BRISTOL BAY RED KING CRAB STOCK ASSESSMENT IN SPRING 2017

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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 2015/16 was about 10 million lbs (4,500 t), similar to the catch in 2014/15. The magnitude of bycatch from groundfish trawl fisheries has been stable and small relative to stock abundance during the last 10 years.
3. Stock biomass: Estimated mature biomass increased dramatically in the mid-1970s and decreased precipitously in the early 1980s. Estimated mature crab abundance had increased during 1985-2009 with mature females being about 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 1984-2016, only in 1984, 1986, 1995, 1999, 2002 and 2005 were estimated recruitments above the historical average for 1976-2016. Estimated recruitment was extremely low during the last nine years.
5. Management performance:

Status and catch specifications (1,000 t) (scenario 2):

Year	MSST	Biomass (MMB)	TAC	Retained Catch	Total Catch	OFL	ABC
2012/13	13.19[A]	29.05[A]	3.56	3.62	3.90	7.96	7.17
2013/14	12.85[B]	27.12[B]	3.90	3.99	4.56	7.07	6.36
2014/15	13.03[C]	27.25[C]	4.49	4.54	5.44	6.82	6.14
2015/16	12.89[D]	27.68[D]	4.52	4.61	5.34	6.73	6.06
2016/17		24.00[D]				6.64	5.97

The stock was above MSST in 2015/16 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
2012/13	29.1[A]	64.0[A]	7.85	7.98	8.59	17.55	15.80
2013/14	28.3[B]	59.9[B]	8.60	8.80	10.05	15.58	14.02
2014/15	28.7[C]	60.1[C]	9.99	10.01	11.99	15.04	13.53
2015/16	28.4[D]	61.0[D]	9.97	10.17	11.77	14.84	13.36
2016/17		52.9[D]				14.63	13.17

Notes:
A – Calculated from the assessment reviewed by the Crab Plan Team in September 2013
B – Calculated from the assessment reviewed by the Crab Plan Team in September 2014
C – Calculated from the assessment reviewed by the Crab Plan Team in September 2015
D – Calculated from the assessment reviewed by the Crab Plan Team in September 2016

6. Basis for the OFL: All table values are in 1000 t (Scenario 2):

Year	Tier	B_{MSY}	Current MMB	B/B_{MSY} (MMB)	F_{OFL}	Years to define B_{MSY}	Natural Mortality
2012/13	3b	27.5	26.3	0.96	0.31	1984-2012	0.18
2013/14	3b	26.4	25.0	0.95	0.27	1984-2013	0.18
2014/15	3b	25.7	24.7	0.96	0.28	1984-2014	0.18
2015/16	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

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
2012/13	3b	60.7	58.0	0.96	0.31	1984-2012	0.18
2013/14	3b	58.2	55.0	0.95	0.27	1984-2013	0.18
2014/15	3b	56.7	54.4	0.96	0.28	1984-2014	0.18
2015/16	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

A. Summary of Major Changes

1. Change to management of the fishery: None.

2. Changes to the input data:

a. Updating BSFRF side-by-side trawl survey data in 2016. Total survey biomass decreased from 87725.1 t initially estimated in September 2016 to 77815.7 t in the final estimate, about 11.3% reduction. The initial estimate mistakenly includes the tows conducted in the recruitment study.

b. Updating groundfish fisheries bycatch data during 2009-2015 and separating bycatch data by trawl fisheries and fixed gear fisheries.

3. Changes to the assessment methodology:

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

Scenario 2: the same as Scenario 2 in the SAFE report in September 2016 with the same data. 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.

Scenario 2a: the same as scenario 2 except with the updated BSFRF side-by-side data in 2016 and changing the fishing time of the groundfish fisheries bycatch from the same time as the directed pot fishery under scenario 2 to the mid-point of the crab year (the same as Tanner crab fishery bycatch) to more accurately reflect the fishing timing. To reduce the number of estimated parameters, all fishing mortalities for the terminal year are not estimated during parameter estimation since the fisheries have not occurred in the model.

Scenario 2b: the same as scenario 2a except with updated groundfish fisheries bycatch data during 2009-2015 and separating groundfish fisheries bycatch by trawl fisheries and fixed gear fisheries.

Scenario 2c: the same as scenario 2b except without trawl survey catchability prior from the double-bag experiment.

Scenario 2d: the same as scenario 2c except using a logit transformation to make sure trawl survey catchability be <1.0.

b. A recruitment breakpoint analysis is conducted (Appendix B).

4. Changes to assessment results:

The population biomass estimates in 2016 are slightly lower than those in 2015. Among the five scenarios, model estimated relative survey biomasses are very similar. The absolute population biomass estimates are higher for scenarios 2, 2a and 2b than for scenarios 2c and 2d due to lower estimated trawl survey catchability values. We recommend either scenario 2b or 2d for September 2017 assessment because of corrected data and refined approaches to estimation of survey catchability.

The recruitment breakpoint analysis (Appendix B) estimates 1986 as the breakpoint brood year, or 1992 recruitment year.

B. Responses to SSC and CPT Comments

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

None.

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

Response to CPT Comments (from May 2016)

"The CPT had several comments about this approach. First, it was noted at NMFS/BSRF ratios were highly variable, and that a better approach would be to consider the ratio of the NMFS survey to the sum of two surveys NMFS/(NMFS+BSFRF). Second, an attempt should be made to fit actual tow-by-tow data rather than survey aggregates. Finally, catchability for the NMFS survey was estimated to be greater than one for some model runs (this only occurred when the prior was omitted).It was suggested that catchability could be limited to values less than one by parameterizing catchability on a logit scale. The CPT concluded that these issues needed to be addressed before scenario 3 could be adopted."

The ratio of the NMFS survey to the sum of two surveys NMFS/(NMFS+BSFRF) was also evaluated in May 2016 and the results were not presented to the CPT meeting but were added to the final draft report. We agree that this approach is better than the NMFS/BSRF ratios.

Due to very small amount of crab caught in each tow, it is not feasible to fit the actual tow-by-tow data.

We examined the approach to parameterize catchability on a logit scale so that it is less or equal to 1.0 in this report (scenario 2d) (May 2017).

"The CPT requests that the following models be brought forward in September 2016: scenario 1 (status quo), scenario 1n, and scenario 2. Since results from the 2016 BSFRF survey will be available on the same timetable as the 2016 NMFS survey, these data should be incorporated into scenarios 1n and 2."

These three scenarios were presented in the September 2016 SAFE report.

Response to CPT Comments (from September 2016)

"The CTP requests that model runs be provided to evaluate the impact of including or excluding the prior on catchability based on the under-bag experiment."

Among five scenarios in this report, scenario 2b is with the prior on catchability, scenario 2c without the prior on catchability, and scenario 2d without the prior on catchability but with a logit transformation of survey catchability parameter so that it is less than 1.0.

Response to SSC Comments specific to this assessment (from June 2016):

"The SSC supports the CPT recommendation to bring forward three scenarios for the stock assessment in fall 2016: (1) scenario 1, which is the status quo (2015) using BSFRF data from 2007 ad 2008 in which the two surveys are treated as independent surveys and survey selectivities are estimated separately and directly in the model; (2) scenario 1n, which is the same as scenario 1 but also includes the 2013-2015 BSFRF survey data, and (3) scenario 2, which is the same as scenario 1n but assumes that the BSFRF survey has capture probabilities of 1.0 for all length groups.

When these scenarios are presented, the terms "capture probabilities" and "selectivity" should be clearly defined. In the report, their descriptions seemed somewhat confusing and contradictory. For instance, Figure 6 implies catchabilities at small sizes in the BSFRF survey that are less than 1.0 for all scenarios, but from the text, this should not be the case. It is important that the definitions and procedures are clearly described."

We reported the results of these three scenarios in this SAFE report and clarified use of the terms "capture probabilities" and "selectivity" throughout the report.

Response to SSC Comments specific to this assessment (from October 2015)

"The SSC recommends that the authors examine whether or not the current time period for estimation of biological reference points is indicative of the expected range of recruitment given current environmental conditions. The SSC also notes that although no barren females were observed, a large number of females had ¾ full clutches. This observation may suggest that the

population may be undergoing environmental stress. Above average recruitment has not been observed in the last 12 years and the apparent spike in recruitment observed in the 2012 survey did not recruit to the adult population. These observations raise concerns about the future status of the stock. The SSC recommends an examination of mechanisms underlying lack of recruitment to this stock. Specifically, the SSC requests that the author uses the breakpoint analysis applied for Tanner crab to BBRKC to evaluate whether there was a detectable break in production in 2006. This analysis should be conducted as a diagnostic tool to identify possible changes in production of this stock but should not be used to change the time frame used to estimate biological reference points."

We conducted a recruitment breakpoint analysis similar to those on Tanner crab in 2013 (Appendix B). With either a Ricker or Beverton-Bolt stock-recruitment model, the estimated breakpoint brood year is 1986, or recruitment year 1992. Low recruitments in recent years are a big concern, and without a field study on the mechanisms underlying lack of recruitment to this stock, it is difficult to figure out what the real causes are. We will continue to look out for environmental data to improve understanding the recruitment dynamics of this stock.

"The SSC is supportive of continued research on trawl performance. It would be useful to examine temperature and size effects on spatial aggregation of BBRKC and the relationship between these factors and trawl performance. Given the importance of the BSFRF survey in this assessment, the SSC concurs with the CPT that further research should be conducted to assess the potential for herding with the BSFRF net. The SSC supports the CPT request for an exploration of the impact of including or excluding the prior on catchability based on the under-bag experiment."

We support the continued research on trawl performance by NMFS and BSFRF.

We have three scenarios in this report to examine the impact of including or excluding the prior on catchability based on the under-bag experiment: scenario 2b is with the prior on catchability, scenario 2c without the prior on catchability, and scenario 2d without the prior on catchability but with a logit transformation of survey catchability parameter so that it is less than 1.0.

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 survey data in 2016.

Catch and biomass data were updated to 2015/16. Groundfish fisheries bycatch data during 2009-2015 were updated and separated into trawl fisheries and fixed gear fisheries bycatches.

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 2015. Bycatch data are available starting from 1990 and were obtained from the ADF&G observer database and reports (Gaeuman 2013). Sample sizes for catch by length and shell condition are summarized in Table 2. Relatively large samples were taken from the retained catch each year. Sample sizes for trawl bycatch were the annual sums of length frequency samples in the National Marine Fisheries Service (NMFS) database.

(i). Catch Biomass

Retained catch and estimated bycatch biomasses are summarized in Table 1 and illustrated in Figure 2. Retained catch and estimated bycatch from the directed fishery include the general, open-access fishery (prior to rationalization), or the individual fishery quota (IFQ) fishery (after rationalization), as well as the Community Development Quota (CDQ) fishery and the ADF&G cost-recovery harvest. Starting in 1973, the fishery generally occurred during the late summer and fall. Before 1973, a small portion of retained catch in some years was caught from April to June. Because most crab bycatch from the groundfish trawl fisheries occurred during the spring, the years in Table 1 are one year less than those from the NMFS trawl bycatch database to approximate the annual bycatch for reporting years defined as June 1 to May 31; e.g., year 2002 in Table 1 for trawl bycatch corresponds to what is reported for year 2003 in the NMFS database. Catch biomass is shown in Figure 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 1975-2016 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 2016.

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

4. Bering Sea Fisheries Research Foundation Survey Data

The BSFRF conducted trawl surveys for Bristol Bay RKC in 2007 and 2008 with a small-mesh trawl net and 5-minute tows. The surveys occurred at similar times as the NMFS standard surveys and covered about 97% of the Bristol Bay area. Few Bristol Bay RKC were found outside of the BSFRF survey area. Because of the small mesh size, the BSFRF surveys were expected to catch more of RKC within the swept area. Crab abundances of different size groups were estimated by the kriging method. Mature male abundances were estimated to be 22.331 in 2007 and 19.747 million in 2008 with respective CVs of 0.0634 and 0.0765. BSFRF also conducted a side-by-side survey concurrent with the NMFS trawl survey during 2013-2016 in Bristol Bay.

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 2016.

2. Model Description

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

a-f. See appendix A.

g. Critical assumptions of the model:

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

ii. Survey and fisheries selectivities are a function of length and were constant over shell condition. Selectivities are also a function of sex except for trawl bycatch selectivities, which are the same for both sexes. Two different survey selectivities were estimated: (1) 1975-1981 and (2) 1982-2016, 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 1994-2016) 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):

2. The base scenario in September 2016. Scenario 2 includes:

(1) Basic *M* = 0.18, with an additional mortality level during 1980-1984 for males and two additional mortality levels (one for 1980-1984 and the other for 1976-1979 and 1985-1993) for females.

(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 and directly 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. Effective sample sizes are estimated as min(0.5*observed-size, N) for trawl surveys and min(0.1*observed-size, N) for catch and bycatch, where N is the maximum sample size (200 for trawl surveys, 100 for males from the pot fishery and 50 for females from pot fishery and both males and females from the groundfish fisheries. There is a

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

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:

(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 2, 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:

$$\hat{N}^b_{s,y,l} = N_{s,y,l} s^b_{s,l}, \qquad \hat{N}^n_{s,y,l} = N_{s,y,l} s^n_{s,l}, \tag{2}$$

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

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

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 2 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):

$$s^n_{s,l} = p_{s,l} s^b_{s,l}. \tag{4}$$

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.

2a. Scenario 2a is the same as scenario 2 except with the updated BSFRF side-by-side data in 2016 and changing the fishing time of the groundfish fisheries bycatch from the same time as the directed pot fishery under scenario 2 to the mid-point of the crab year (the same as Tanner crab fishery bycatch) to more accurately reflect the fishing timing. To reduce the number of estimated parameters, all fishing mortalities for the terminal year are not estimated during parameter estimation since the fisheries have not occur in the model.

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. Scenario 2b is the same as scenario 2a except with updated groundfish fisheries bycatch data during 2009-2015 and separating bycatch by trawl fisheries and fixed gear fisheries.

2c. Scenario 2c is the same as scenario 2b except without trawl survey catchability prior from the double-bag experiment.

2d. Scenario 2d is the same as scenario 2c except using a logit transformation to make sure trawl survey catchability be <1.0:

$$Q = \exp(x)/(1+\exp(x)), \tag{6}$$

where x is estimated as a parameter.

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:

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

with the final jittered starting parameter value backtransformed as:

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

where P_{max} and P_{min} are upper and lower bounds of parameters and P_{val} is the estimated parameter value before the jittering. The jittering results are summarized in Table 3 for three scenarios. Most runs converge to the highest log likelihood values.

4. Results

a. Effective sample sizes and weighting factors.

i. The effective sample sizes are:

(1) Trawl surveys: 200 for males and females except for females: 184 in 1986, 180 in 1992, and 133 in 1994, and except for males 187 in 2016.
(2) Retained catch: 100.
(3) Pot male discard: 100 except 87 in 1990 and 23 in 1996.
(4) Pot female discard: 50 except 38 in 1991, 1 in 1996, 4 in 1999, and 30 in 2002.
(5) Trawl bycatch (scenarios 2 and 2a): 50 for males and females except for males 44 in 1988, 21 in 1991 and 1992, 33 in 1994, 10 in 1995, and for females 28 in 1986 and 1988, 19 in 1989, 40 in 1991, 11 in 1992, 25 in 1994, 4 in 1995, 48 in 1997.

Trawl bycatch (scenarios 2b, 2c and 2d): 50 for males and females except for males 44 in 1988, 21 in 1991 and 1992, 33 in 1994, 10 in 1995, 44 in 2010, 22 inn 2011, 14 in 2012, 30 in 2013, 15 in 2014 and 12 in 2015, and for females 28 in 1986 and 1988, 19 in 1989, 40 in 1991, 11 in 1992, 25 in 1994, 4 in 1995, 48 in 1997, 46 in 2009, 43 in 2010, 21 in 2011, 13 in 2012, 17 in 2013, 8 in 2014, and 15 in 2015.

Fixed gear bycatch (scenarios 2b, 2c, and 2d): 0 before 2009 and 50 for males and females except for males 15 in 2010 and 34 in 2011, and for females 36 in 2009 and 40 in 2010.

(6) Tanner fishery bycatch: 50 for males and females except for males 28 in 1992, 23 in 1993, 22 in 2013, and 26 inn 2014, and for females 27 in 1993 and 38 in 2014.

(7) BSFRF survey:

Year:	2007	2008	2013	2014	2015	2016
Females:	200	200	56	103	92	99
Males:	200	200	95	109	106	48

For scenario 2, effective sample sizes are illustrated in Figures 6 and 7.

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

iii. Initial trawl survey catchability (*Q*) is estimated to be 0.896 with a standard deviation of 0.025 (CV about 0.03) based on the double-bag experiment results. These values are used as a prior for estimating *Q* in the model for scenarios 2, 2a and 2b.

b. Tables of estimates.

i. Parameter estimates for scenarios 2 and 2d are summarized in Tables 4 and 5.

ii. Abundance and biomass time series are provided in Table 6 for scenarios 2 and 2d.

iii. Recruitment time series for scenarios 2 and 2d 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 low selectivities for male pot bycatch, relative to the retained catch, reflected the 20% handling mortality rate (Figure 8). Both selectivities were applied to the same level of full fishing mortality. Estimated selectivities for female pot bycatch were close to 1.0 for all mature females, and the estimated full fishing mortalities for female pot bycatch were lower than for male retained catch and bycatch (Table 5).

c. Graphs of estimates.

i. Selectivities and molting probabilities by length are provided in Figures 8 and 9 for scenarios 2, 2b and 2d.

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, which is higher than that estimated from the BSFRF surveys (0.854). The reliability of estimated survey selectivities will greatly affect the application of the model to fisheries management. Under- or overestimates of survey selectivities will cause a systematic upward or downward bias of abundance estimates. Information about crab availability to the survey area at survey times will help estimate the survey selectivities.

For all scenarios, estimated molting probabilities during 1975-2016 (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 five scenarios and fit the survey data quite well. The absolute population biomass estimates are slightly higher for scenarios 2, 2a, and 2b than for scenarios 2c and 2d during recent years due to a slightly lower estimate of trawl survey selectivities for scenarios 2, 2a and 2b.

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

iv. Estimated fishing mortality rates are plotted against mature male biomass in Figure 13 for scenarios 2 and 2d.

The average of estimated male recruits from 1984 to 2016 (Figure 12) and mature male biomass per recruit were used to estimate $B_{35\%}$. Alternative periods of 1976-present and 1976-1983 were compared in our report. The full fishing mortalities for the directed pot fishery at the time of fishing were plotted against mature male biomass on Feb. 15 (Figure 13). Estimated fishing mortalities in most years before the current harvest strategy was adopted in 1996 were above $F_{35\%}$ (Figure 13). Under the current harvest strategy, estimated fishing mortalities were at or above the $F_{35\%}$ limits in 1998, 2005, 2007-2009 for scenarios 2 and 2a but below the $F_{35\%}$ limits in the other post-1995 years. The higher estimated survey selectivities from scenario 2c result in relatively higher fishing mortalities than those with scenarios 2, 2a, 2b and 2d.

For scenario 2d, estimated full pot fishing mortalities ranged from 0.00 to 2.15 during 1975-2015. Estimated values were greater than 0.40 during 1975-1981, 1985-1987, 1993 and 2007-2008 (Table 5, Figure 13). For scenario 2a, estimated full pot fishing mortalities ranged from 0.00 to 2.08 during 1975-2015, with estimated values over 0.40 during 1975-1981, 1985-1987 and 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 1 (Figure 14a). Annual stock productivities are illustrated in Figure 14b.

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

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

d. Graphic evaluation of the fit to the data.

   i. Observed vs. estimated catches are plotted in Figure 16.
   ii. Model fits to total survey biomass are shown in Figure 10 with a standardized residual plot in Figure 17.
   iii. Model fits to catch and survey proportions by length are illustrated in Figures 18-24 and residual bubble plots are shown in Figures 25-26.

The model (five 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, and trawl bycatch, the deviations of observed and predicted (estimated) fishery biomass are mainly due to size composition differences.

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

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

Standardized residuals of total survey biomass and proportions of length are plotted to examine their patterns. Residuals were calculated as observed minus predicted and standardized by the estimated standard deviation. Standardized residuals of total survey biomass did not show any consistent patterns (Figure 17). Standardized residuals of proportions of survey males appear to be random over length and year (Figure 25). There is an interesting pattern for residuals of proportions of survey females. Residuals were generally negative for large-sized mature females during 1975-1987 for scenarios 1 and 1n (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 (**not updated from fall 2016**).

Two kinds of retrospective analyses were conducted for this report: (1) the 2016 model (scenario 2d) hindcast results and (2) historical results. The 2016 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 2016 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 2016 model includes sequentially excluding one-year of data. The model with scenario 1 performed reasonably well during 2008-2015 with a lower terminal year estimates in 2012 and 2013 and higher estimates during 2008-2010 (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 2016 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 2016 model results (retrospective analysis) performed reasonably well. No great overestimates or underestimates occurred as was observed in assessments for Pacific halibut (*Hippoglossus stenolepis*) (Parma 1993) and some eastern Bering Sea groundfish stocks (Zheng and Kruse 2002; Ianelli et al. 2003). Since the most recent model was not used to set TAC or overfishing limits until 2009, historical implications for management from the stock assessment errors cannot be evaluated at the current time. However, management implications of the ADF&G stock assessment model were evaluated by Zheng and Kruse (2002).

f. Uncertainty and sensitivity analyses

i. Estimated standard deviations of parameters are summarized in Table 5 for scenarios 2 and 2d. 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 2d using the mcmc approach; estimated Qs are generally less than 1.0. Probabilities for mature male biomass and OFL in 2016 are illustrated in Figure 31 for scenarios 2d 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 (May 2017), five scenarios are compared. Model estimated relative survey biomasses are very similar among the scenarios except for higher relative biomass estimates for scenario 2c during 1970s. The absolute population biomass estimates are higher for scenarios 2, 2a, 2b and 2d than for scenario 2c for all years due to lower trawl survey catchability estimates for the those scenarios. A slightly higher estimate of NMFS trawl survey catchability for scenario 2d also results in slightly lower absolute biomass than for scenarios 2, 2a and 2b. Overall, the results for all five scenarios are similar except those impacted by estimates of NMFS trawl survey catchability. We recommend either scenario 2b or 2d for September 2017 assessment because of corrected data and refined approaches to estimation of survey catchability.

F. Calculation of the OFL and ABC

1. Bristol Bay RKC is currently placed in Tier 3b (NPFMC 2007).

2. For Tier 3 stocks, estimated biological reference points include $B_{35\%}$ and $F_{35\%}$. Estimated model parameters were used to conduct mature male biomass-per-recruit analysis.
3. Specification of the OFL:

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

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

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

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

   Where

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

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

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

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

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

   Because trawl bycatch fishing mortality was not related to pot fishing mortality, average trawl bycatch fishing mortality during 2006 to 2015 was used for the per recruit analysis as well as for projections in the next section. Pot female bycatch fishing mortality was set equal to pot male fishing mortality times 0.02, an intermediate level during 1990-2015. 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 2013-2015 were used to represent current trends for per recruit analysis and projections. Average molting probabilities during 2006-2015 were used for per recruit analysis and projections.

   Average recruitments during three periods were used to estimate $B_{35\%}$: 1976-1983, 1976-2016, and 1984-2016 (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 1984-2016 as the baseline.

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

The estimated probability distribution of MMB in 2016 is illustrated in Figure 30. Based the SSC suggestion in 2011, ABC = 0.9*OFL is used to estimate ABC.

Status and catch specifications (1,000 t) (scenario 2):

Year	MSST	Biomass (MMB)	TAC	Retained Catch	Total Catch	OFL	ABC
2012/13	13.19[A]	29.05[A]	3.56	3.62	3.90	7.96	7.17
2013/14	12.85[B]	27.12[B]	3.90	3.99	4.56	7.07	6.36
2014/15	13.03[C]	27.25[C]	4.49	4.54	5.44	6.82	6.14
2015/16	12.89[D]	27.68[D]	4.52	4.61	5.34	6.73	6.06
2016/17		24.00[D]				6.64	5.97

The stock was above MSST in 2015/16 and is hence not overfished. Overfishing did not occur.

Status and catch specifications (million lbs):

Year	MSST	Biomass (MMB)	TAC	Retained Catch	Total Catch	OFL	ABC
2012/13	29.1[A]	64.0[A]	7.85	7.98	8.59	17.55	15.80
2013/14	28.3[B]	59.9[B]	8.60	8.80	10.05	15.58	14.02
2014/15	28.7[C]	60.1[C]	9.99	10.01	11.99	15.04	13.53
2015/16	28.4[D]	61.0[D]	9.97	10.17	11.77	14.84	13.36
2016/17		52.9[D]				14.63	13.17

Notes:

A – Calculated from the assessment reviewed by the Crab Plan Team in September 2013
B – Calculated from the assessment reviewed by the Crab Plan Team in September 2014
C – Calculated from the assessment reviewed by the Crab Plan Team in September 2015
D – Calculated from the assessment reviewed by the Crab Plan Team in September 2016

4. Based on the $B_{35\%}$ estimated from the average male recruitment during 1984-2016, the biological reference points and OFL were estimated as follows:

	Scenario 2		Scenario 2a		Scenario 2b		Scenario 2c		Scenario 2d	
	1,000t	Mi. lbs	1,000t	Mi. lbs	1,000t	Mi. lbs	1,000t	Mi. lbs	1,000t	Mi. lbs
$B_{35\%}$	25.785	56.846	25.818	56.919	25.930	57.166	24.487	53.984	25.588	56.411
$F_{35\%}$	0.29		0.29		0.29		0.29		0.29	
MMB_{2016}	23.999	52.908	24.086	53.101	24.726	54.510	22.027	48.562	24.116	53.167
OFL_{2016}	6.637	14.633	6.692	14.753	7.047	15.536	5.791	12.767	6.770	14.926
ABC_{2016}	5.937	13.169	6.022	13.277	6.342	13.983	5.212	11.490	6.093	13.434

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

G. Rebuilding Analyses

NA.

H. Data Gaps and Research Priorities

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

I. Projections and Future Outlook

1. Projections

Future population projections primarily depend on future recruitment, but crab recruitment is difficult to predict. Therefore, annual recruitment for the projections was a random selection from estimated recruitments during 1984-2016. Besides recruitment, the other major uncertainty for the projections is estimated abundance in 2016. The 2016 abundance was randomly selected from the estimated normal distribution of the assessment model output for each replicate. Three scenarios of fishing mortality for the directed pot fishery were used in the projections:

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

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

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

Each scenario was replicated 1,000 times and projections made over 10 years beginning in 2016 (Table 7).

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

2. Near Future Outlook

The near future outlook for the Bristol Bay RKC stock is a declining trend. The three recent above-average year classes (hatching years 1990, 1994, and 1997) had entered the legal population by 2006 (Figure 34). Most individuals from the 1997 year class will continue to gain weight to offset loss of the legal biomass to fishing and natural mortalities. The above-average year class (hatching year 2000) with lengths centered around 87.5 mm CL for both males and females in 2006 and with lengths centered around 112.5-117.5 mm CL for males and around 107.5 mm CL for females in 2008 has largely entered the mature male population in 2009 and the legal population by 2014 (Figure 34). No strong cohorts have been observed in the survey data after this cohort through 2010 (Figure 34). There was a huge tow of juvenile crab of size 45-55 mm in 2011, but these juveniles were not observed during 2012-2016 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 2015-2016 survey results (Figure 34). Due to lack of recruitment, mature and legal crab should continue to decline next year. Current crab abundance is still low relative to the late 1970s, and without favorable environmental conditions, recovery to the high levels of the late 1970s is unlikely.

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

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

2001	3811.5	54.6	0	3866.2	417.9	173.5	164.6	0.0	4622.1
2002	4340.9	43.6	0	4384.5	442.7	7.3	155.1	0.0	4989.6
2003	7120.0	15.3	0	7135.3	918.9	430.4	172.3	0.0	8656.9
2004	6915.2	91.4	0	7006.7	345.5	187.0	119.6	0.0	7658.8
2005	8305.0	94.7	0	8399.7	1359.5	498.3	155.2	0.0	10412.8
2006	7005.3	137.9	0	7143.2	563.8	37.0	116.7	3.8	7864.4
2007	9237.9	66.1	0	9303.9	1001.3	186.1	138.5	1.8	10631.6
2008	9216.1	0.0	0	9216.1	1165.5	148.4	159.5	4.0	10693.5
2009	7226.9	45.5	0	7272.5	888.1	85.2	103.7	1.6	8351.2
2010	6728.5	33.0	0	6761.5	797.5	122.6	85.3	0.0	7767.0
2011	3553.3	53.8	0	3607.1	395.0	24.0	68.8	0.0	4094.9
2012	3560.6	61.1	0	3621.7	205.2	12.3	61.2	0.0	3900.5
2013	3901.1	89.9	0	3991.0	310.6	99.8	136.2	28.5	4566.0
2014	4530.0	8.6	0	4538.6	584.7	86.2	221.9	42.0	5473.4
2015	4522.3	91.4	0	4613.7	266.1	222.9	149.4	84.2	5336.3

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/Trawl		Standardized Crab/tan
	Catch	Crab/tan	Catch	Crab/tan	Catch	Crab/Potlift	
1960	1.949	15.2	1.995	10.4	0.088		15.8
1961	3.031	11.8	3.441	8.9	0.062		12.9
1962	4.951	11.3	3.019	7.2	0.010		11.3
1963	5.476	8.5	3.019	5.6	0.101		8.6
1964	5.895	9.2	2.800	4.6	0.123		8.5
1965	4.216	9.3	2.226	3.6	0.223		7.7
1966	4.206	9.4	2.560	4.1	0.140	52	8.1
1967	3.764	8.3	1.592	2.4	0.397	37	6.3
1968	3.853	7.5	0.549	2.3	1.278	27	7.8
1969	2.073	7.2	0.369	1.5	1.749	18	5.6
1970	2.080	7.3	0.320	1.4	1.683	17	5.6
1971	0.886	6.7	0.265	1.3	2.405	20	5.8
1972	0.874	6.7			3.994	19	
1973	0.228				4.826	25	
1974	0.476				7.710	36	
1975					8.745	43	
1976					10.603	33	
1977					11.733	26	
1978					14.746	36	
1979					16.809	53	
1980					20.845	37	
1981					5.308	10	
1982					0.541	4	
1983					0.000		
1984					0.794	7	
1985					0.796	9	
1986					2.100	12	
1987					2.122	10	
1988					1.236	8	
1989					1.685	8	
1990					3.130	12	
1991					2.661	12	
1992					1.208	6	
1993					2.270	9	
1994					0.015		
1995					0.014		
1996					1.264	16	
1997					1.338	15	
1998					2.238	15	
1999					1.923	12	
2000					1.272	12	
2001					1.287	19	
2002					1.484	20	
2003					2.510	18	
2004					2.272	23	
2005					2.763	30	
2006					2.477	31	
2007					3.154	28	
2008					3.064	22	
2009					2.553	21	
2010					2.410	18	
2011					1.298	28	
2012					1.176	30	
2013					1.272	27	
2014					1.501	26	
2015					1.527	31	

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

Year	Trawl Survey		Retained Catch	Pot Bycatch		Trawl Bycatch		Tanner Fishery Bycatch	
	Males	Females		Males	Females	Males	Females	Males	Females
1975	2,943	2,139	29,570						
1976	4,724	2,956	26,450			2,327	676		
1977	3,636	4,178	32,596			14,014	689		
1978	4,132	3,948	27,529			8,983	1,456		
1979	5,807	4,663	27,900			7,228	2,821		
1980	2,412	1,387	34,747			47,463	39,689		
1981	3,478	4,097	18,029			42,172	49,634		
1982	2,063	2,051	11,466			84,240	47,229		
1983	1,524	944	0			204,464	104,910		
1984	2,679	1,942	4,404			357,981	147,134		
1985	792	415	4,582			169,767	30,693		
1986	1,962	367	5,773			1,199	284		
1987	1,168	1,018	4,230			723	927		
1988	1,834	546	9,833			437	275		
1989	1,257	550	32,858			3,147	194		
1990	858	603	7,218	873	699	761	1,570		
1991	1,378	491	36,820	1,801	375	208	396	885	2,198
1992	513	360	23,552	3,248	2,389	214	107	280	685
1993	1,009	534	32,777	5,803	5,942			232	265
1994	443	266	0	0	0	330	247		
1995	2,154	1,718	0	0	0	103	35		
1996	835	816	8,896	230	11	1,025	968		
1997	1,282	707	15,747	4,102	906	1,202	483		
1998	1,097	1,150	16,131	11,079	9,130	1,627	915		
1999	764	540	17,666	1,048	36	2,154	858		
2000	731	1,225	14,091	8,970	1,486	994	671		
2001	611	743	12,854	9,102	4,567	4,393	2,521		
2002	1,032	896	15,932	9,943	302	3,372	1,464		
2003	1,669	1,311	16,212	17,998	10,327	1,568	1,057		
2004	2,871	1,599	20,038	8,258	4,112	1,689	1,506		
2005	1,283	1,682	21,938	55,019	26,775	1,815	1,872		
2006	1,171	2,672	18,027	32,252	3,980	1,481	1,983		
2007	1,219	2,499	22,387	59,769	12,661	1,011	1,097		
2008	1,221	3,352	14,567	49,315	8,488	1,867	1,039		
2009	830	1,857	16,708	52,359	6,041	1,482	870		
2010	705	1,633	20,137	36,654	6,868	734	846		
2011	525	994	10,706	20,629	1,920	600	1,069		
2012	580	707	8,956	7,206	561	1,577	1,752		
2013	633	560	10,197	13,828	6,048	4,681	4,198	218	596
2014	1,106	1,255	9,618	13,040	1,950	1,966	2,580	256	381
2015	600	677	11,746	8,037	5,889	1,126	3,704	726	2163
2016	374	803							

Table 4a. Number of parameters and the list of likelihood components for the model (Scenarios 2, 2a, 2b, 2c and 2d).

Parameter counts	**Sce. 2,**	**Sce. 2a**	**Sce. 2b, 2c, 2d**
Fixed growth parameters	9	9	9
Fixed recruitment parameters	2	2	2
Fixed length-weight relationship parameters	6	6	6
Fixed mortality parameters	4	4	4
Fixed survey catchability parameter	1	1	1
Fixed high grading parameters	11	11	11
Total number of fixed parameters	33	33	33
Free survey catchability parameter	1	1	1
Free growth parameters	6	6	6
Initial abundance (1975)	1	1	1
Recruitment-distribution parameters	2	2	2
Mean recruitment parameters	1	1	1
Male recruitment deviations	41	41	41
Female recruitment deviations	41	41	41
Natural and fishing mortality parameters	4	4	4
Pot male fishing mortality deviations	43	42	42
Bycatch mortality from the Tanner crab fishery	11	11	11
Pot female bycatch fishing mortality deviations	28	27	27
Trawl bycatch fishing mortality deviations	42	41	41
Fixed gear bycatch fishing mortality deviations	0	0	8
Initial (1975) length compositions	35	35	35
BSFRF survey extra CV	1	1	1
Free selectivity parameters	22	22	24
Total number of free parameters	279	276	286
Total number of fixed and free parameters	312	309	319

Table 4b. Negative log likelihood components for scenarios 2, 2a, 2b, 2c and 2d and differences in negative log-likelihood components among model scenarios.

