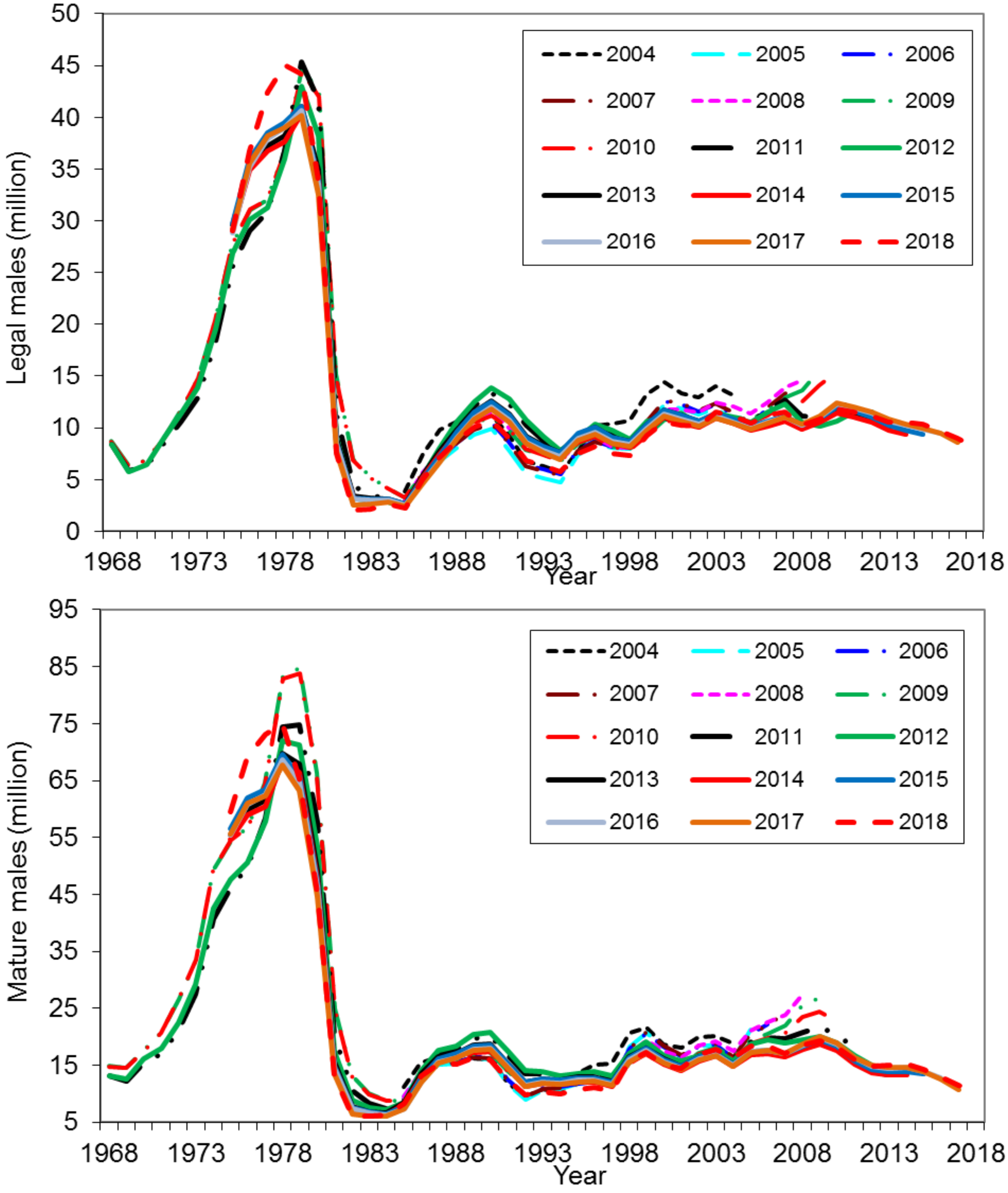


Figure 29. Comparison of estimates of legal male abundance (top) and mature males (bottom) of Bristol Bay red king crab from 1968 to 2018 made with terminal years 2004-2018 with the base scenarios. Scenario 18.0 is used for 2018. These are results of historical assessments. Legend shows the year in which the assessment was conducted. Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively.

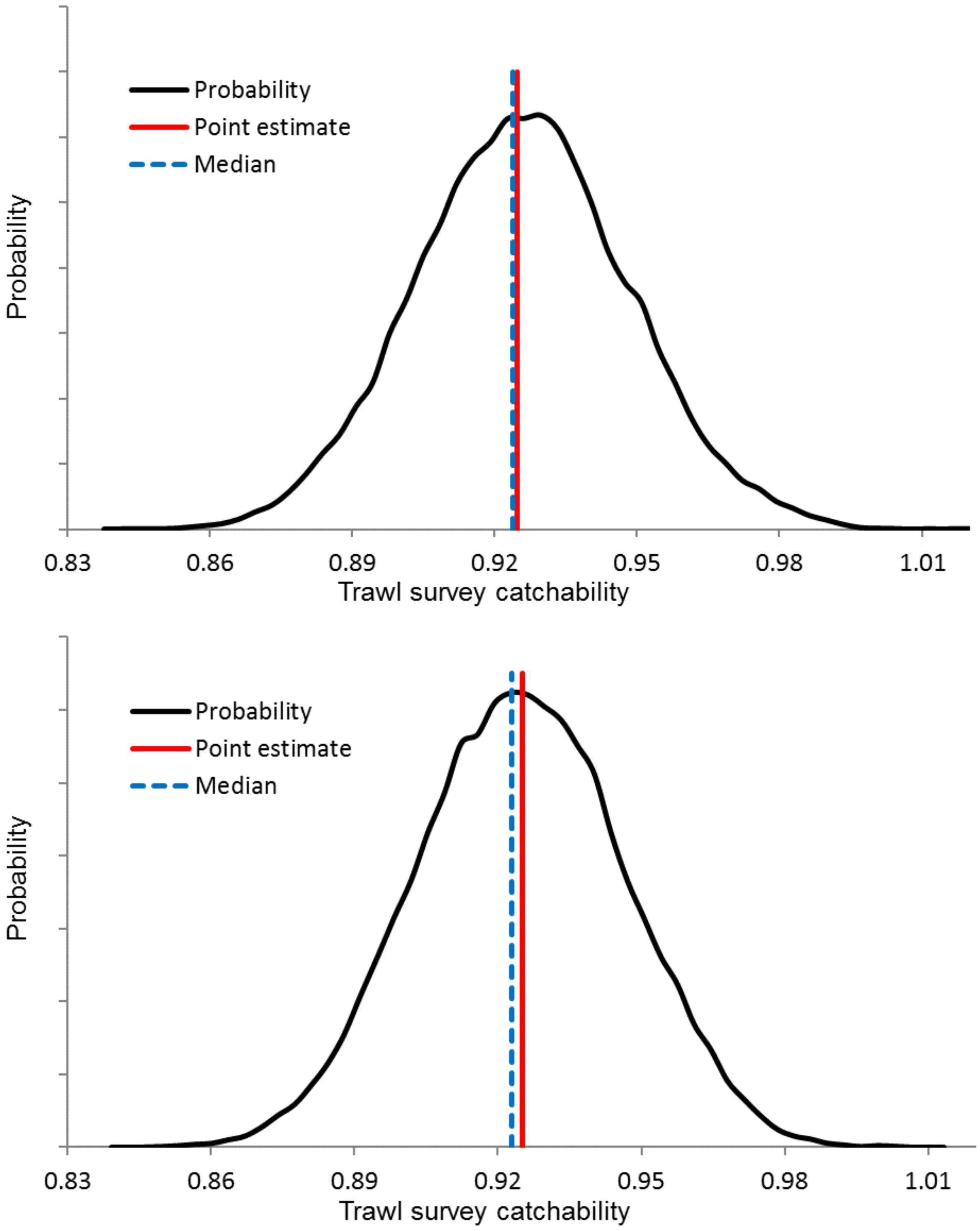


Figure 30. Probability distributions of estimated trawl survey catchability (*Q*) under scenario 18.0 (upper panel) and 18.0a (lower panel) with the mcmc approach. Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively.

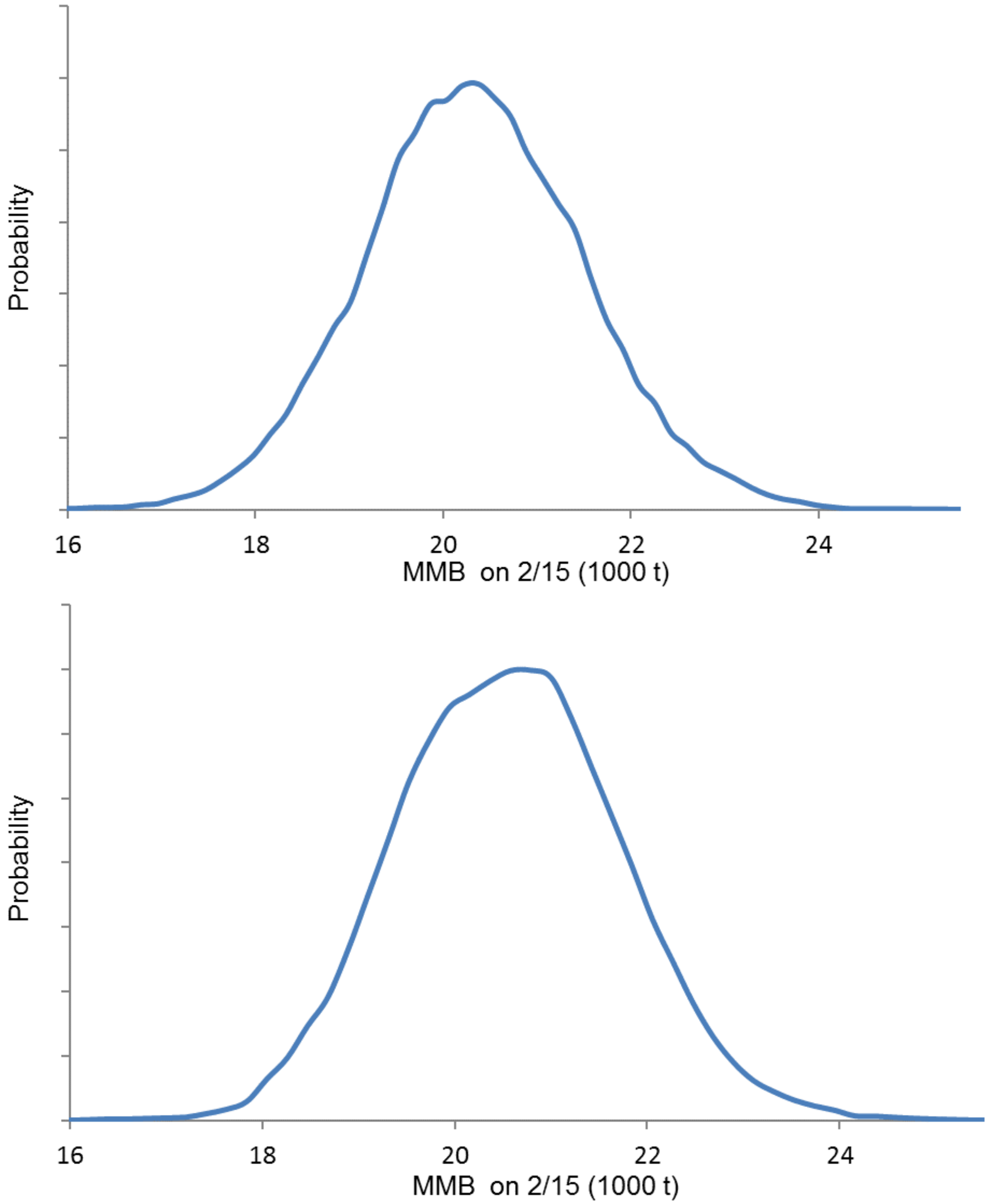


Figure 31a(18.0 & 18.0a). Probability distributions of estimated mature male biomass on Feb. 15, 2018 with $F_{35\%}$ under scenarios 18.0 (upper panel) and 18.0a (lower panel) with the mcmc approach. Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively.

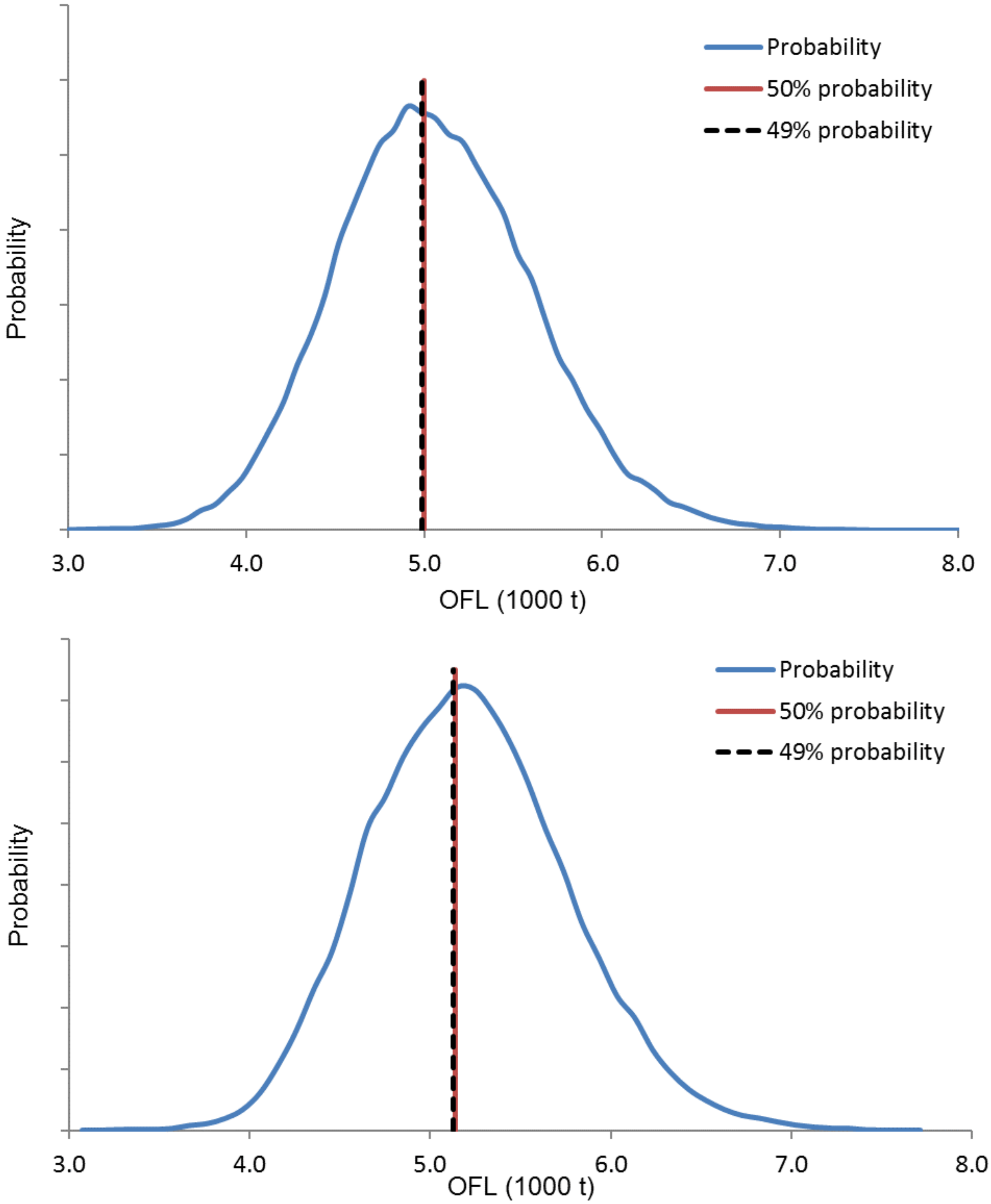


Figure 31b(18.0 & 18.0a). Probability distributions of the 2018 estimated OFL with scenarios 18.0 (upper panel) and 18.0a (lower panel) with the mcmc approach. Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively.

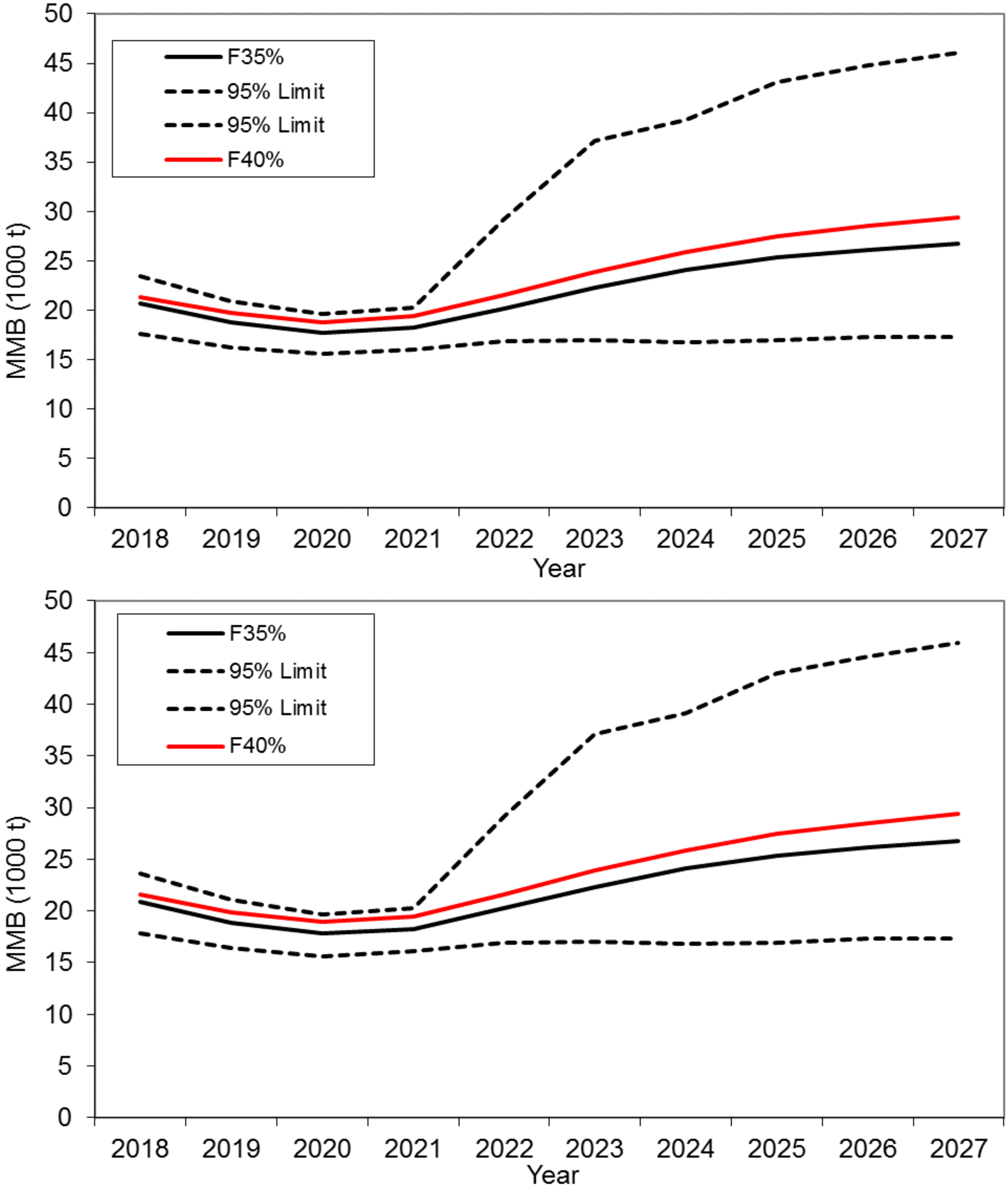


Figure 32(18.0 & 18.0a). Projected mature male biomass on Feb. 15 with $F_{40\%}$ and $F_{35\%}$ harvest strategy during 2018-2027. Input parameter estimates are based on scenarios 18.0 (upper panel) and 18.0a (lower panel). Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively, and the confidence limits are for the $F_{35\%}$ harvest strategy.