	Scenario							
Negative log likelihood	2	2a	2b	2c	2d	2b-2a	2b-2c	2b-2d
R-variation	86.87	83.79	83.85	84.45	83.77	0.05	-0.61	0.08
Length-like-retained	-1005.2	-1010.28	-1011.33	-1012.4	-1011.80	-1.05	1.05	0.47
Length-like-discmale	-1047.2	-1047.3	-1047.5	-1046.0	-1047.2	-0.23	-1.52	-0.35
Length-like-discfemale	-758.31	-757.84	-758.04	-757.49	-757.85	-0.19	-0.55	-0.19
Length-like-survey	-47410	-47411	-47411	-47420	-47413	-0.30	8.40	2.00
Length-like-disctrawl	-3726.3	-3743.9	-3684.7	-3685.0	-3684.8	59.21	0.31	0.04
Length-like-discfix	0.00	0.00	-681.94	-681.76	-681.92	-681.9	-0.18	-0.02
Length-like-discTanner	-465.88	-466.04	-466.20	-467.28	-466.53	-0.16	1.08	0.32
Length-like-bsfrfsurvey	-646.36	-645.03	-645.38	-647.24	-645.67	-0.35	1.86	0.29
Catchbio_retained	48.59	50.92	50.95	52.16	51.15	0.03	-1.21	-0.20
Catchbio_discmale	227.80	227.30	228.83	227.31	228.56	1.52	1.52	0.27
Catchbio-discfemale	0.13	0.10	0.11	0.11	0.11	0.00	-0.01	0.00
Catchbio-disctrawl	0.92	0.22	0.21	0.25	0.22	-0.01	-0.04	-0.01
Catchbio-discfix	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Catchbio-discTanner	0.12	0.13	0.13	0.17	0.14	0.00	-0.03	-0.01
Biomass-trawl survey	97.75	102.91	102.55	101.46	101.44	-0.36	1.08	1.11
Biomass-bsfrfsurvey	-8.07	-8.29	-8.45	-7.37	-8.27	-0.16	-1.08	-0.18
Q-trawl survey	2.76	3.63	3.26	0	0	-0.38	3.26	3.26
Others	21.00	16.41	17.91	17.94	18.00	1.50	-0.03	-0.09
Total	-54581	-54604	-55227	-55241	-55234	-622.8	13.30	6.80
Free parameters	279	276	286	286	286	10	0	0
Bmsy(t)	25785	25818	25930	24487	25588	112.0	1443.3	342.2
MMB2016(t)	23999	24086	24726	22027	24116	639.3	2698.3	609.2
OFL2016(t)	6637	6692	7047	5791	6771	355.5	1256.3	276.6
Fofl2016	0.268	0.268	0.275	0.258	0.271	0.007	0.017	0.017

Table 5(2). Summary of estimated model parameter values and standard deviations and limits for scenario 2 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	15.843	0.024	15.843	0.024	-1.971	0.041	0.012	0.001	-5.300	0.062
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					1.123	0.101				
1976	-0.003	0.277	0.813	0.137	1.117	0.071			0.183	0.107
1977	0.531	0.161	0.697	0.103	1.109	0.061			0.707	0.105
1978	0.466	0.137	0.904	0.086	1.316	0.055			0.701	0.104
1979	0.741	0.103	1.178	0.077	1.587	0.052			0.739	0.104
1980	0.247	0.117	1.374	0.076	2.384	0.048			0.783	0.104
1981	0.092	0.150	0.565	0.102	2.425	0.007			0.354	0.104
1982	0.089	0.059	2.138	0.051	0.571	0.047			2.077	0.106
1983	0.018	0.075	1.458	0.051	-10.21	0.713			1.954	0.105
1984	0.465	0.061	1.476	0.049	0.929	0.056			2.914	0.103
1985	0.125	0.199	-0.631	0.122	1.037	0.064			1.863	0.105
1986	0.581	0.064	0.720	0.047	1.596	0.063			0.796	0.105
1987	-0.051	0.144	-0.159	0.074	1.212	0.058			0.485	0.104
1988	0.301	0.176	-0.851	0.107	0.246	0.050			1.461	0.102
1989	0.103	0.158	-0.710	0.089	0.335	0.047			0.051	0.102
1990	-0.025	0.073	0.435	0.046	0.938	0.043	1.996	0.099	0.344	0.102
1991	-0.061	0.098	-0.025	0.056	0.916	0.045	-0.133	0.100	0.683	0.103
1992	-0.586	0.433	-1.771	0.170	0.397	0.046	2.170	0.100	0.859	0.103
1993	-0.249	0.103	-0.257	0.056	1.046	0.048	2.051	0.101	1.111	0.103
1994	-0.464	0.486	-2.116	0.197	-4.100	0.048	1.428	0.128	-0.349	0.104
1995	0.033	0.046	1.311	0.036	-4.444	0.045	1.547	0.133	0.282	0.103
1996	-0.823	0.286	-0.514	0.114	0.102	0.042	-3.650	0.151	-0.428	0.103
1997	-0.916	0.431	-1.381	0.167	0.211	0.043	-0.998	0.102	-0.812	0.103
1998	-0.306	0.127	-0.120	0.068	0.908	0.044	2.070	0.098	-0.093	0.102
1999	0.085	0.064	0.708	0.043	0.462	0.043	-2.064	0.104	0.126	0.102
2000	-0.092	0.148	-0.237	0.081	0.087	0.042	-0.260	0.099	-0.628	0.102
2001	0.673	0.189	-0.890	0.138	0.105	0.042	1.106	0.098	-0.181	0.102
2002	0.236	0.059	1.156	0.041	0.208	0.042	-2.227	0.104	-0.279	0.101
2003	-0.038	0.255	-0.590	0.143	0.732	0.041	1.180	0.099	-0.217	0.101
2004	-0.190	0.159	0.145	0.083	0.591	0.042	0.381	0.098	-0.566	0.102
2005	0.351	0.065	1.072	0.047	1.012	0.043	0.901	0.099	-0.339	0.101
2006	-0.716	0.175	0.468	0.065	0.728	0.042	-1.510	0.100	-0.630	0.102
2007	-0.264	0.161	-0.100	0.083	1.051	0.043	-0.288	0.099	-0.515	0.102
2008	0.151	0.161	-0.558	0.101	1.140	0.045	-0.603	0.099	-0.385	0.102
2009	0.288	0.142	-0.541	0.096	0.838	0.047	-0.830	0.100	-0.832	0.103
2010	0.026	0.103	0.059	0.064	0.692	0.048	-0.289	0.100	-1.060	0.104
2011	0.142	0.107	-0.013	0.071	0.010	0.049	-1.215	0.101	-1.267	0.105
2012	-0.068	0.148	-0.327	0.085	-0.099	0.051	-1.754	0.103	-1.395	0.105
2013	-0.588	0.200	-0.513	0.089	0.076	0.054	0.189	0.100	-0.591	0.105
2014	-0.179	0.386	-1.817	0.190	0.311	0.057	-0.136	0.102	-0.082	0.106
2015	-0.114	0.211	-0.982	0.126	0.264	0.062	0.938	0.103	-0.431	0.107
2016	-0.011	0.367	-1.570	0.198						

Table 5(2) (continued). Summary of estimated model parameter values and standard deviations and limits for scenario 2 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	0.460	0.016	0.184, 1.0	68	1.148	0.103	-5, 5
Mf80-84	0.807	0.021	0.276, 1.5	73	1.176	0.089	-5, 5
Mf76-79,85-93	0.091	0.007	0.0, 0.108	78	0.514	0.108	-5, 5
log_betal, females	0.312	0.058	-0.67, 1.32	83	0.592	0.089	-5, 5
log_betal, males	0.634	0.081	-0.67, 1.32	88	0.405	0.089	-5, 5
log_betar, females	-0.618	0.061	-1.14, 0.5	93	0.215	0.094	-5, 5
log_betar, males	-0.599	0.052	-1.14, 0.5	98	0.222	0.093	-5, 5
Bsfrf_CV	0.000	0.000	0.00, 0.40	103	0.010	0.105	-5, 5
moltp_slope, 75-78	0.134	0.022	0.01, 0.259	108	0.087	0.103	-5, 5
moltp_slope, 79-14	0.099	0.004	0.01, 0.259	113	0.217	0.101	-5, 5
log_moltp_L50, 75-78	4.972	0.013	4.445, 5.52	118	0.017	0.119	-5, 5
log_moltp_L50, 79-14	4.948	0.004	4.445, 5.52	123	0.057	0.124	-5, 5
log_N75	19.994	0.034	15.0, 21.0	128	-0.027	0.140	-5, 5
log_avg_L50_ret	4.921	0.002	4.467, 5.51	133	-0.041	0.149	-5, 5
ret_fish_slope	0.533	0.031	0.05, 0.70	138	-0.142	0.139	-5, 5
pot disc.males, φ	-0.330	0.014	-0.40, 0.00	143	-0.266	0.144	-5, 5
pot disc.males, κ	0.004	0.000	0.0, 0.005	148	-0.454	0.155	-5, 5
pot disc.males, γ	-0.015	0.001	-0.025, 0.0	153	-0.797	0.190	-5, 5
pot disc.fema., slope	0.189	0.062	0.05, 0.43	158	-1.332	0.265	-5, 5
log_pot disc.fema., L50	4.439	0.025	4.20, 4.666	163	-1.354	0.279	-5, 5
trawl disc slope	0.064	0.004	0.01, 0.20	68	1.628	0.105	-5, 5
log_trawl disc L50	4.932	0.028	4.50, 5.40	73	1.529	0.101	-5, 5
log_srv_L50, m, bsfrf	4.338	0.026	3.59, 5.48	78	1.491	0.094	-5, 5
srv_slope, f, bsfrf	0.037	0.006	0.01, 0.435	83	1.324	0.093	-5, 5
log_srv_L50, f, bsfrf	4.475	0.044	4.09, 5.54	88	1.273	0.086	-5, 5
log_srv_L50, m, 75-81	4.348	0.010	4.09, 4.554	93	0.814	0.102	-5, 5
srv_slope, f, 75-81	0.069	0.004	0.01, 0.303	98	0.443	0.125	-5, 5
log_srv_L50, f, 75-81	4.482	0.017	4.09, 4.70	103	0.151	0.149	-5, 5
log_srv_L50, m, 82-14	4.301	0.079	4.09, 5.10	108	-0.004	0.155	-5, 5
srv_slope, f, 82-14	0.064	0.009	0.01, 0.30	113	-0.238	0.180	-5, 5
log_srv_L50, f, 82-14	4.246	0.029	4.09, 4.90	118	-0.824	0.280	-5, 5
TC_slope, females	0.379	0.135	0.02, 0.40	123	-0.924	0.315	-5, 5
log_TC_L50, females	4.532	0.014	4.24, 4.90	128	-1.205	0.408	-5, 5
TC_slope, males	0.245	0.099	0.05, 0.90	133	-2.113	0.880	-5, 5
log_TC_L50, males	4.571	0.019	4.25, 5.14	138	-2.132	0.977	-5, 5
Q	0.955	0.021	0.59, 1.2	143	NA	NA	
log_TC_F, males, 91	-4.137	0.085	-10.0, 1.00				
log_TC_F, males, 92	-6.111	0.087	-10.0, 1.00				
log_TC_F, males, 93	-6.835	0.089	-10.0, 1.00				
log_TC_F, males, 13	-8.301	0.094	-10.0, 1.00				
log_TC_F, males, 14	-7.442	0.093	-10.0, 1.00				
log_TC_F, males, 15	-7.032	0.095	-10.0, 1.00				
log_TC_F, females, 91	-2.921	0.087	-10.0, 1.00				
log_TC_F, females, 92	-4.566	0.087	-10.0, 1.00				
log_TC_F, females, 93	-6.451	0.089	-10.0, 1.00				
log_TC_F, females, 13	-7.743	0.085	-10.0, 1.00				
log_TC_F, females, 14	-7.597	0.085	-10.0, 1.00				
log_TC_F, females, 15	-6.564	0.083	-10.0, 1.00				

Table 5(2d). Summary of estimated model parameter values and standard deviations and limits for scenario 2d 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	15.821	0.022	15.821	0.022	-1.660	0.037	0.012	0.001	-4.562	0.068
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					0.809	0.096				
1976	-0.024	0.275	0.773	0.137	0.791	0.067			0.160	0.111
1977	0.521	0.161	0.642	0.103	0.783	0.057			0.667	0.107
1978	0.452	0.136	0.842	0.085	0.991	0.053			0.737	0.105
1979	0.727	0.102	1.101	0.076	1.286	0.050			0.907	0.105
1980	0.238	0.116	1.276	0.076	2.152	0.045			1.626	0.105
1981	0.097	0.149	0.469	0.102	2.425	0.009			1.177	0.107
1982	0.098	0.058	2.077	0.052	0.583	0.049			2.352	0.107
1983	0.038	0.074	1.409	0.052	-10.589	0.908			2.006	0.104
1984	0.491	0.060	1.450	0.049	0.725	0.056			3.059	0.104
1985	0.132	0.198	-0.617	0.122	0.808	0.064			1.904	0.106
1986	0.588	0.063	0.731	0.047	1.335	0.062			0.969	0.107
1987	-0.034	0.143	-0.152	0.074	0.939	0.057			0.553	0.106
1988	0.311	0.176	-0.850	0.107	-0.031	0.050			1.333	0.102
1989	0.115	0.157	-0.705	0.090	0.059	0.047			-0.107	0.102
1990	-0.018	0.072	0.437	0.046	0.667	0.043	1.996	0.079	0.267	0.102
1991	-0.058	0.098	-0.025	0.056	0.650	0.045	-0.132	0.080	0.606	0.104
1992	-0.550	0.422	-1.771	0.170	0.137	0.046	2.169	0.081	0.659	0.103
1993	-0.255	0.103	-0.257	0.056	0.794	0.048	2.044	0.081	1.082	0.104
1994	-0.424	0.473	-2.122	0.197	-4.348	0.048	1.420	0.113	-0.682	0.103
1995	0.026	0.045	1.318	0.036	-4.704	0.045	1.545	0.119	-0.090	0.102
1996	-0.820	0.281	-0.498	0.113	-0.159	0.043	-3.648	0.139	-0.705	0.103
1997	-0.892	0.422	-1.376	0.168	-0.049	0.043	-1.002	0.084	-1.068	0.103
1998	-0.321	0.128	-0.105	0.068	0.649	0.044	2.054	0.078	-0.202	0.101
1999	0.074	0.064	0.728	0.043	0.201	0.044	-2.080	0.085	-0.038	0.101
2000	-0.100	0.148	-0.216	0.080	-0.177	0.043	-0.270	0.079	-0.858	0.102
2001	0.659	0.190	-0.872	0.139	-0.164	0.043	1.097	0.078	-0.429	0.101
2002	0.220	0.059	1.182	0.041	-0.065	0.043	-2.237	0.086	-0.520	0.101
2003	-0.045	0.255	-0.570	0.144	0.457	0.042	1.176	0.079	-0.375	0.101
2004	-0.211	0.159	0.174	0.082	0.313	0.043	0.384	0.079	-0.743	0.101
2005	0.328	0.065	1.100	0.046	0.733	0.044	0.894	0.078	-0.433	0.101
2006	-0.729	0.175	0.494	0.065	0.444	0.043	-1.510	0.080	-0.769	0.101
2007	-0.280	0.161	-0.074	0.083	0.760	0.044	-0.282	0.079	-0.596	0.102
2008	0.137	0.161	-0.531	0.101	0.844	0.046	-0.597	0.079	-0.449	0.102
2009	0.279	0.142	-0.508	0.095	0.538	0.048	-0.821	0.080	-1.043	0.103
2010	0.022	0.102	0.088	0.064	0.392	0.049	-0.281	0.080	-1.243	0.104
2011	0.135	0.107	0.014	0.071	-0.295	0.050	-1.204	0.082	-1.729	0.105
2012	-0.071	0.148	-0.296	0.085	-0.406	0.052	-1.742	0.084	-2.281	0.107
2013	-0.591	0.199	-0.478	0.089	-0.234	0.055	0.202	0.081	-1.583	0.107
2014	-0.164	0.380	-1.790	0.191	0.001	0.058	-0.124	0.083	-2.180	0.109
2015	-0.131	0.212	-0.945	0.126	-0.046	0.063	0.947	0.085	-1.943	0.111
2016	0.030	0.362	-1.549	0.200						

Table 5(2d) (continued). Summary of estimated model parameter values and standard deviations and limits for scenario 2d 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	0.428	0.016	0.184, 1.0	68	1.161	0.102	-5, 5
Mf80-84	0.792	0.021	0.276, 1.5	73	1.191	0.089	-5, 5
Mf76-79,85-93	0.096	0.007	0.0, 0.108	78	0.530	0.107	-5, 5
log_betal, females	0.310	0.058	-0.67, 1.32	83	0.610	0.090	-5, 5
log_betal, males	0.638	0.080	-0.67, 1.32	88	0.432	0.090	-5, 5
log_betar, females	-0.614	0.061	-1.14, 0.5	93	0.249	0.094	-5, 5
log_betar, males	-0.600	0.052	-1.14, 0.5	98	0.261	0.093	-5, 5
Bsfrf_CV	0.000	0.000	0.00, 0.40	103	0.053	0.105	-5, 5
moltp_slope, 75-78	0.135	0.018	0.01, 0.259	108	0.132	0.104	-5, 5
moltp_slope, 79-14	0.099	0.004	0.01, 0.259	113	0.264	0.101	-5, 5
log_moltp_L50, 75-78	4.976	0.011	4.445, 5.52	118	0.066	0.119	-5, 5
log_moltp_L50, 79-14	4.949	0.004	4.445, 5.52	123	0.109	0.123	-5, 5
log_N75	19.943	0.031	15.0, 21.0	128	0.028	0.138	-5, 5
log_avg_L50_ret	4.922	0.002	4.467, 5.51	133	0.010	0.148	-5, 5
ret_fish_slope	0.524	0.031	0.05, 0.70	138	-0.081	0.138	-5, 5
pot disc.males, φ	-0.322	0.013	-0.40, 0.00	143	-0.202	0.142	-5, 5
pot disc.males, κ	0.004	0.000	0.0, 0.005	148	-0.391	0.154	-5, 5
pot disc.males, γ	-0.015	0.001	-0.025, 0.0	153	-0.733	0.188	-5, 5
pot disc.fema., slope	0.173	0.059	0.05, 0.43	158	-1.276	0.263	-5, 5
log_pot disc.fema., L50	4.446	0.029	4.20, 4.666	163	-1.278	0.272	-5, 5
trawl disc slope	0.058	0.003	0.01, 0.20	68	1.613	0.106	-5, 5
log_trawl disc L50	5.116	0.048	4.50, 5.40	73	1.512	0.102	-5, 5
log_srv_L50, m, bsfrf	4.341	0.026	3.59, 5.48	78	1.474	0.095	-5, 5
srv_slope, f, bsfrf	0.035	0.006	0.01, 0.435	83	1.310	0.093	-5, 5
log_srv_L50, f, bsfrf	4.469	0.046	4.09, 5.54	88	1.262	0.087	-5, 5
log_srv_L50, m, 75-81	4.341	0.010	4.09, 4.554	93	0.809	0.103	-5, 5
srv_slope, f, 75-81	0.071	0.004	0.01, 0.303	98	0.442	0.126	-5, 5
log_srv_L50, f, 75-81	4.466	0.017	4.09, 4.70	103	0.149	0.151	-5, 5
log_srv_L50, m, 82-14	4.383	0.088	4.09, 5.10	108	-0.005	0.158	-5, 5
srv_slope, f, 82-14	0.063	0.008	0.01, 0.30	113	-0.242	0.184	-5, 5
log_srv_L50, f, 82-14	4.272	0.025	4.09, 4.90	118	-0.841	0.292	-5, 5
TC_slope, females	0.377	0.133	0.02, 0.40	123	-0.956	0.333	-5, 5
log_TC_L50, females	4.534	0.014	4.24, 4.90	128	-1.269	0.447	-5, 5
TC_slope, males	0.243	0.098	0.05, 0.90	133	-2.287	1.073	-5, 5
log_TC_L50, males	4.572	0.019	4.25, 5.14	138	-2.400	1.294	-5, 5
Logit Q parameter	3.343	4129.0	-4.5, 10.96	143	NA	NA	
log_TC_F, males, 91	-4.092	0.082	-10.0, 1.00	Fixed gear bycatch parameters:			
log_TC_F, males, 92	-6.063	0.084	-10.0, 1.00	log_avg	-8.051	0.119	
log_TC_F, males, 93	-6.779	0.085	-10.0, 1.00	fmortf_	-1.278	0.111	
log_TC_F, males, 13	-8.303	0.092	-10.0, 1.00	fmortf_	-2.172	0.128	
log_TC_F, males, 14	-7.445	0.090	-10.0, 1.00	fmortf_	-0.661	0.102	
log_TC_F, males, 15	-7.038	0.092	-10.0, 1.00	fmortf_	-0.126	0.099	
log_TC_F, females, 91	-2.874	0.086	-10.0, 1.00	fmortf_	0.999	0.096	
log_TC_F, females, 92	-4.517	0.086	-10.0, 1.00	fmortf_	1.805	0.096	
log_TC_F, females, 93	-6.398	0.088	-10.0, 1.00	fmortf_	1.432	0.097	
log_TC_F, females, 13	-7.730	0.084	-10.0, 1.00	Fix_slo	0.070	0.018	
log_TC_F, females, 14	-7.585	0.084	-10.0, 1.00	log_l50	4.722	0.067	
log_TC_F, females, 15	-6.554	0.083	-10.0, 1.00				

Table 6(2). Annual abundance estimates (million crab), mature male biomass (MMB, 1000 t), and total survey biomass (1000t) for red king crab in Bristol Bay estimated by length-based analysis (scenario 2) from 1975-2016. Mature male biomass for year *t* is on Feb. 15, year *t*+1. Size measurements are mm carapace length.

Year (t)	Males				Females	Total Recruits	Total Survey Biomass	
	Mature (>119 mm)	Legal (>134mm)	MMB (>119 mm)	SD MMB	Mature (>89 mm)		Model Est. (>64 mm)	Area-Swept (>64 mm)
1975	55.363	28.789	80.956	5.290	74.312		252.302	202.731
1976	60.873	35.220	90.717	4.492	112.493	34.194	290.193	331.868
1977	62.507	37.943	94.074	3.762	139.728	41.164	300.239	375.661
1978	68.634	39.040	97.136	3.126	132.567	48.616	291.471	349.545
1979	64.702	40.612	82.947	2.620	114.820	76.346	268.500	167.627
1980	46.356	33.515	24.784	0.982	104.447	68.362	231.675	249.322
1981	14.470	8.418	8.313	0.450	48.423	28.014	95.515	132.669
1982	7.333	3.107	8.158	0.411	22.560	134.830	48.635	143.740
1983	6.568	3.036	8.593	0.394	14.566	65.834	42.064	49.320
1984	6.196	3.053	6.491	0.372	15.011	86.115	42.207	155.311
1985	7.350	2.503	10.386	0.533	14.183	8.616	34.935	34.535
1986	12.034	4.699	15.127	0.797	20.795	43.495	46.709	48.158
1987	15.533	6.724	21.636	0.990	24.640	12.627	53.470	70.263
1988	16.373	9.106	27.636	1.097	29.468	7.620	57.663	55.372
1989	17.809	10.966	31.317	1.153	26.952	7.869	61.050	55.941
1990	17.986	11.983	29.178	1.173	22.963	23.158	61.475	60.321
1991	14.599	10.734	24.245	1.154	20.744	14.367	56.069	85.055
1992	11.519	8.618	22.124	1.107	20.488	2.011	50.161	37.687
1993	12.078	7.804	19.574	1.082	18.315	10.447	48.331	53.703
1994	11.889	7.186	25.045	1.110	15.066	1.490	42.788	32.335
1995	12.356	8.997	27.809	1.081	14.565	57.298	49.244	38.396
1996	12.360	9.619	25.767	1.029	20.032	6.533	56.623	44.649
1997	11.612	8.671	23.898	0.984	29.120	2.671	60.605	85.277
1998	15.888	8.377	26.162	1.067	27.161	11.693	63.652	85.176
1999	17.509	9.956	30.664	1.174	23.696	32.191	63.493	65.604
2000	15.582	11.344	30.535	1.166	26.075	11.449	65.773	68.342
2001	14.526	10.858	29.357	1.122	30.261	9.228	68.265	53.188
2002	16.123	10.361	31.147	1.115	29.959	54.649	72.578	69.786
2003	16.825	11.138	29.742	1.099	35.601	8.259	77.323	116.794
2004	15.016	10.559	27.614	1.057	43.179	16.037	78.862	131.910
2005	17.336	10.011	27.848	1.076	41.329	53.682	83.666	107.341
2006	17.578	10.537	29.786	1.128	45.331	18.047	86.734	95.676
2007	17.022	11.085	27.042	1.151	52.581	12.141	91.696	104.841
2008	18.618	10.295	28.195	1.282	49.502	9.395	91.644	114.430
2009	19.808	11.071	31.981	1.470	45.048	10.314	89.142	91.673
2010	18.806	12.288	32.224	1.577	41.437	16.315	86.783	81.642
2011	16.233	11.918	32.350	1.599	39.332	16.129	83.272	67.053
2012	14.779	11.429	31.140	1.581	38.760	10.595	82.268	61.248
2013	14.489	10.672	30.002	1.593	37.704	7.071	80.661	62.410
2014	14.578	10.247	28.843	1.649	34.671	2.266	77.179	114.103
2015	13.893	9.903	27.680	1.707	30.473	5.380	71.787	64.240
2016	12.715	9.475	23.999	1.379	26.482	3.142	65.697	61.231

Table 6(2d). Annual abundance estimates (million crab), mature male biomass (MMB, 1000 t), and total survey biomass (1000t) for red king crab in Bristol Bay estimated by length-based analysis (scenario 2d) from 1975-2016. Mature male biomass for year *t* is on Feb. 15, year *t*+1. Size measurements are mm carapace length.

Year (t)	Males				Females	Total Recruits	Total Survey Biomass	
	Mature (>119 mm)	Legal (>134mm)	MMB (>119 mm)	SD MMB	Mature (>89 mm)		Model Est. (>64 mm)	Area-Swept (>64 mm)
1975	55.348	28.935	81.185	4.873	68.804		259.398	202.731
1976	60.699	35.422	90.990	4.109	104.431	31.824	297.498	331.868
1977	61.989	38.067	93.824	3.444	129.053	37.913	305.961	375.661
1978	67.246	38.843	95.695	2.875	121.703	44.352	294.826	349.545
1979	62.787	39.906	80.045	2.411	104.719	68.590	269.125	167.627
1980	44.290	32.330	22.137	0.802	94.449	60.356	228.420	249.322
1981	13.340	7.641	6.185	0.307	44.018	24.961	92.605	132.669
1982	6.326	2.435	6.642	0.311	20.531	124.636	44.859	143.740
1983	5.962	2.584	7.707	0.319	13.486	61.960	39.886	49.320
1984	5.931	2.827	5.958	0.319	14.276	83.470	41.519	155.311
1985	7.265	2.382	10.003	0.460	13.858	8.581	35.237	34.535
1986	11.909	4.587	14.721	0.686	20.353	43.229	47.198	48.158
1987	15.286	6.585	21.070	0.840	24.119	12.549	54.013	70.263
1988	16.062	8.902	26.869	0.925	28.827	7.512	58.234	55.372
1989	17.455	10.701	30.457	0.964	26.285	7.787	61.644	55.941
1990	17.617	11.695	28.191	0.972	22.301	22.797	62.047	60.321
1991	14.213	10.412	23.176	0.950	20.082	14.083	56.302	85.055
1992	11.121	8.277	21.022	0.911	19.775	1.993	50.031	37.687
1993	11.650	7.461	18.379	0.886	17.611	10.193	48.066	53.703
1994	11.411	6.811	23.825	0.908	14.413	1.473	42.256	32.335
1995	11.903	8.620	26.609	0.887	13.964	56.274	48.947	38.396
1996	11.934	9.255	24.601	0.845	19.382	6.504	56.557	44.649
1997	11.200	8.320	22.776	0.811	28.325	2.646	60.623	85.277
1998	15.428	8.036	24.984	0.875	26.457	11.544	63.809	85.176
1999	17.025	9.586	29.430	0.969	23.084	31.952	63.697	65.604
2000	15.131	10.957	29.341	0.968	25.473	11.403	66.153	68.342
2001	14.120	10.490	28.229	0.936	29.655	9.116	68.852	53.188
2002	15.759	10.024	30.110	0.934	29.399	54.423	73.408	69.786
2003	16.507	10.838	28.812	0.925	35.010	8.221	78.447	116.794
2004	14.743	10.294	26.805	0.894	42.528	15.998	80.171	131.910
2005	17.129	9.787	27.182	0.909	40.723	53.313	85.263	107.341
2006	17.421	10.359	29.254	0.958	44.662	18.042	88.547	95.676
2007	16.908	10.949	26.637	0.980	51.794	12.121	93.832	104.841
2008	18.565	10.197	27.940	1.097	48.774	9.378	93.953	114.430
2009	19.806	11.024	31.864	1.273	44.402	10.373	91.588	91.673
2010	18.833	12.284	32.170	1.383	40.880	16.403	89.391	81.642
2011	16.262	11.928	32.347	1.419	38.877	16.148	85.909	67.053
2012	14.821	11.450	31.188	1.419	38.388	10.674	85.011	61.248
2013	14.551	10.705	30.099	1.448	37.395	7.158	83.473	62.410
2014	14.654	10.295	29.009	1.522	34.429	2.293	79.983	114.103
2015	13.989	9.972	27.877	1.597	30.291	5.419	74.542	64.240
2016	12.819	9.551	24.116	1.304	26.340	3.205	68.325	61.231

Table 7(2). 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 2016-2025. Parameter estimates with scenario 2 are used for the projection.

Year	MMB	95% LCI	95% UCI	Catch	95% LCI	95% UCI
No Directed Fishery						
2016	29.955	25.862	33.821	0.000	0.000	0.000
2017	30.270	26.134	34.176	0.000	0.000	0.000
2018	29.516	25.482	33.325	0.000	0.000	0.000
2019	28.617	24.898	32.505	0.000	0.000	0.000
2020	30.065	24.788	40.330	0.000	0.000	0.000
2021	34.074	24.953	52.124	0.000	0.000	0.000
2022	38.903	25.615	62.270	0.000	0.000	0.000
2023	43.715	26.626	73.162	0.000	0.000	0.000
2024	48.215	27.666	79.749	0.000	0.000	0.000
2025	52.264	28.763	85.190	0.000	0.000	0.000
$F_{40\%}$						
2016	24.824	21.933	27.762	5.155	3.947	6.087
2017	21.618	19.425	23.767	4.037	3.179	4.962
2018	18.806	17.085	20.448	3.041	2.457	3.645
2019	16.875	15.474	18.405	2.352	1.949	2.794
2020	17.542	14.267	25.365	2.225	1.638	3.597
2021	20.342	13.916	33.692	2.651	1.456	4.943
2022	23.279	14.297	40.077	3.378	1.465	6.511
2023	25.622	14.895	44.978	4.094	1.567	7.893
2024	27.332	15.476	47.566	4.658	1.722	8.860
2025	28.532	16.086	49.502	5.039	1.905	9.277
$F_{35\%}$						
2016	24.038	21.337	26.663	5.945	4.546	7.192
2017	20.548	18.565	22.414	4.393	3.498	5.312
2018	17.677	16.147	19.087	3.212	2.626	3.793
2019	15.783	14.531	17.161	2.444	2.047	2.866
2020	16.480	13.326	24.114	2.317	1.696	3.817
2021	19.195	12.983	31.769	2.833	1.507	5.569
2022	21.926	13.457	37.667	3.665	1.529	7.259
2023	23.998	14.020	41.777	4.447	1.646	8.753
2024	25.433	14.607	43.592	5.030	1.810	9.682
2025	26.383	15.133	45.362	5.410	2.018	10.147

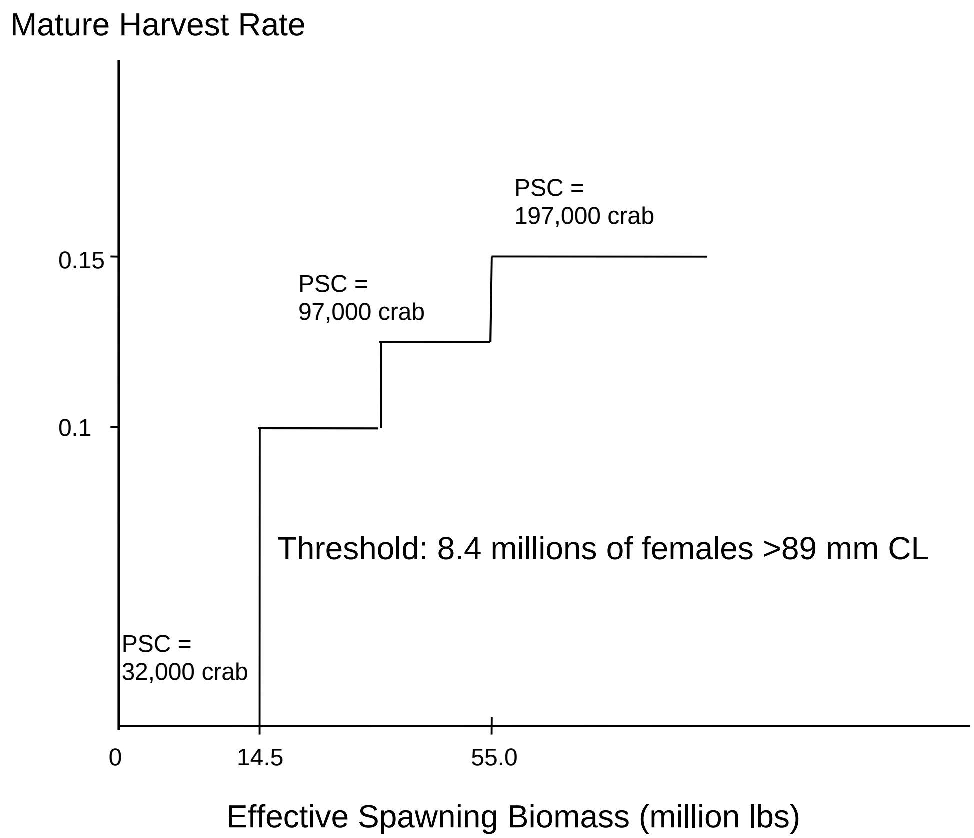


Figure 1. Current harvest rate strategy (line) for the Bristol Bay red king crab fishery and annual prohibited species catch (PSC) limits (numbers of crab) of Bristol Bay red king crab in the groundfish fisheries in zone 1 in the eastern Bering Sea. Harvest rates are based on current-year estimates of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

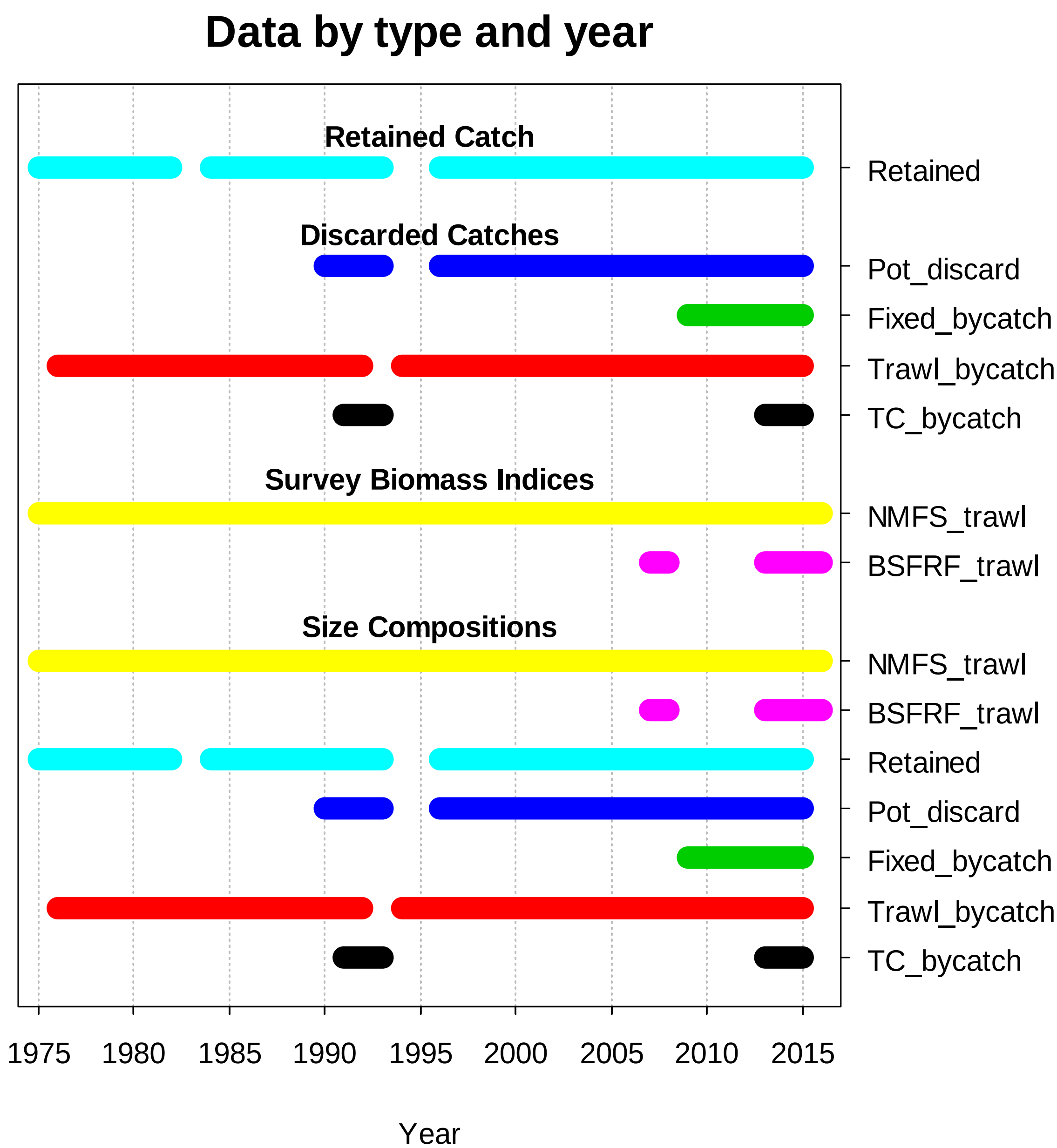


Figure 2. Data types and ranges used for the stock assessment.