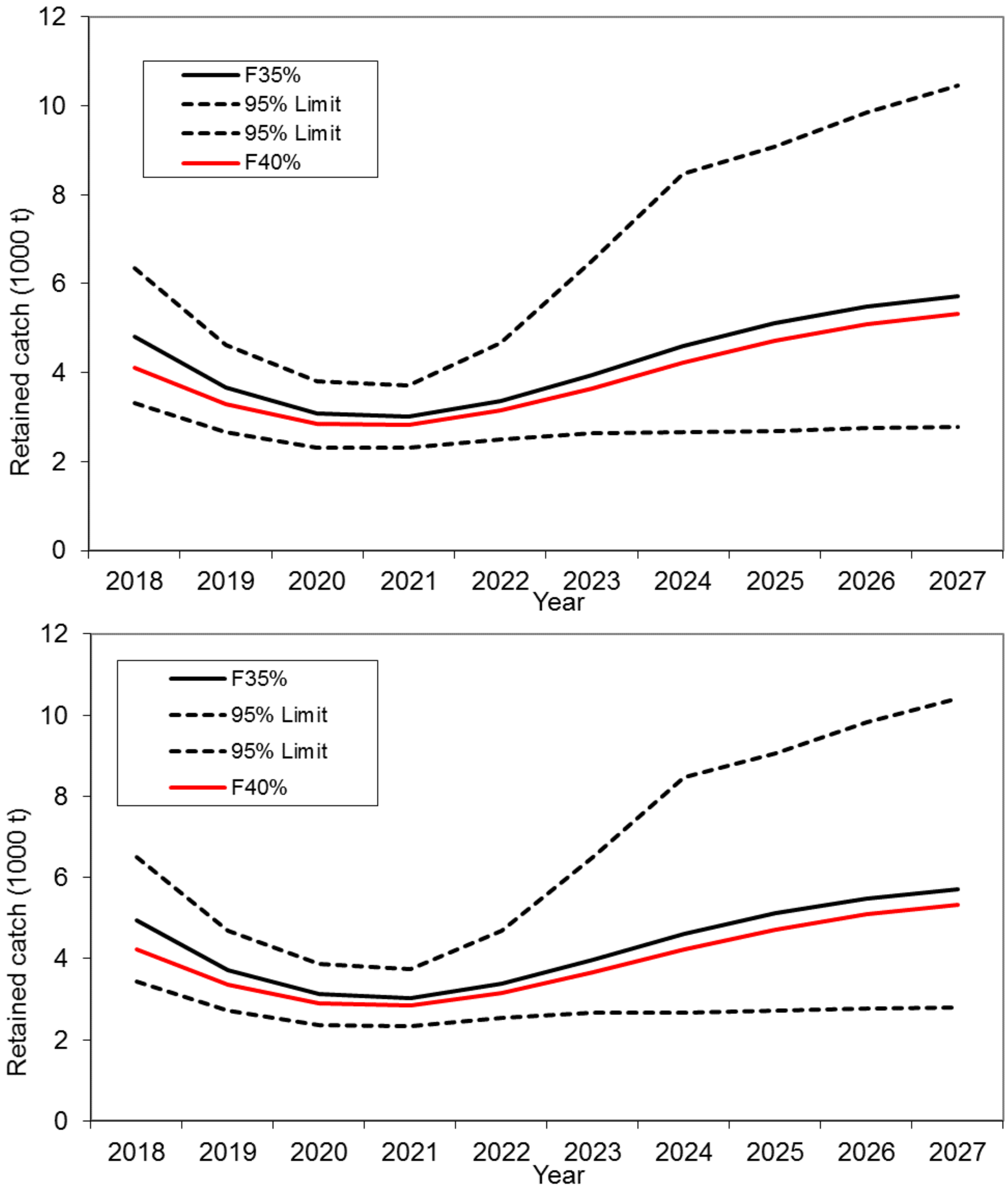


Figure 33(18.0 & 18.0a). Projected retained catch biomass with $F_{40\%}$ and $F_{35\%}$ harvest strategy during 2018-2127. Input parameter estimates are based on scenarios 18.0 (upper panel) and 18.0a (lower panel). Pot, Tanner crab, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.25, 0.5 and 0.8, respectively, and the confidence limits are for the $F_{35\%}$ harvest strategy.

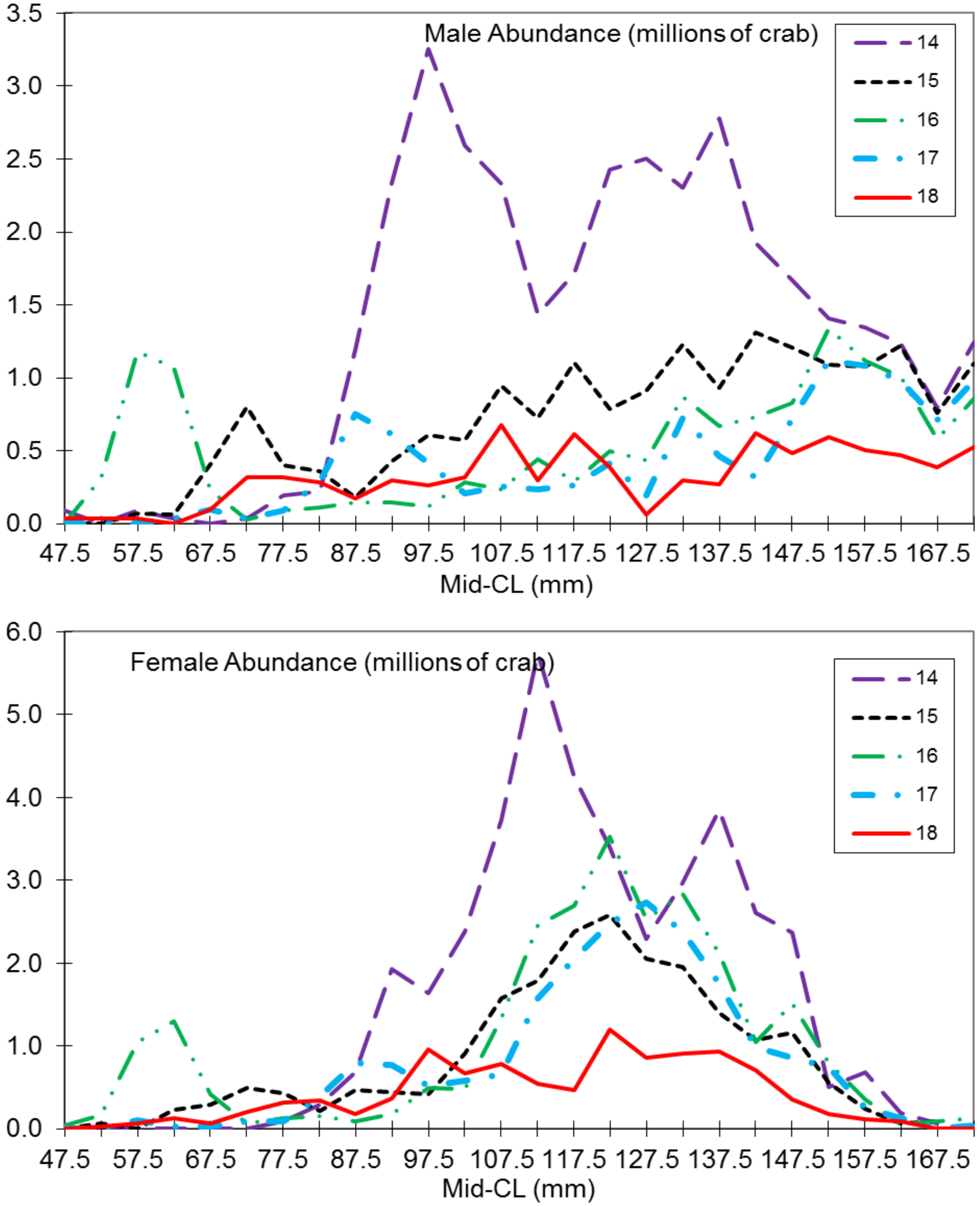


Figure 34. Length frequency distributions of male (top panel) and female (bottom panel) red king crab in Bristol Bay from NMFS trawl surveys during 2014-2018. For purposes of these graphs, abundance estimates are based on area-swept methods.

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:

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

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, $T^s_{l,t}$ the discarded catch of animals of sex *s* in length-class *l* during year *t* in the Tanner crab fishery and the groundfish fisheries, y_t the time in years between survey and the directed pot fishery during year *t*, and j_t the time in years between survey and the Tanner and groundfish fisheries 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.:

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

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; 1994-2017) 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.:

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

where β, 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.

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. All bycatches are death catches because the model fits the estimated observed death bycatches.

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

$$G_{l,t}^s = (N_{l,t}^s + O_{l,t}^s) e^{-y_t M_t^s} (1 - e^{-F_{l,t}^s}) \qquad \text{(A4)}$$

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

$$F_{l,t}^{s}=\begin{cases}[(S_l^{dir,land}(1+h_t\phi)+S_l^{dir,disc,mal}]\,F_t^{dir} & \text{if } s=\text{mal}\\ S_l^{dir,disc,\,fem}\;F_t^{disc,\,fem} & \text{if } s=\text{fem}\end{cases}\qquad \text{(A5)}$$

$$F_{l,t}^{s}=\begin{cases}\left[S_l^{dir,land}(1+h_t\emptyset)+S_l^{dir,disc,mal}\right]F_t^{dir} & if\ s=mal\ and\ scen.2b\\ \left[S_l^{tot,mal}S_{l,t}^{ret}+S_l^{tot,mal}\left(1-S_{l,t}^{ret}\right)\emptyset\right]F_t^{dir} & if\ s\ is\ male\ and\ other\ scen.\\ S_l^{dir,disc,fem}F_t^{disc,fem} & if\ s=fem\end{cases}\qquad \text{(A5)}$$

where $S_l^{\text{dir,land}}$ is the selectivity pattern for the landings by the directed fishery, $S_l^{\text{dir,disc},s}$ the selectivity pattern for the discards in the directed fishery by sex, $S_l^{tot,mal}$ the total male selectivity in the directed fishery, $S_{l,t}^{ret}$ the retained proportions of males in the directed fishery, F_t^{dir} the fully-selected fishing mortality during year *t* (on males), $F_t^{disc,fem}$ the fully-selected fishing mortality on female animals during year *t* related to discards in the directed 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 2005-2016).

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 fishery are:

$$\begin{aligned}C_{l,t}^{\text{mal}}&=(N_{l,t}^{\text{mal}}+O_{l,t}^{\text{mal}})e^{-y_tM_t^{\text{mal}}}(1-e^{-S_l^{\text{dir,land}}F_t^{\text{dir}}})\\ D_{l,t}^{\text{mal}}&=G_{l,t}^{\text{mal}}-C_{l,t}^{\text{mal}}\end{aligned}\qquad \text{(A6)}$$

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

$$T_{l,t}^{s}=(N_{l,t}^{s}+O_{l,t}^{s})e^{-j_tM_t^s}\;e^{-F_{l,t}^{s}}\;(1-e^{-\tilde{F}_{l,t}^{s}})\qquad \text{(A7)}$$

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 and groundfish fisheries:

$$\tilde{F}_{l,t}^{s}=S_l^{Tanner,s}\,F_t^{Tanner,s}+S_l^{trawl}\,F_t^{trawl}+S_l^{fix}\,F_t^{fix}\qquad \text{(A8)}$$

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

The bycatches by sex are estimated from the Tanner crab fishery, $TC^s_{l,t}$, groundfish trawl fishery, $GT^s_{l,t}$, and groundfish fixed gear fishery, $GF^s_{l,t}$, as follow:

$$
\begin{aligned}
TC^s_{l,t} &= (N^s_{l,t} + O^s_{l,t}) e^{-j_t M^s_t}\, e^{-F^s_{l,t}} (1 - e^{-\tilde{F}^s_{l,t}})\, S_l^{Tanner,s}\, F_t^{Tanner,s} / \tilde{F}^s_{l,t} \\
GT^s_{l,t} &= (N^s_{l,t} + O^s_{l,t}) e^{-j_t M^s_t}\, e^{-F^s_{l,t}} (1 - e^{-\tilde{F}^s_{l,t}})\, S_l^{trawl}\, F_t^{trawl} / \tilde{F}^s_{l,t} \qquad \text{(A9)} \\
GF^s_{l,t} &= (N^s_{l,t} + O^s_{l,t}) e^{-j_t M^s_t}\, e^{-F^s_{l,t}} (1 - e^{-\tilde{F}^s_{l,t}})\, S_l^{fixed}\, F_t^{fixed} / \tilde{F}^s_{l,t}
\end{aligned}
$$

For scenarios separating mature and immature crab, discarded female bycatch in numbers is separated into immature and mature bycatches. The female bycatches in the directed fishery in length-class *l* and during year *t*, $D^i_{l,t}$ and $D^m_{l,t}$, and $T^i_{l,t}$ and $T^m_{l,t}$, are:

$$
\begin{aligned}
D^i_{l,t} &= N^i_{l,t}\, e^{-y_t M_t^{fem}} (1 - e^{-F^{fem}_{l,t}}) \\
D^m_{l,t} &= N^m_{l,t}\, e^{-y_t M_t^{fem}} (1 - e^{-F^{fem}_{l,t}})
\end{aligned}
\qquad \text{(A10)}
$$

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

$$
\begin{aligned}
T^i_{l,t} &= N^i_{l,t}\, e^{-j_t M_t^{fem}} e^{-F^{fem}_{l,t}} (1 - e^{-\tilde{F}^{fem}_{l,t}}) \\
T^m_{l,t} &= N^m_{l,t}\, e^{-j_t M_t^{fem}} e^{-F^{fem}_{l,t}} (1 - e^{-\tilde{F}^{fem}_{l,t}})
\end{aligned}
\qquad \text{(A11)}
$$

Retained selectivity, $S^{\text{dir,land}}$, selectivity for females in the directed fishery, $S^{\text{dir,disc,fem}}$, total male selectivity, $S_l^{tot,mal}$, retained proportions, $S_{l,t}^{ret}$, selectivities for males and females in the groundfish trawl and fixed gear fisheries, S^{trawl} and S^{fix}, and selectivity for males and females in the Tanner crab fishery, $S^{\text{Tanner,s}}$, are all assumed to be logistic functions of length:

$$
S_l^{type} = \frac{1}{1 + e^{-\beta^{type}\,(\iota - L_{50}^{type})}} \qquad \text{(A12)}
$$

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.

For scenario 2b, male pot bycatch selectivity in the directed fishery is modeled by two linear functions:

$$
\begin{aligned}
s_l &= \varphi + \kappa\,\iota, \quad if\ \ \iota < 135 \text{ mm CL}, \\
s_l &= s_{l-1} + 5\gamma, \quad if\ \ \iota > 134 \text{ mm CL}
\end{aligned}
\qquad \text{(A13)}
$$

where φ, κ, γ are parameters.

iii. Trawl Survey Selectivities

Trawl survey selectivities are estimated as

$$S_{l,t}^{s} = \frac{Q}{1 + e^{-\beta_t^s \; (l - L_{50,t}^{s})}} \qquad \text{(A14)}$$

with different sets of parameters (*β*, *L₅₀*) estimated for males and females as well as two different periods (1975-81 and 1982-17). 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 selectivity consists of capture probability and crab availability.

iv. *Estimating Bycatch Fishing Mortalities for Years without Observer Data*

Observer data are not available for the directed pot fishery before 1990 and the Tanner crab fishery before 1991. There are also extremely low observed bycatches in the Tanner crab fishery during 1994 and 2006-2009. Bycatch fishing mortalities for male and females during 1975-1989 in the directed pot fishery were estimated as

$$F_t^{disc,s} = r^s \; F_t^{dir} \qquad \text{(A15)}$$

where r^s is the median ratio of estimated bycatch discard fishing mortalities to the estimated directed pot fishing mortalities during 1990-2004 for sex *s*. Directed pot fishing practice has changed after 2004 due to fishery rationalization.

We used pot fishing effort (potlifts) east of 163^o W in the Tanner crab fishery to estimate red king crab bycatch discard fishing mortalities in that fishery when observer data are not available (1975-1990, 1994, 2006-2009):

$$F_t^{Tanner,s} = a^s \; E_t \qquad \text{(A16)}$$

where a^s is the mean ratio of estimated Tanner crab fishery bycatch fishing mortalities to fishing efforts during 1991-1993 for sex s, and E_t is Tanner crab fishery fishing efforts east of 163^o W in year *t*. Due to fishery rationalization after 2004, we used the data only during 1991-1993 to estimate the ratio.

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 :

$$Rf = \prod_{l=1}^{L}\prod_{t=1}^{T}\prod_{s=1}^{2}\prod_{sh=1}^{2}\frac{\left\{\exp\left[-\frac{(p_{l,t,s,sh}-\hat{p}_{l,t,s,sh})^2}{2\sigma^2}\right]+0.01\right\}}{\sqrt{2\pi\sigma^2}} \qquad \text{(A17)}$$

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

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:

$$\begin{aligned}
&\textit{Length compositions}: \quad -\sum \ln(Rf_i)\\
&\textit{Biomasses other than survey}: \quad \lambda_j \sum \left[\ln(C_t/\hat{C}_t)^2\right]\\
&\textit{NMFS survey biomass}: \quad \sum \left[\ln(B_t/\hat{B}_t)^2/(2\ln(CV_t^2+1))\right]\\
&\textit{BSFRF mature males}: \quad \sum[\ln(\ln(CV_t^2+1))^{0.5}+\ln(B_t/\hat{B}_t)^2/(2\ln(CV_t^2+1))]\\
&\textit{R variation}: \quad \lambda_R \sum[\ln(R_t/\overline{R})^2]\\
&\textit{R sex ratio}: \quad \lambda_s[\ln(\overline{R}_M/\overline{R}_F)^2]\\
&\textit{Trawl bycatch fishing mortalities}: \lambda_t[\ln(F_{t,t}/\overline{F}_t)^2]\\
&\textit{Pot female bycatch fishing mortalities}: \lambda_p[\ln(F_{t,f}/\overline{F}_f)^2]\\
&\textit{Trawl survey catchability}: (Q-\hat{Q})^2/(2\sigma^2)
\end{aligned} \qquad \text{(A18)}$$

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, and 0.1 for trawl bycatch fishing mortality. These λ_j values correspond to CV values of 0.03, 0.07, 0.53, 0.23, 3.34, and 12.14, respectively, representing prior assumptions about the accuracy of the observed catch biomass data.

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, 0.1605 in 2014, 0.07 in 2015, 0.0826 in 2016, and 0.0749 in 2017, 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, 0.5 for the groundfish fixed gear fishery, and 0.8 for the groundfish trawl fishery.

(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.

(2). Length-weight Relationship

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

Immature Females: $W = 0.000408\ L^{3.127956}$

Ovigerous Females: $W = 0.003593\ L^{2.666076}$ (A19)

Males: $W = 0.0004031\ L^{3.141334}$

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 1994-2017, respectively, and the data presented in Gray (1963) were used to estimate those for mature females for scenarios 1, 1n and 2 (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 1994-2017, 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).

(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 1994-2017).

(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 Southeast 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 1980-1984 for males, 3 out of 5 years had low mature harvest rates. During the 1981-1984 decline 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^o 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^o 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 $0.18yr^{-1}$, 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 2018), 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 were estimated for the survey data from the Bering Fisheries Research Foundation. Annual fishing mortalities were also estimated for the directed pot fishery for males (1975-2017), pot-discarded females from the directed fishery (1990-2017), pot-discarded males and females from the eastern Bering Sea Tanner crab fishery (1991-93, 2013-15), and groundfish trawl discarded males and females (1976-2017). 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 entry of number of males in the 1st seven length classes (65- 99 mm CL) and new entry of number of females in the 1st five length classes (65-89 mm CL).

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

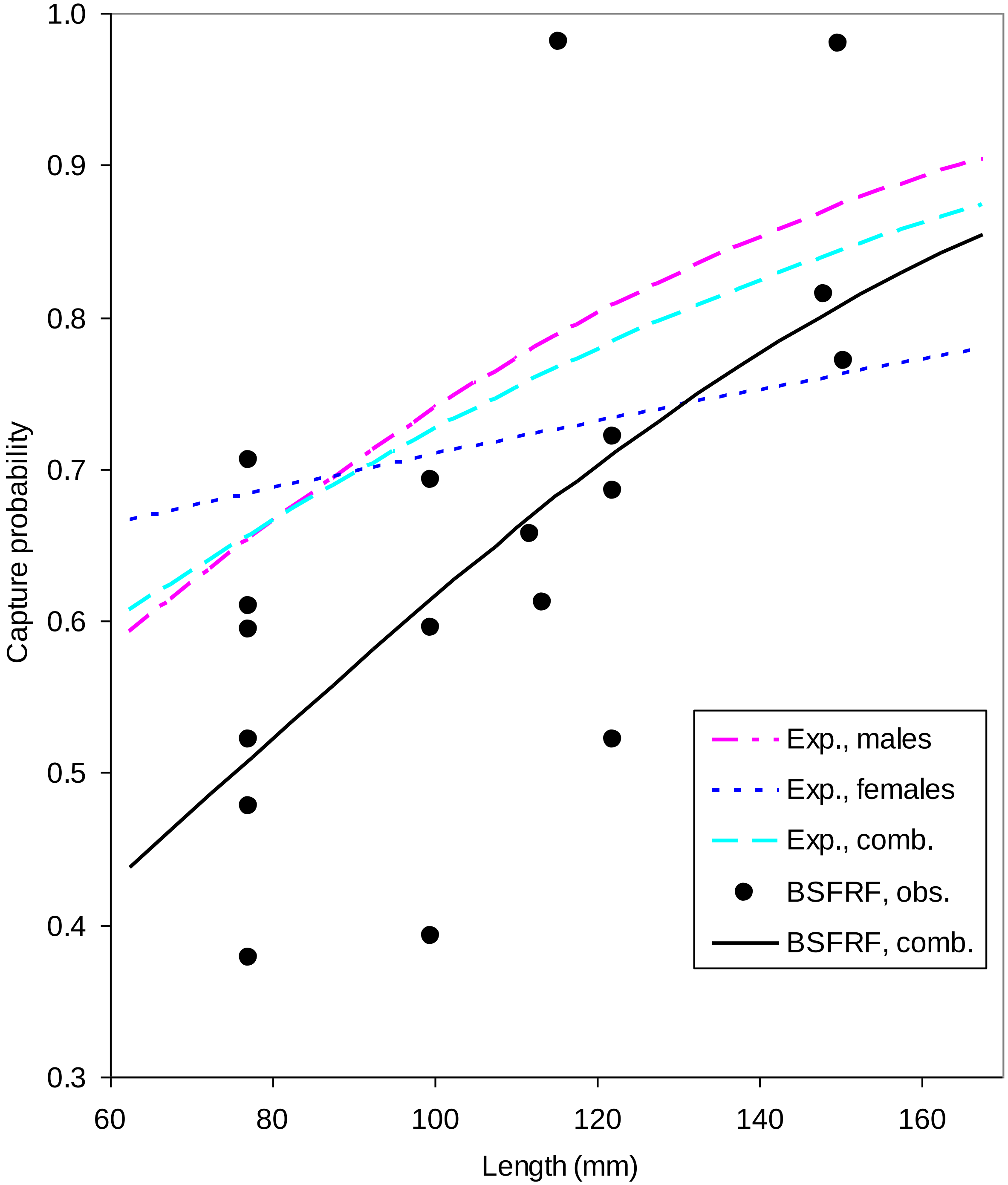


Figure A1. Estimated capture probabilities for NMFS Bristol Bay red king crab trawl surveys by Weinberg et al. (2004) and the Bering Sea Fisheries Research Foundation surveys.

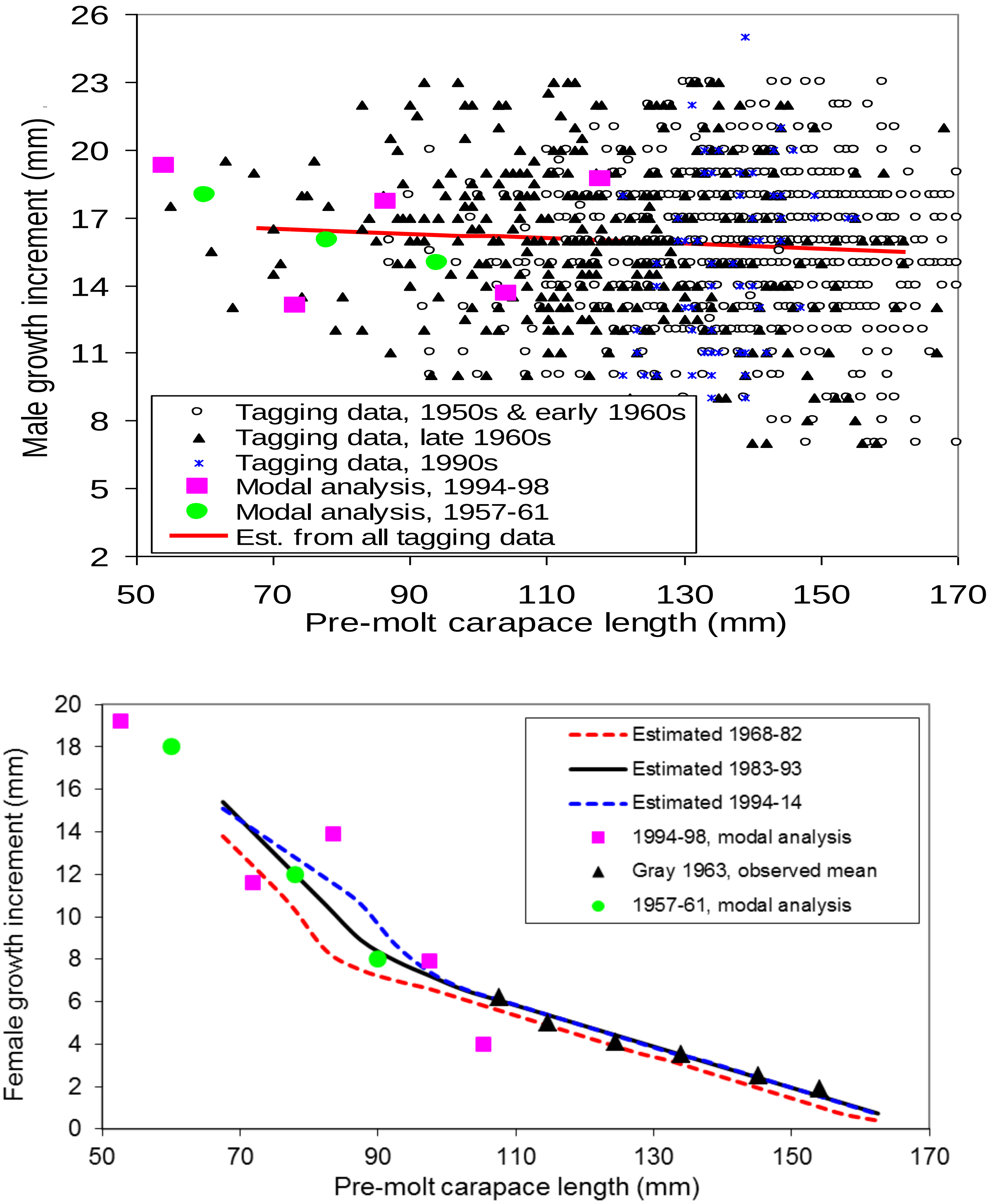


Figure A2. Mean growth increments per molt for Bristol Bay red king crab. Note: "tagging"---based on tagging data; "mode"---based on modal analysis. The female growth increments per molt are for scenarios 1, 1n and 2.

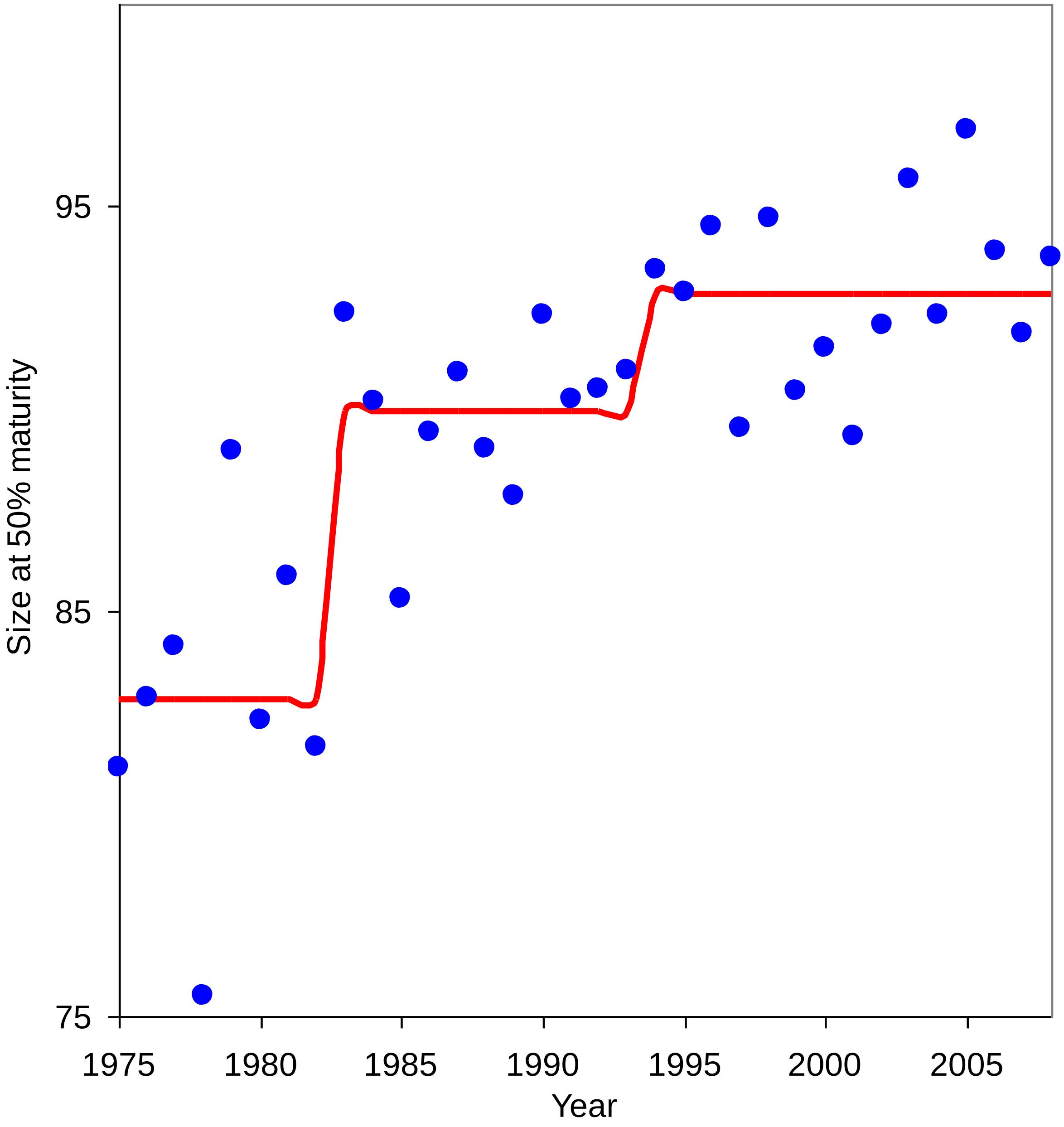


Figure A3. Estimated sizes at 50% maturity for Bristol Bay female red king crab from 1975 to 2008. Averages for three periods (1975-82, 1983-93, and 1994-08) are plotted with a line.

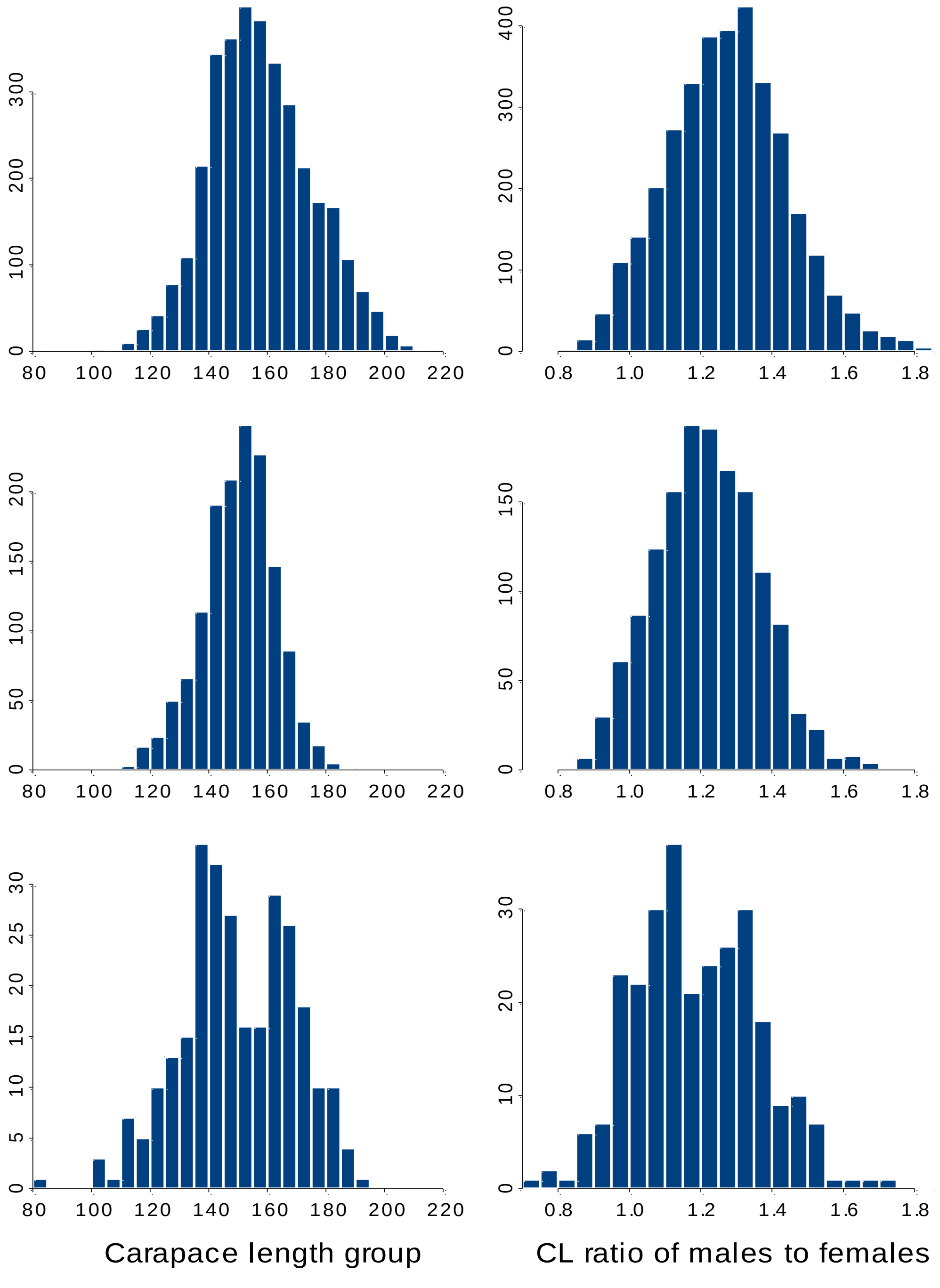


Figure A4. Histograms of carapace lengths (CL) and CL ratios of males to females for male shell ages ≤13 months of red king crab males in grasping pairs; Powell's Kodiak data. Upper plot: all locations and years pooled; middle plot: location 11; lower plot: locations 4 and 13. Sizes at maturity for Kodiak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