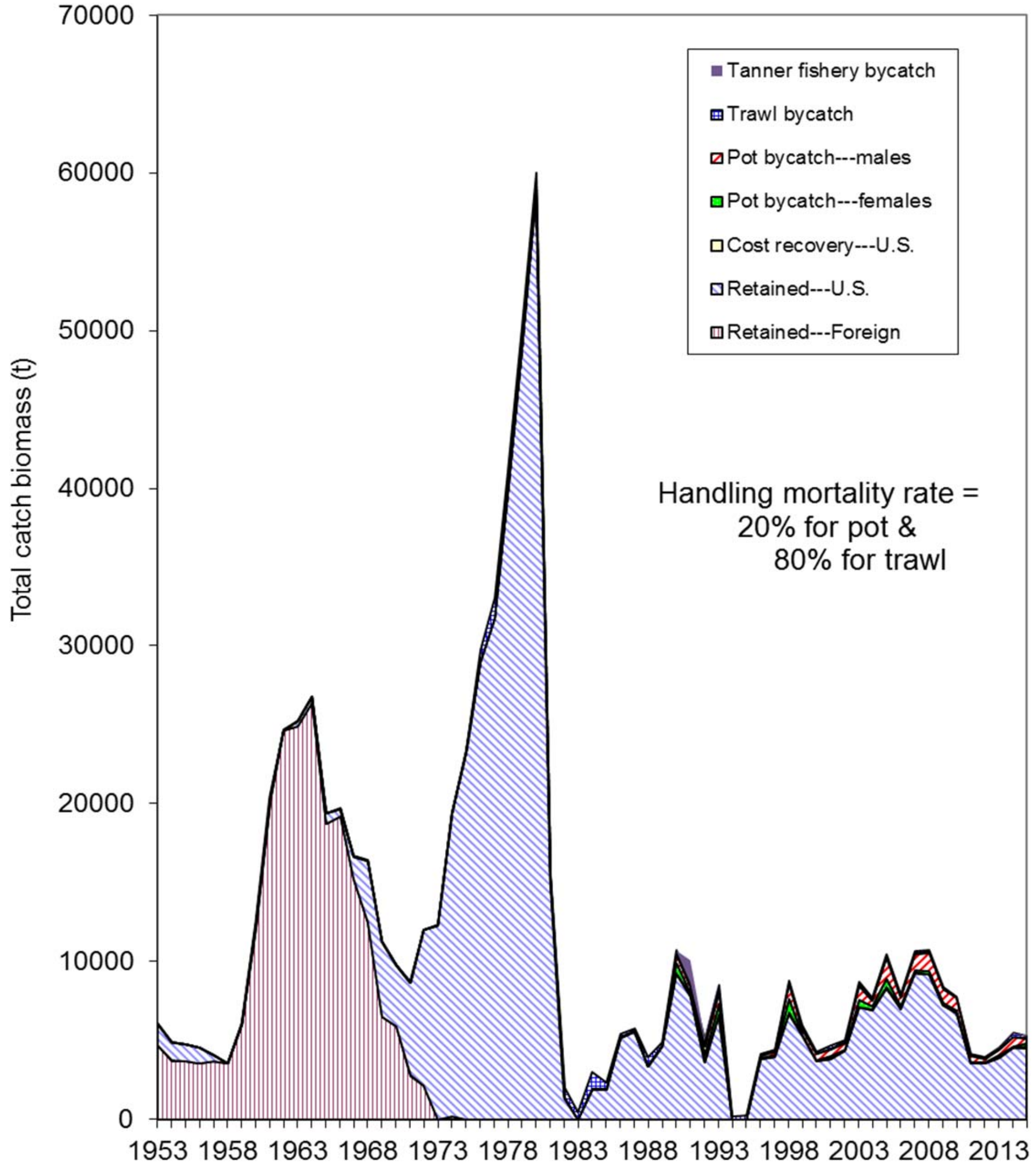


Figure 3. Retained catch biomass and bycatch mortality biomass (t) for Bristol Bay red king crab from 1953 to 2015. Handling mortality rates were assumed to be 0.2 for the directed pot fishery 0.25 for the Tanner crab fishery and 0.8 for the trawl fisheries.

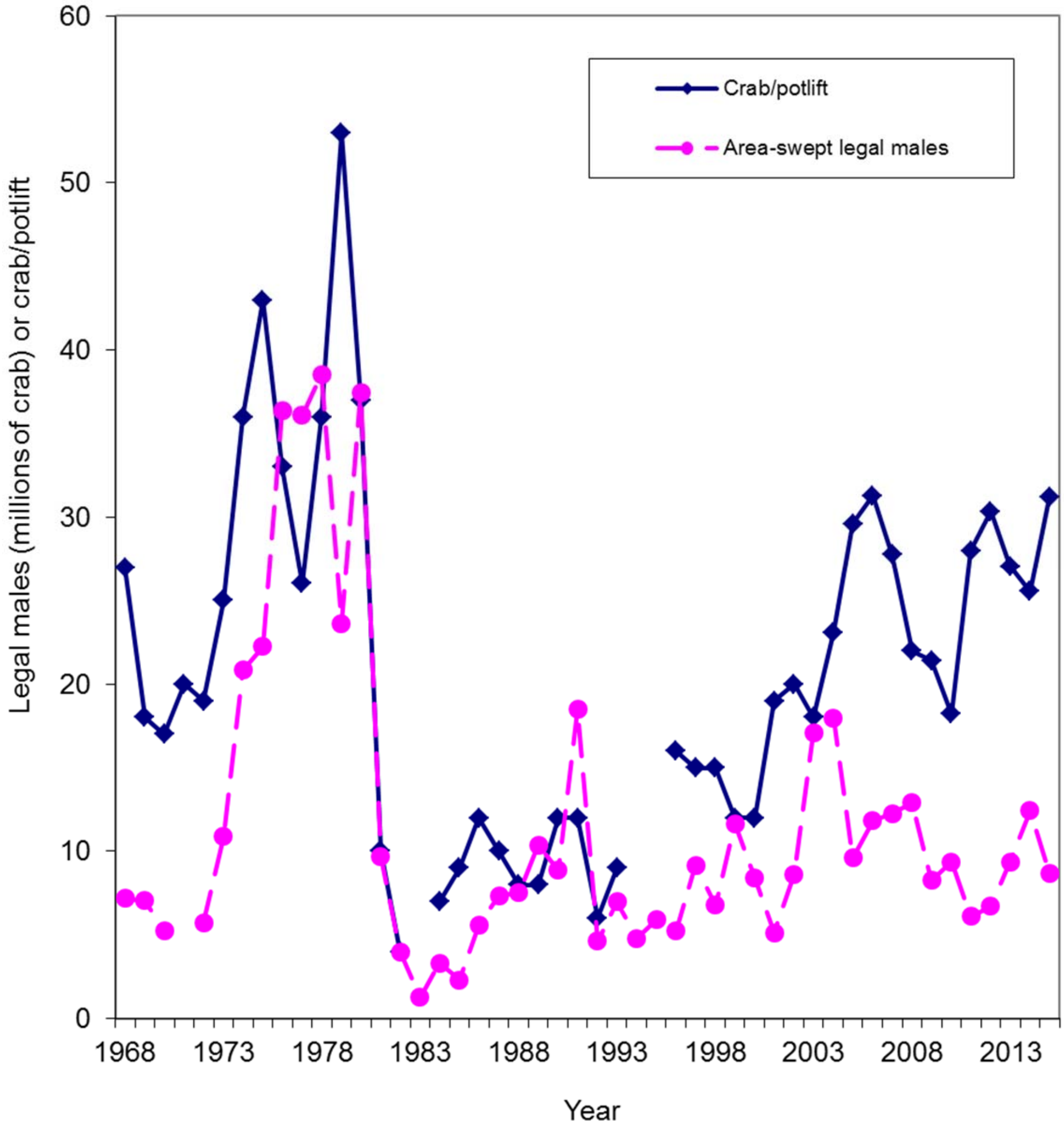


Figure 4. Comparison of survey legal male abundances and catches per unit effort for Bristol Bay red king crab from 1968 to 2015.

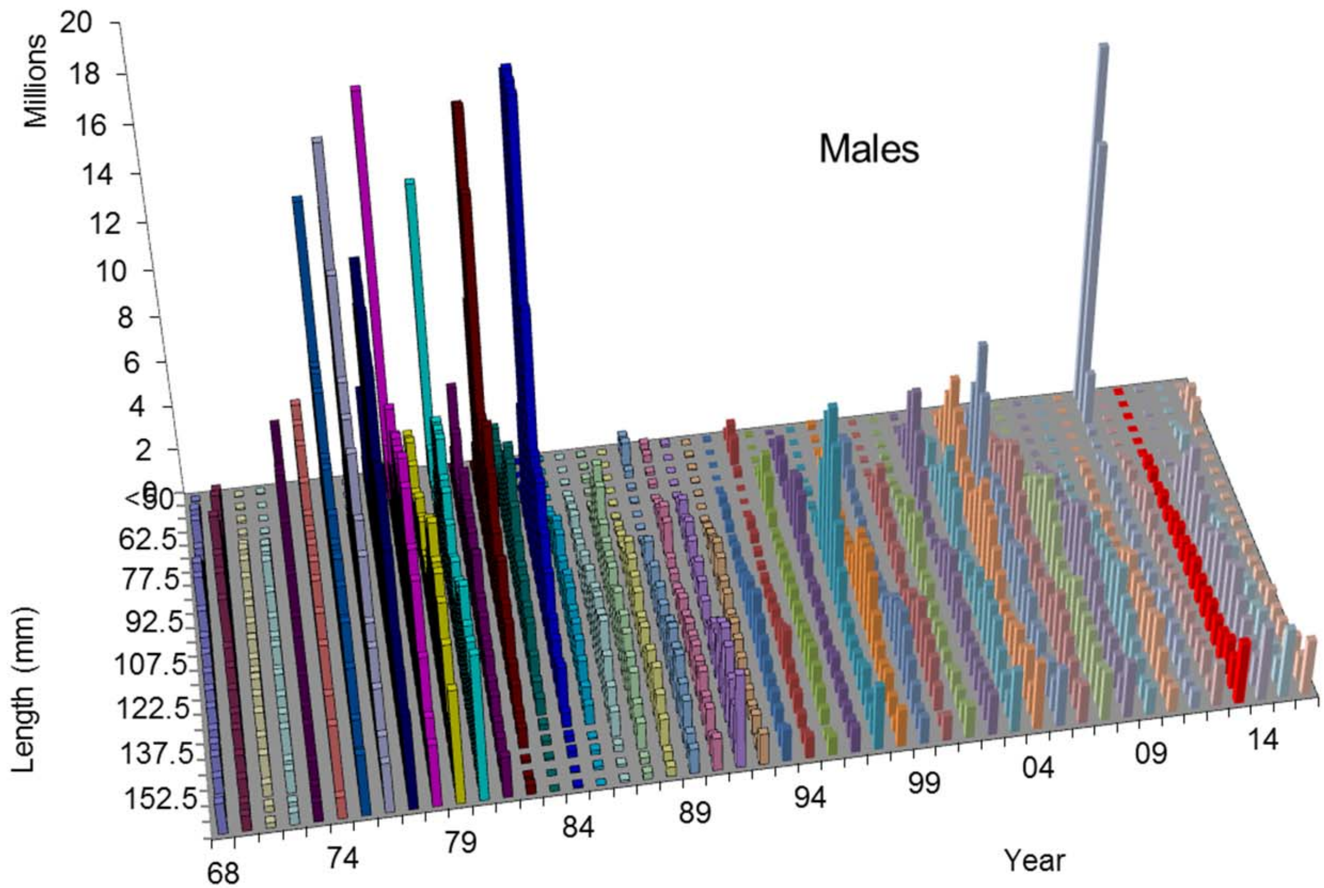


Figure 5a. Survey abundances by 5-mm carapace length bin for male Bristol Bay red king crab from 1968 to 2016.

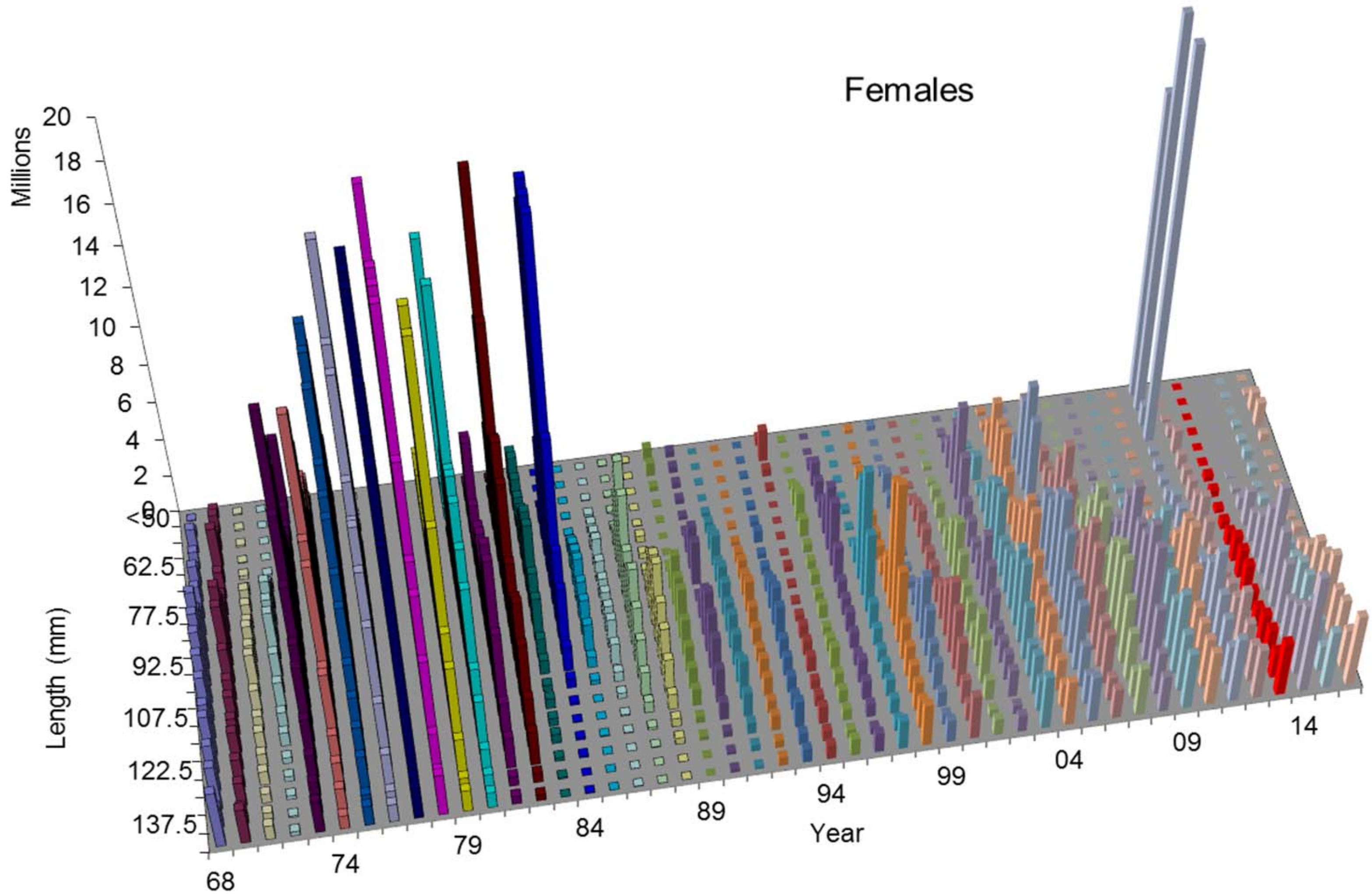
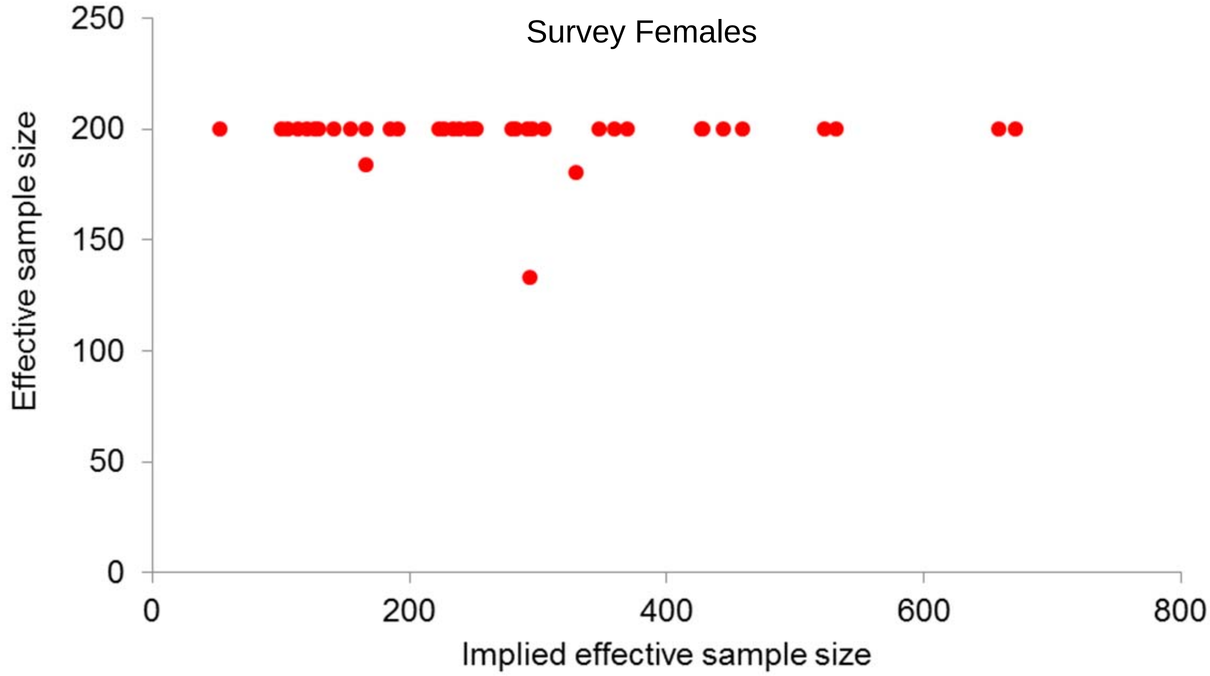


Figure 5b. Survey abundances by 5 mm carapace length bin for female Bristol Bay red king crab from 1968 to 2016.



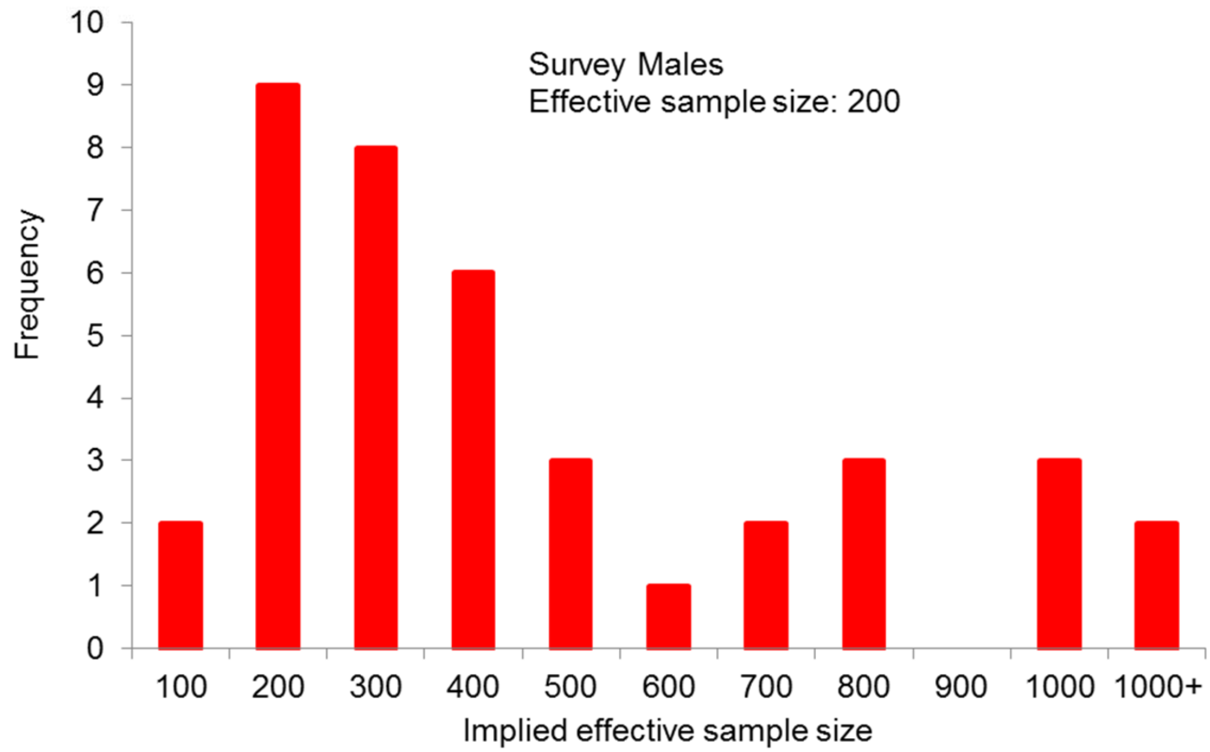


Figure 6. Relationship between implied effective sample sizes (section 3(a)(5)(i)) and effective sample sizes (see effective sample sizes for scenario 2d) for length/sex composition data with scenario 2d: trawl survey data.

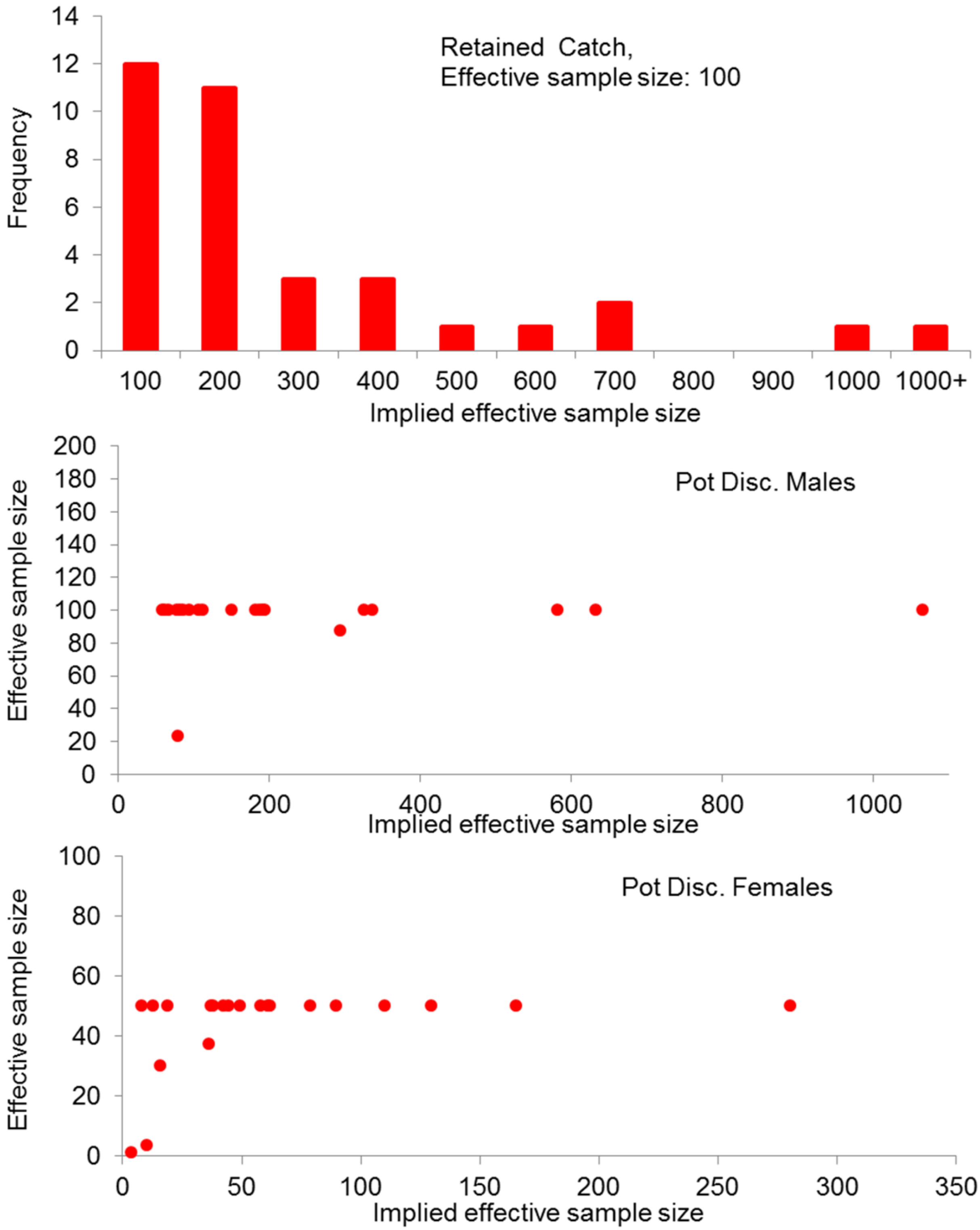


Figure 7. Relationship between implied effective sample sizes (section 3(a)(5)(i)) and effective sample sizes (see effective sample sizes for scenario 2d) for length/sex composition data with scenario 2d: directed pot fishery data.

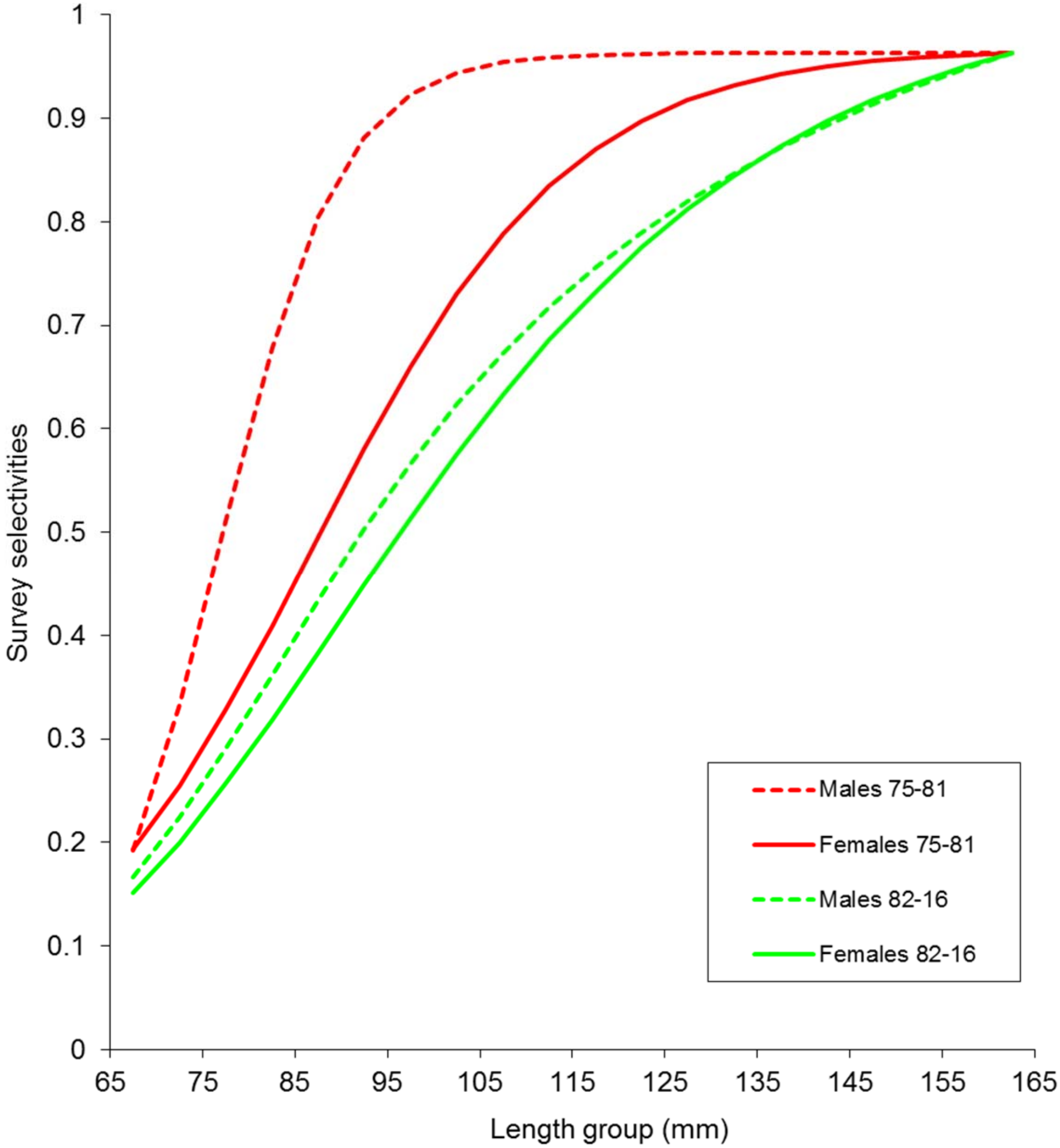


Figure 8a(2a). Estimated trawl survey selectivities under scenario 2a. Pot, fixed gear and trawl handling mortality rates were assumed to be 0.2 0.5 and 0.8, respectively.