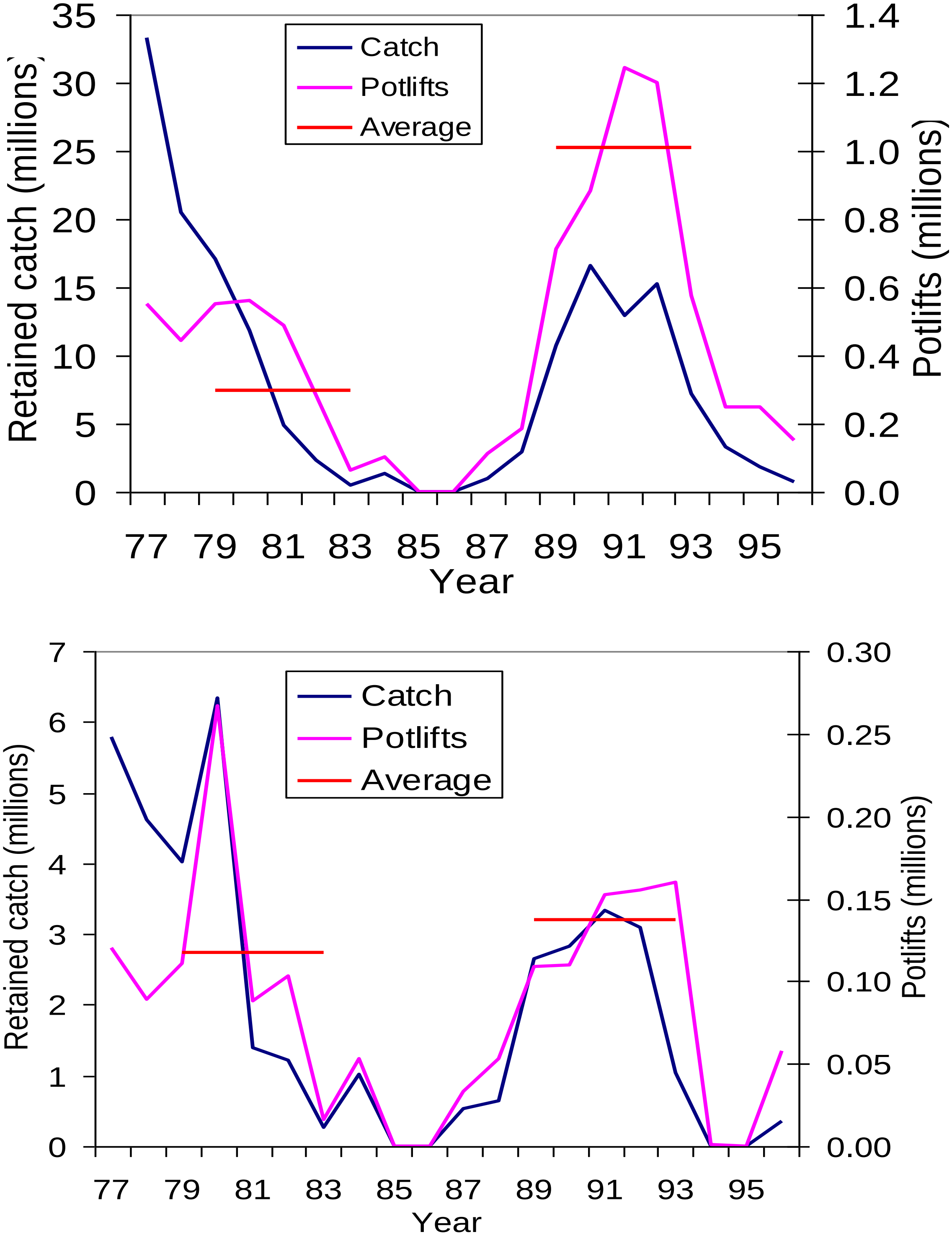


Figure A5. Retained catch and potlifts for total eastern Bering Sea Tanner crab fishery (upper plot) and the Tanner crab fishery east of 163^{o} W (bottom).

Appendix B. Recruitment Breakpoint Analysis in May 2017

Introduction

SSC asked authors to conduct a recruitment breakpoint analysis similar to that conducted for eastern Bering Sea Tanner crab in 2013 (Stockhausen 2013). We obtained the R codes from Dr. William (Buck) Stockhausen of NMFS and slightly modified them to conduct the analysis for Bristol Bay red king crab for better understanding the temporal change of stock productivity and the recruitment time series used for overfishing/overfished definitions. Results from assessment model scenario 2d are used for this analysis. We are very grateful for the help of Dr. Stockhausen for this analysis.

Methods

The methods are the same as Punt et al. (2014) and Stockhausen (2013). Stock productivity is represented by ln(*R/MMB*), where *R* is recruitment and *MMB* is mature male biomass, with recruitment lagging to the brood year of mature biomass. Let y_t = ln(*R/MMB*) and y_t can be estimated directly from the stock assessment model as observed values or from a stock-recruitment model as $\hat{y}_t$. For Ricker stock-recruitment models,

$$\begin{aligned} \hat{y}_t &= \alpha_1 + \beta_1 \cdot MMB \qquad t < b, \\ \hat{y}_t &= \alpha_2 + \beta_2 \cdot MMB \qquad t \geq b, \end{aligned} \tag{1}$$

where α_1 and β_1 are the Ricker stock-recruit function parameters for the early time period before the potential breakpoint in year *b* and α_2 and β_2 are the parameters for the time period after the breakpoint in year *b*. For Beverton-Holt stock-recruitment models,

$$\begin{aligned} \hat{y}_t &= \alpha_1 - \log(1 + e^{\beta_1} \cdot MMB) \qquad t < b, \\ \hat{y}_t &= \alpha_2 + \log(1 + e^{\beta_2} \cdot MMB) \qquad t \geq b, \end{aligned} \tag{2}$$

where α_1 and β_1 are the Beverton-Holt stock-recruit function log-transformed parameters for the early time period before the potential breakpoint in year *b* and α_2 and β_2 are the log-transformed parameters for the time period after the breakpoint in year *b*.

A maximum likelihood approach is used to estimate stock-recruitment model and error parameters. Because y_t is measured with error, the negative log-likelihood function is

$$-\ln(L) = 0.5 \cdot \ln(|\mathbf{\Omega}|) + 0.5 \cdot \sum_t \sum_j (y_t - \hat{y}_t) \cdot \left[\mathbf{\Omega}^{-1}\right]_{t,j} \cdot (y_j - \hat{y}_j), \tag{3}$$

where Ω contains observation and process error as

$$\mathbf{\Omega} = \mathbf{O} + \mathbf{P}, \tag{4}$$

where **O** is the observation error covariance matrix estimated from the stock assessment model and **P** is the process error matrix and is assumed to reflect a first-order autoregressive process to have σ^2 on the diagonal and $\sigma^2 \rho^{|t-j|}$ on the off-diagonal elements. σ^2 represents process error variance and ρ represents the degree of autocorrelation.

For each candidate breakpoint year *b*, the negative log likelihood value of equation (3) is minimized with respect to the six model parameters: α_1, β_1, α_2, β_2, $\ln(\sigma)$ and $\tan(\rho)$. The minimum time span considered as a potential regime is 5 years. Each brood year from 1980 to 2005 is evaluated as a potential breakpoint *b* using time series of ln(R/MMB) and MMB for brood years 1975-2010. A model with no breakpoint is also evaluated. Models with different breakpoints are then ranked using AICc (AIC corrected for small sample size; Burnham and Anderson 2004),

$$AIC_c = -2 \cdot \ln(L) + \frac{2 \cdot k \cdot (k+1)}{n-k-1}, \qquad (5)$$

where *k* is the number of parameters and *n* is the number of observations. Using AICc, the model with the smallest AICc is regarded as the “best” model among the set of models evaluated. Different models can be compared in terms of θ_m, the relative probability (odds) that the model with the minimum AICc score is a better model than model *m*, where

$$\theta_m = \exp([(AICc_m - AICc_{\min})/2]. \qquad (6)$$

Results

Results are summarized in Tables B1-B4 and Figures B1-B6. Discarding the implausible breakpoint year of 1980 for the Ricker model due to implausible stock-recruitment model parameters, both Ricker model and Beverton-Holt model result in the same breakpoint brood year of 1986, which corresponds to recruitment year of 1992. The model with no breakpoint (i.e., a single time period) is about 5 times less probable than the 1986 breakpoint model for Beverton-Holt stock-recruitment models and about eight times less probable for Ricker stock-recruitment relationships, which may suggest a possible change in stock productivity from the early high period to the recent low period. Alternative breakpoint brood years of 1980-1985 for both Ricker and Beverton-Holt models are also reasonably reported. Both Ricker and Beverton-Holt stock-recruitment models fit the data poorly.

Discussion

A recruitment breakpoint analysis was conducted on Bristol Bay red king crab by Punt et al. (2014) with data from 1968 to 2010 to estimate a breakpoint brood year of 1984, corresponding to recruitment year of 1990, which is two years earlier than our estimate, even though our results show that brood year of 1984 is also a likely breakpoint. The different time series of data may explain the different results. Our data start in 1975 and have only two brood-year data points before the regime shift of 1976/77 and thus we cannot detect any stock productivity changes due to the 1976/77 regime shift because of lack of data. Without the early data, the fits of stock-recruitment models to the data are also more poorly.

Time series of estimated recruitment during 1984-present have been used to compute Bmsy proxy. The mean recruitment with scenario 2d during 1984-present is 17.77 million of crab, compared to the mean recruitment of 15.45 million of crab during 1992-present, about 13.0% reduction (Figure

12(2d)). If the estimated breakpoint year is used to set the new recruitment time series, estimated Bmsy proxy will be correspondingly lower than the current estimated value.

References

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

Stockhausen, W.T. 2013 Recruitment Analysis for Stock Status Determination and Harvest Recommendations. Appendix to: 2013 Stock Asssessment and Fishery Evaluation Report for the Tanner Crab Fisheries in the Bering Sea and Aleutian Islands Regions. In: Stock Assessment and Fishery Evaluation Report for the King and Tanner Crab Fisheries of the Bering Sea and Aleutian Islands Regions. North Pacific Fishery Management Council, Anchorage. pp.450-478.

Table B1. Results of the breakpoint analysis, with AICc and the relative probability (odds) against the Ricker stock-recruitment model being correct by breakpoint year. The model with no breakpoint is listed first in the table. The “best” model is shaded with a plausible stock-recruitment model. Years are brood year.

Year	AICc	Odds
NA	46.4933	15.0232
1980	41.0741	1.0000
1981	43.5372	3.4266
1982	43.4335	3.2535
1983	43.5460	3.4417
1984	43.5839	3.5075
1985	43.0025	2.6227
1986	42.4169	1.9570
1987	45.4294	8.8255
1988	46.1588	12.7097
1989	49.4106	64.6036
1990	46.6891	16.5684
1991	47.9850	31.6723
1992	48.2826	36.7550
1993	48.0169	32.1822
1994	48.9392	51.0375
1995	48.9373	50.9899
1996	49.2335	59.1297
1997	48.8284	48.2862
1998	48.8394	48.5532
1999	48.8440	48.6658
2000	46.3349	13.8795
2001	45.4607	8.9648
2002	45.5360	9.3088
2003	45.9752	11.5951
2004	46.2300	13.1701
2005	45.8085	10.6673

Table B2. Parameter estimates and standard deviations for the Ricker stock-recruitment model with no breakpoint (first row) and the single breakpoint models (by year of breakpoint). The "best" model is shaded. Years are brood year.

Year	α_1	std.dev.	α_2	std.dev.	β_1	std.dev.	β_2	std.dev.	ln(σ)	std.dev.	tan(ρ)	std.dev.
			-0.523	0.319			0.005	0.008	0.001	0.122	0.191	0.285
1980	-7.356	5.342	0.708	0.505	-0.077	0.061	0.061	0.021	-0.117	0.122	-0.052	0.286
1981	0.428	1.239	0.688	0.494	0.012	0.016	0.062	0.021	-0.111	0.122	-0.102	0.279
1982	0.517	0.750	0.615	0.540	0.013	0.010	0.060	0.022	-0.112	0.122	-0.100	0.275
1983	0.337	0.582	0.675	0.602	0.011	0.008	0.062	0.024	-0.111	0.122	-0.107	0.273
1984	0.265	0.493	0.747	0.694	0.010	0.008	0.065	0.028	-0.111	0.122	-0.108	0.274
1985	0.512	0.431	0.035	0.872	0.013	0.007	0.037	0.034	-0.118	0.122	-0.116	0.275
1986	0.500	0.397	-0.677	1.148	0.013	0.007	0.011	0.044	-0.132	0.122	-0.083	0.281
1987	0.179	0.380	0.578	1.468	0.009	0.007	0.057	0.056	-0.088	0.122	-0.102	0.273
1988	0.089	0.392	0.706	1.693	0.009	0.007	0.062	0.064	-0.081	0.121	0.002	0.279
1989	-0.174	0.384	0.819	1.738	0.007	0.007	0.063	0.066	-0.038	0.121	-0.029	0.281
1990	-0.069	0.389	1.505	1.759	0.008	0.007	0.093	0.067	-0.076	0.122	0.080	0.274
1991	-0.173	0.385	1.457	1.805	0.007	0.008	0.090	0.069	-0.057	0.122	0.088	0.272
1992	-0.342	0.374	2.270	1.875	0.005	0.008	0.118	0.071	-0.051	0.122	0.090	0.271
1993	-0.354	0.358	2.646	2.036	0.005	0.007	0.131	0.076	-0.054	0.121	0.068	0.270
1994	-0.259	0.357	1.700	2.961	0.006	0.008	0.097	0.109	-0.042	0.121	0.079	0.283
1995	-0.290	0.344	2.037	3.181	0.006	0.007	0.109	0.116	-0.041	0.121	0.064	0.276
1996	-0.336	0.333	2.213	3.163	0.006	0.007	0.114	0.116	-0.036	0.121	-0.036	0.121
1997	-0.236	0.342	-0.002	3.514	0.007	0.008	0.038	0.127	-0.048	0.122	0.111	0.292
1998	-0.293	0.322	1.265	4.351	0.006	0.007	0.082	0.156	-0.044	0.121	0.060	0.272
1999	-0.298	0.312	0.359	5.150	0.006	0.007	0.051	0.183	-0.045	0.121	0.041	0.270
2000	-0.249	0.294	2.030	5.027	0.006	0.007	0.116	0.179	-0.082	0.122	0.013	0.268
2001	-0.260	0.275	2.972	4.984	0.006	0.006	0.153	0.178	-0.096	0.122	-0.060	0.268
2002	-0.281	0.269	2.991	5.003	0.005	0.006	0.155	0.179	-0.095	0.122	-0.076	0.269
2003	-0.312	0.268	3.717	5.370	0.005	0.006	0.183	0.193	-0.089	0.122	-0.079	0.270
2004	-0.336	0.266	4.122	5.359	0.005	0.006	0.200	0.193	-0.086	0.122	-0.078	0.267
2005	-0.338	0.261	2.435	5.684	0.005	0.006	0.143	0.203	-0.093	0.122	-0.082	0.267

Table B3. Results of the breakpoint analysis, with AICc and the relative probability (odds) against the Beverton-Holt stock-recruitment model being correct by breakpoint year. The model with no breakpoint is listed first in the table. The "best" model is shaded. Years are brood year.

Year	AICc	Odds
NA	45.3981	5.0697
1980	43.8995	2.3964
1981	42.3954	1.1297
1982	42.3742	1.1177
1983	42.5415	1.2153
1984	42.6196	1.2637
1985	42.6775	1.3008
1986	42.1516	1.0000
1987	45.3144	4.8618
1988	45.9970	6.8395
1989	49.1365	32.8664
1990	47.0869	11.7947
1991	48.2198	20.7824
1992	49.4103	37.6892
1993	49.4378	38.2106
1994	49.0962	32.2110
1995	49.2897	35.4830
1996	49.7282	44.1816
1997	48.3534	22.2179
1998	48.8959	29.1420
1999	48.7480	27.0641
2000	46.5764	9.1378
2001	45.9210	6.5844
2002	45.8966	6.5046
2003	46.4147	8.4280
2004	46.6195	9.3366
2005	45.6408	5.7238

Table B4. Parameter estimates and standard deviations for the Beverton-Holt stock-recruitment model with no breakpoint (first row) and the single breakpoint models (by year of breakpoint). The “best” model is shaded. Years are brood year.

Year	α_1	std.dev.	α_2	std.dev.	β_1	std.dev.	β_2	std.dev.	ln(σ)	std.dev.	tan(ρ)	std.dev.
			-0.159	0.894			-3.713	2.225	-0.005	0.123	0.215	0.295
1980	-0.625	0.391	7.820	66.239	-11.19	60.247	5.471	66.254	-0.101	0.123	-0.164	0.282
1981	1.500	4.577	7.493	50.669	-2.440	5.381	5.185	50.685	-0.129	0.122	-0.078	0.287
1982	0.796	1.109	6.982	47.358	-3.321	1.661	4.681	47.381	-0.129	0.122	-0.097	0.276
1983	0.460	0.724	7.357	43.960	-3.817	1.354	5.044	43.974	-0.126	0.122	-0.108	0.275
1984	0.349	0.586	8.411	65.301	-3.999	1.241	6.091	65.308	-0.126	0.122	-0.111	0.274
1985	0.666	0.573	0.959	3.804	-3.492	1.065	-1.508	4.519	-0.123	0.122	-0.108	0.276
1986	0.647	0.530	-0.690	1.307	-3.514	1.031	-4.454	5.662	-0.135	0.122	-0.080	0.280
1987	0.292	0.483	5.501	41.505	-3.983	1.175	3.163	41.573	-0.092	0.122	-0.096	0.274
1988	0.227	0.528	6.910	83.603	-3.992	1.316	4.571	83.636	-0.084	0.121	0.031	0.276
1989	-0.005	0.560	5.507	42.863	-4.127	1.569	3.080	42.939	-0.042	0.121	0.007	0.280
1990	0.103	0.571	5.404	31.615	-4.034	1.491	3.066	31.672	-0.071	0.122	0.107	0.279
1991	0.016	0.593	5.997	43.869	-4.059	1.603	3.631	43.913	-0.054	0.122	0.107	0.276
1992	-0.179	0.584	6.277	42.024	-4.316	1.863	3.830	42.059	-0.037	0.122	0.115	0.277
1993	-0.194	0.571	6.265	41.986	-4.334	1.867	3.820	42.021	-0.037	0.122	0.121	0.277
1994	-0.049	0.608	4.133	30.922	-4.054	1.719	1.753	31.120	-0.040	0.122	0.135	0.282
1995	-0.090	0.592	4.862	43.254	-4.112	1.752	2.481	43.386	-0.038	0.122	0.118	0.279
1996	-0.143	0.583	4.980	43.179	-4.170	1.810	2.577	43.299	-0.033	0.121	-0.033	0.121
1997	-0.027	0.598	0.689	17.930	-4.018	1.685	-1.771	21.766	-0.052	0.122	0.129	0.297
1998	-0.112	0.548	3.575	39.931	-4.175	1.718	1.269	40.335	-0.047	0.122	0.078	0.275
1999	-0.124	0.528	1.114	24.395	-4.213	1.703	-1.266	27.474	-0.050	0.121	0.051	0.273
2000	-0.096	0.481	3.838	44.284	-4.274	1.592	1.729	44.563	-0.084	0.122	0.030	0.272
2001	-0.117	0.449	5.966	109.07	-4.344	1.556	3.936	109.14	-0.094	0.122	-0.033	0.270
2002	-0.133	0.450	4.710	58.628	-4.345	1.571	2.726	58.765	-0.094	0.122	-0.038	0.269
2003	-0.150	0.470	4.518	51.104	-4.308	1.611	2.561	51.245	-0.086	0.122	-0.031	0.269
2004	-0.169	0.476	4.207	43.439	-4.307	1.638	2.300	43.595	-0.082	0.121	-0.036	0.269
2005	-0.176	0.459	2.668	27.512	-4.331	1.609	0.892	27.915	-0.096	0.122	-0.058	0.268