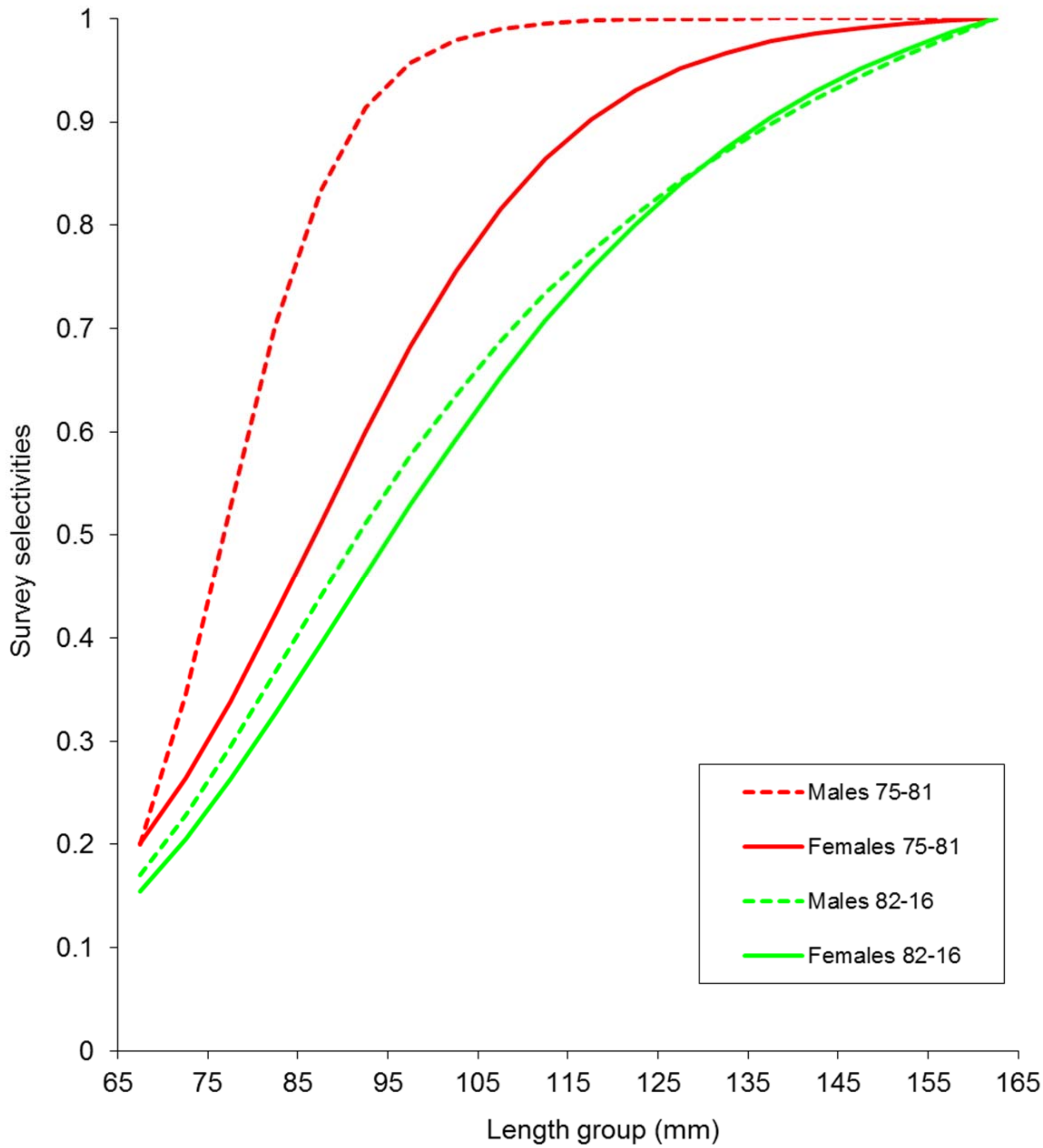


Figure 8a(2d). Estimated trawl survey selectivities under scenario 2d. Pot, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.5 and 0.8, respectively.

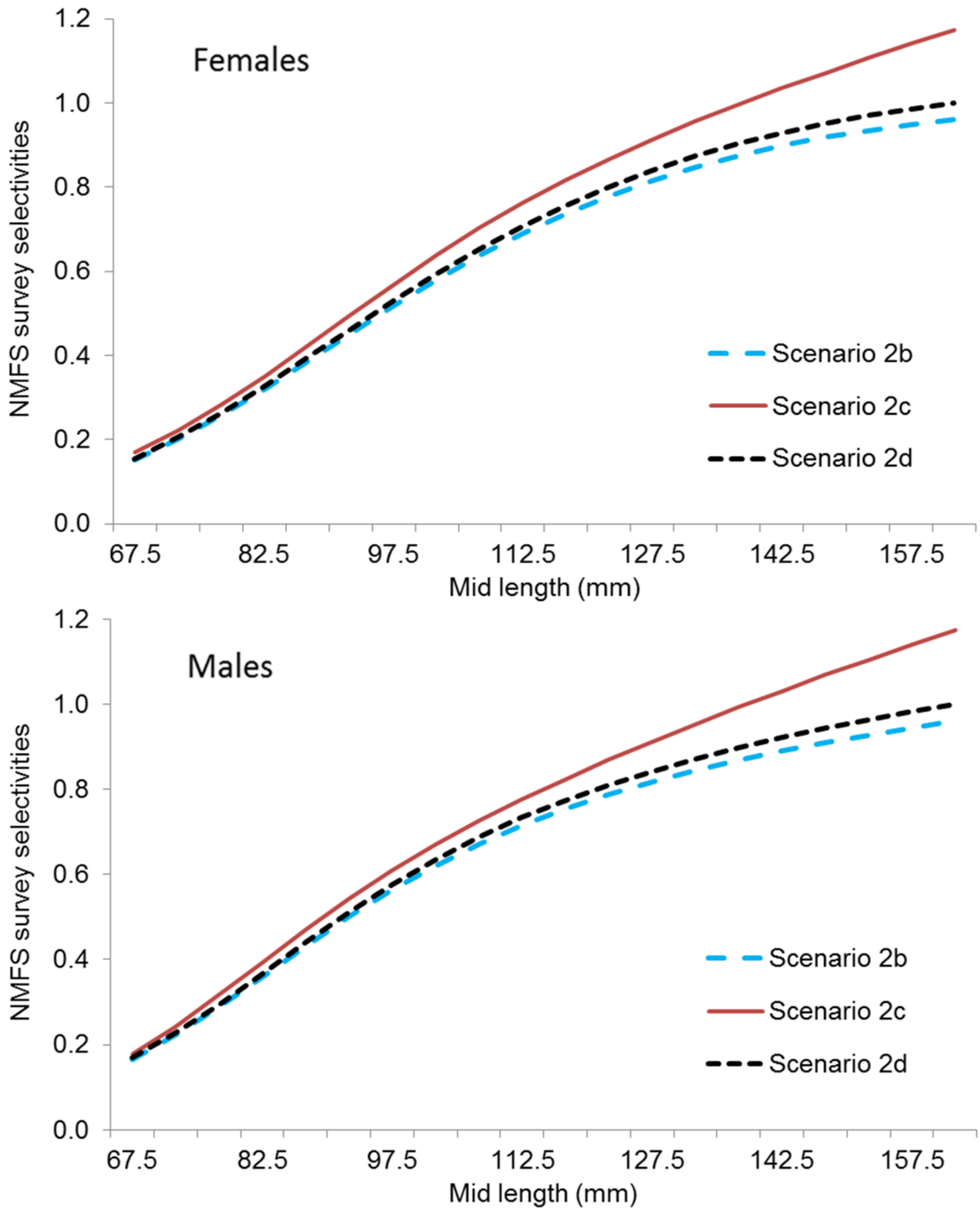
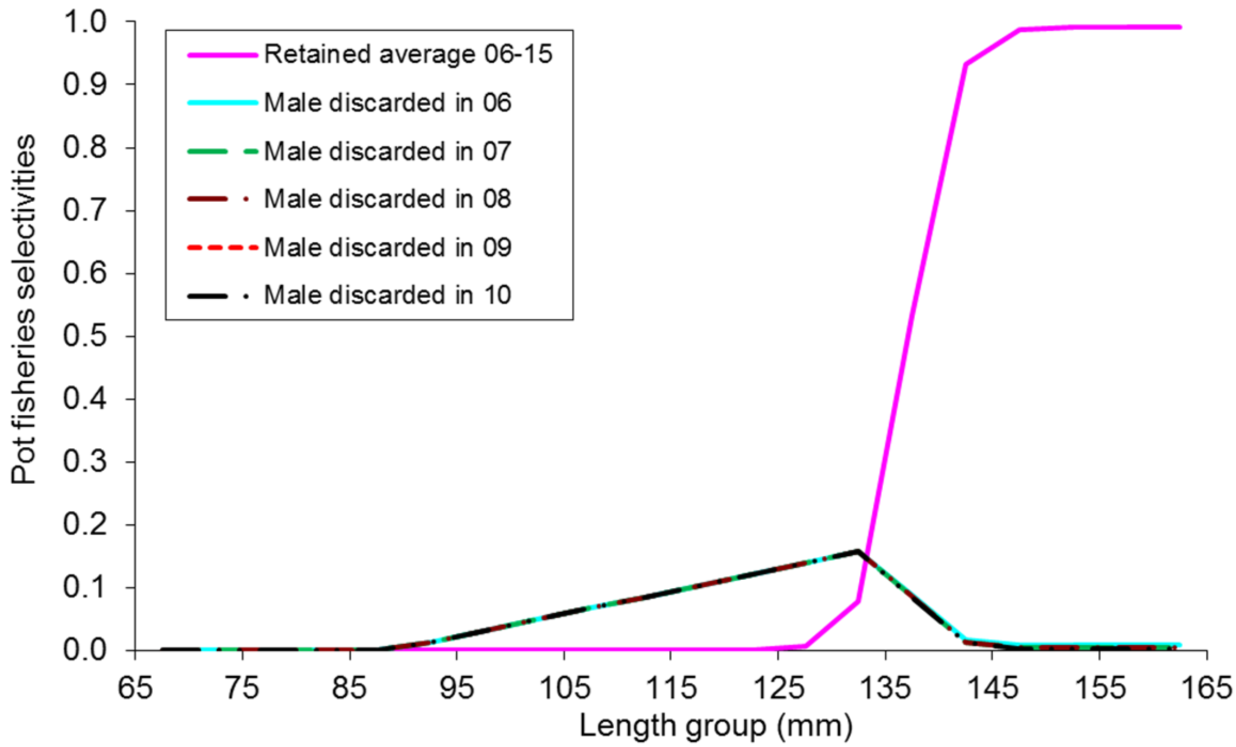


Figure 8b. Comparisons of estimated NMFS trawl survey selectivities for period 1982-2016 under scenarios 2b, 2c and 2d. Pot, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.5 and 0.8, respectively.



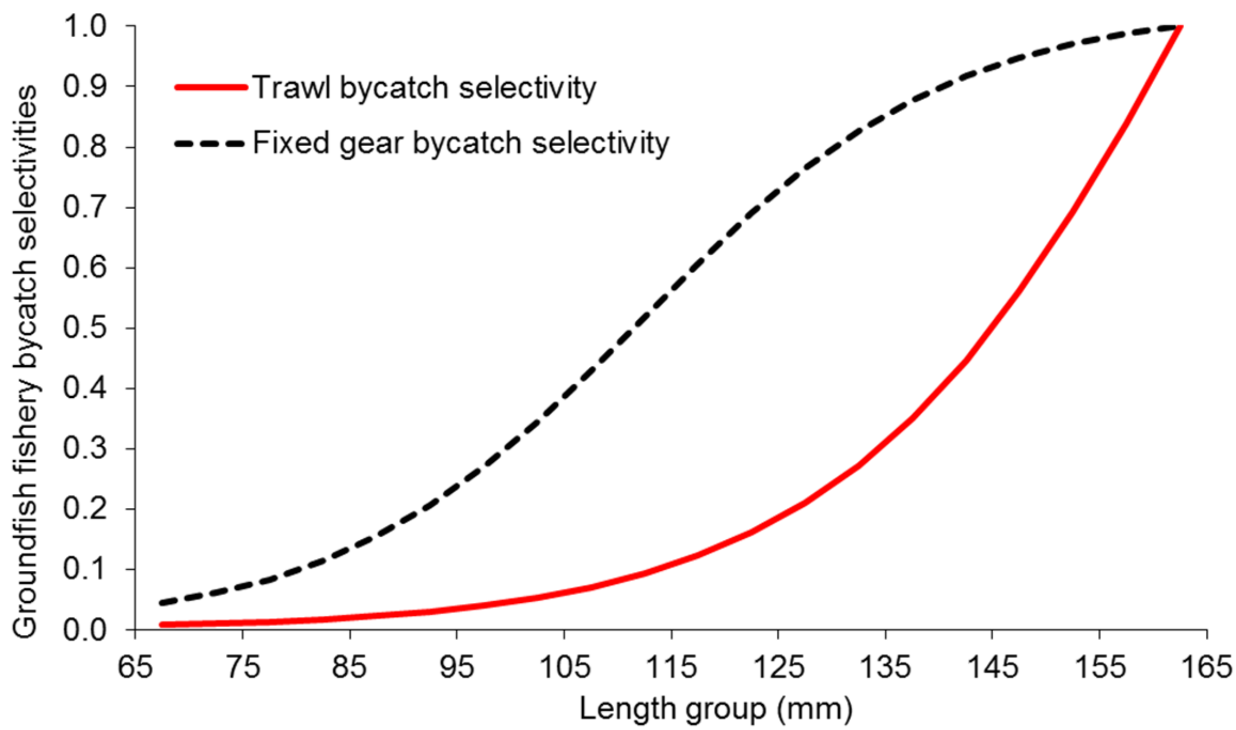


Figure 8c. Estimated pot fishery selectivities and groundfish trawl bycatch selectivities under scenario 2d. Pot, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.5 and 0.8, respectively.

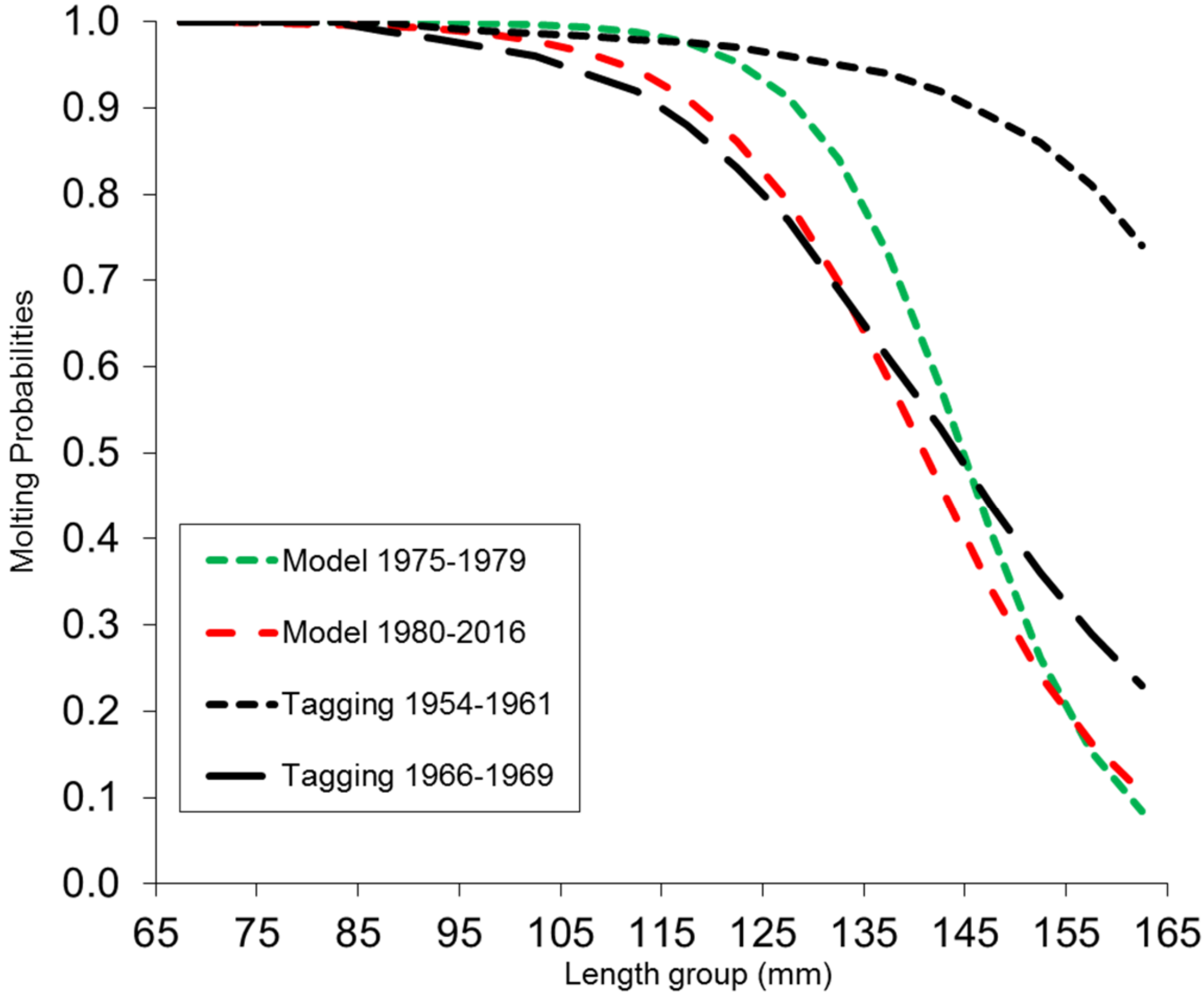


Figure 9(2d). Comparison of estimated probabilities of molting of male red king crab in Bristol Bay for different periods. Molting probabilities for periods 1954-1961 and 1966-1969 were estimated by Balsiger (1974) from tagging data. Molting probabilities for 1975-2016 were estimated with a length-based model with pot handling mortality rate of 0.2 under scenario 2d.

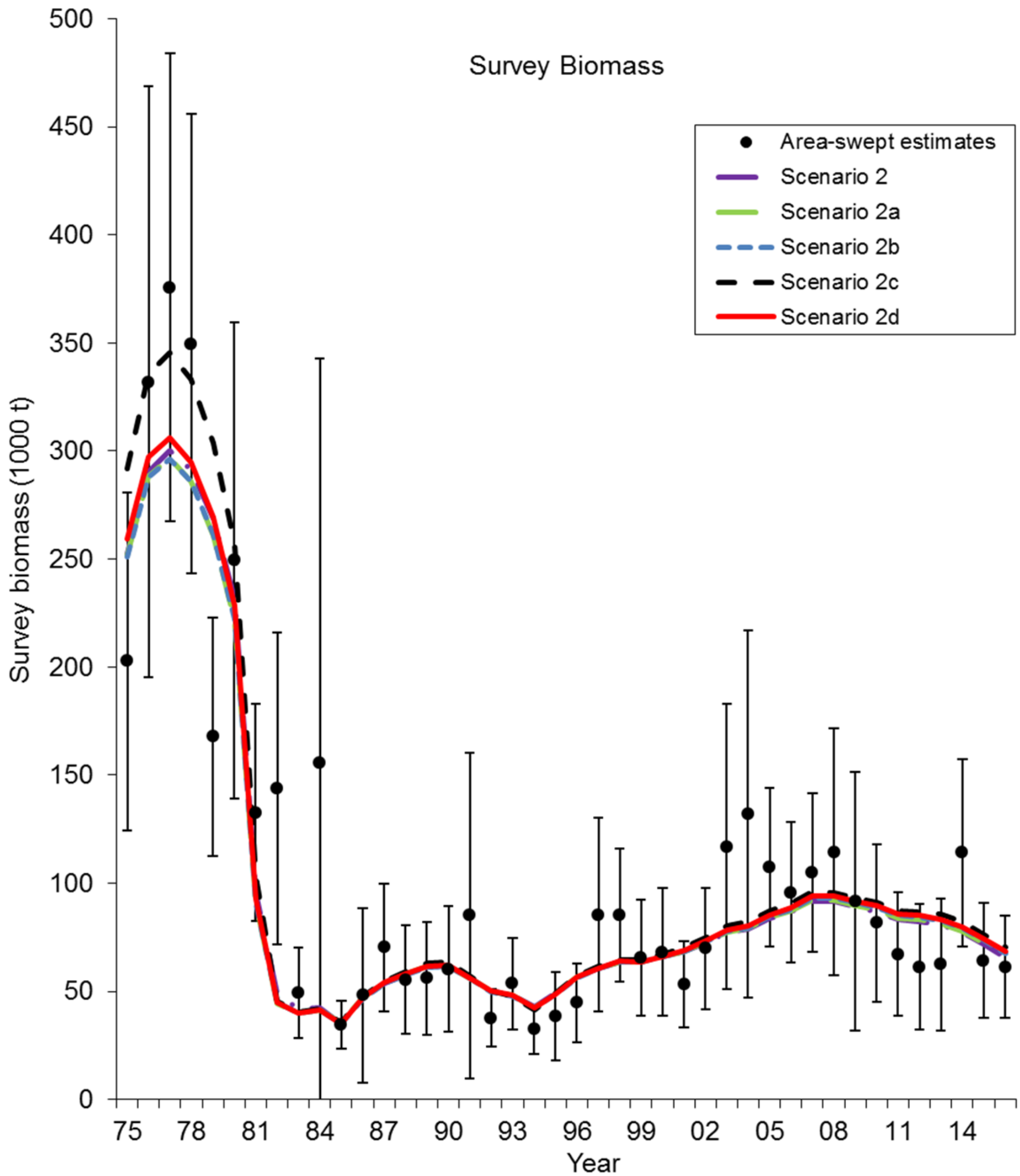


Figure 10a(2, 2a, 2b, 2c & 2d). Comparisons of area-swept estimates of total survey biomass and model prediction for model estimates in 2016 under scenarios 2, 2a, 2bb, 2c and 2d. Pot, fixed gear, and trawl handling mortality rates were assumed to be 0.2, 0.5 and 0.8, respectively. The error bars are plus and minus 2 standard deviations.

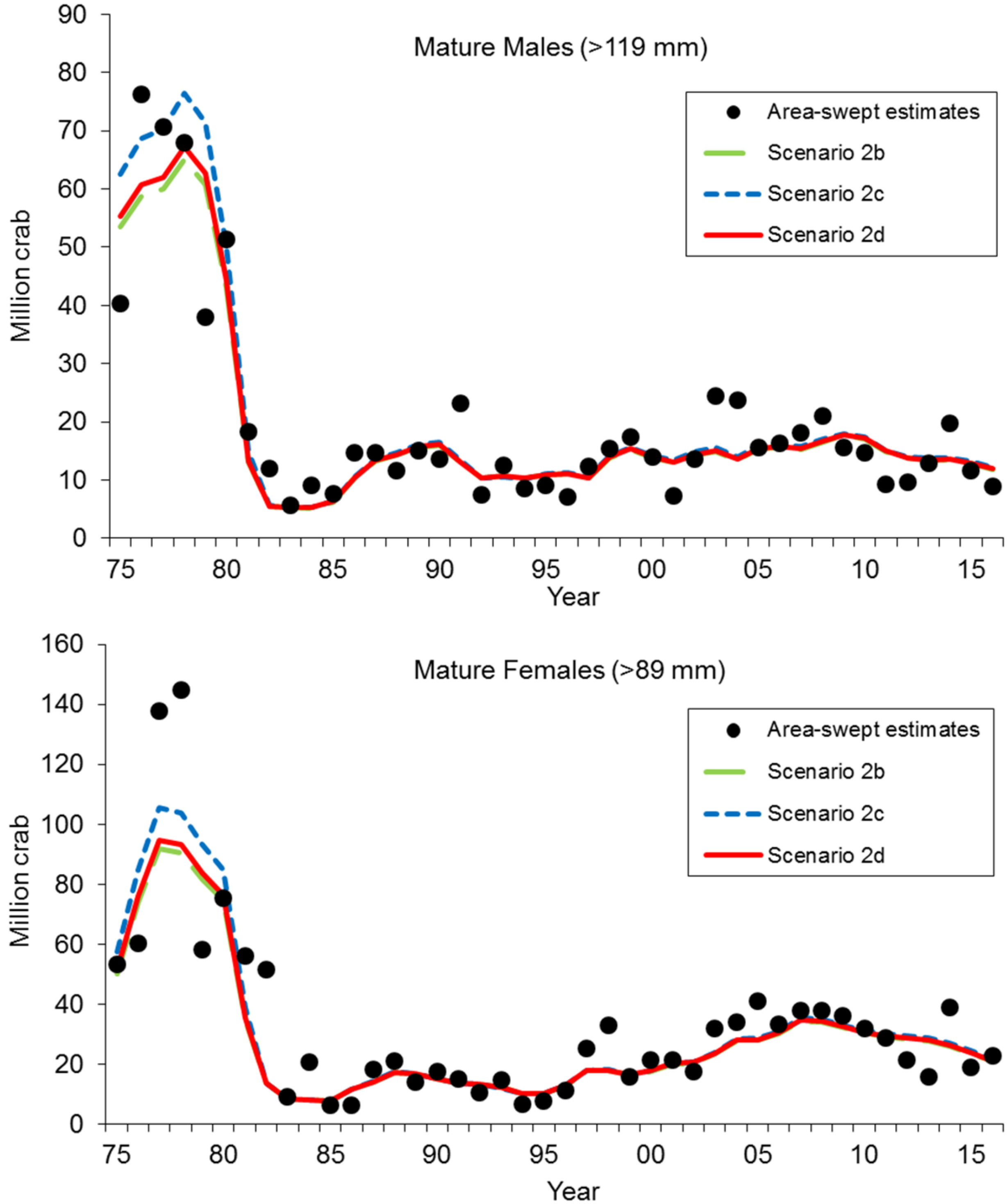


Figure 10b(2b, 2c & 2d). Comparisons of area-swept estimates of male (>119 mm) and female (>89 mm) abundance and model prediction for model estimates in 2016 under scenarios 2b, 2c and 2d. Pot, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.5 and 0.8, respectively.

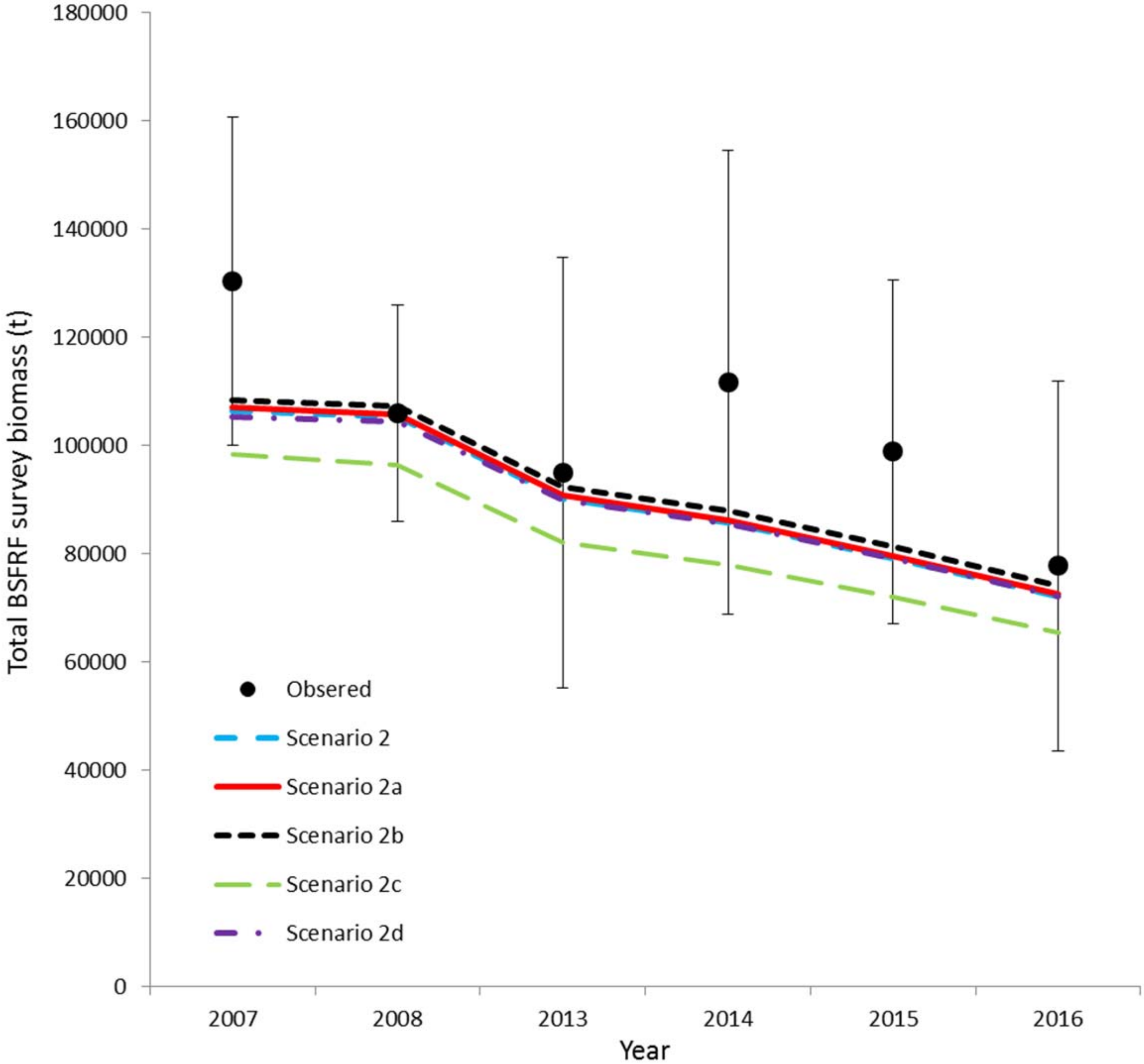


Figure 10c. Comparisons of total survey biomass estimates by the BSFRF survey and the model for model estimates in 2016 (scenarios 2, 2a, 2b, 2c & 2d). The error bars are plus and minus 2 standard deviations of scenario 2d.

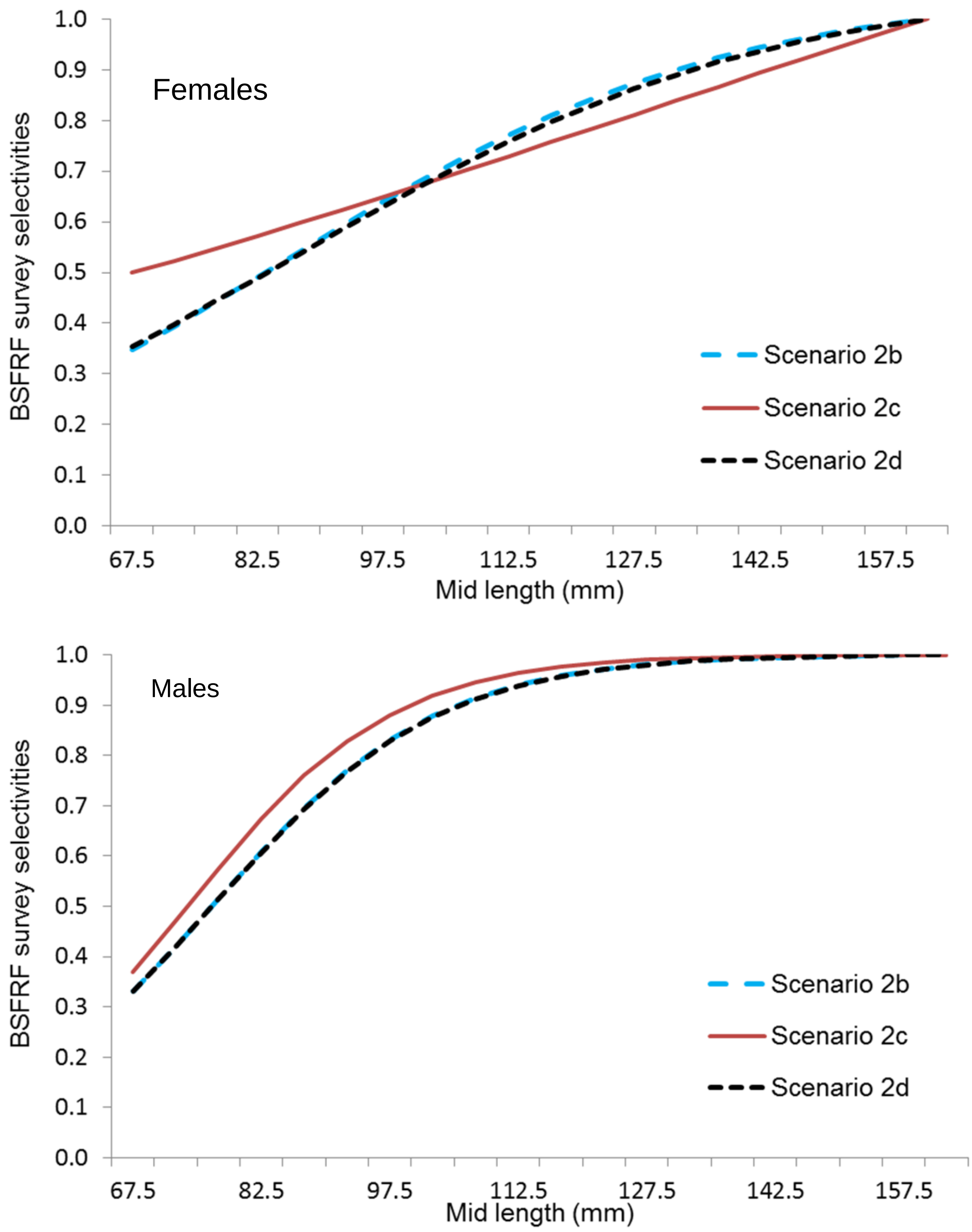


Figure 10d(2b, 2c & 2d). Comparisons of estimated BSFRF survey selectivities with scenarios 2b, 2c and 2d. The catchability is assumed to be 1.0.

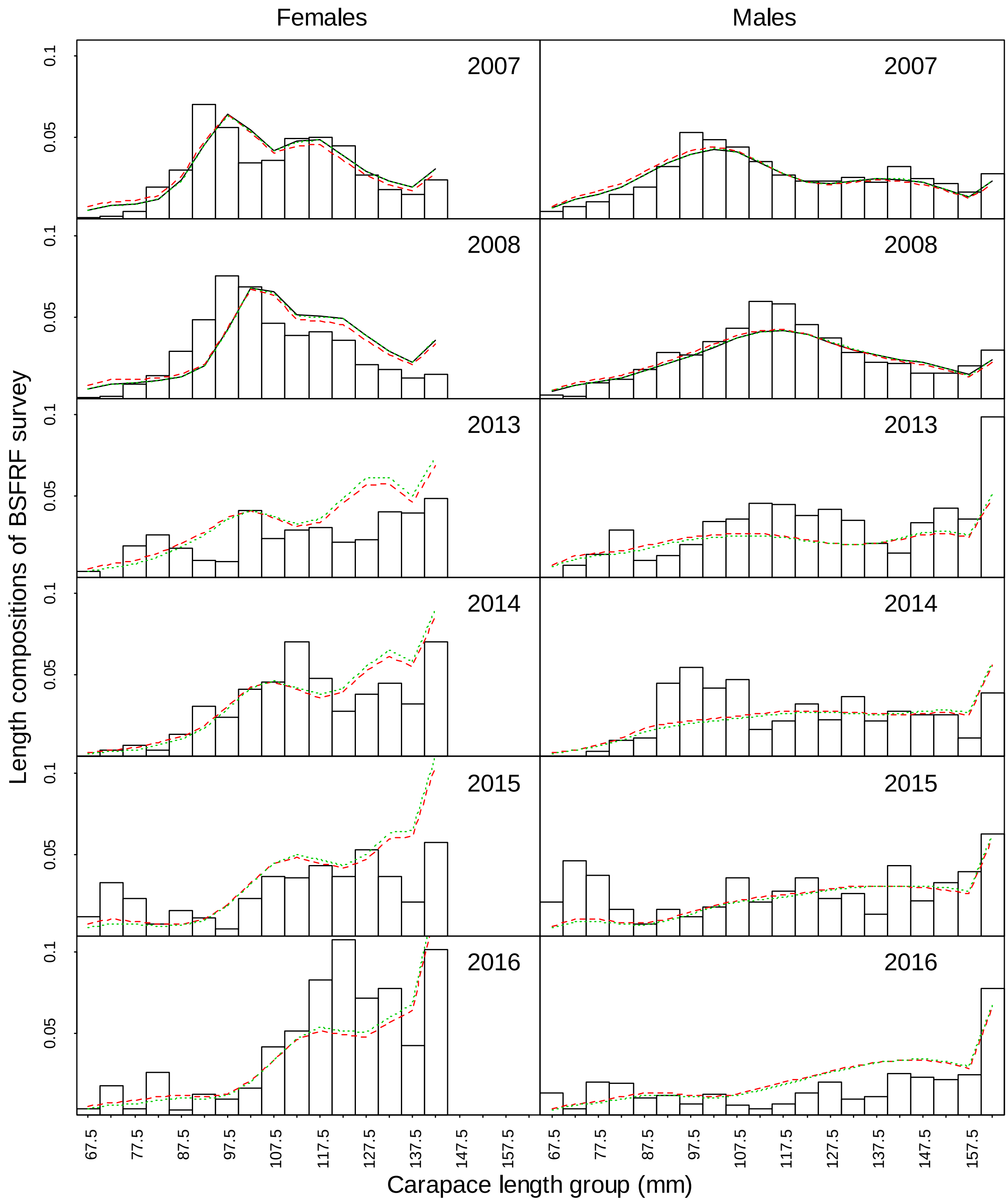


Figure 10e(2b, 2c & 2d). Comparisons of length compositions by the BSFRF survey and the model estimates during 2007-2008 and 2013-2016 with scenarios 2b (solid black), 2c (dashed red), and 2d (green lines).

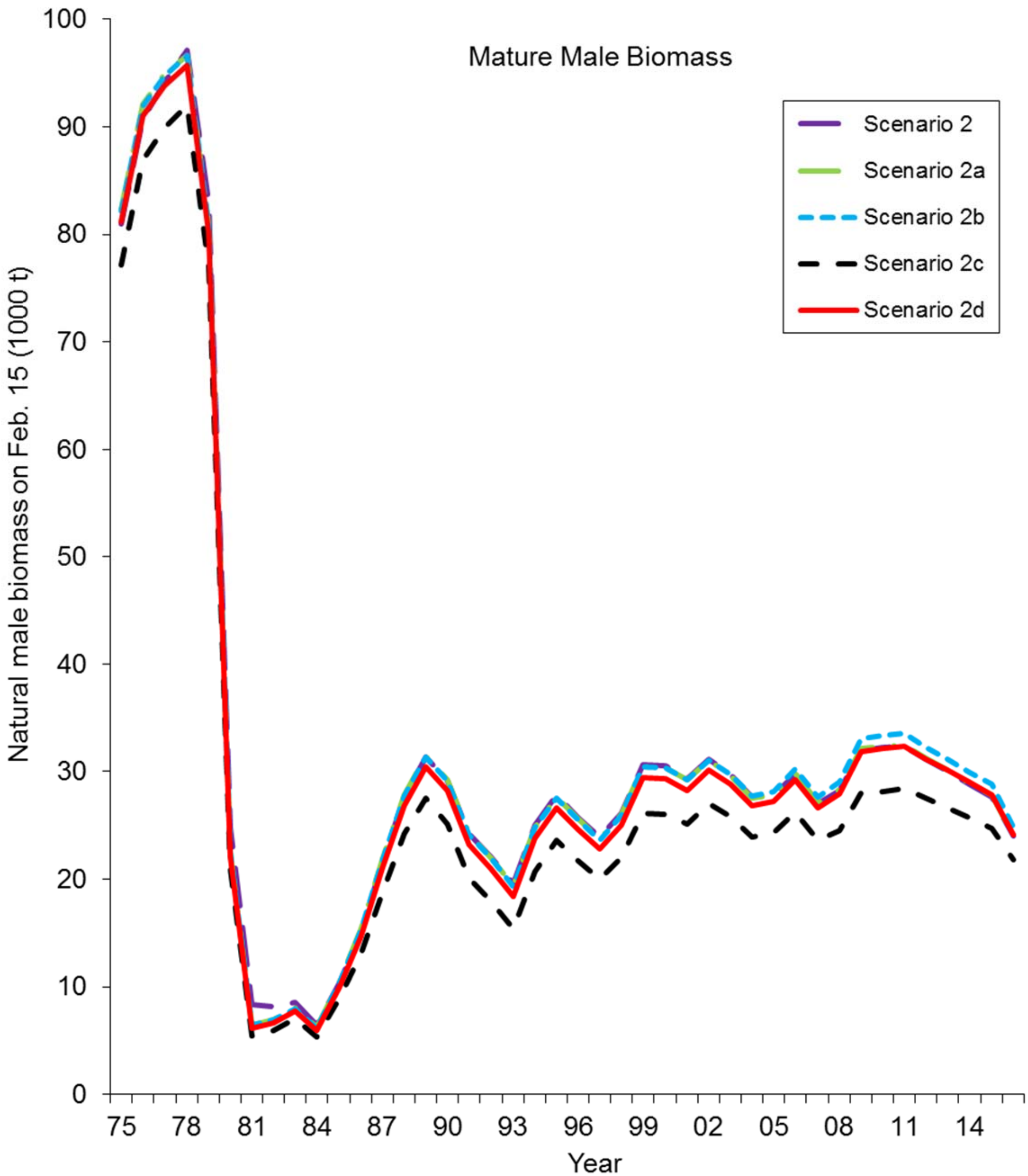


Figure 11. Estimated absolute mature male biomasses during 1975-2016 for scenarios 2, 2a, 2b, 2c, and 2d.

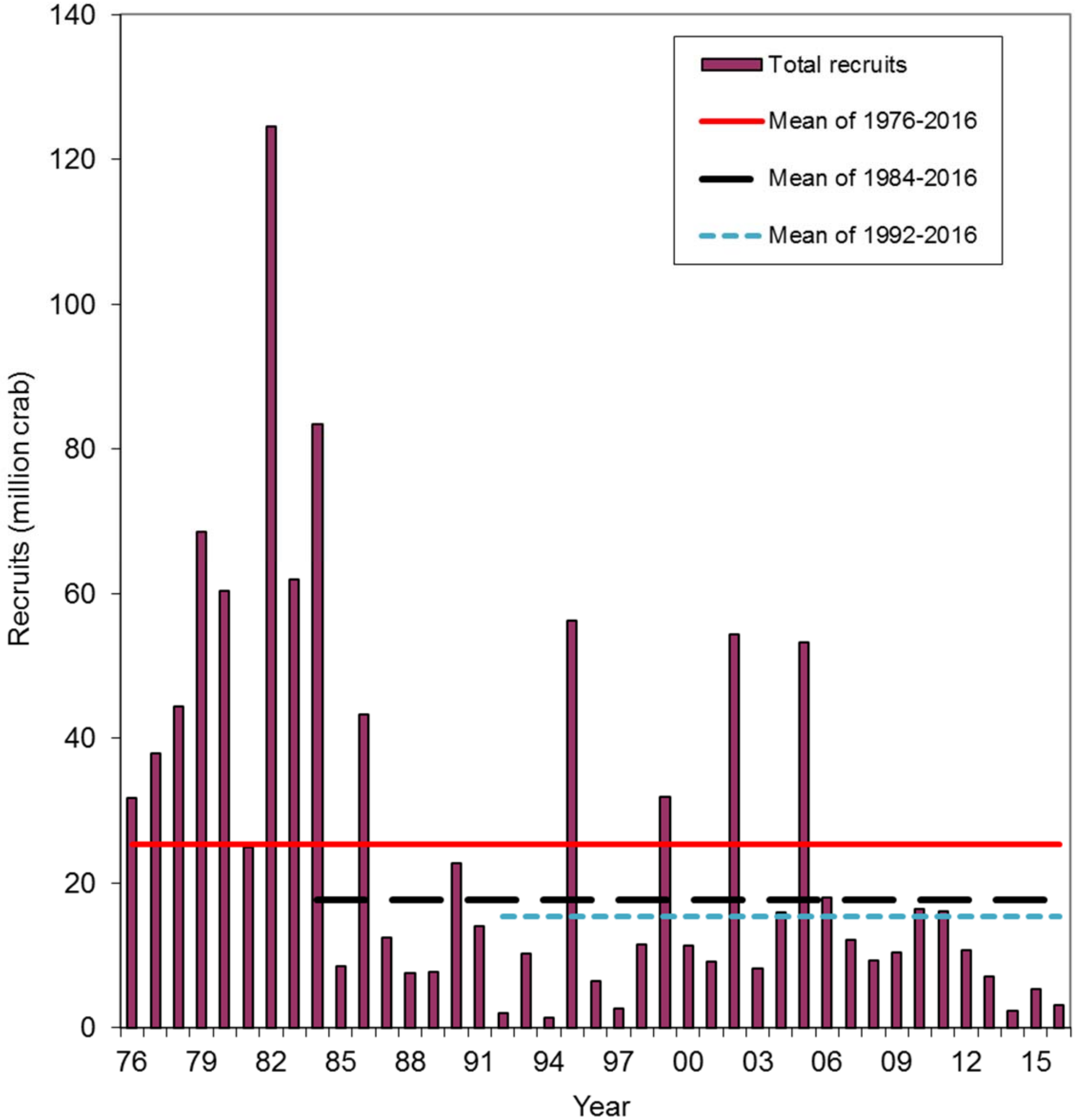


Figure 12(2d). Estimated recruitment time series during 1976-2016 with scenario 2d. Mean male recruits during 1984-2016 was used to estimate $B_{35\%}$.

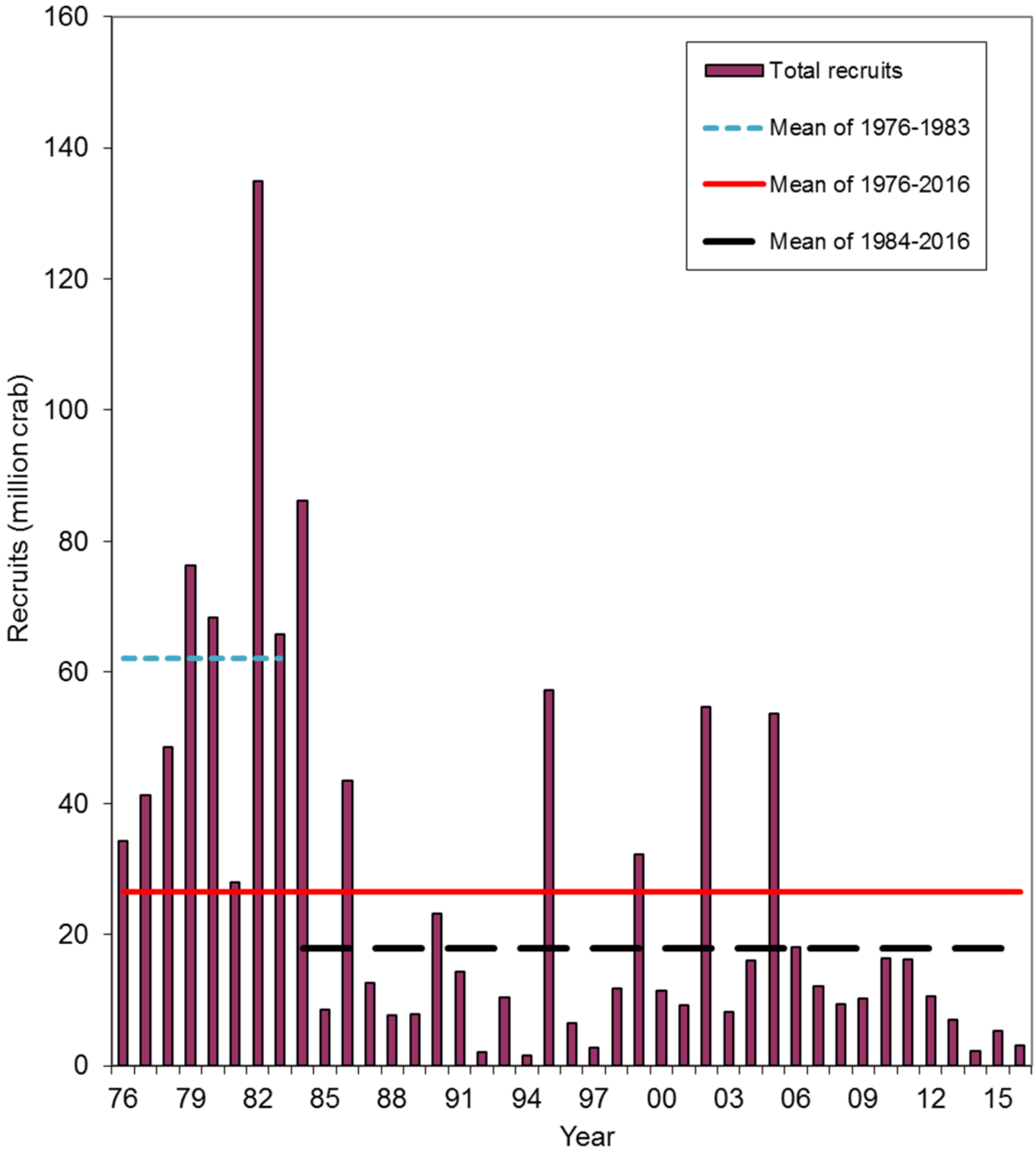


Figure 12(2). Estimated recruitment time series during 1976-2016 with scenario 2. Mean male recruits during 1984-2016 was used to estimate B35%.

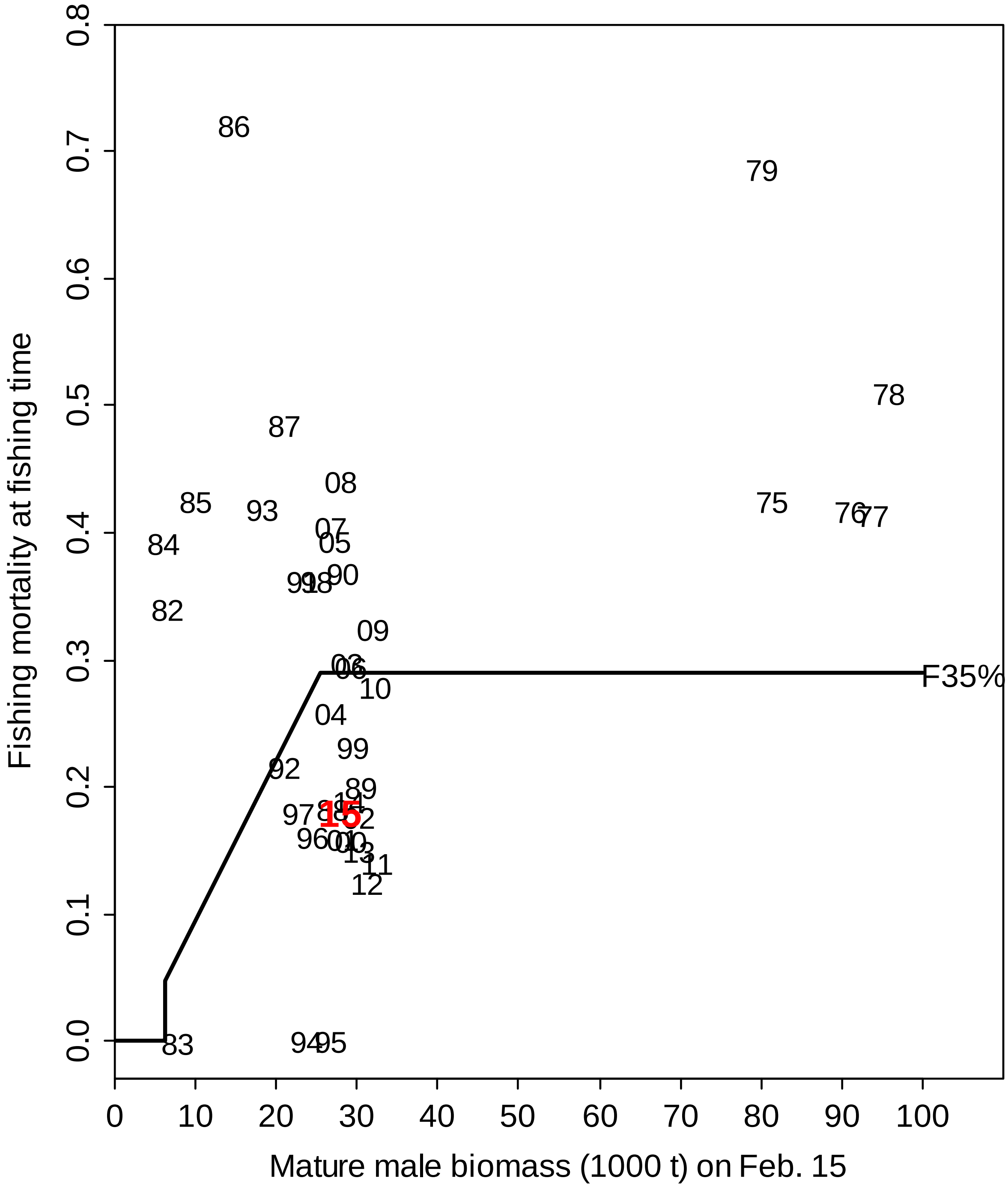


Figure 13(2d). Relationships between full fishing mortalities for the directed pot fishery and mature male biomass on Feb. 15 during 1975-2015 under scenario 2d. Average of recruitment from 1984 to 2016 was used to estimate B_{MSY}. Pot, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.5 and 0.8, respectively.

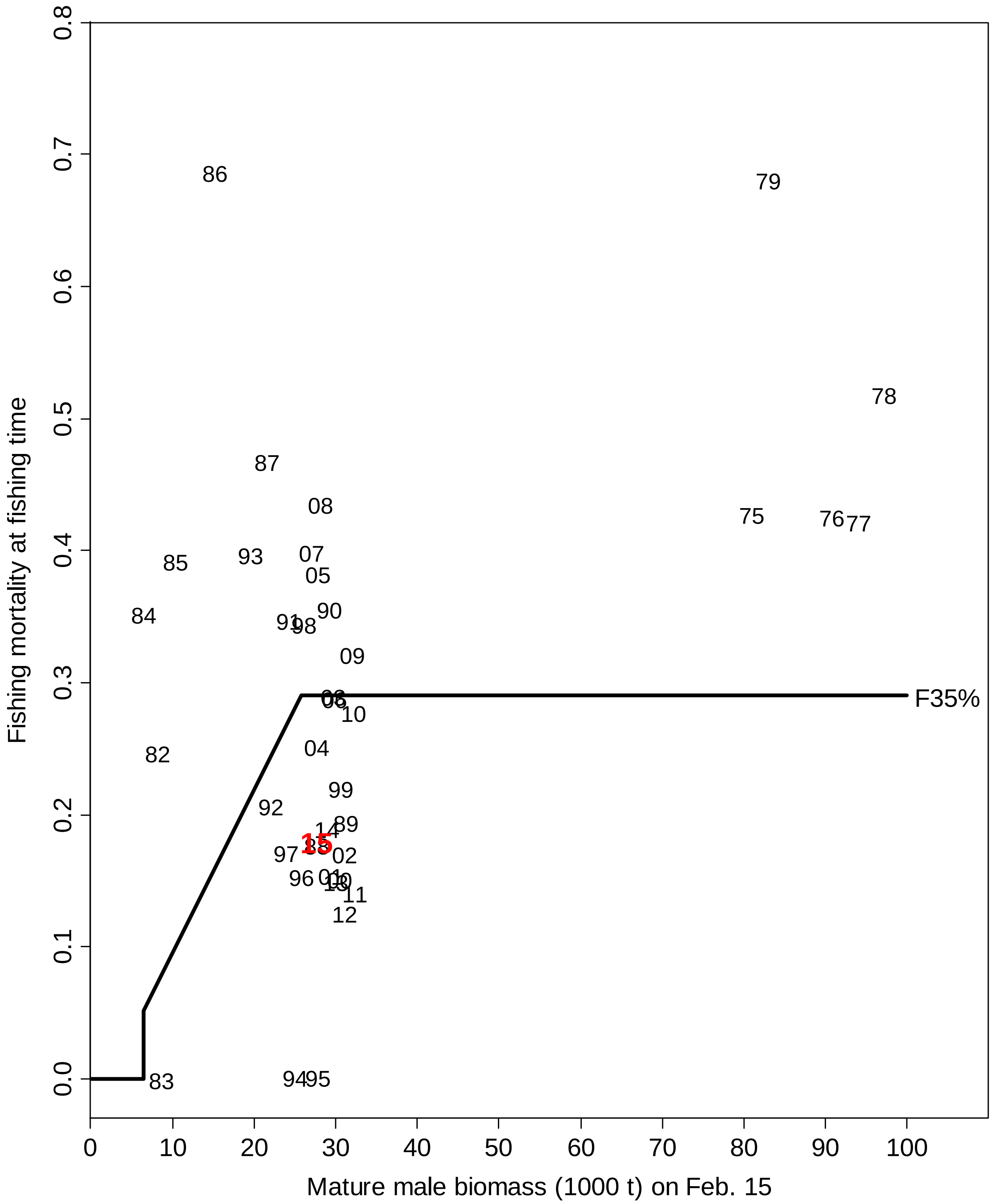


Figure 13(2). Relationships between full fishing mortalities for the directed pot fishery and mature male biomass on Feb. 15 during 1975-2015 under scenario 2. Average of recruitment from 1984 to 2016 was used to estimate BMSY. Pot, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.5 and 0.8, respectively.

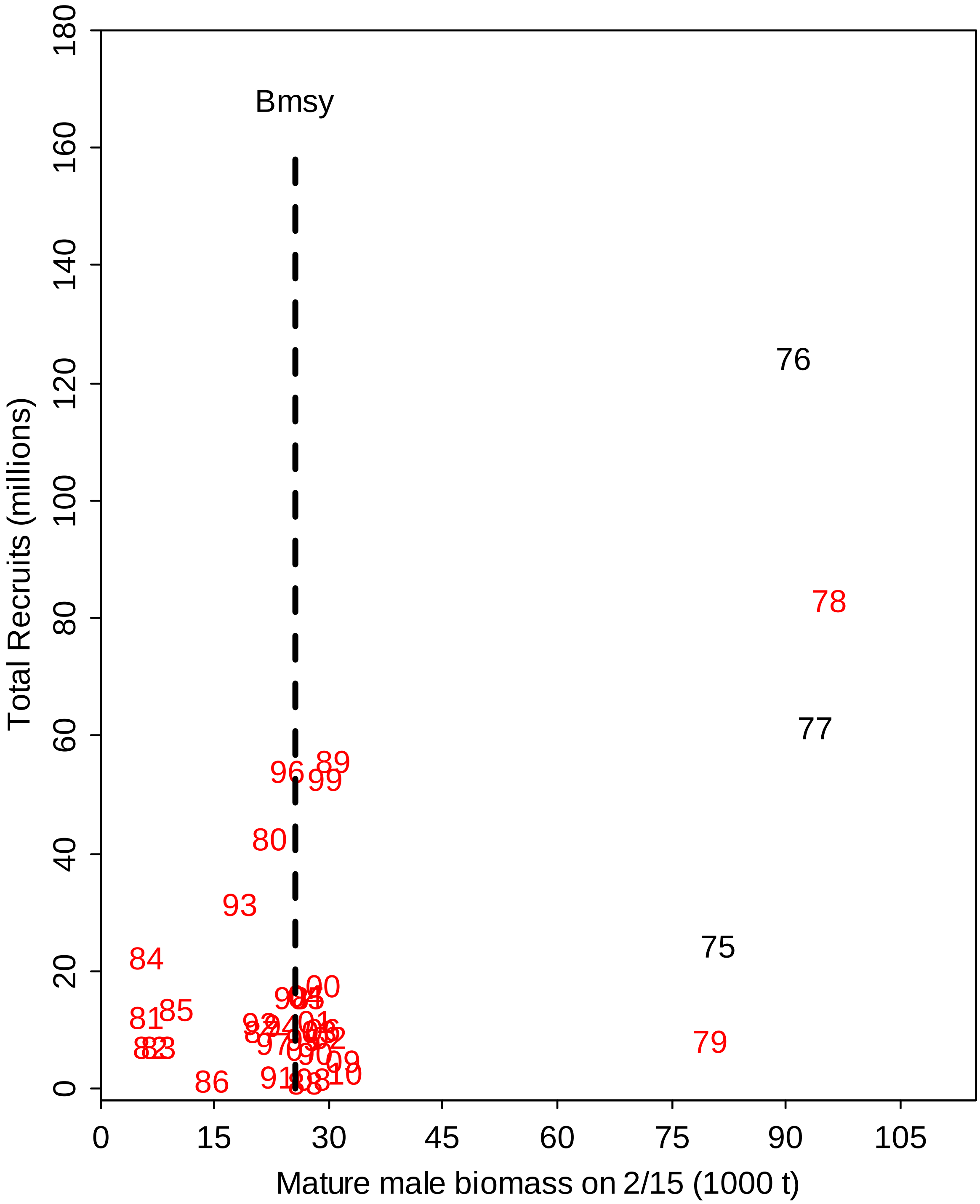


Figure 14a. Relationships between mature male biomass on Feb. 15 and total recruits at age 5 (i.e., 6-year time lag) for Bristol Bay red king crab with pot handling mortality rate of 0.2 under scenario 2d. Numerical labels are years of mating, and the vertical dotted line is the estimated $B_{35\%}$ based on the mean recruitment level during 1984 to 2016.

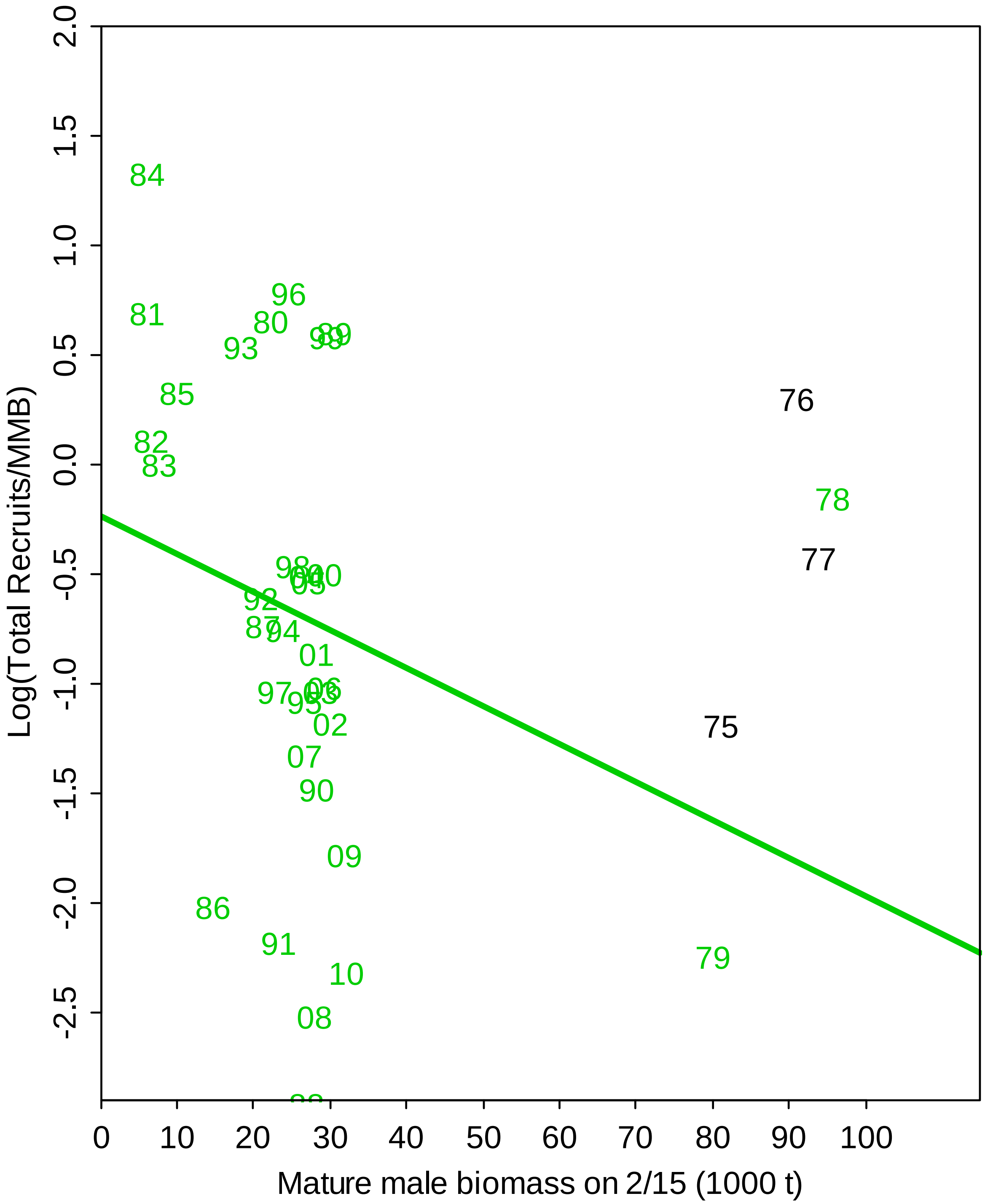


Figure 14b. Relationships between log recruitment per mature male biomass and mature male biomass on Feb. 15 for Bristol Bay red king crab with pot handling mortality rate of 0.2 under scenario 2d. Numerical labels are years of mating, and the line is the regression line for data of 1978-2010.

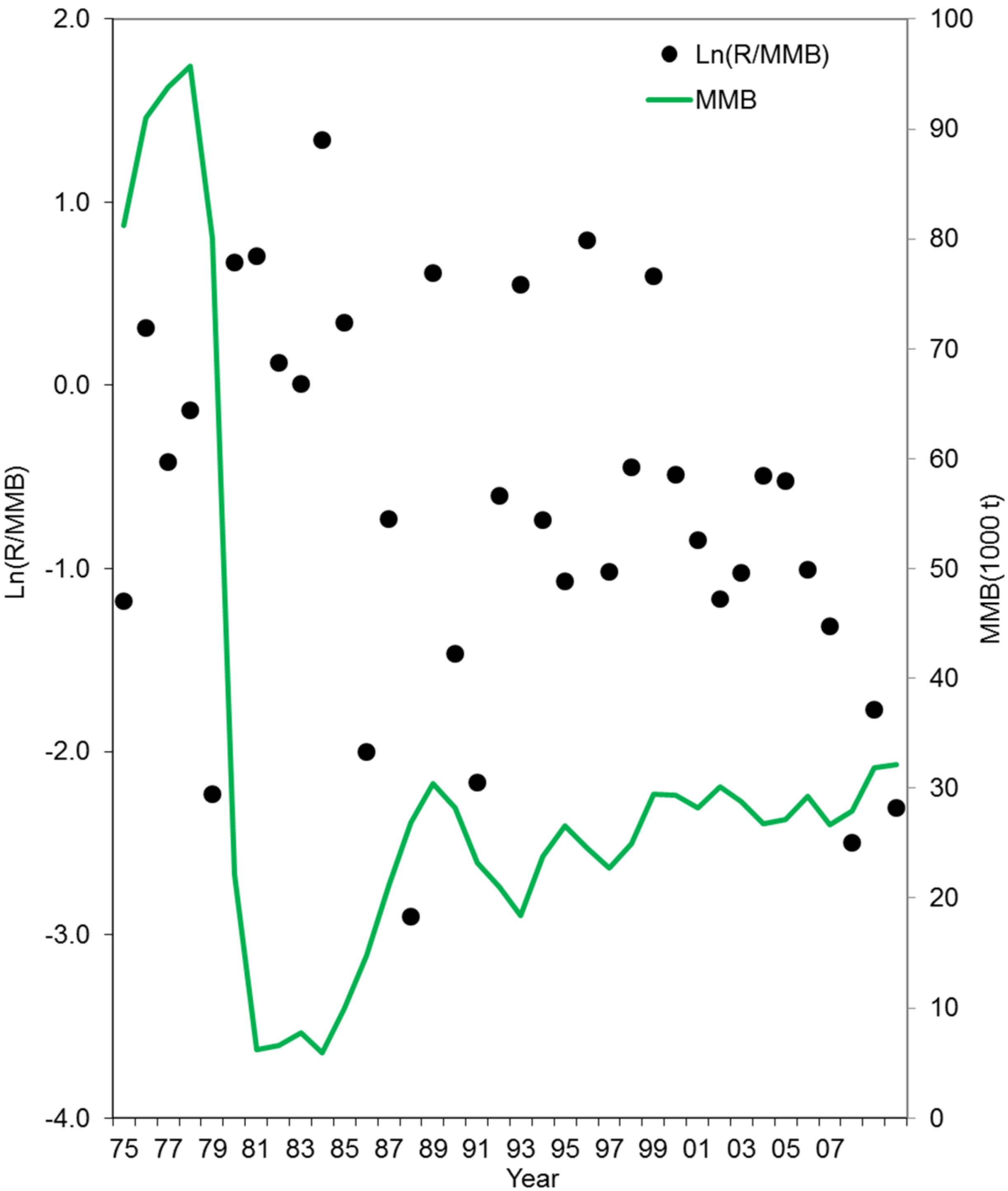


Figure 14c. Time series of log recruitment per mature male biomass and mature male biomass on Feb. 15 for Bristol Bay red king crab with pot handling mortality rate of 0.2 under scenario 2d.