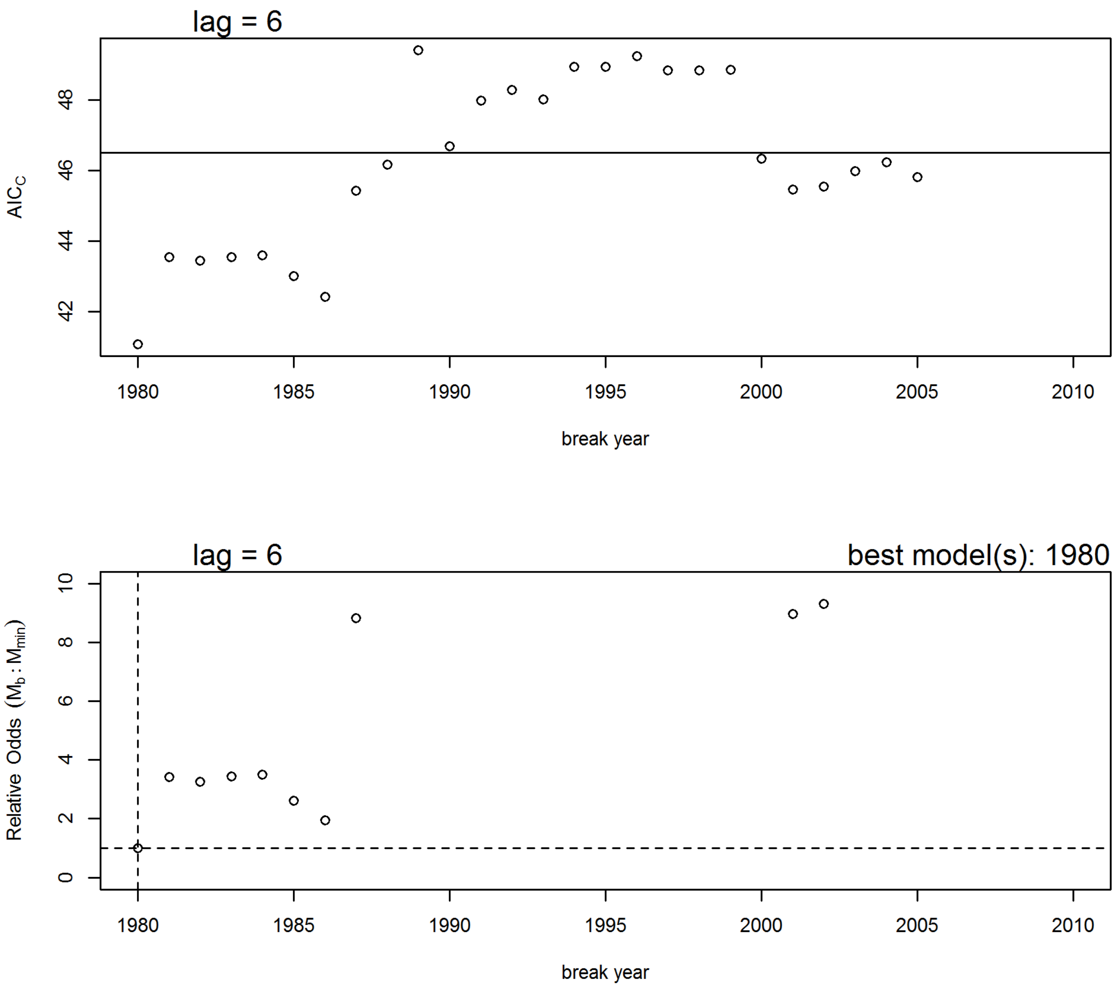


Figure B1. Results from the Ricker stock-recruit breakpoint analysis. Upper graph: AICc vs. year of breakpoint for the 1-breakpoint models (circles) and AICc for the model with no breakpoint (horizontal line). Lower graph: probabilistic odds for all 1-breakpoint models (circles) and the no breakpoint model (horizontal solid line) relative to the model with the smallest AICc score. The dashed lines indicate the value for the model with the lowest AICc score. Not shown are 1-breakpoint models with high odds (>10) of being incorrect.

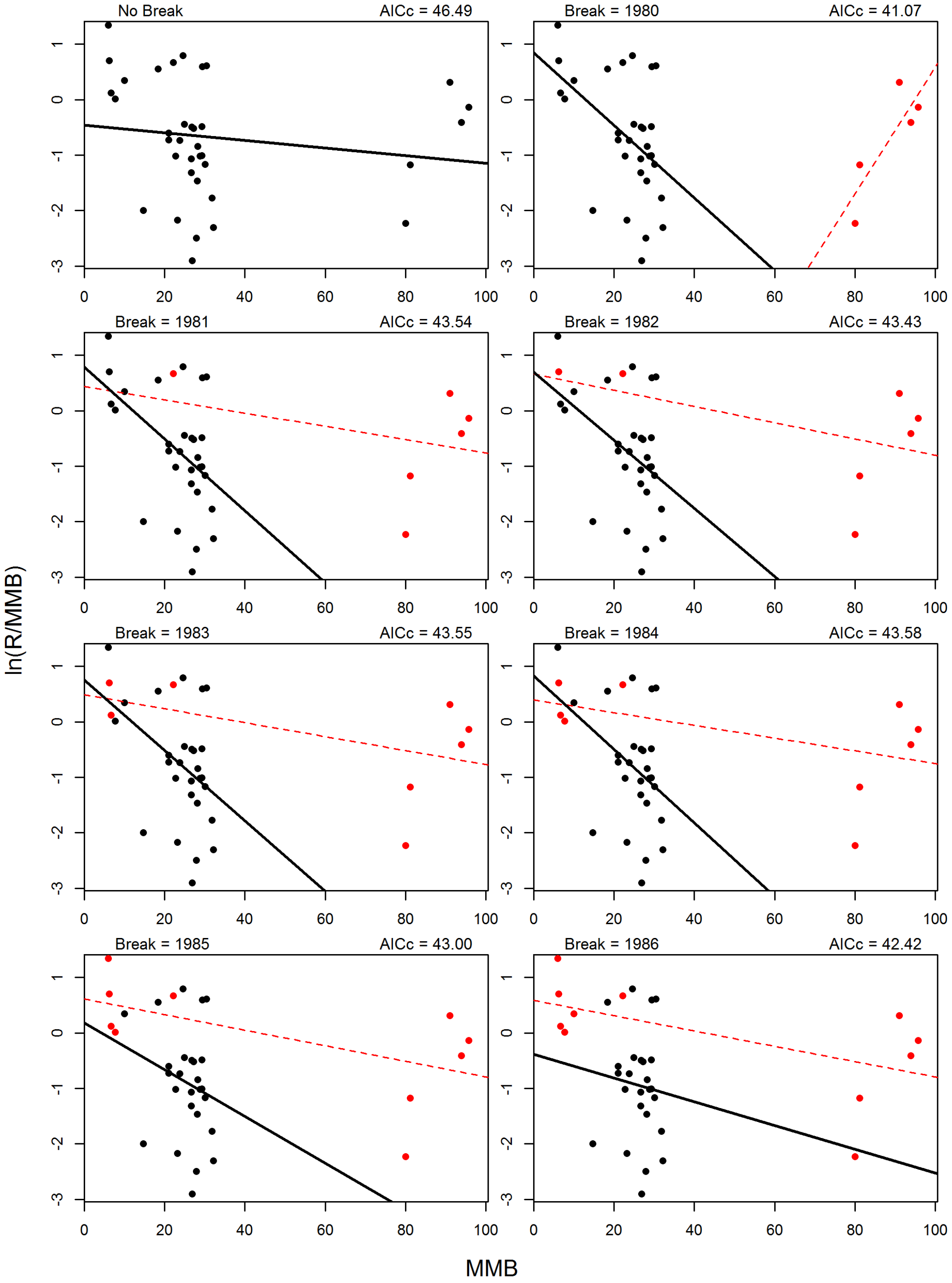
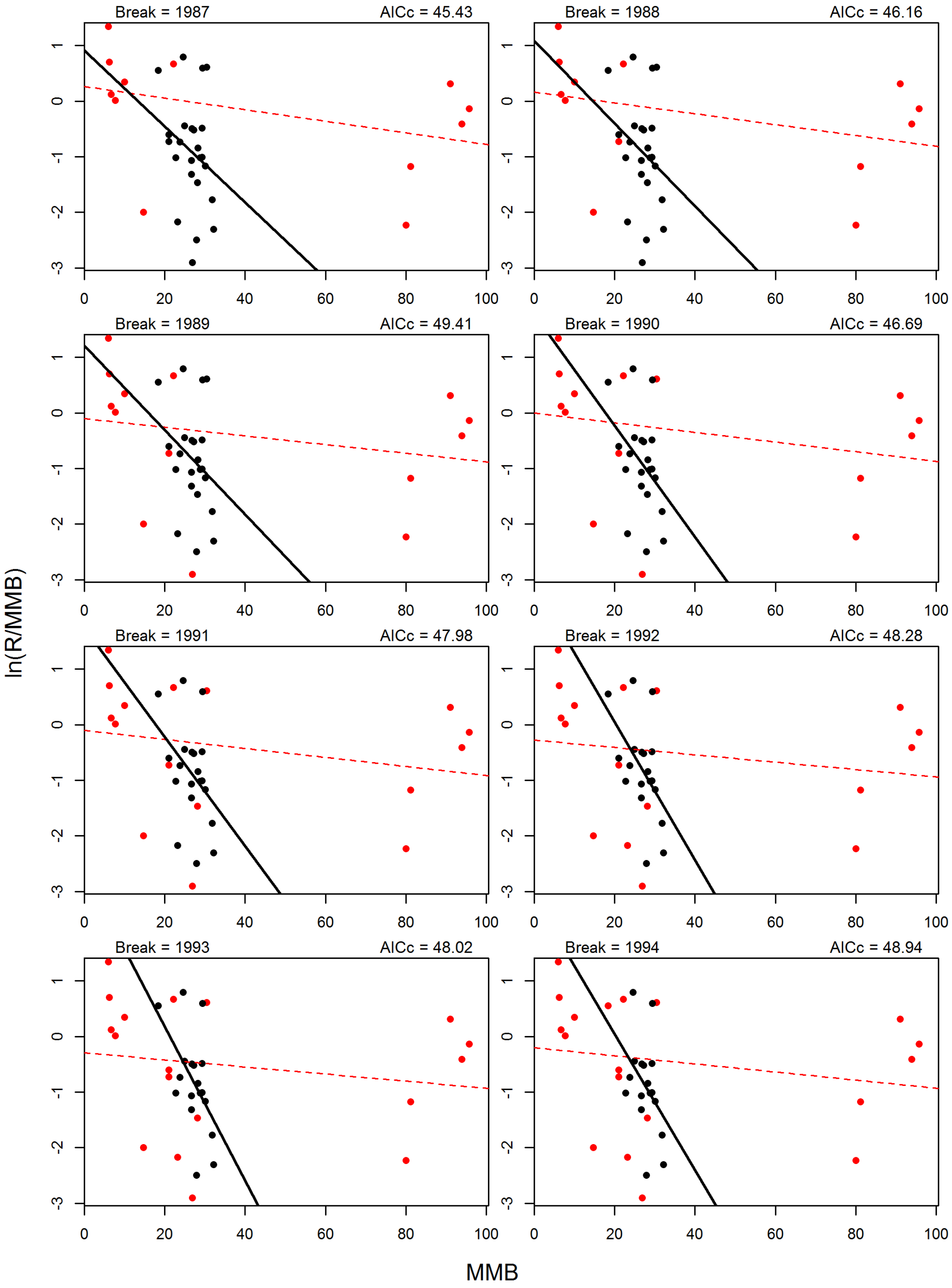


Figure B2. Fits for Ricker models with no breakpoint (upper left graph) and with 1-breakpoint for break years 1975-2005. For 1-breakpoint models, the pre-break data (circles) and model fit (line) are shown in red, whereas the post-break data and fit are shown in black.



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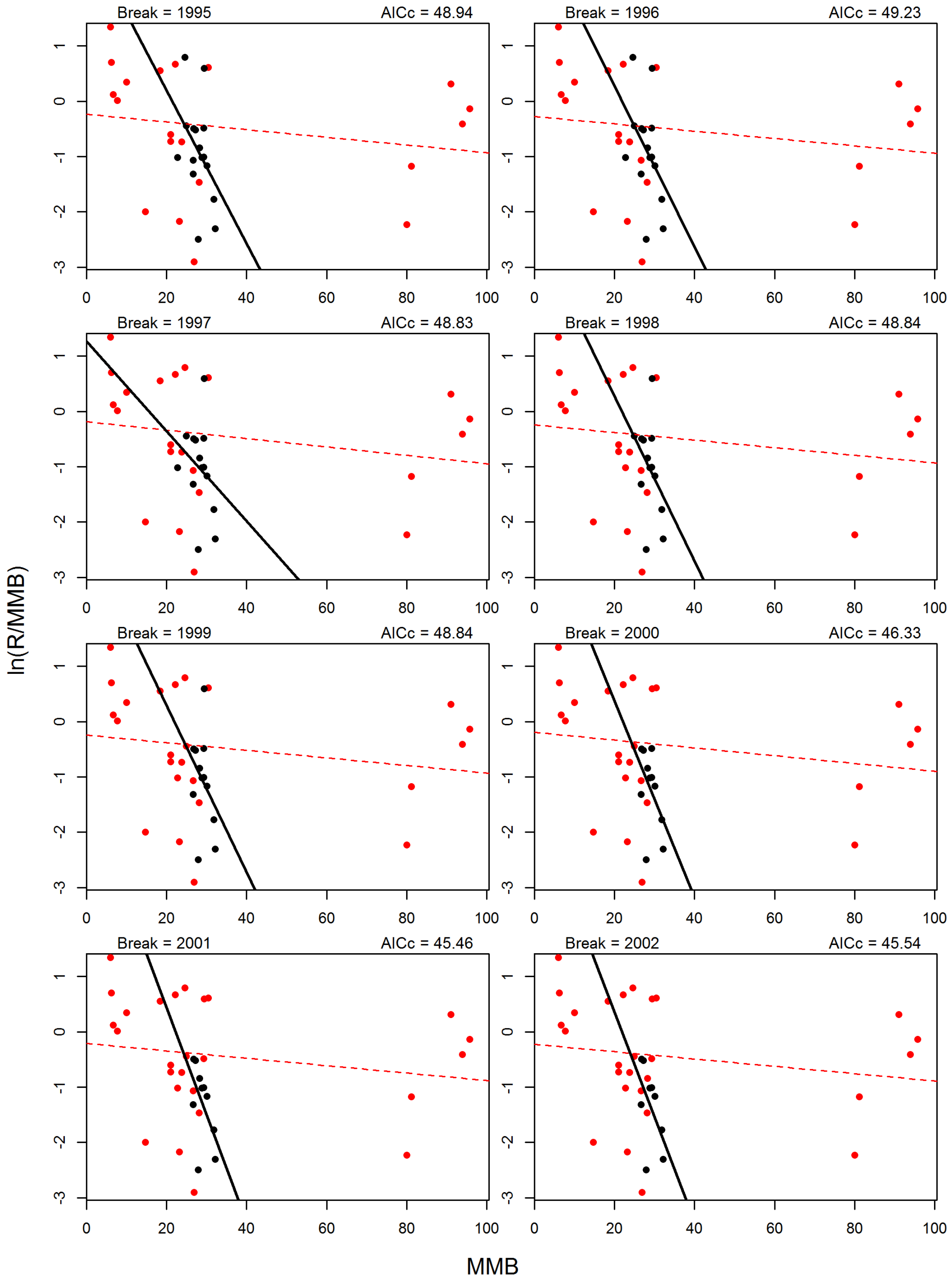

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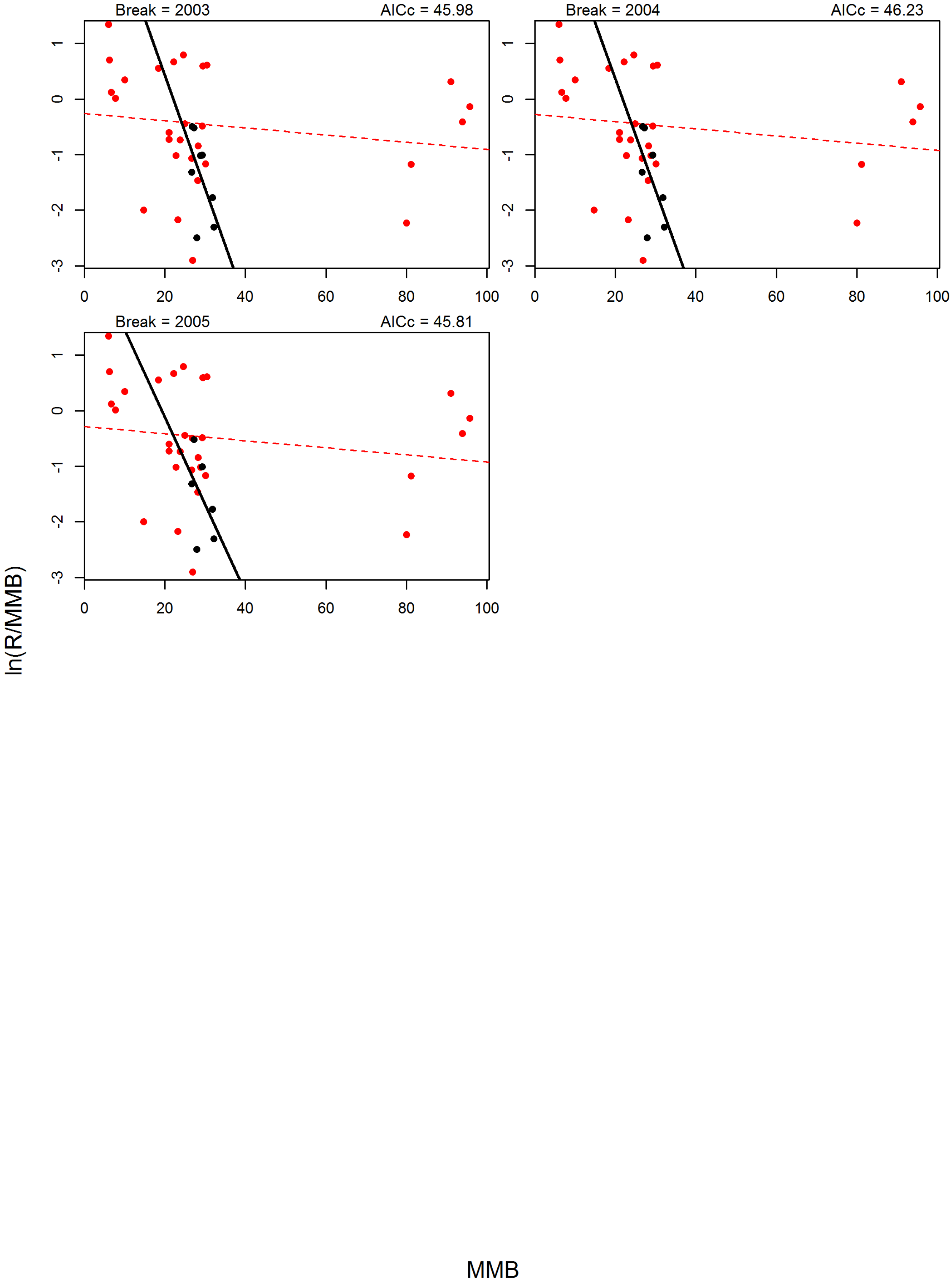