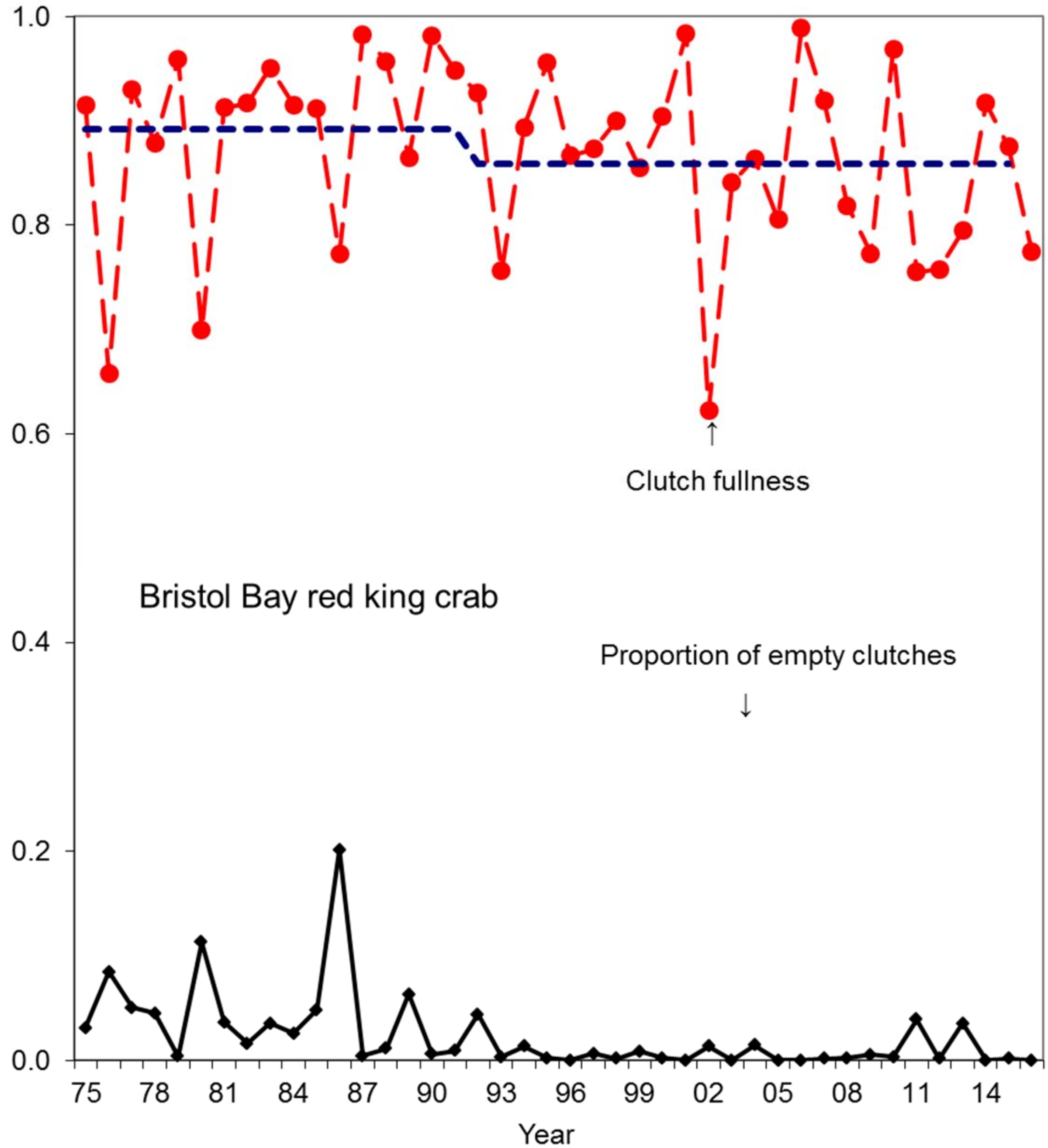


Figure 15. Average clutch fullness and proportion of empty clutches of newshell (shell conditions 1 and 2) mature female crab >89 mm CL from 1975 to 2016 from survey data. Oldshell females were excluded.

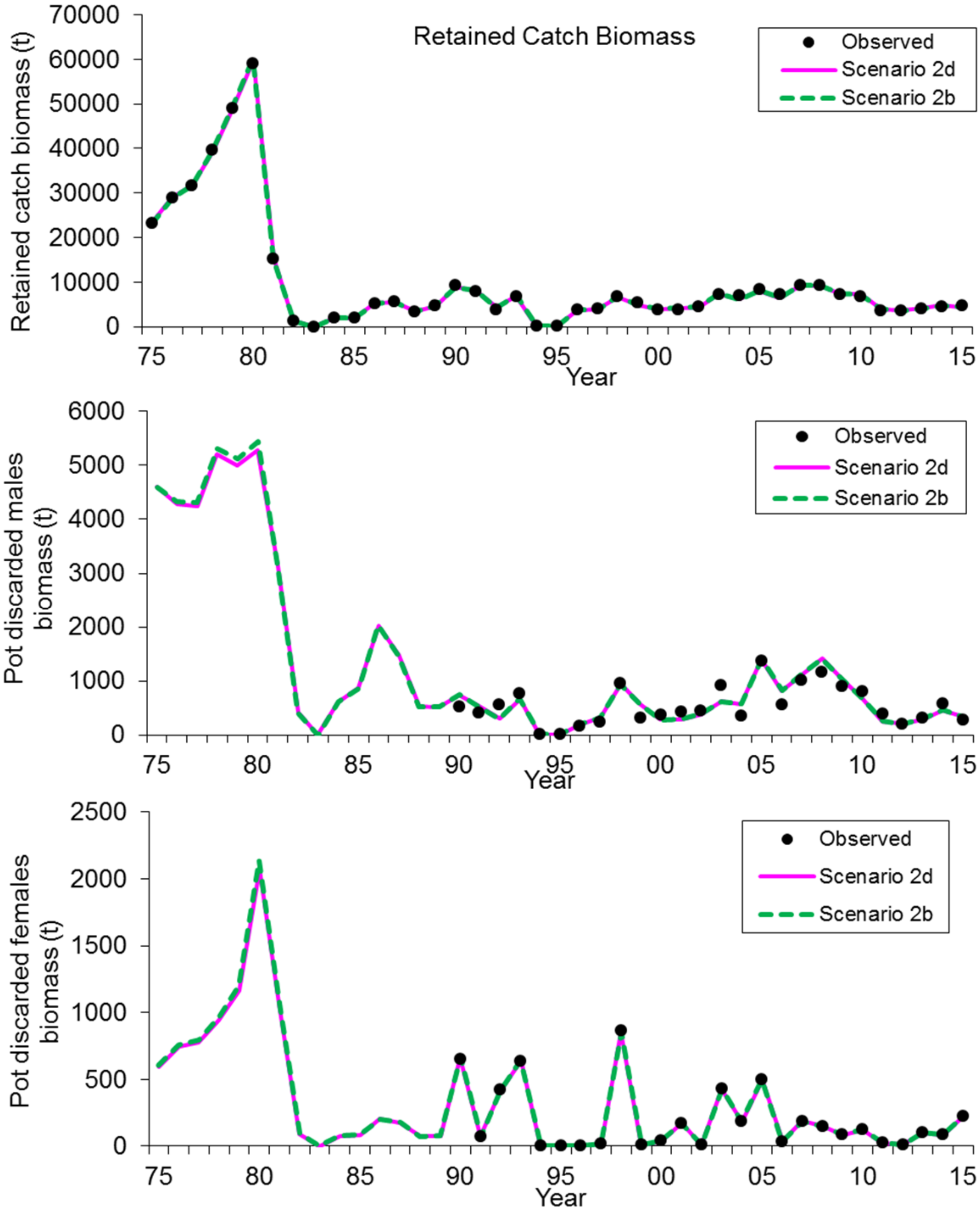


Figure 16a. Observed and predicted catch mortality biomass under scenarios 2b and 2d. Mortality biomass is equal to caught biomass times a handling mortality rate. Pot handling mortality rate is 0.2.

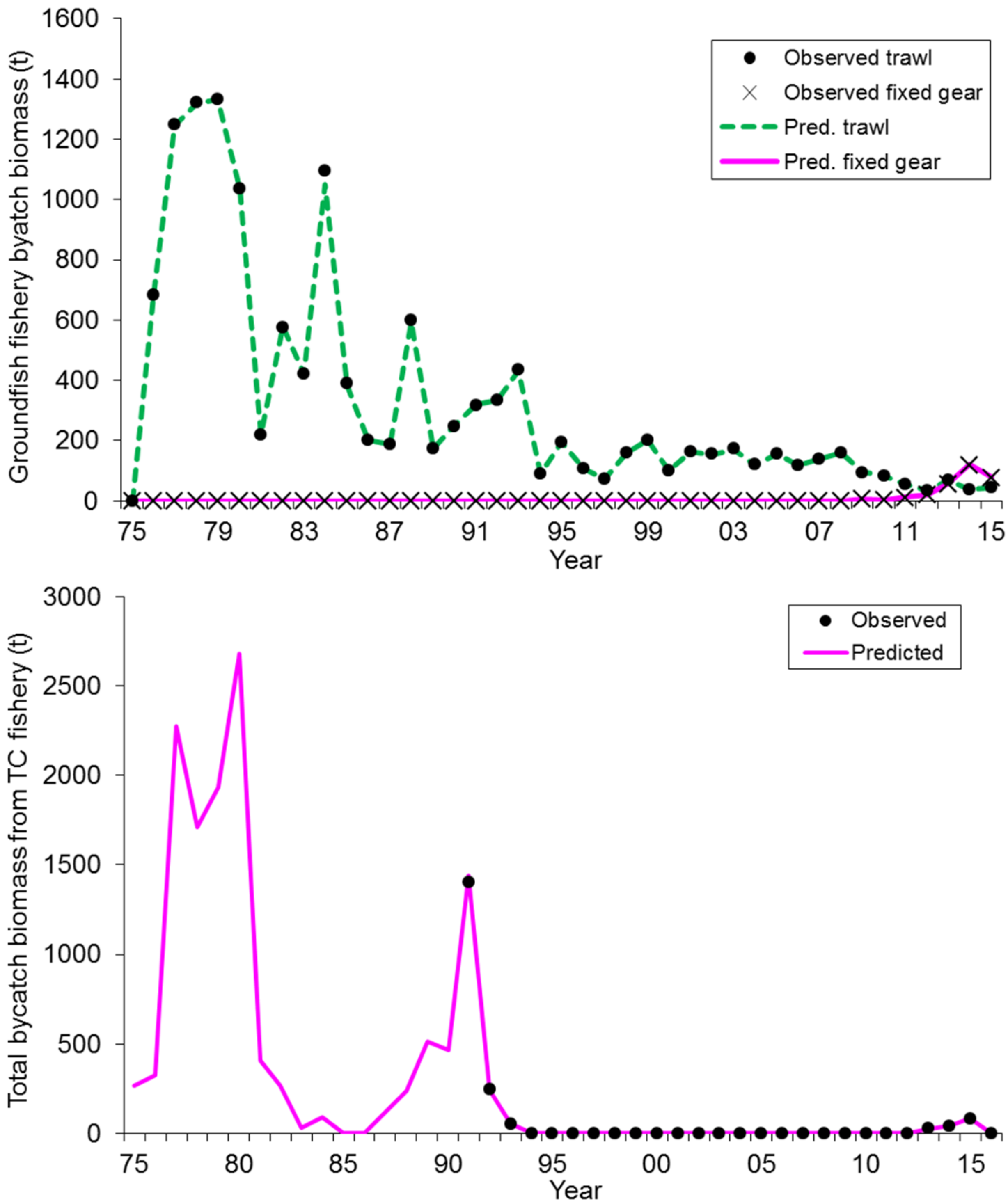


Figure 16b. Observed and predicted bycatch mortality biomass from groundfish fisheries and the Tanner crab fishery under scenario 2d. Mortality biomass is equal to caught biomass times a handling mortality rate. Trawl handling mortality rate is 0.8, fixed gear handling mortality rate is 0.5, and Tanner crab pot handling mortality is 0.25. Trawl bycatch biomass was 0 before 1976.

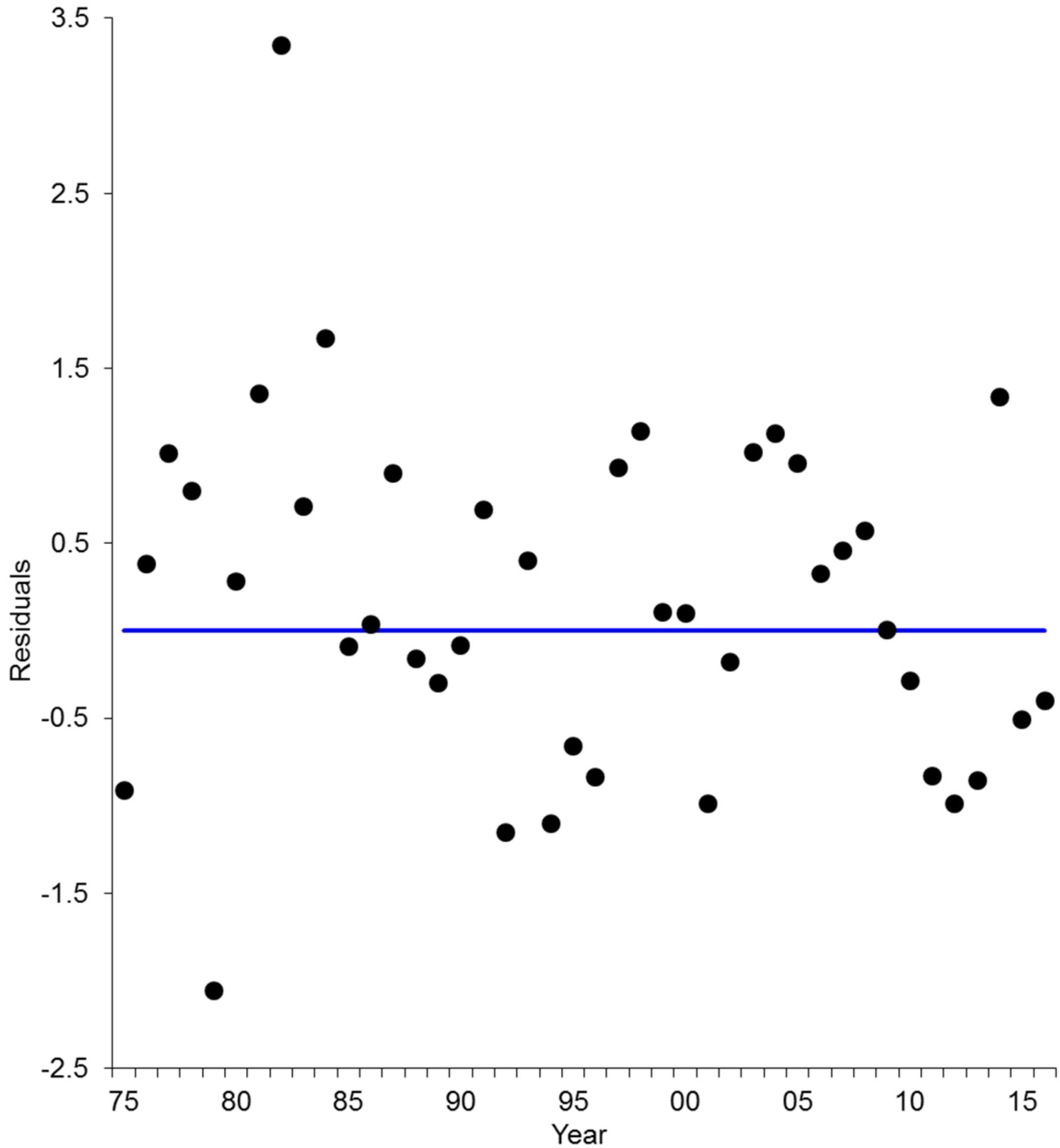


Figure 17(2d). Standardized residuals of total survey biomass under scenario 2d. Pot, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.5 and 0.8, respectively.

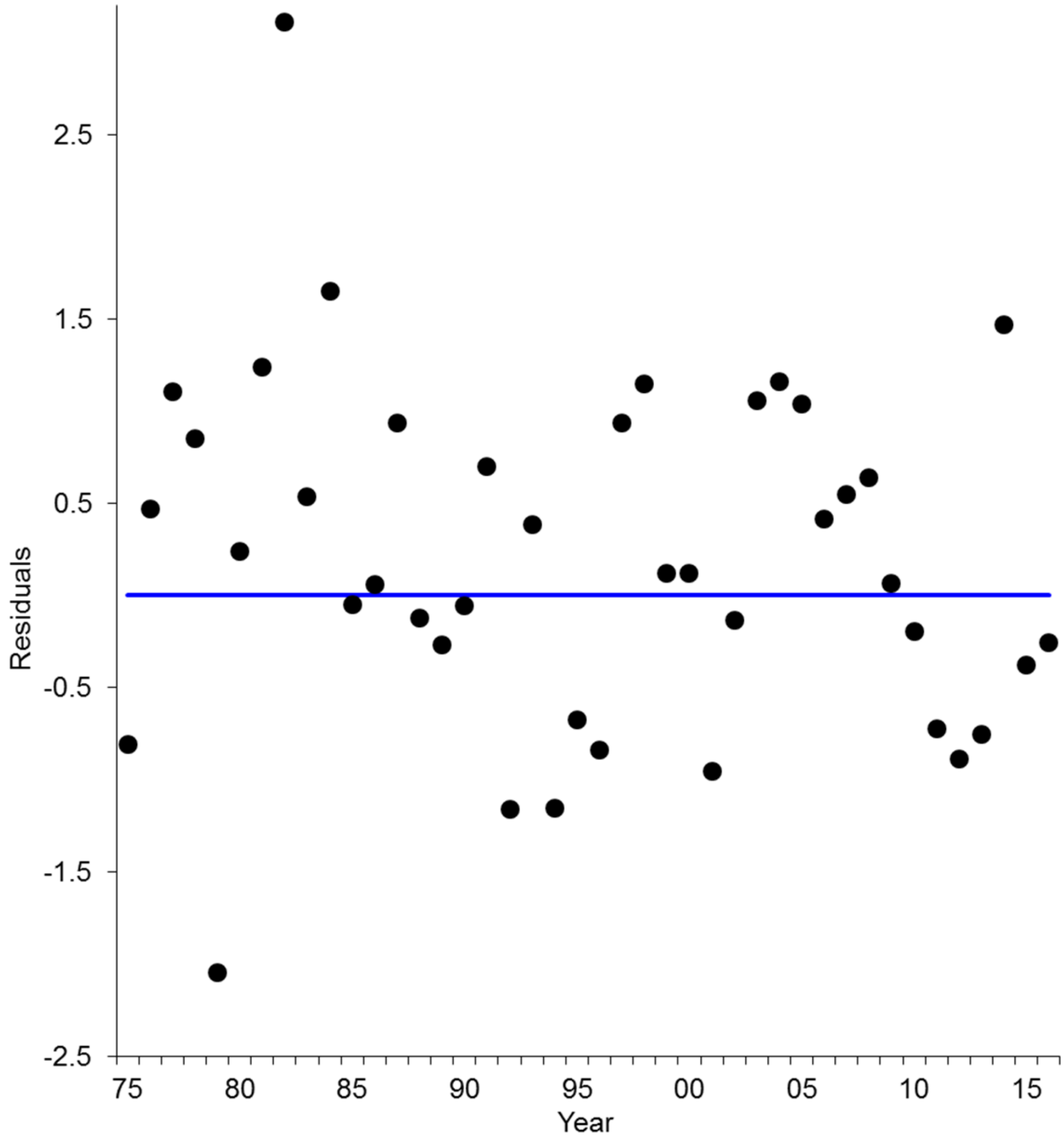


Figure 17(2). Standardized residuals of total survey biomass under scenario 2. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

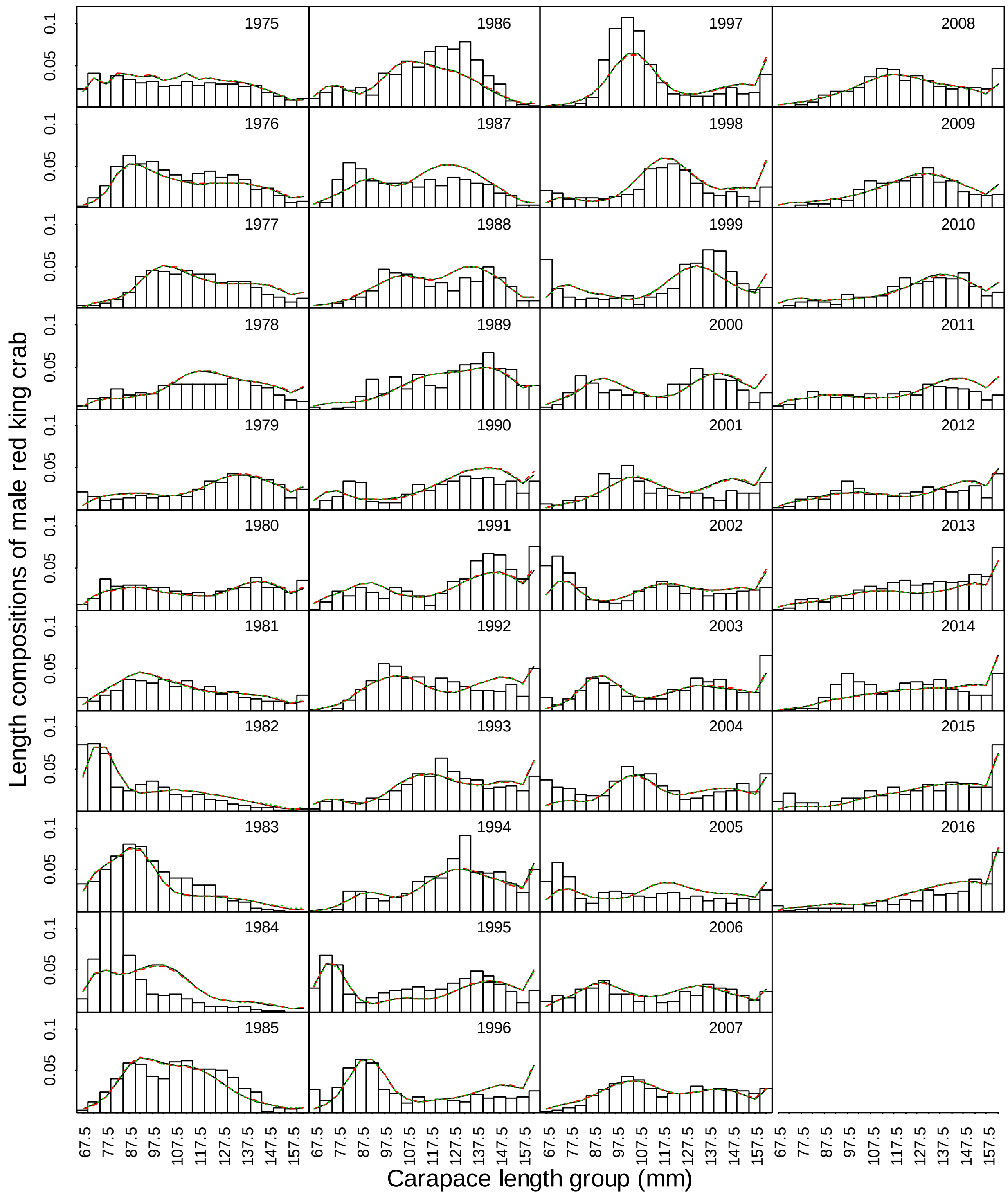


Figure 18(2b, 2c & 2d). Comparison of area-swept and model estimated survey length frequencies of Bristol Bay male red king crab by year under scenarios 2b(solid black), 2c (dashed red), and 2d (green lines). Pot, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.5 and 0.8.

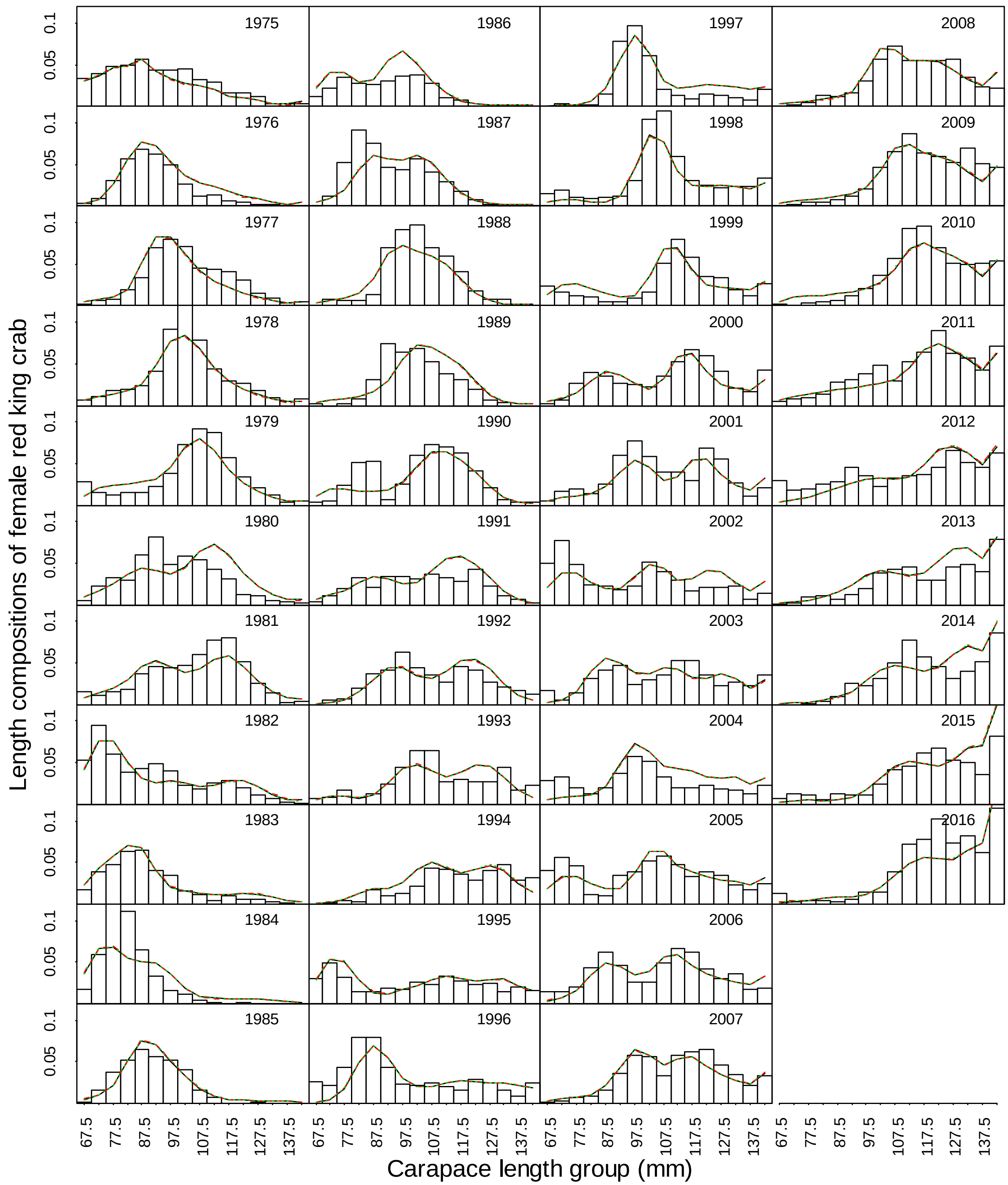


Figure 19(2b, 2c & 2d). Comparison of area-swept and model estimated survey length frequencies of Bristol Bay female red king crab by year under scenarios 2b(solid black), 2c (dashed red), and 2d (green lines). Pot, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.5 and 0.8.

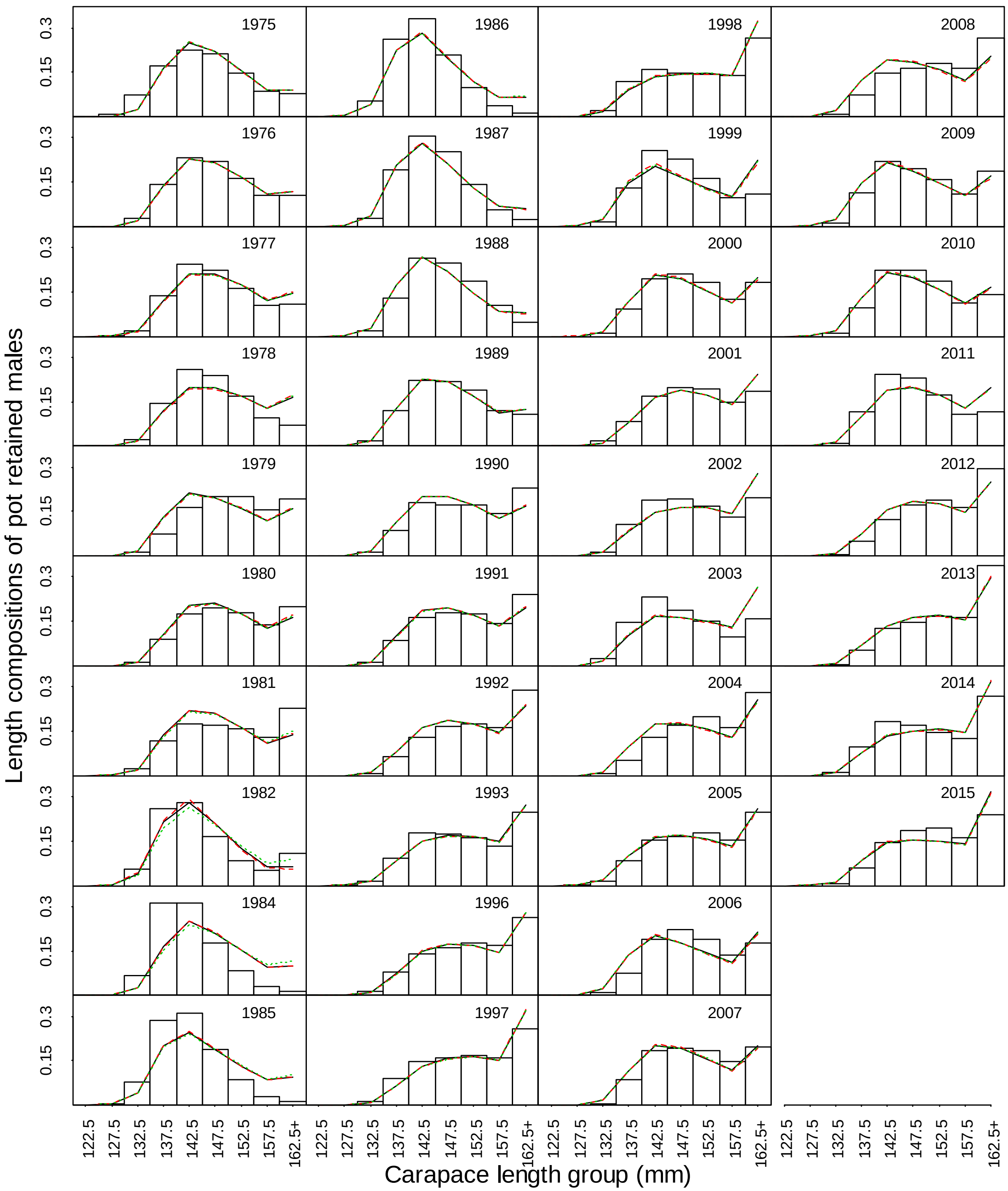


Figure 20(2b, 2c & 2d). Comparison of observed and model estimated retained length frequencies of Bristol Bay male red king crab by year in the directed pot fishery under scenarios 2b(solid black), 2c (dashed red), and 2d (green lines). Pot, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.5 and 0.8.

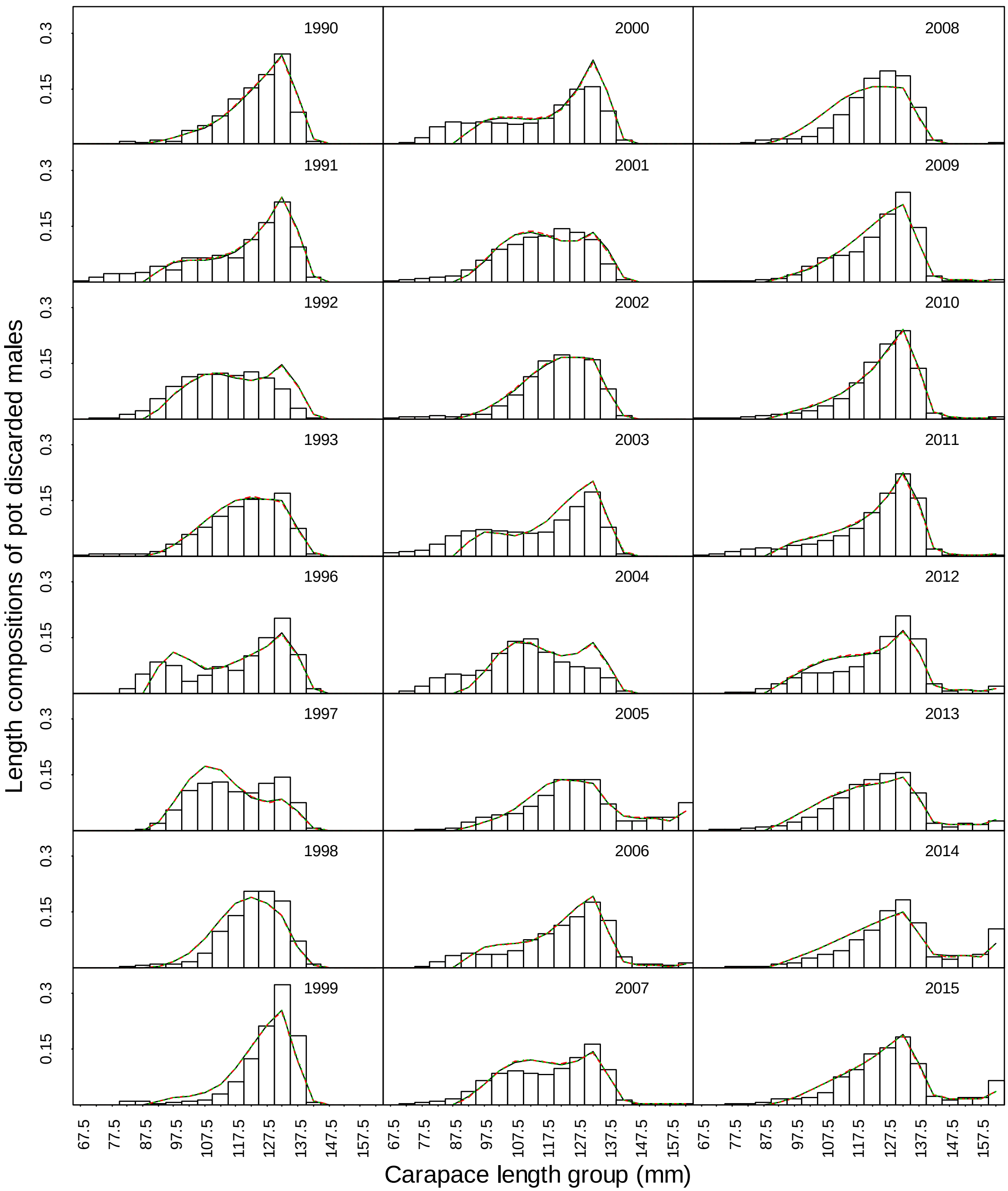


Figure 21(2b, 2c & 2d). Comparison of observer and model estimated discarded length frequencies of Bristol Bay male red king crab by year in the directed pot fishery under scenarios 2b(solid black), 2c (dashed red), and 2d (green lines). Pot, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.5 and 0.8.

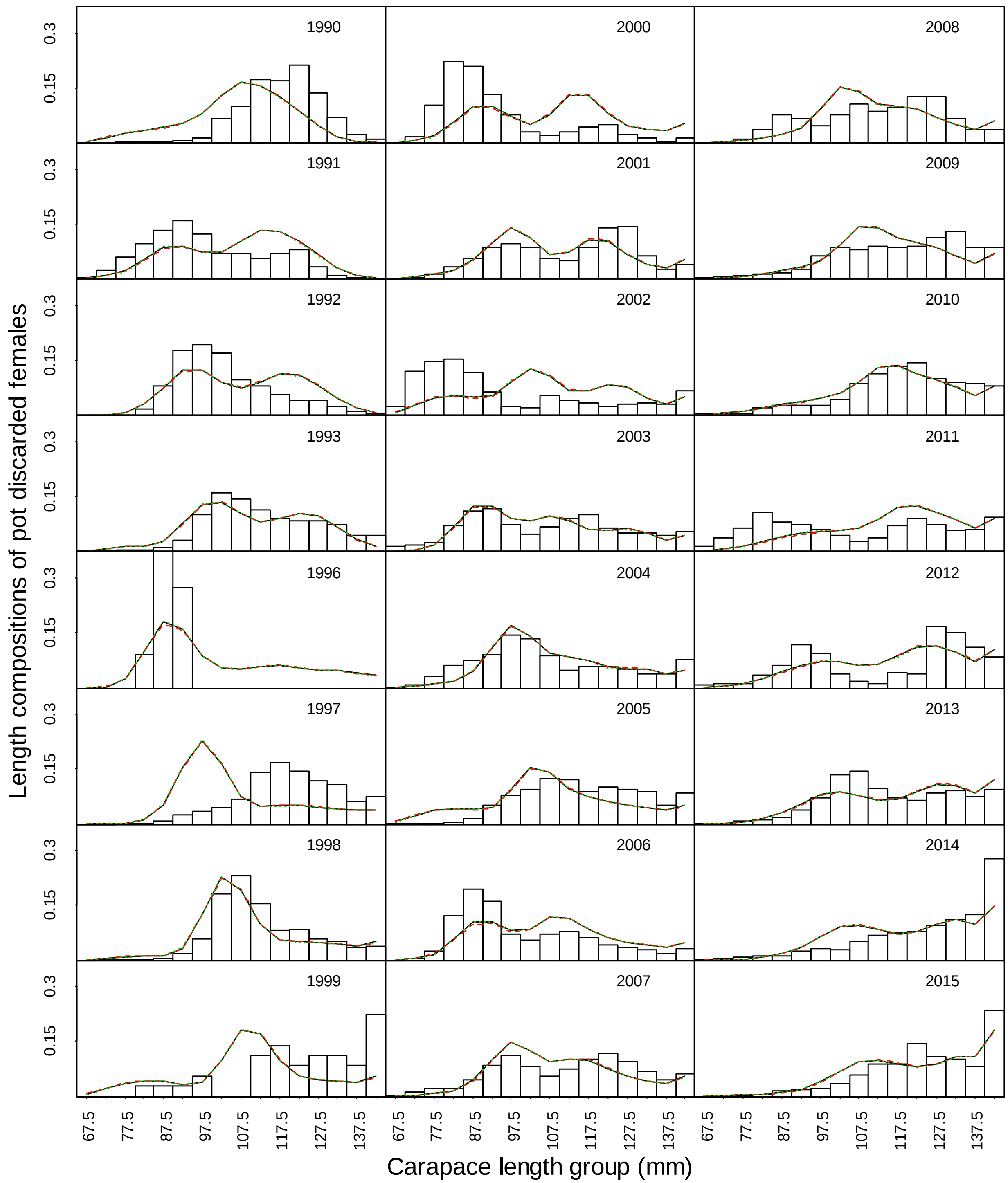


Figure 22(2b, 2c & 22d). Comparison of observer and model estimated discarded length frequencies of Bristol Bay female red king crab by year in the directed pot fishery under scenarios 2b(solid black), 2c (dashed red), and 2d (green lines). Pot, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.5 and 0.8.

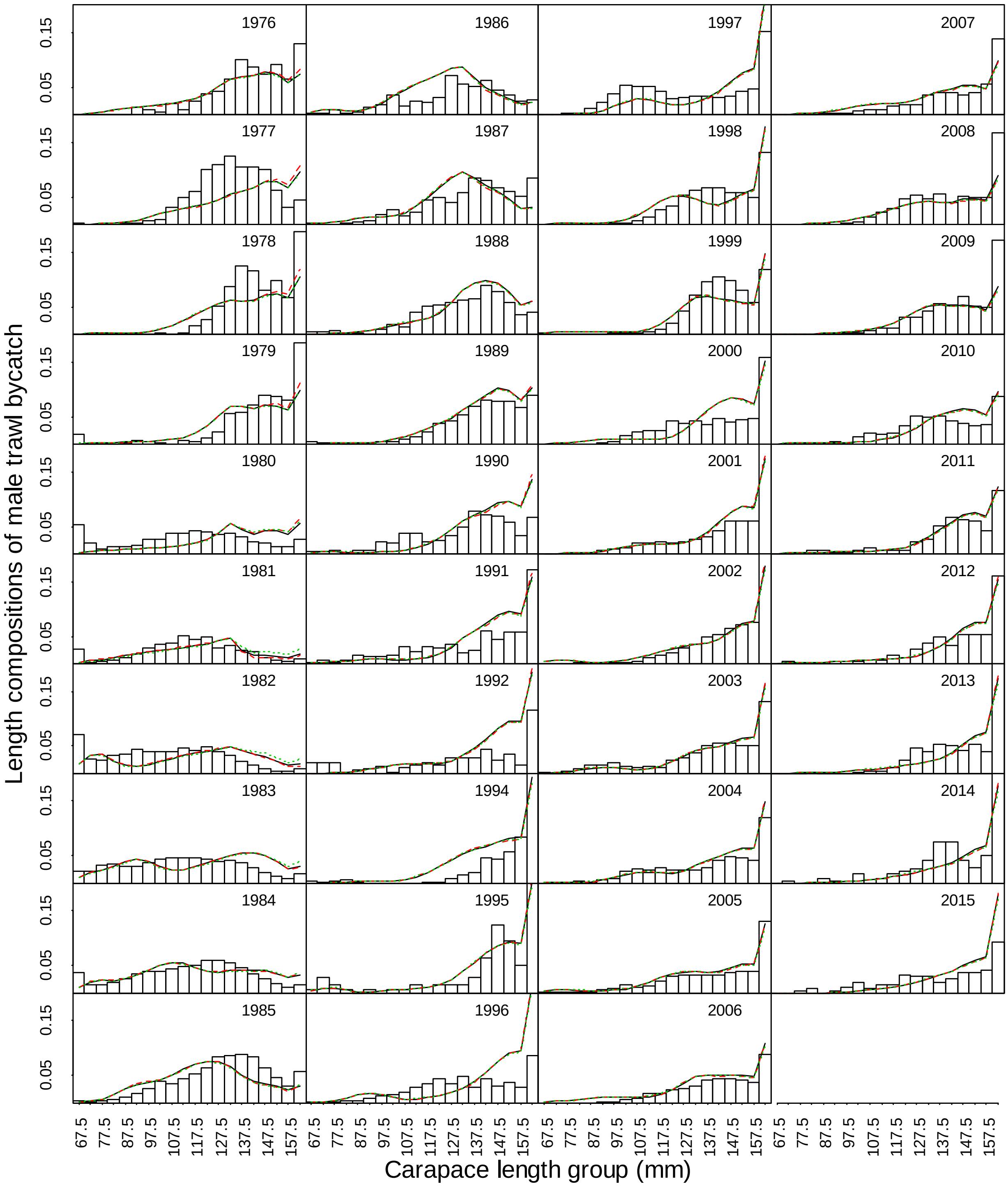


Figure 23(2b, 2c & 2d). Comparison of observer and model estimated discarded length frequencies of Bristol Bay male red king crab by year in the groundfish trawl fisheries under scenarios 2b(solid black), 2c (dashed red), and 2d (green lines). Pot, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.5 and 0.8.

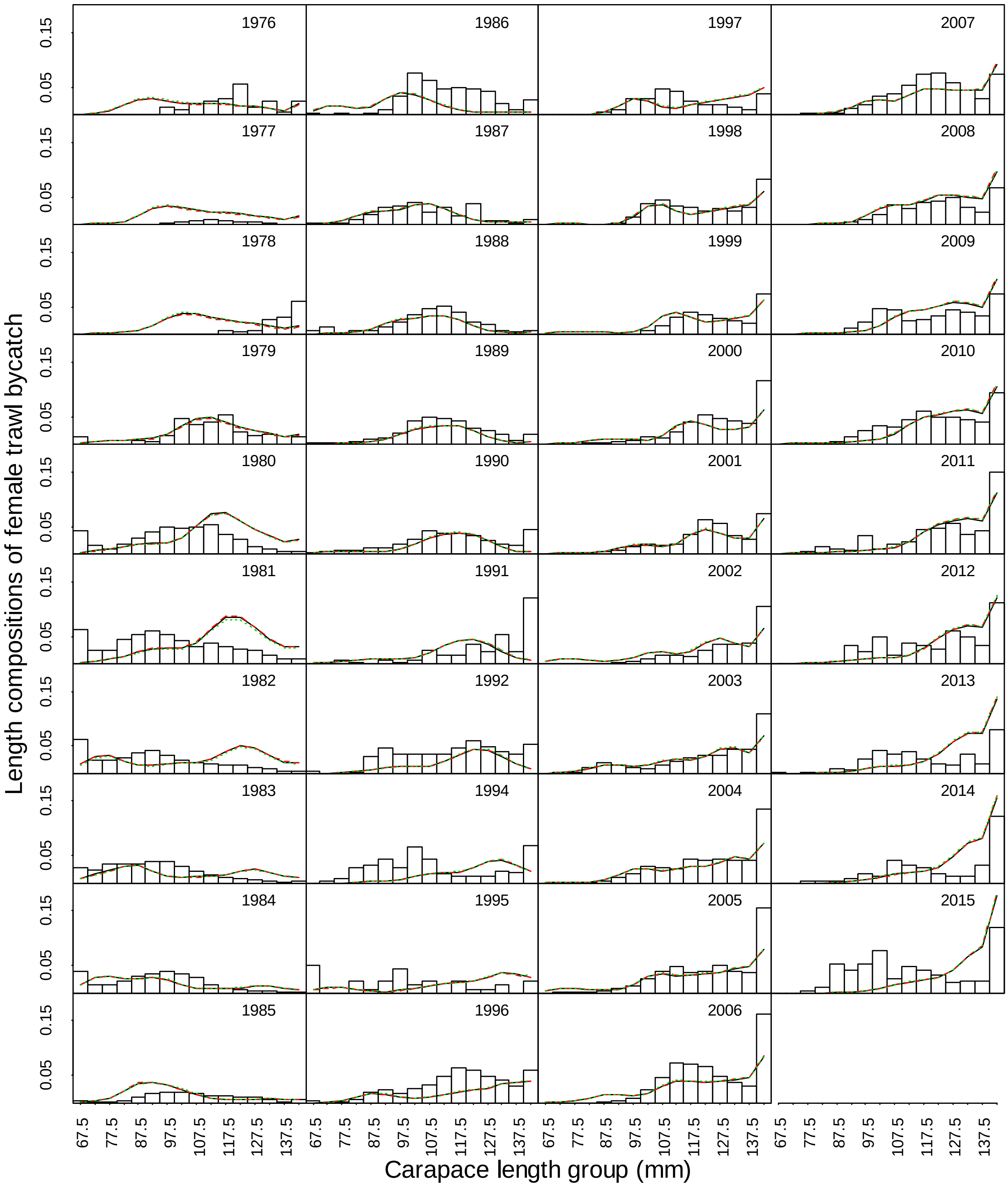


Figure 23(2b, 2c & 2d). Comparison of observer and model estimated discarded length frequencies of Bristol Bay female red king crab by year in the groundfish trawl fisheries under scenarios 2b(solid black), 2c (dashed red), and 2d (green lines). Pot, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.5 and 0.8.

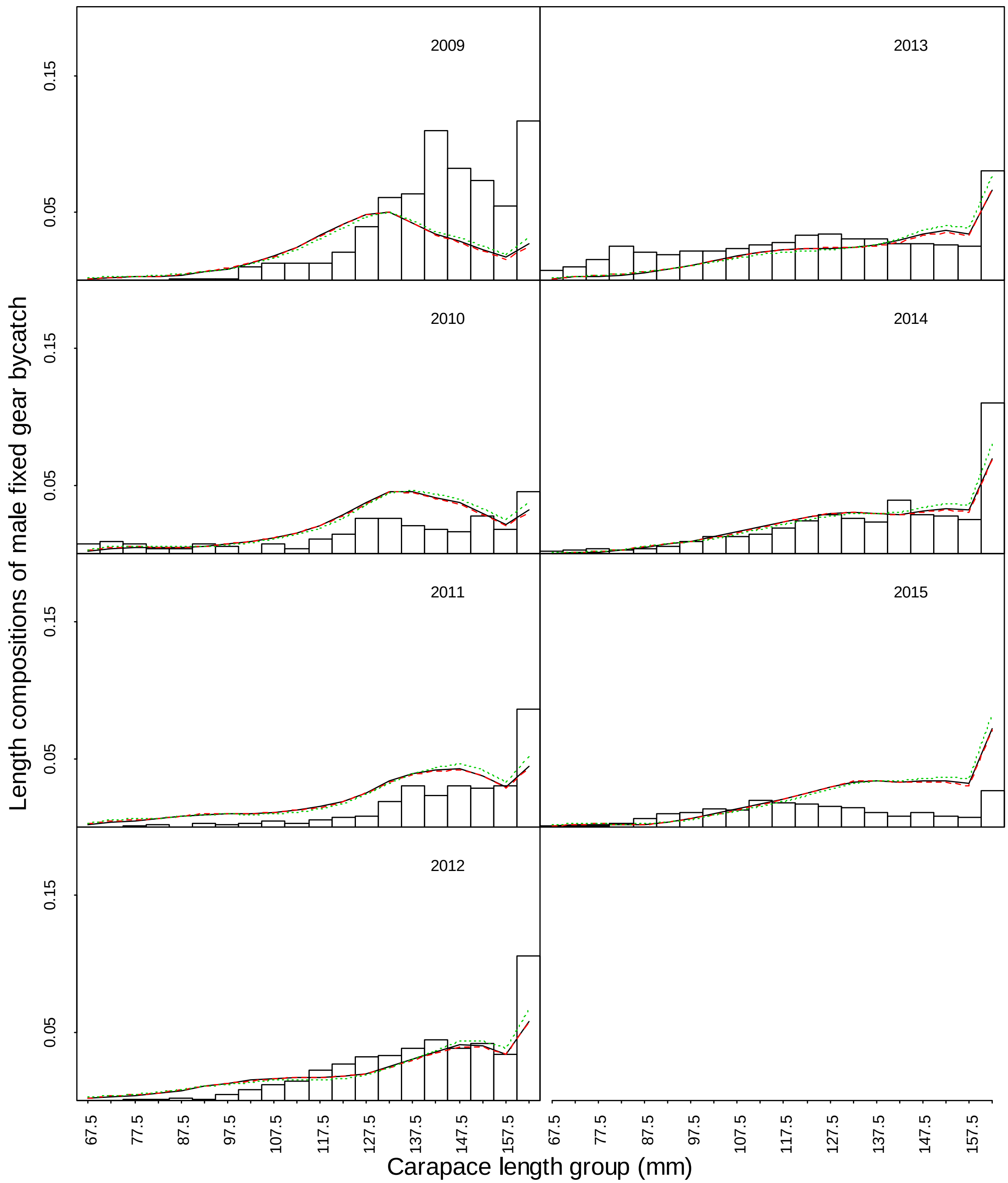


Figure 24(2b, 2c & 2d). Comparison of observer and model estimated discarded length frequencies of Bristol Bay male red king crab by year in the groundfish fixed gear fisheries under scenarios 2b(solid black), 2c (dashed red), and 2d (green lines). Pot, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.5 and 0.8.

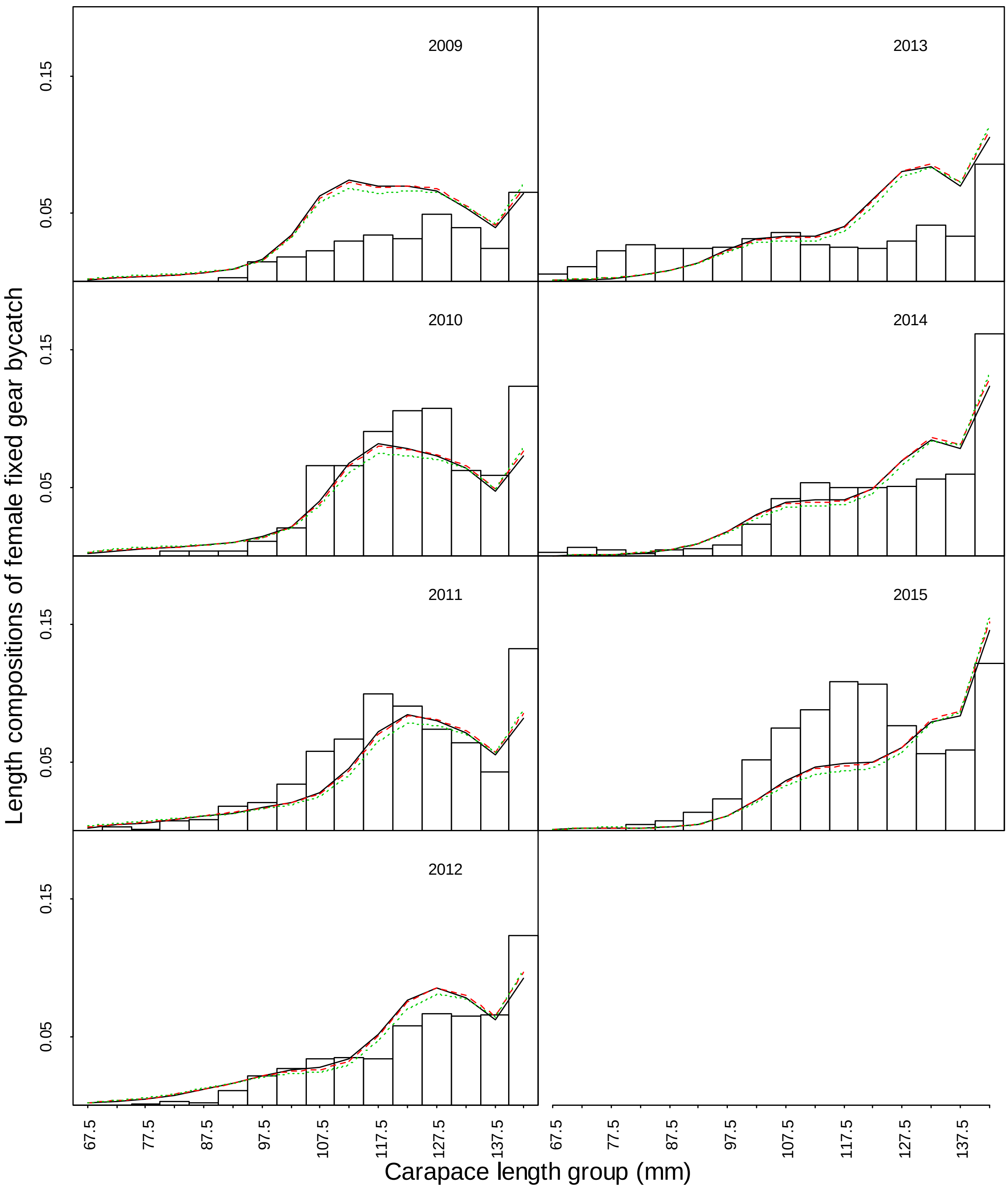


Figure 24(2b, 2c & 2d). Comparison of observer and model estimated discarded length frequencies of Bristol Bay female red king crab by year in the groundfish fixed gear fisheries under scenarios 2b(solid black), 2c (dashed red), and 2d (green lines). Pot, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.5 and 0.8.

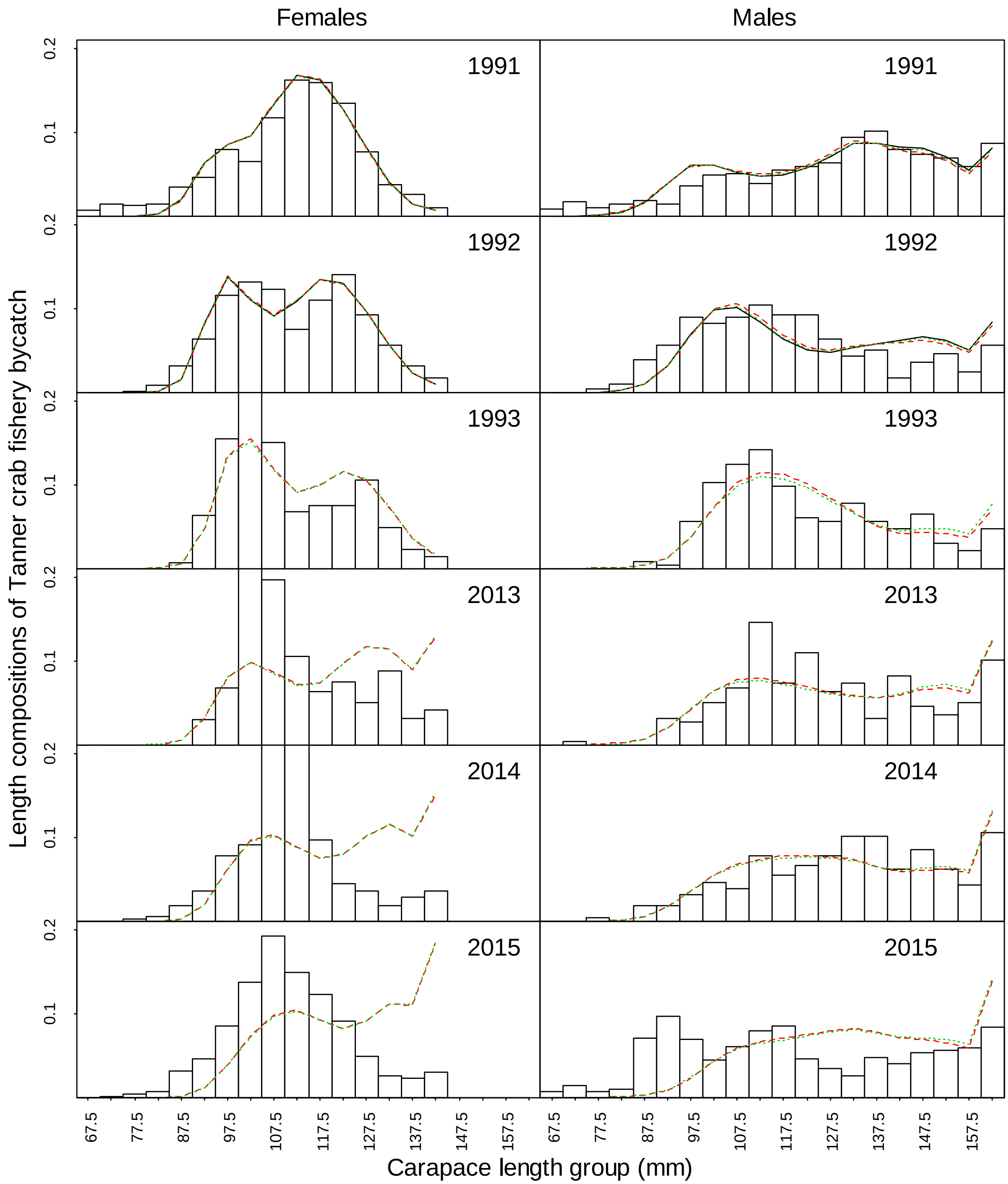


Figure 24(2b, 2c & 2d). Comparison of observer and model estimated discarded length frequencies of Bristol Bay red king crab by year in the Tanner crab fishery under scenarios 2b(solid black), 2c (dashed red), and 2d (green lines). Pot, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.5 and 0.8.

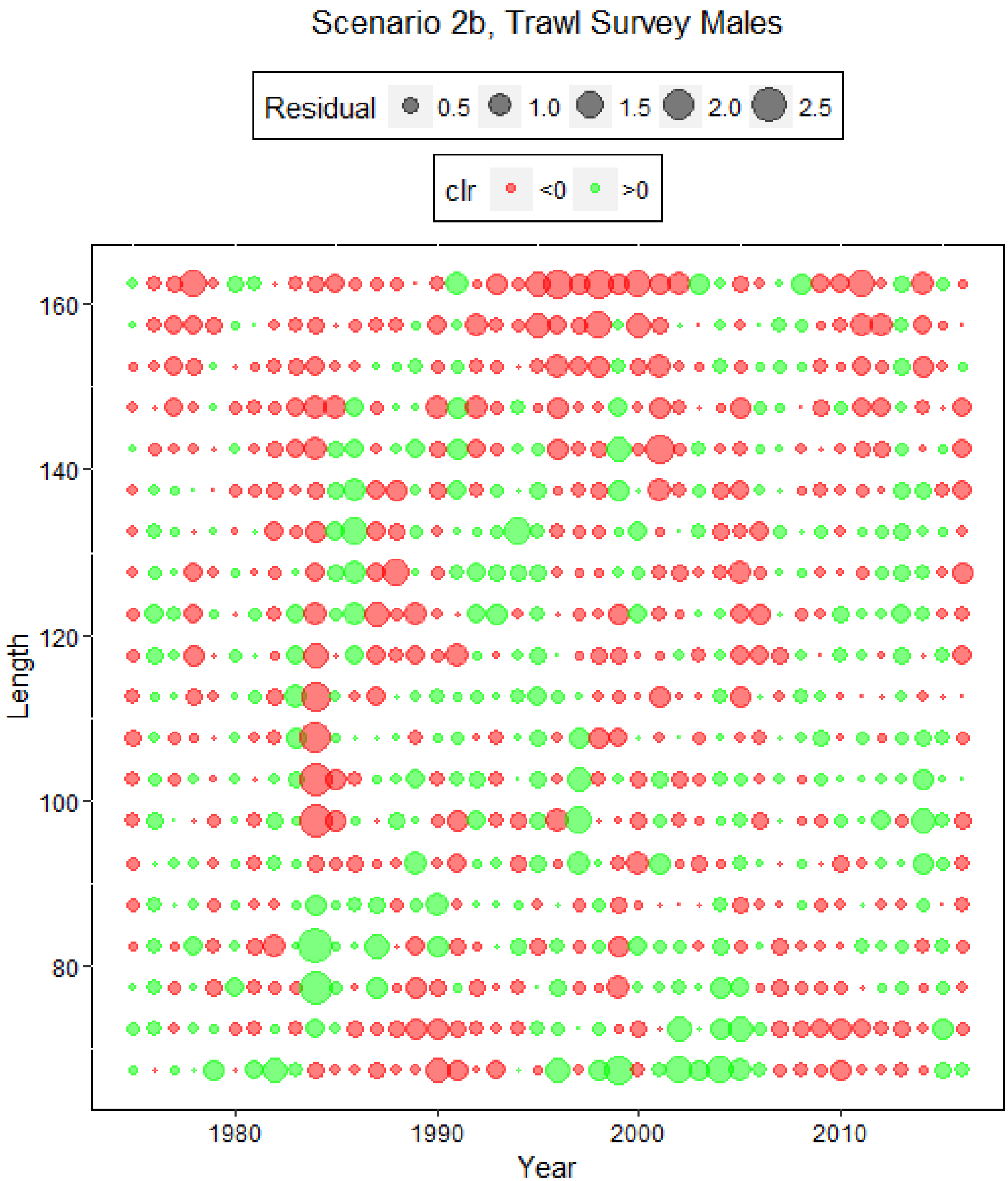


Figure 25(2b). Standardized residuals of proportions of survey male red king crab by year and carapace length (mm) under scenario 2b. Green circles are positive residuals, and red circles are negative residuals. Pot, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.5 and 0.8, respectively.

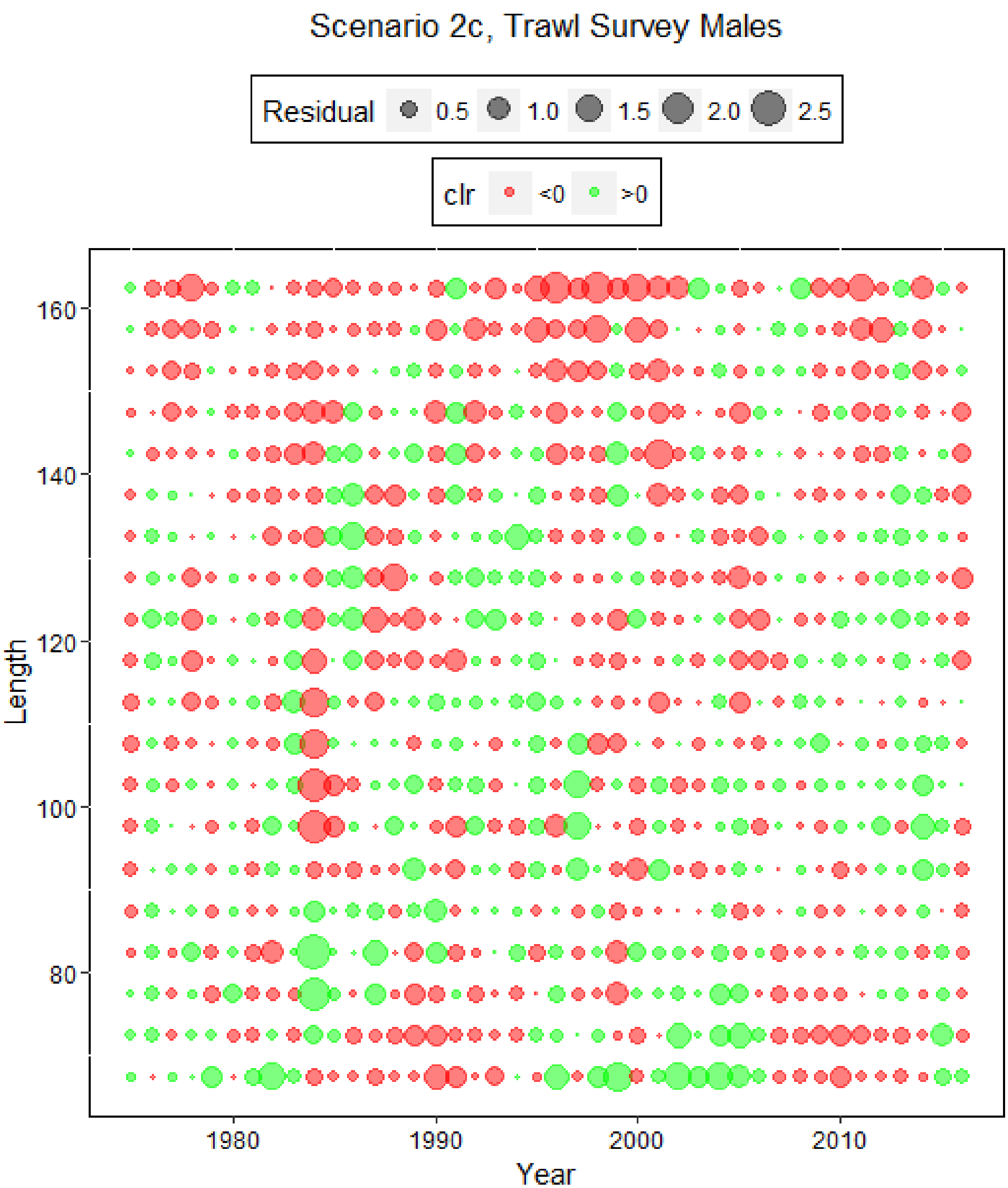


Figure 25(2c). Standardized residuals of proportions of survey male red king crab by year and carapace length (mm) under scenario 2c. Green circles are positive residuals, and red circles are negative residuals. Pot, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.5 and 0.8, respectively.

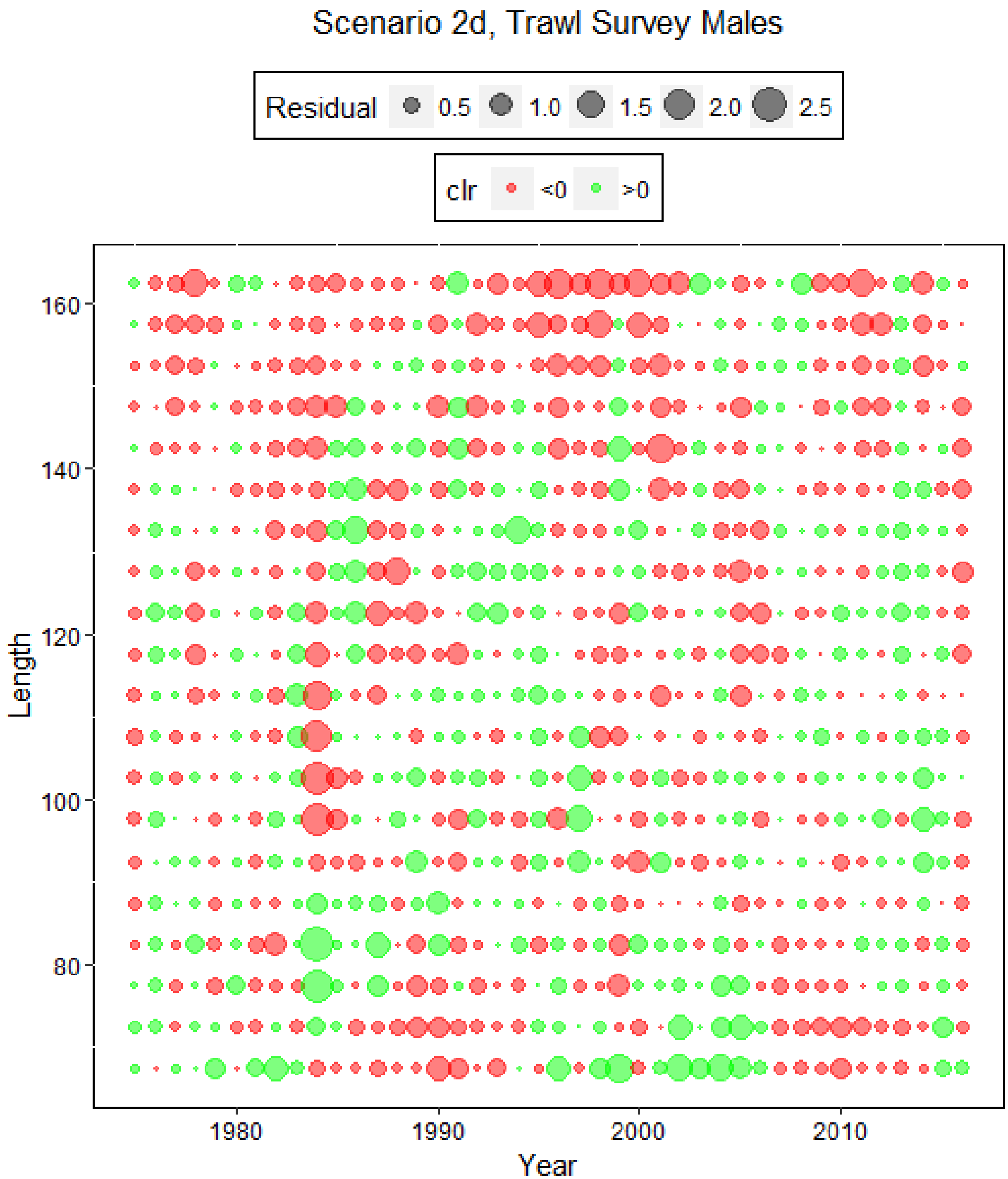


Figure 25(2d). Standardized residuals of proportions of survey male red king crab by year and carapace length (mm) under scenario 2d. Green circles are positive residuals, and red circles are negative residuals. Pot, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.5 and 0.8, respectively.