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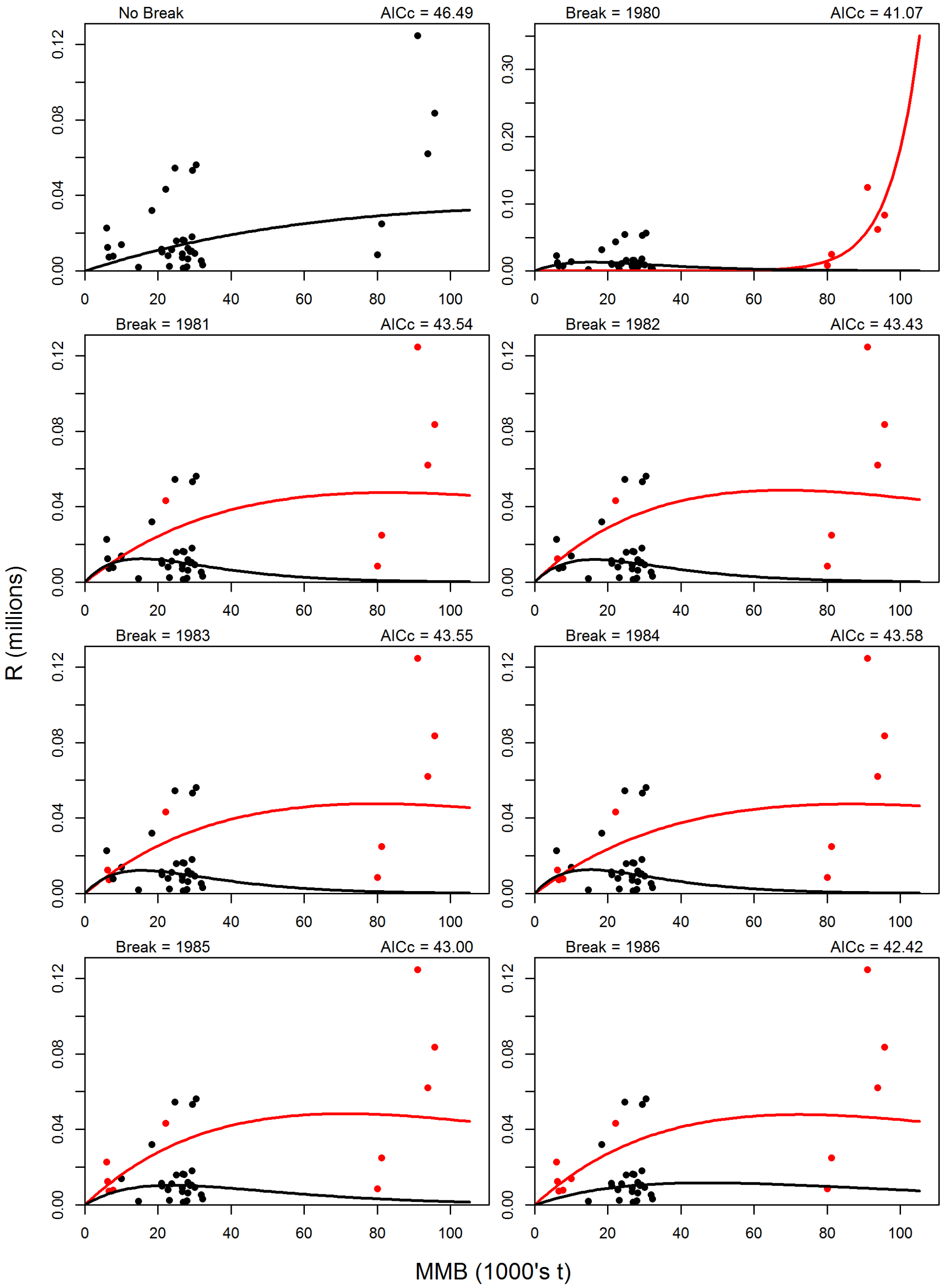
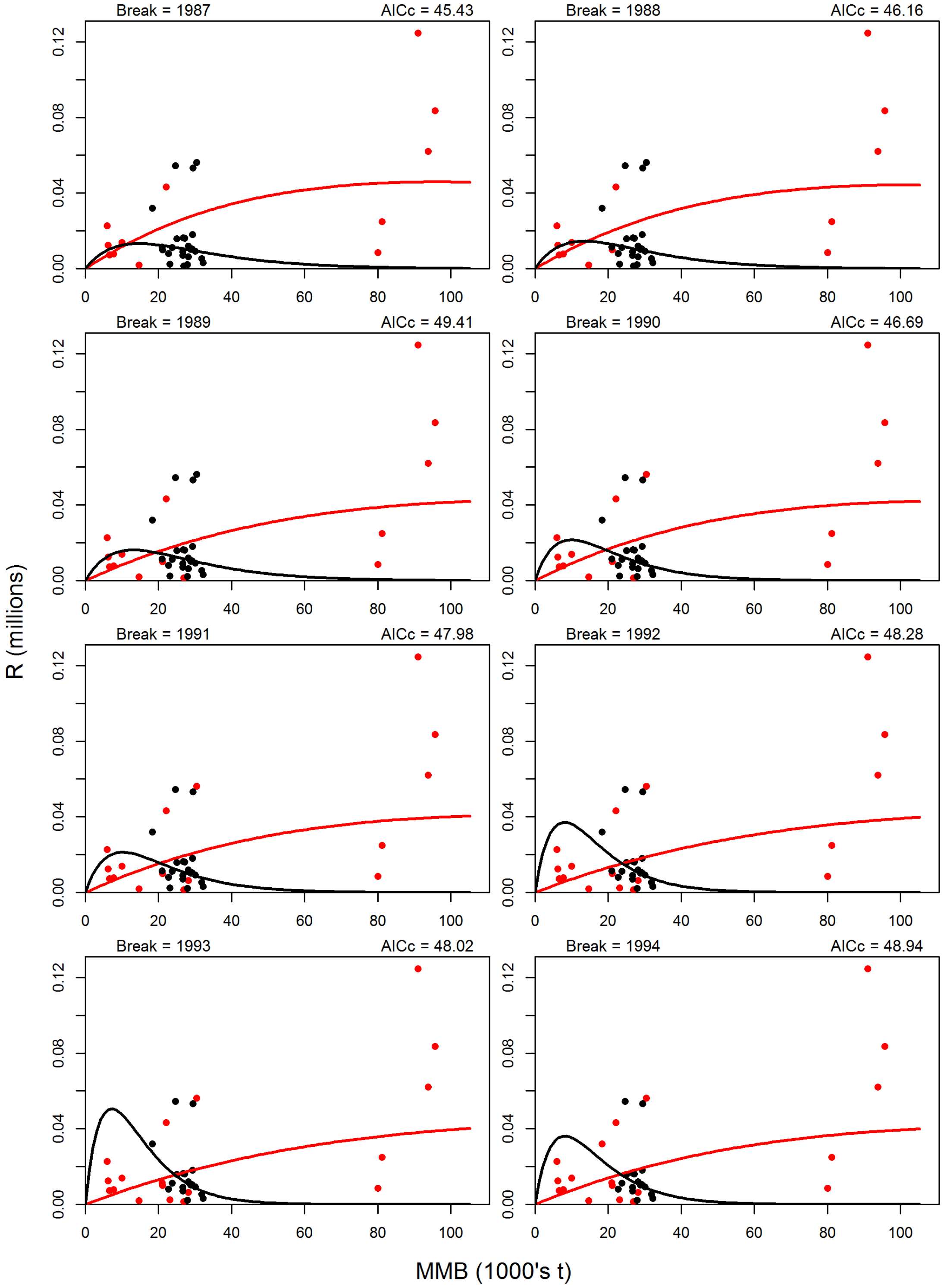


Figure B3. Fits on the arithmetic scale for Ricker models with no breakpoint (upper left graph) and with 1-breakpoint for break years 1975-2005. For 1-breakpoint models, the pre-break data (circles) and model fit (line) are shown in red, whereas the post-break data and fit are shown in black.



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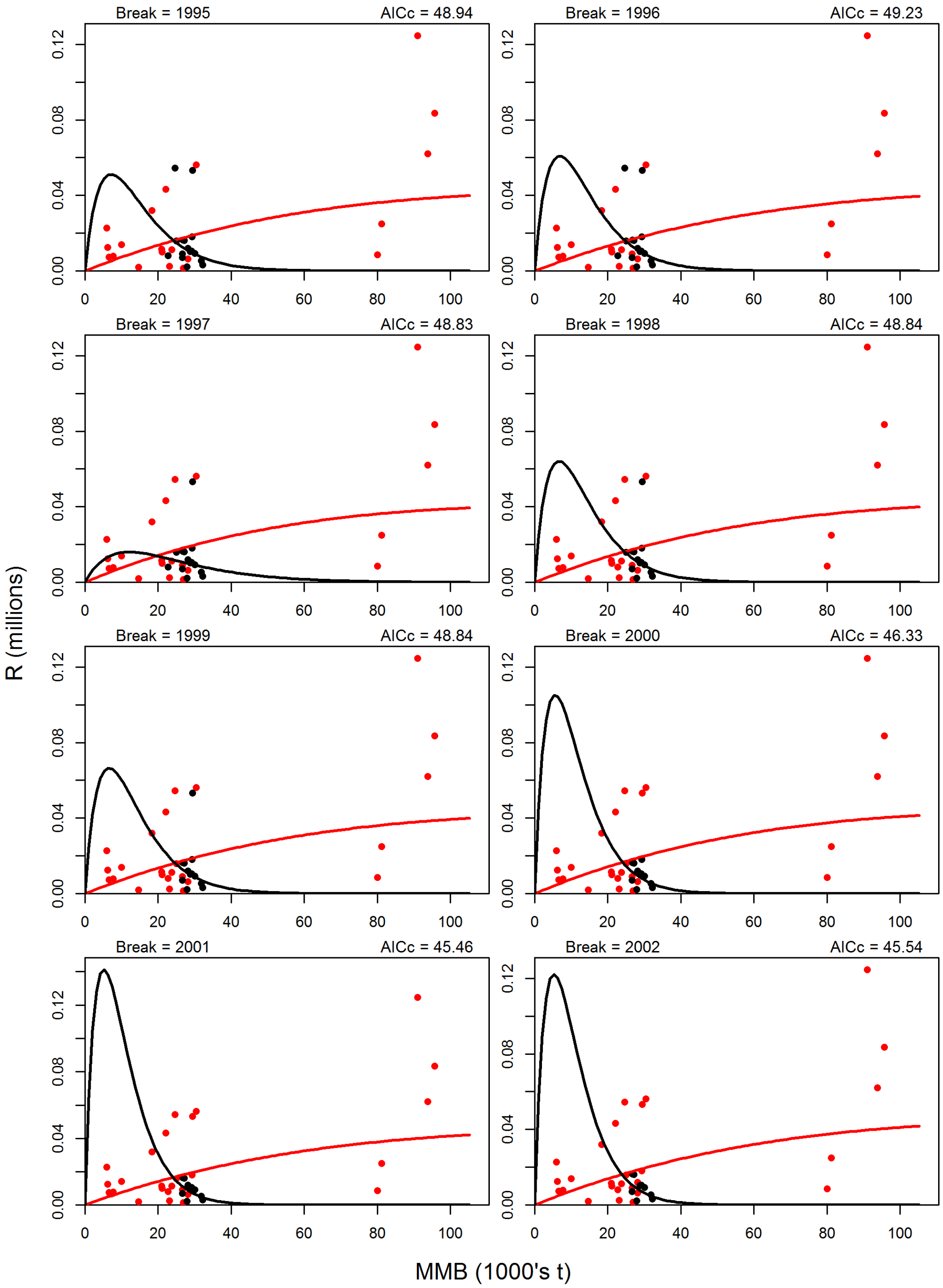

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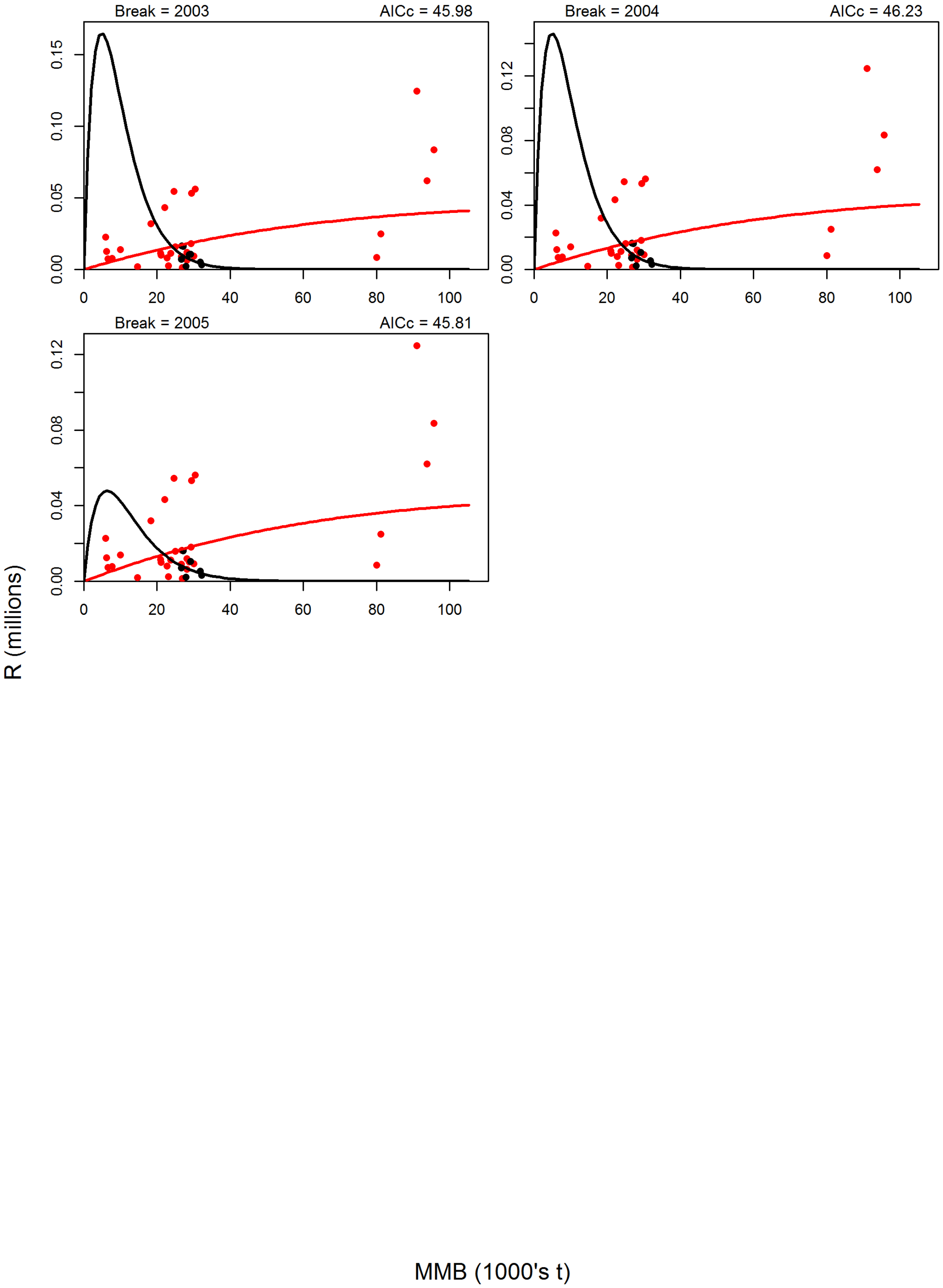

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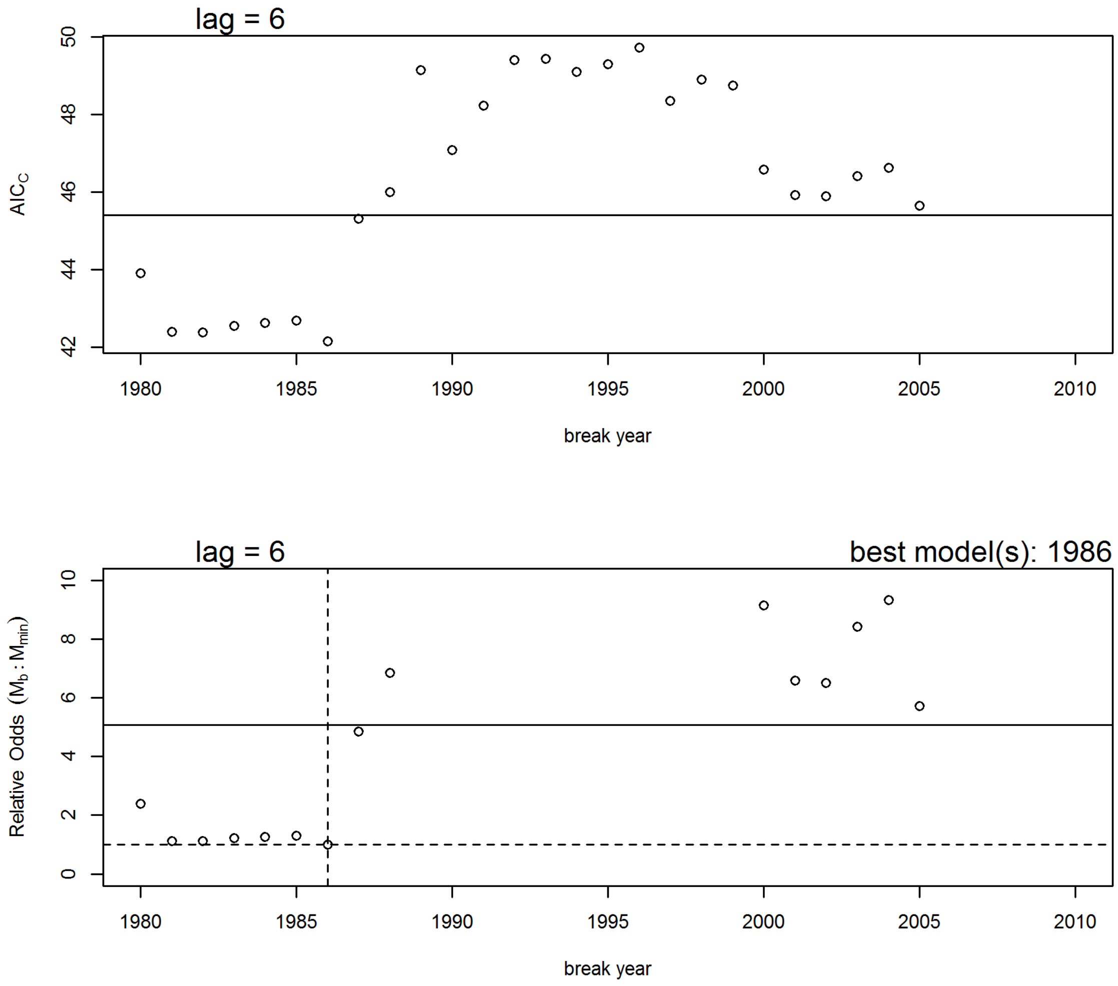


Figure B4. Results from the B-H stock-recruit breakpoint analysis. Upper graph: AICc vs. year of breakpoint for the 1-breakpoint models (circles) and AICc for the model with no breakpoint (horizontal line). Lower graph: probabilistic odds for all 1-breakpoint models (circles) and the no breakpoint model (horizontal solid line) relative to the model with the smallest AICc score. The dashed lines indicate the value for the model with the lowest AICc score (breakpoint in 1986). Not shown are 1-breakpoint models with high odds (>10) of being incorrect.

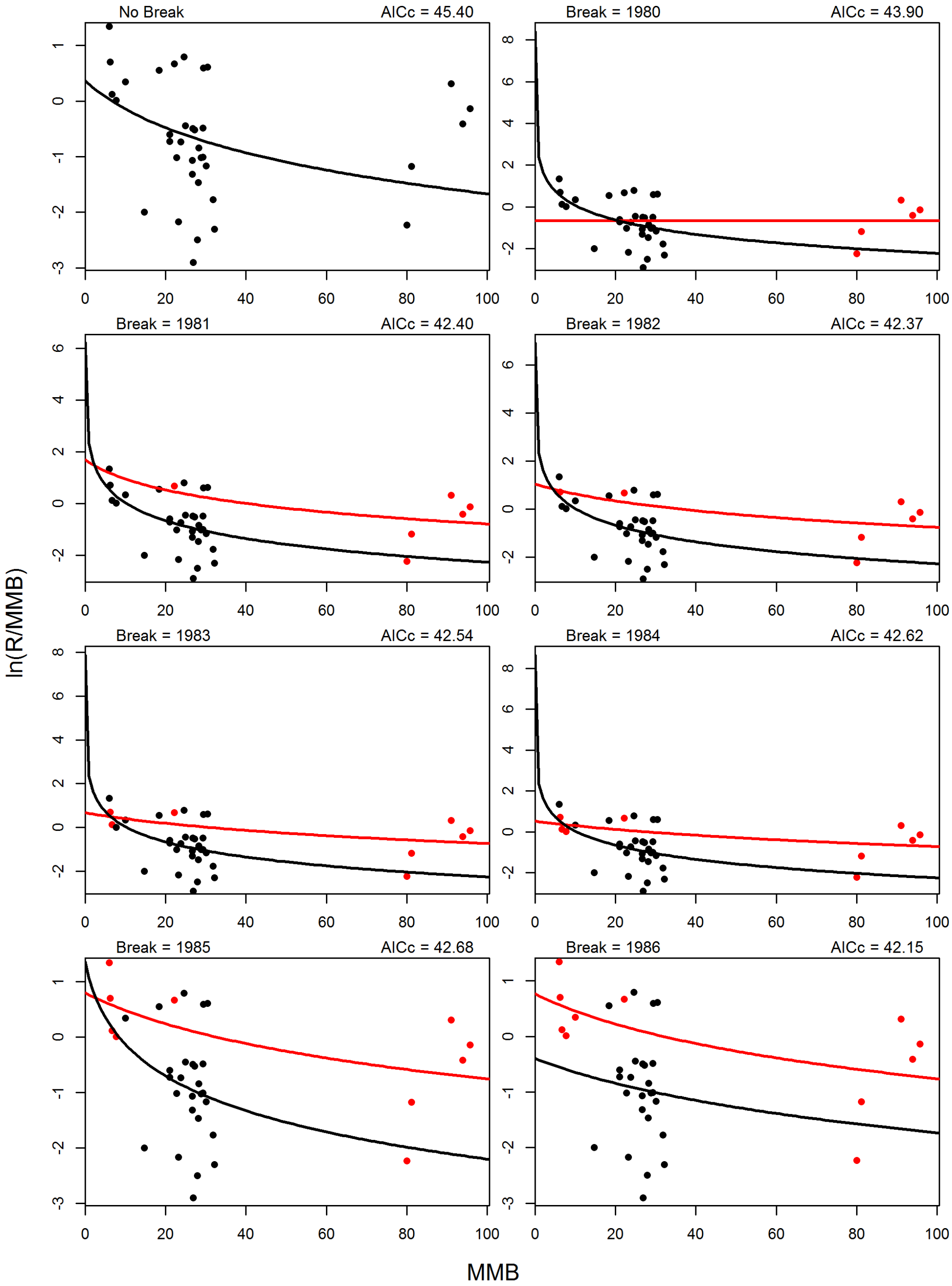
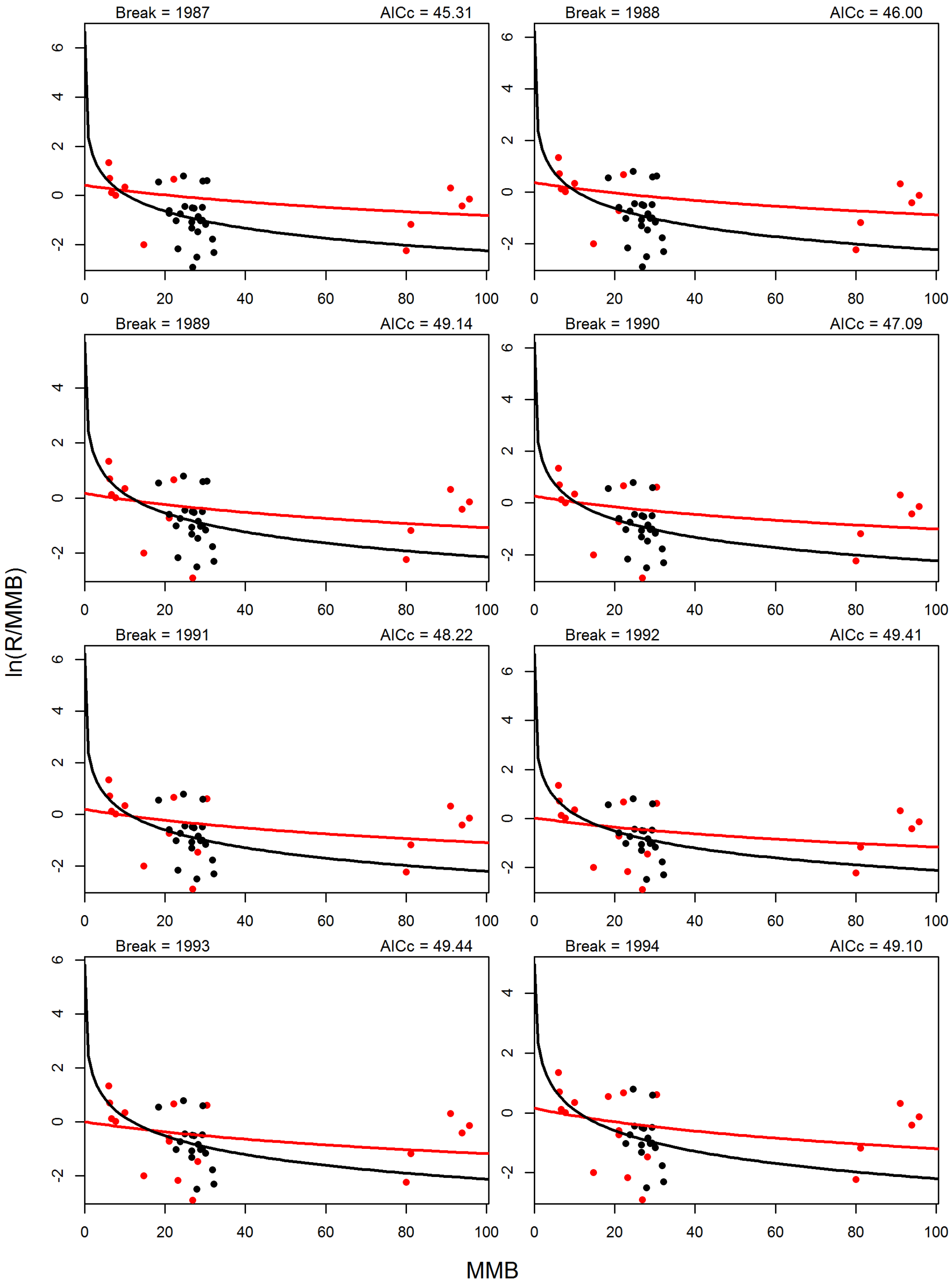


Figure B5. Fits for B-H models with no breakpoint (upper left graph) and with 1-breakpoint for break years 1975-2005. For 1-breakpoint models, the pre-break data (circles) and model fit (line) are shown in red, whereas the post-break data and fit are shown in black.



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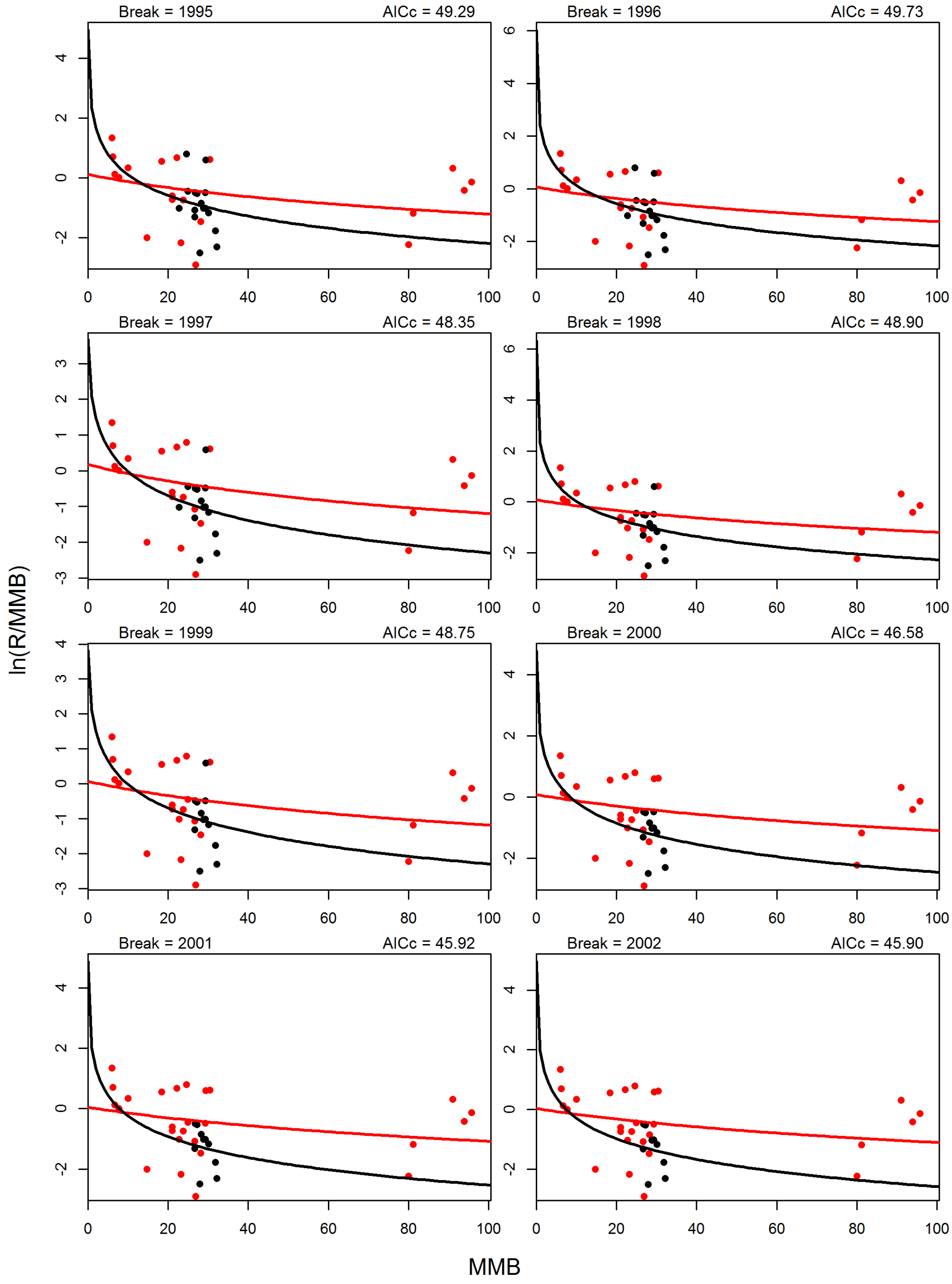

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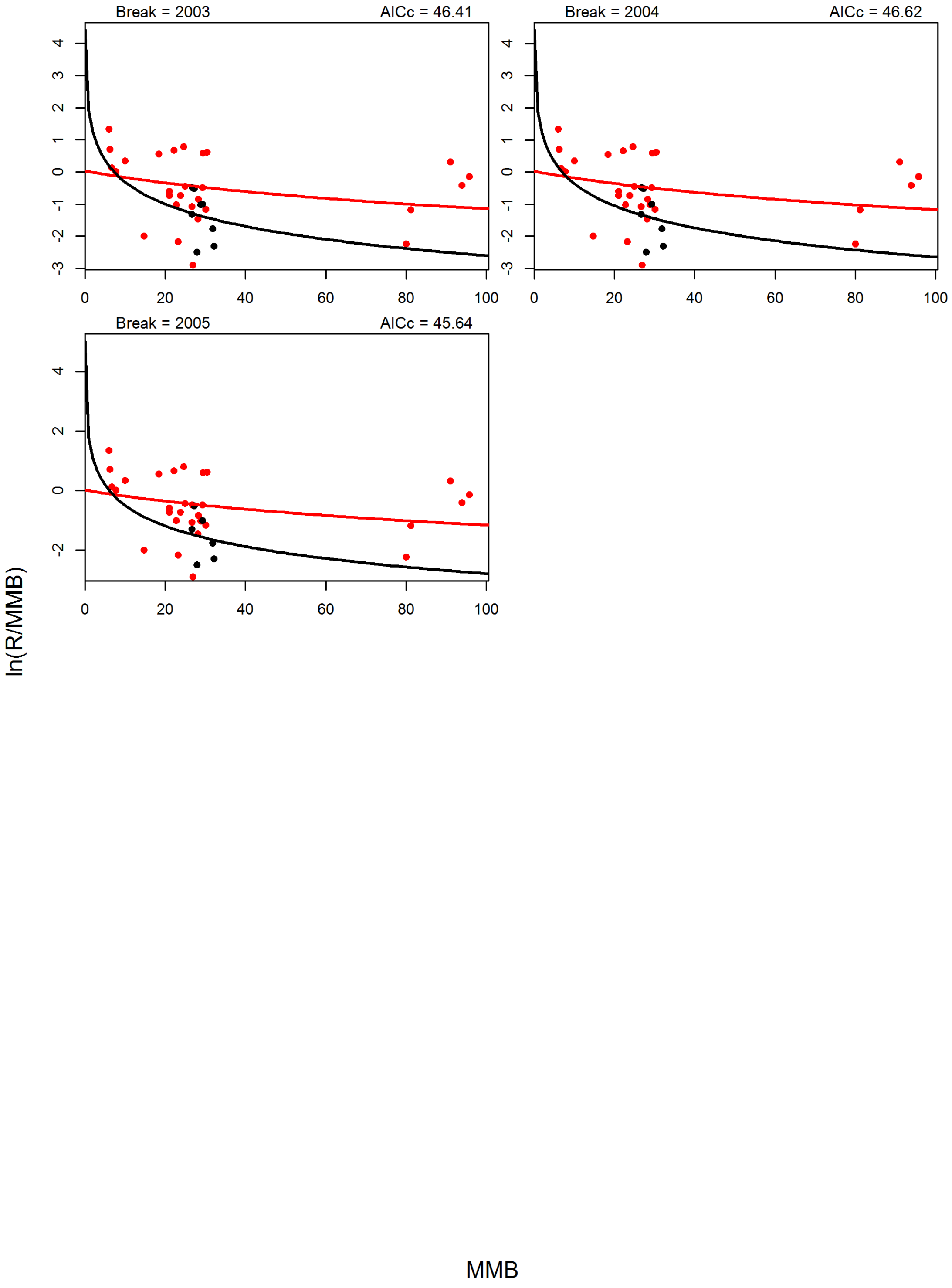

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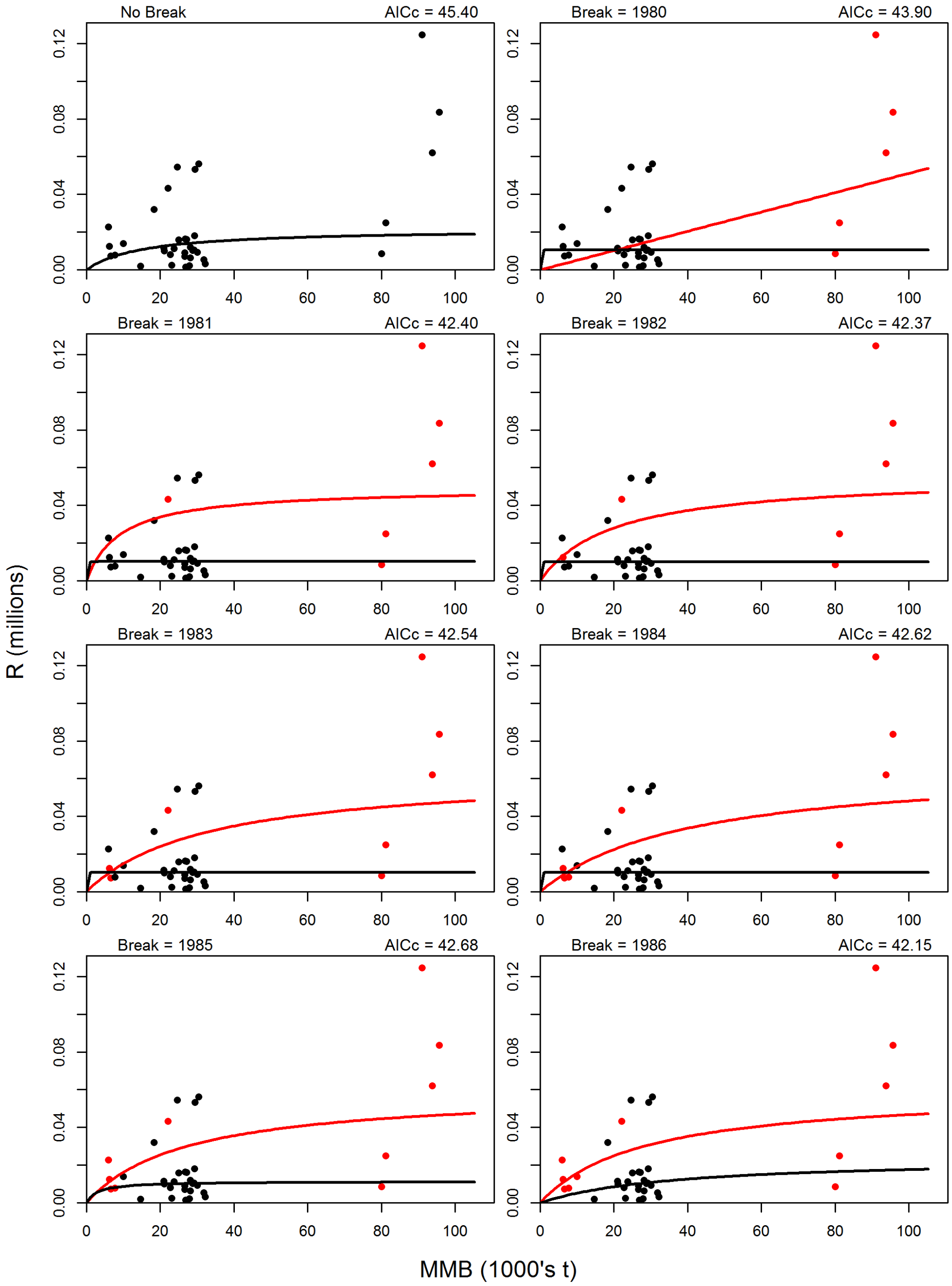
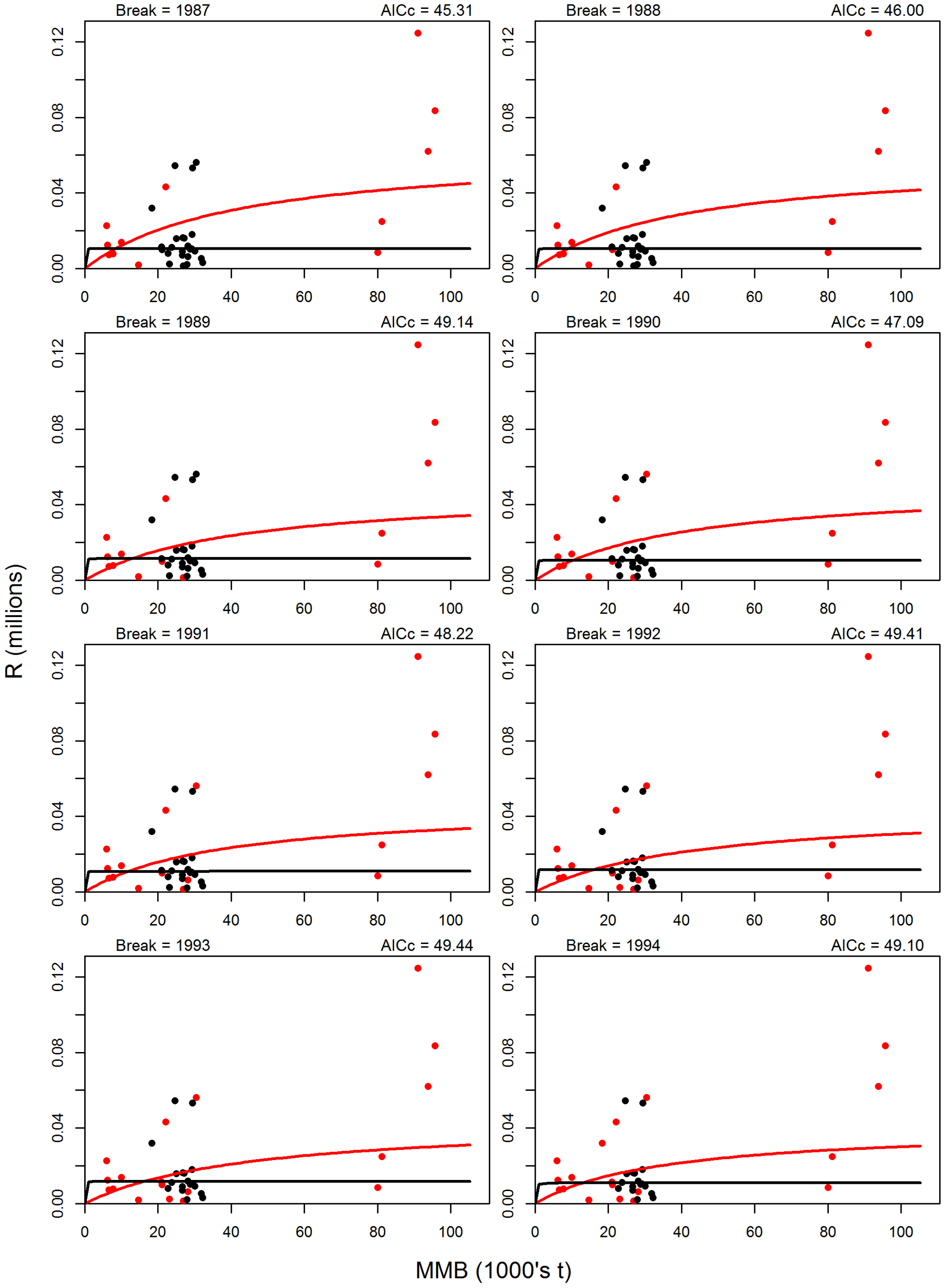


Figure B6. Fits on the arithmetic scale for B-H models with no breakpoint (upper left graph) and with 1-breakpoint for break years 1975-2005. For 1-breakpoint models, the pre-break data (circles) and model fit (line) are shown in red, whereas the post-break data and fit are shown in black.



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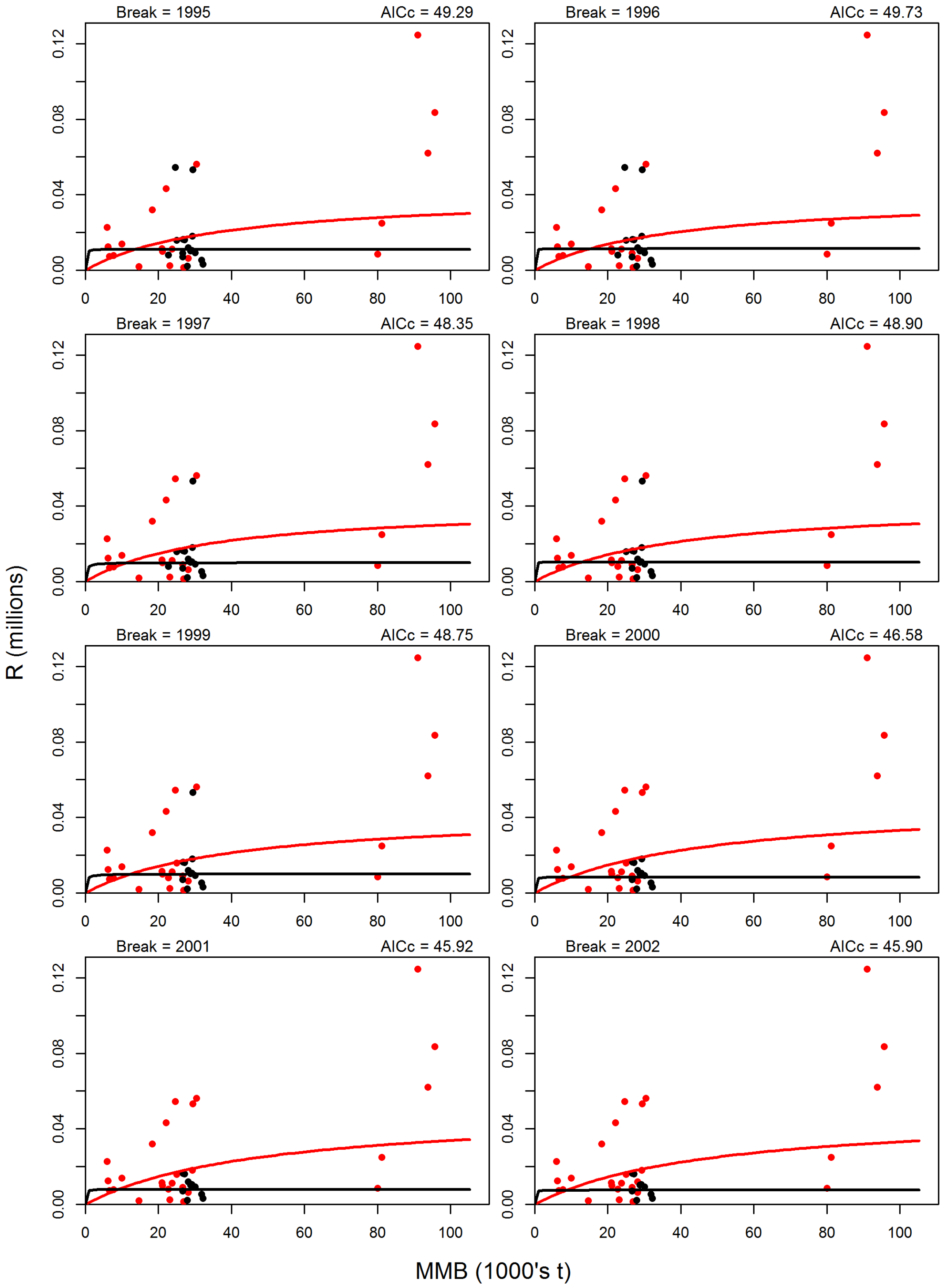

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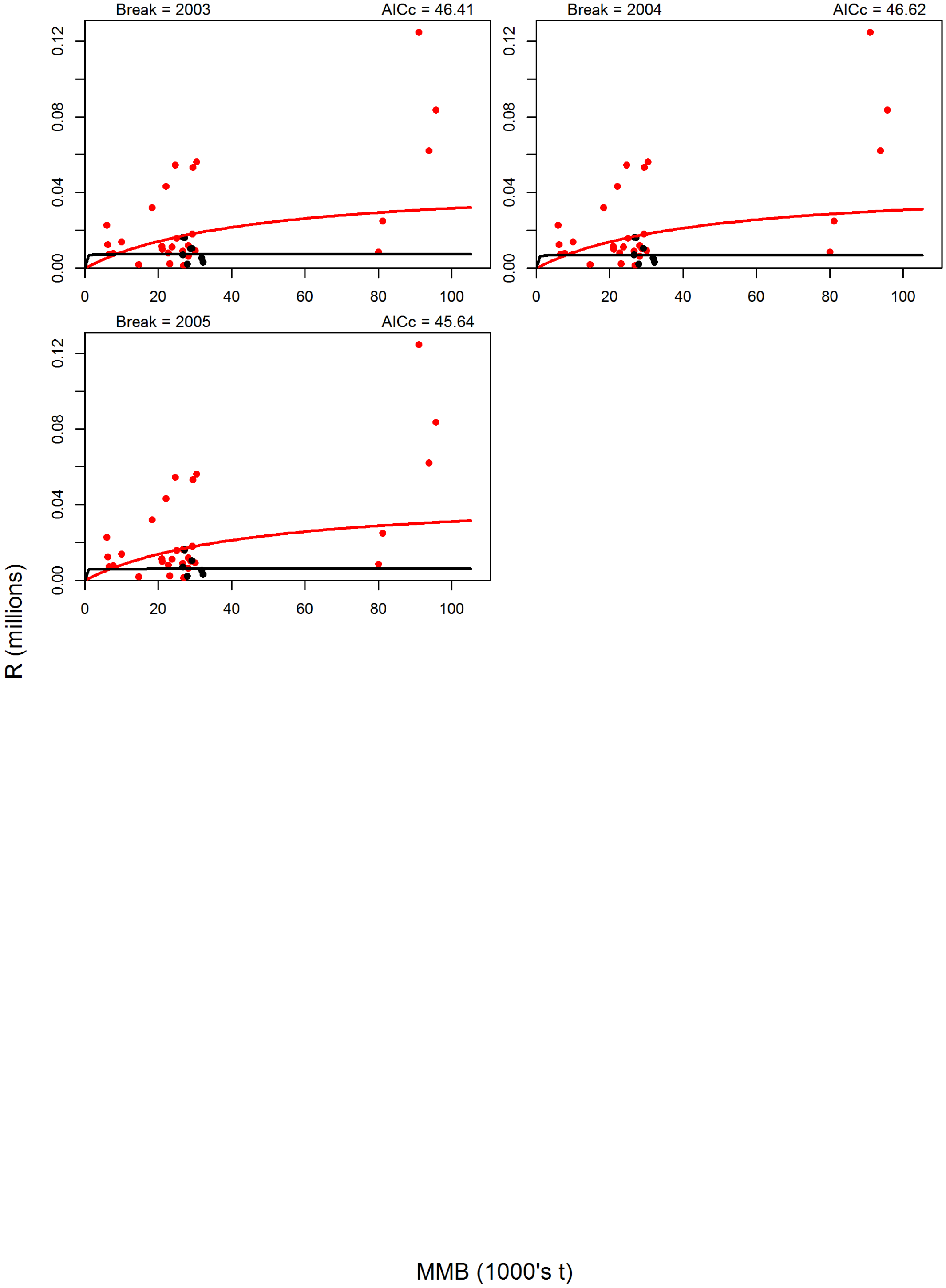

Figure B6. Continue.

Appendix C. Simple B0 Analysis

Ideally, a stock-recruitment relationship and impacts of environmental factors on recruitment are developed before doing B0 analysis. For Bristol Bay red king crab, there is hardly any relationship between estimated recruits and MMB (Figure 14a). The impacts of environmental factors on recruitment have not been quantified. We simply computed B0 values over time using the same recruitment time series estimated from the assessment model through setting all directed and bycatch fishing mortality to be zero. Figure C1 shows the time series of estimated B0, MMB with fishing, and ratios of MMB to B0 for scenario 18.0. As expected, estimated B0 values change greatly over time.

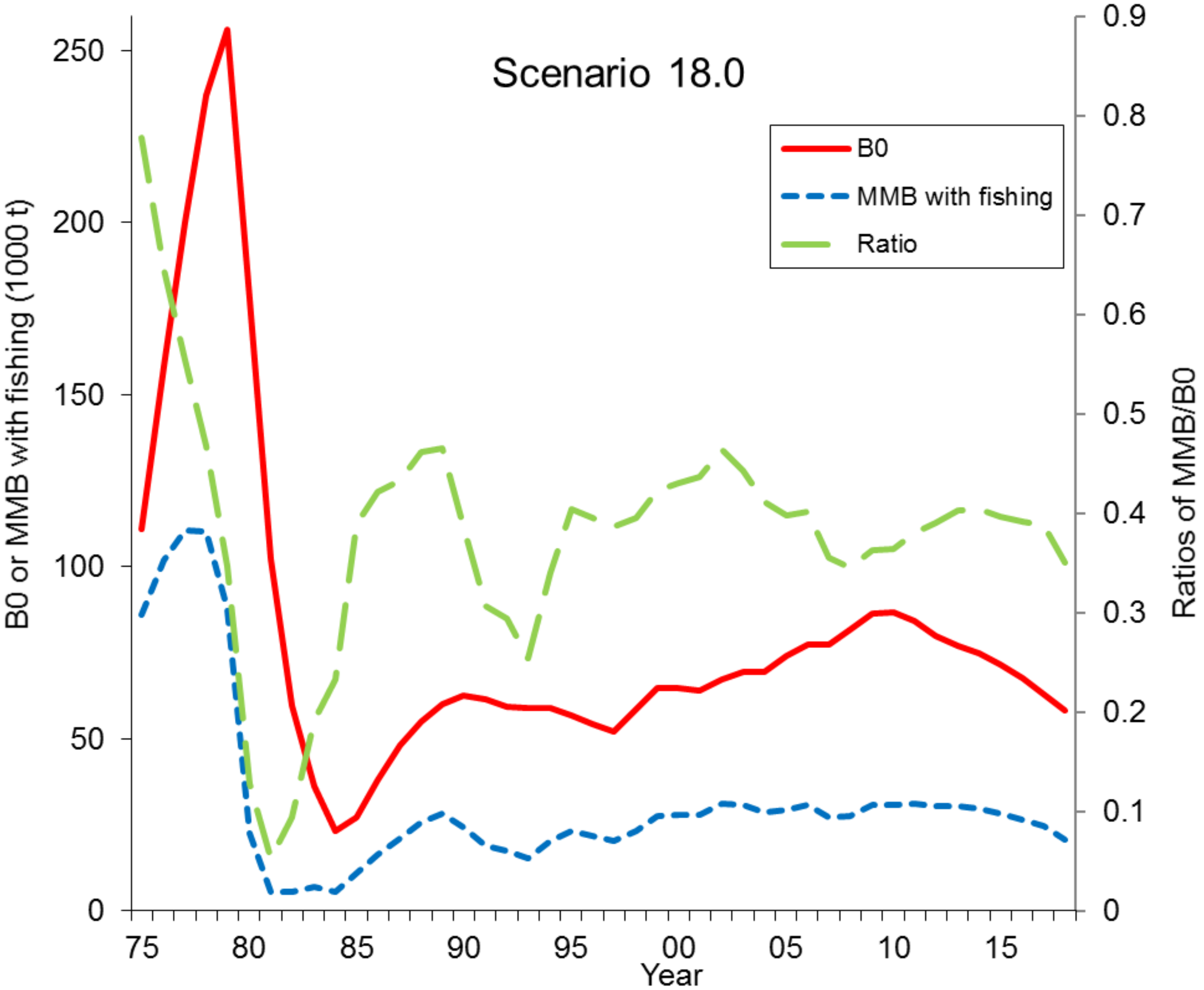

Figure D1. Estimated B0, MMB with fishing, and ratios of MMB/B0 from 1975 to 2018 for scenario 18.0 for Bristol Bay red king crab.