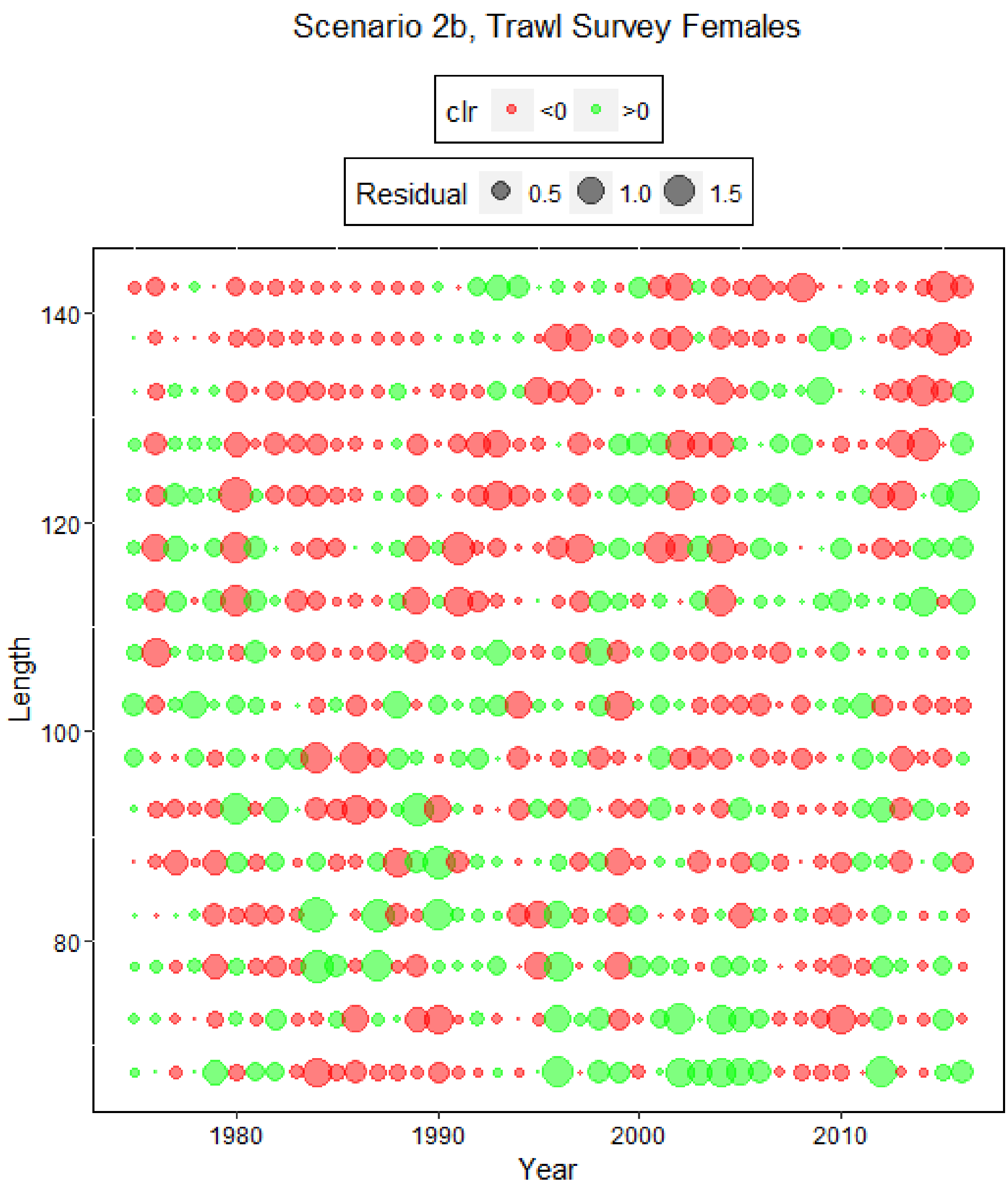


Figure 25(2b). Standardized residuals of proportions of survey female red king crab by year and carapace length (mm) under scenario 2b. Green circles are positive residuals, and red circles are negative residuals. Pot, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.5 and 0.8, respectively.

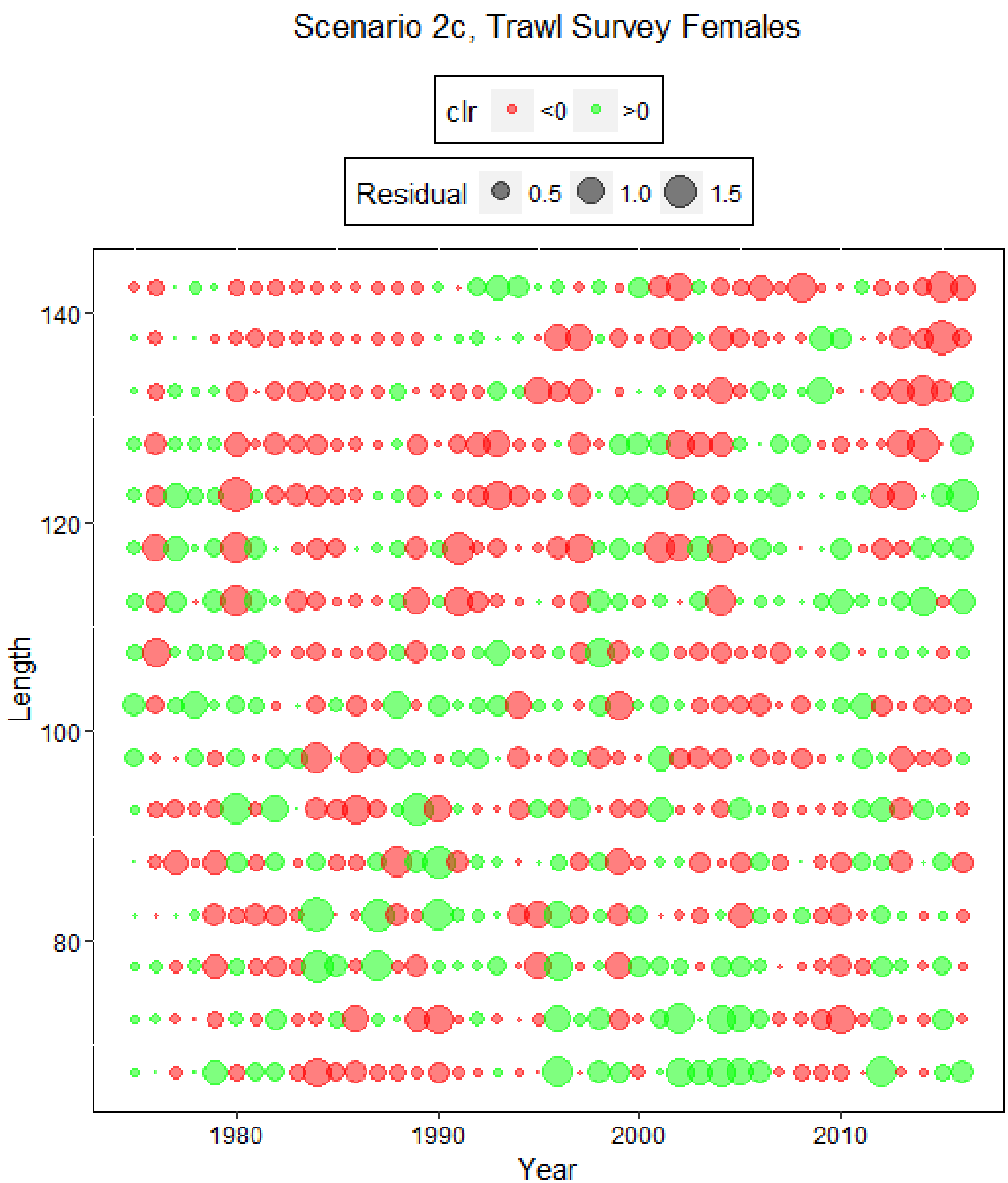


Figure 25(2c). Standardized residuals of proportions of survey female red king crab by year and carapace length (mm) under scenario 2c. Green circles are positive residuals, and red circles are negative residuals. Pot, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.5 and 0.8, respectively.

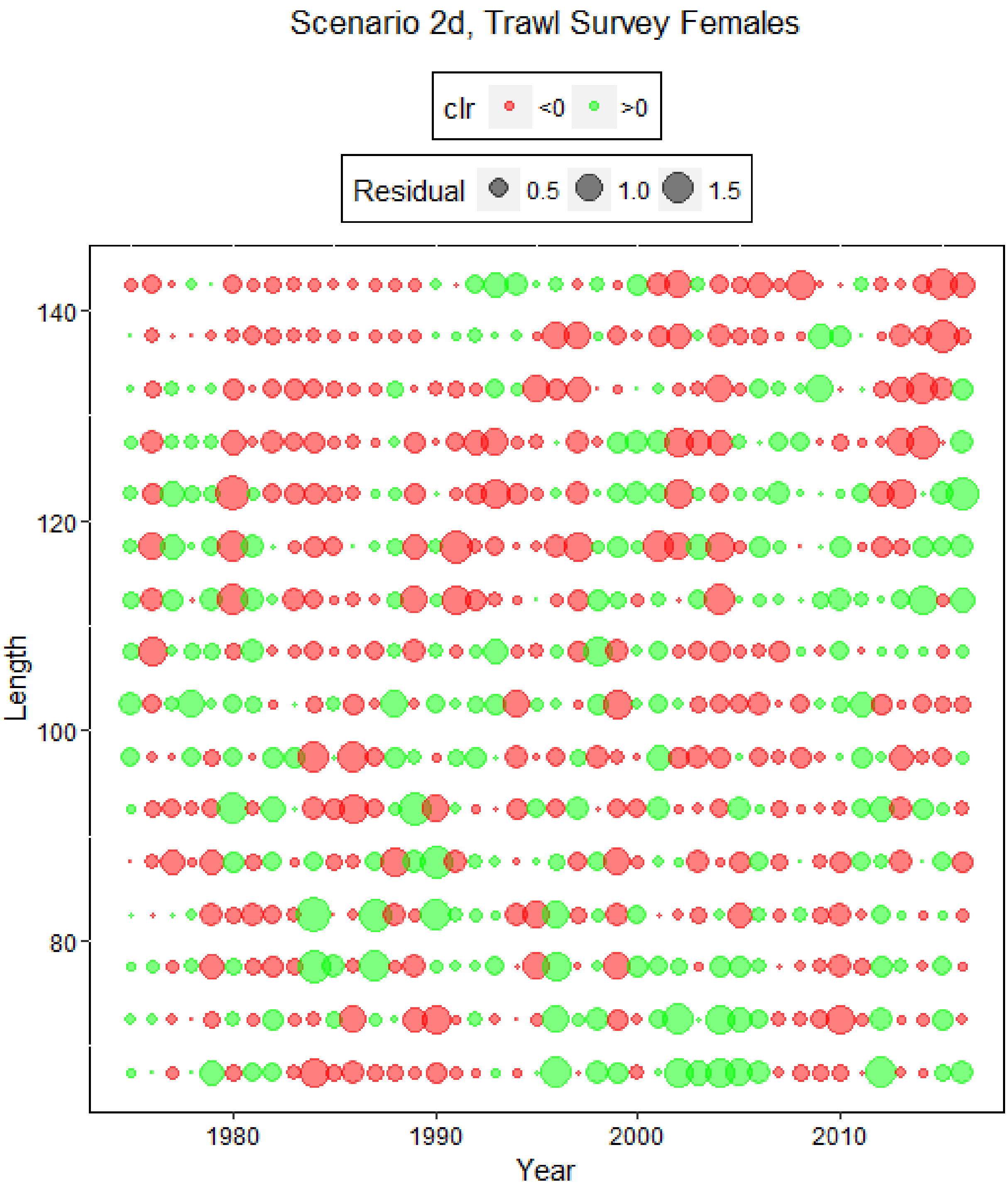


Figure 25(2d). Standardized residuals of proportions of survey female red king crab by year and carapace length (mm) under scenario 2d. Green circles are positive residuals, and red circles are negative residuals. Pot, fixed gear and trawl handling mortality rates were assumed to be 0.2, 0.5 and 0.8, 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 2016 made with terminal years 2008-2016 with scenario 2d. These are results of the 2016 model. Legend shows the terminal year. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

Figure 28. Comparison of hindcast estimates of total recruitment for scenario 2d of Bristol Bay red king crab from 1976 to 2016 made with terminal years 2008-2016. These are results of the 2016 model. Legend shows the terminal year. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

Figure 29. Comparison of estimates of legal male abundance (top) and mature males (bottom) of Bristol Bay red king crab from 1968 to 2016 made with terminal years 2004-2016 with the base scenarios. Scenario 2d is used for 2014-2016. These are results of historical assessments. Legend shows the year in which the assessment was conducted. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

Figure 30(1, 1n & 2). Probability distributions of estimated trawl survey catchability (*Q*) under scenarios 1 (upper panel), 1n (middle panel) and 2 (lower panel) with the mcmc approach. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively. (This figure is not updated)

Figure 31a(1, 1n & 2). Probability distributions of estimated mature male biomass on Feb. 15, 2016 with $F_{35\%}$ under scenarios 1 (upper panel), 1n (middle panel) and 2 (lower panel) with the mcmc approach. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively. (This figure is not updated)

Figure 31b(1, 1n & 2). Probability distributions of the 2016 estimated OFL with scenarios 1 (upper panel), 1n (middle panel) and 2 (lower panel) with the mcmc approach. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively. (This figure is not updated)

Figure 32(1&1n). Projected mature male biomass on Feb. 15 with $F_{40\%}$ and $F_{35\%}$ harvest strategy during 2016-2025. Input parameter estimates are based on scenarios 2b (upper panel) and 2d (lower panel). Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively, and the confidence limits are for the $F_{35\%}$ harvest strategy.

Figure 33(2b&2d). Projected retained catch biomass with $F_{40\%}$ and $F_{35\%}$ harvest strategy during 2015-2124. Input parameter estimates are based on scenarios 2b (upper panel) and 2d (lower panel). Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively, and the confidence limits are for the $F_{35\%}$ harvest strategy.

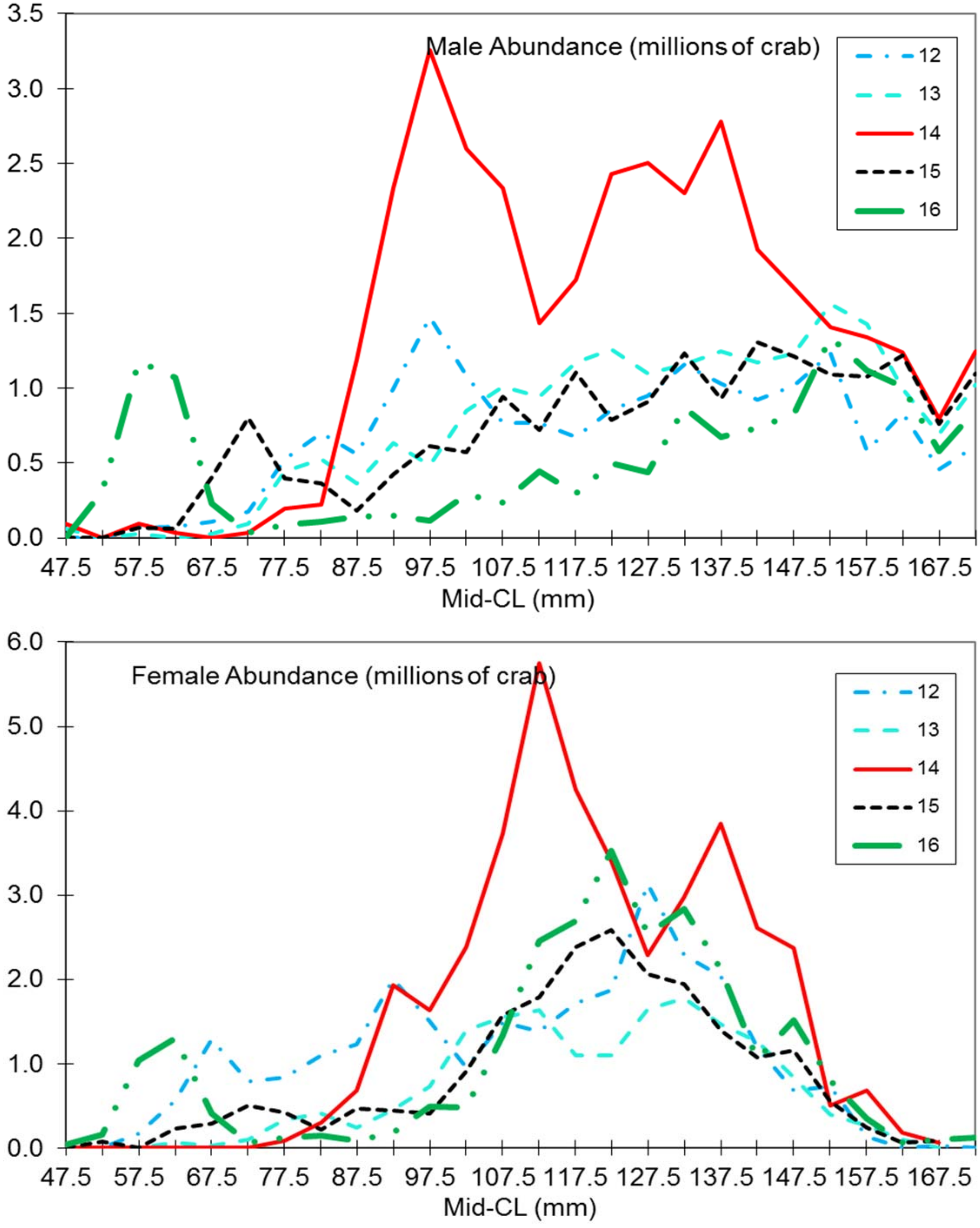


Figure 34. Length frequency distributions of male (top panel) and female (bottom panel) red king crab in Bristol Bay from NMFS trawl surveys during 2012-2016. For purposes of these graphs, abundance estimates are based on area-swept methods.

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

a. Model Description

i. Population model

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

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

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

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

where L_l is the mid-point of length-class *l*, ΔL the width of each size-class (5 mm carapace length), a_t^s, b_t^s the parameters of the length–growth increment relationship for sex *s* and year *t*, and β^s the parameter determining the variance of the growth increment. Growth is time-invariant for males, and specified for three time-blocks for females (1968-82; 1983-93; 1994-2016) based on changes to the size at maturity for females. The probability of moulting as a function of length for males is given by an inverse logistic function, i.e.:

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

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

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

ii. Catches and Fisheries Selectivities

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

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

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

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, 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 2005-2014).

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

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

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

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

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:

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

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

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*, $D_{l,t}^i$ and $D_{l,t}^m$, and $T_{l,t}^i$ and $T_{l,t}^m$, are:

$$\begin{aligned} D_{l,t}^i &= N_{l,t}^i \, e^{-y_t M_t^{fem}} (1 - e^{-F_{l,t}^{fem}}) \\ D_{l,t}^m &= N_{l,t}^m \, e^{-y_t M_t^{fem}} (1 - e^{-F_{l,t}^{fem}}) \end{aligned} \tag{A9}$$

The 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:

$$T_{l,t}^{i} = N_{l,t}^{i}\, e^{-j_t M_t^{fem}}\, e^{-F_{l,t}^{fem}}\, (1 - e^{-\widetilde{F}_{l,t}^{fem}})$$
$$T_{l,t}^{m} = N_{l,t}^{m}\, e^{-j_t M_t^{fem}}\, e^{-F_{l,t}^{fem}}\, (1 - e^{-\widetilde{F}_{l,t}^{fem}}) \tag{A10}$$

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

$$S_{l}^{type} = \frac{1}{1 + e^{-\beta^{type}\ (\iota - L_{50}^{type})}} \tag{A11}$$

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

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

$$s_l = \varphi + \kappa\,\iota, \quad if\ \iota < 135\,\text{mm CL},$$
$$s_l = s_{l-1} + 5\gamma, \quad if\ \iota > 134\,\text{mm CL} \tag{A12}$$

where φ, κ, γ are parameters.

iii. Trawl Survey Selectivities

Trawl survey selectivities are estimated as

$$S_{l,t}^{s} = \frac{Q}{1 + e^{-\beta_t^{s}\ (\iota - L_{50,t}^{s})}} \tag{A13}$$

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

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

$$F_t^{disc,s} = r^s \, F_t^{dir} \tag{A14}$$

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° 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):

$$F_t^{Tanner,s} = a^s \, E_t \tag{A15}$$

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° 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 :

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

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

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

The weighted negative log likelihood functions are:

$$\begin{aligned}
&\textit{Length compositions}: \quad -\sum \ln(Rf_i) \\
&\textit{Biomasses other than survey}: \quad \lambda_j \sum \left[\ln(C_t / \hat{C}_t)^2\right] \\
&\textit{NMFS survey biomass}: \quad \sum \left[\ln(B_t / \hat{B}_t)^2 / (2\ln(CV_t^2 + 1))\right] \\
&\textit{BSFRF mature males}: \quad \sum [\ln(\ln(CV_t^2 + 1))^{0.5} + \ln(B_t / \hat{B}_t)^2 / (2\ln(CV_t^2 + 1))] \\
&\textit{R variation}: \quad \lambda_R \sum [\ln(R_t / \overline{R})^2] \\
&\textit{R sex ratio}: \quad \lambda_s [\ln(\overline{R}_M / \overline{R}_F)^2] \qquad \text{(A17)} \\
&\textit{Trawl bycatch fishing mortalities}: \lambda_t [\ln(F_{t,t} / \overline{F}_t)^2] \\
&\textit{Pot female bycatch fishing mortalities}: \lambda_p [\ln(F_{t,f} / \overline{F}_f)^2] \\
&\textit{Trawl survey catchability}: (Q - \hat{Q})^2 / (2\sigma^2)
\end{aligned}$$

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 represent 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, and 0.07 in 2015, based on the proportions of discarded legal males to total caught legal males. Handling mortality rates were set to 0.2 for the directed pot fishery, 0.25 for the Tanner crab fishery, and 0.8 for the trawl fisheries.

(1). Natural Mortality

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

(2). Length-weight Relationship

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

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

Ovigerous Females: $W = 0.003593\ L^{2.666076}$ (A18)

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 1994-2016, 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 1994-2016, 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 1994-2015).

(5). Sizes at Maturity for Males

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

In the laboratory, male RKC as small as 80 mm CL from Kodiak and 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° 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 2016), 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 (1975-2015), pot-discarded females from the directed fishery (1990-2015), pot-discarded males and females from the eastern Bering Sea Tanner crab fishery (1991-93, 2013-15), and groundfish trawl discarded males and females (1976-2015). 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 1^{st} seven length classes (65- 99 mm CL) and new entry of number of females in the 1^{st} five length classes (65-89 mm CL).

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

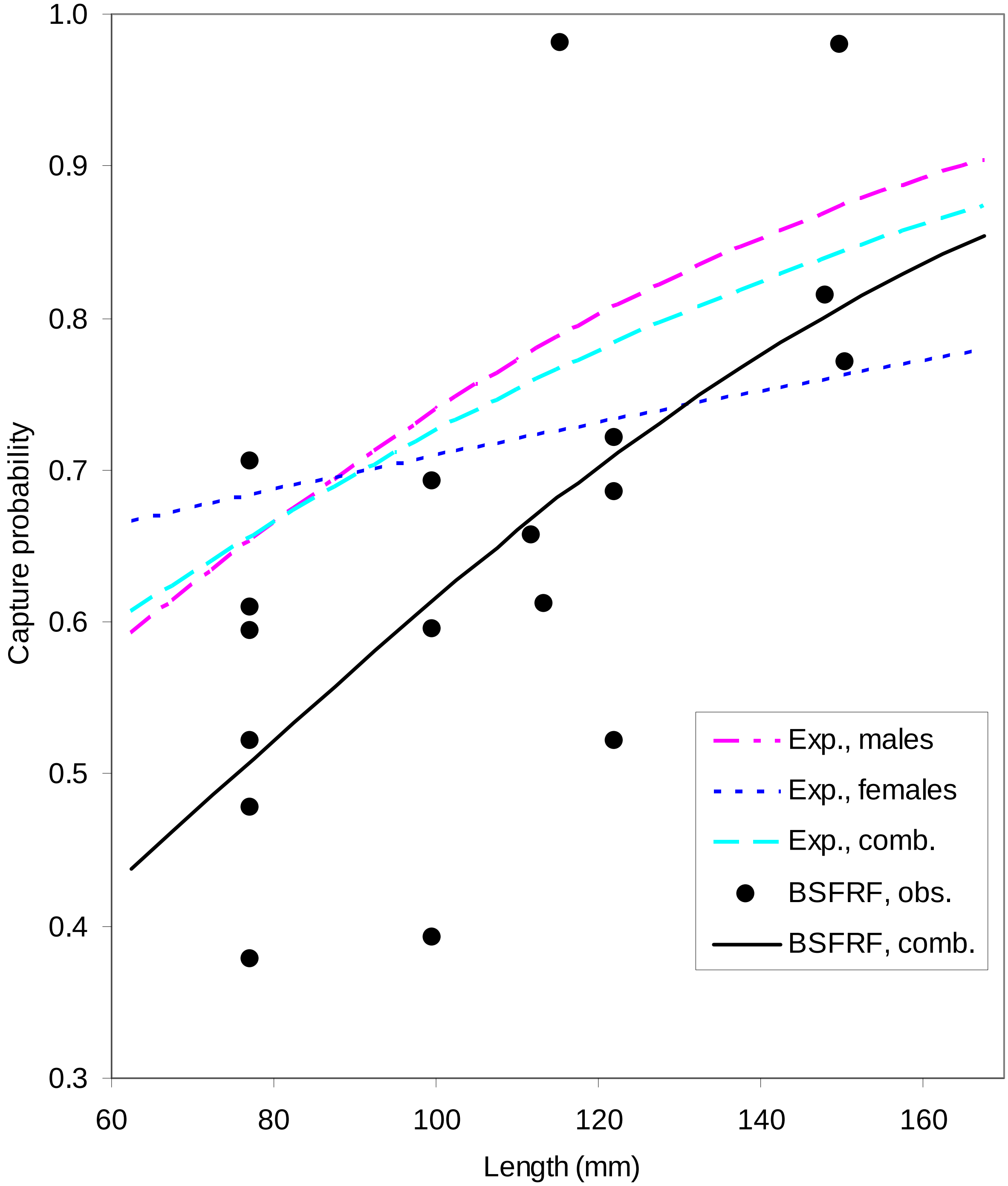


Figure A1. Estimated capture probabilities for NMFS Bristol Bay red king crab trawl surveys by Weinberg et al. (2004) and the Bering Sea Fisheries Research Foundation surveys.

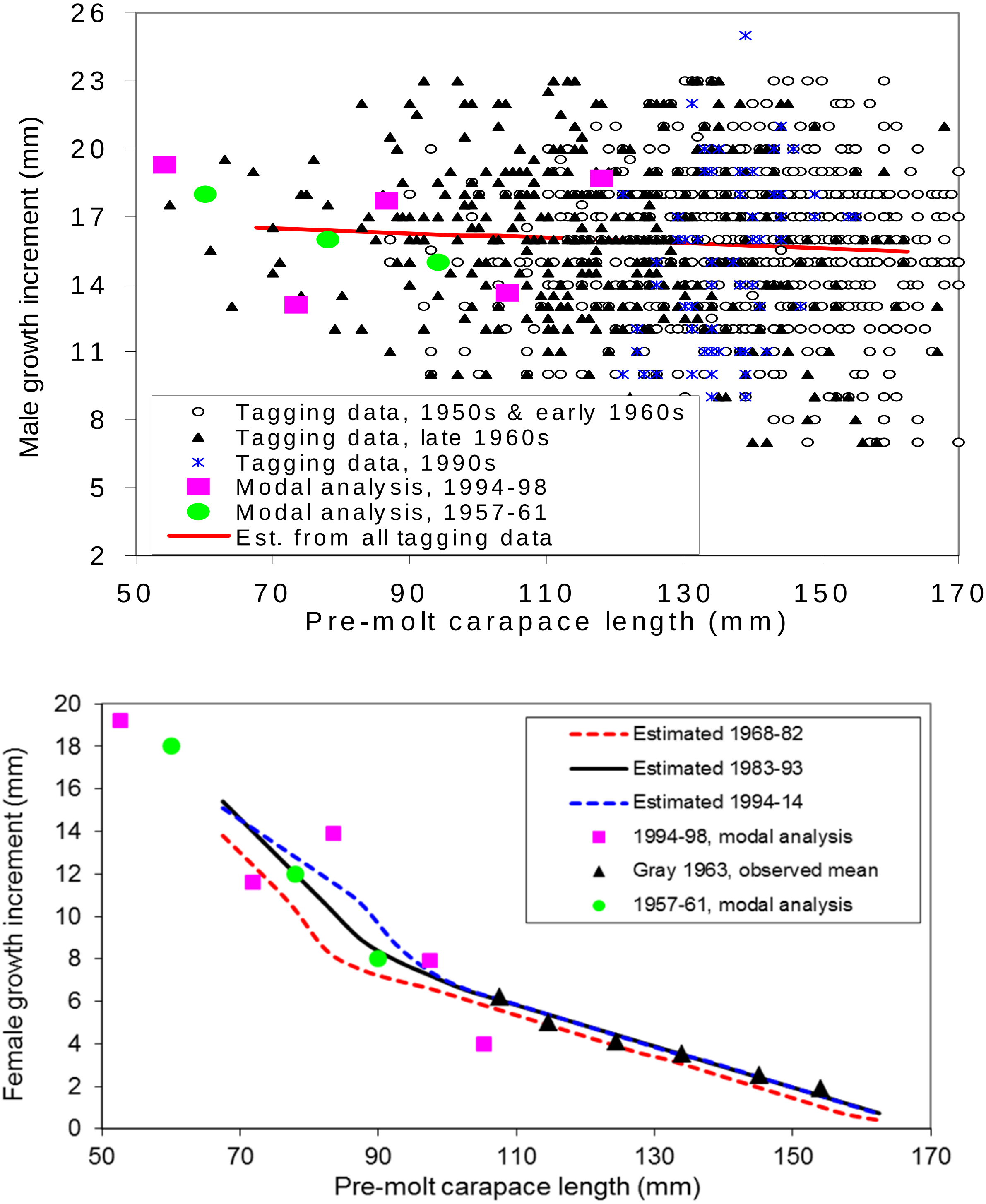


Figure A2. Mean growth increments per molt for Bristol Bay red king crab. Note: "tagging"---based on tagging data; "mode"---based on modal analysis. The female growth increments per molt are for scenarios 1, 1n and 2.

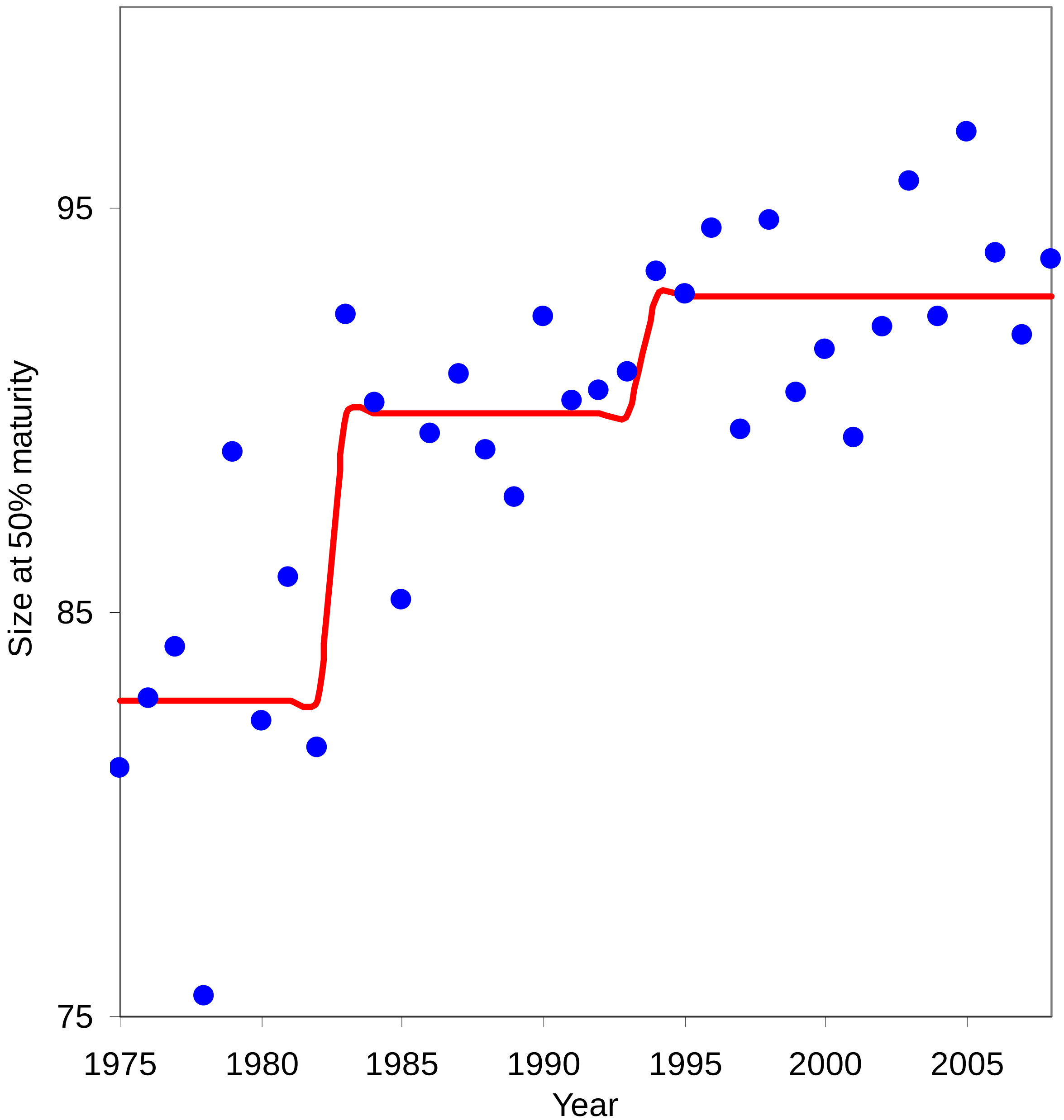


Figure A3. Estimated sizes at 50% maturity for Bristol Bay female red king crab from 1975 to 2008. Averages for three periods (1975-82, 1983-93, and 1994-08) are plotted with a line.

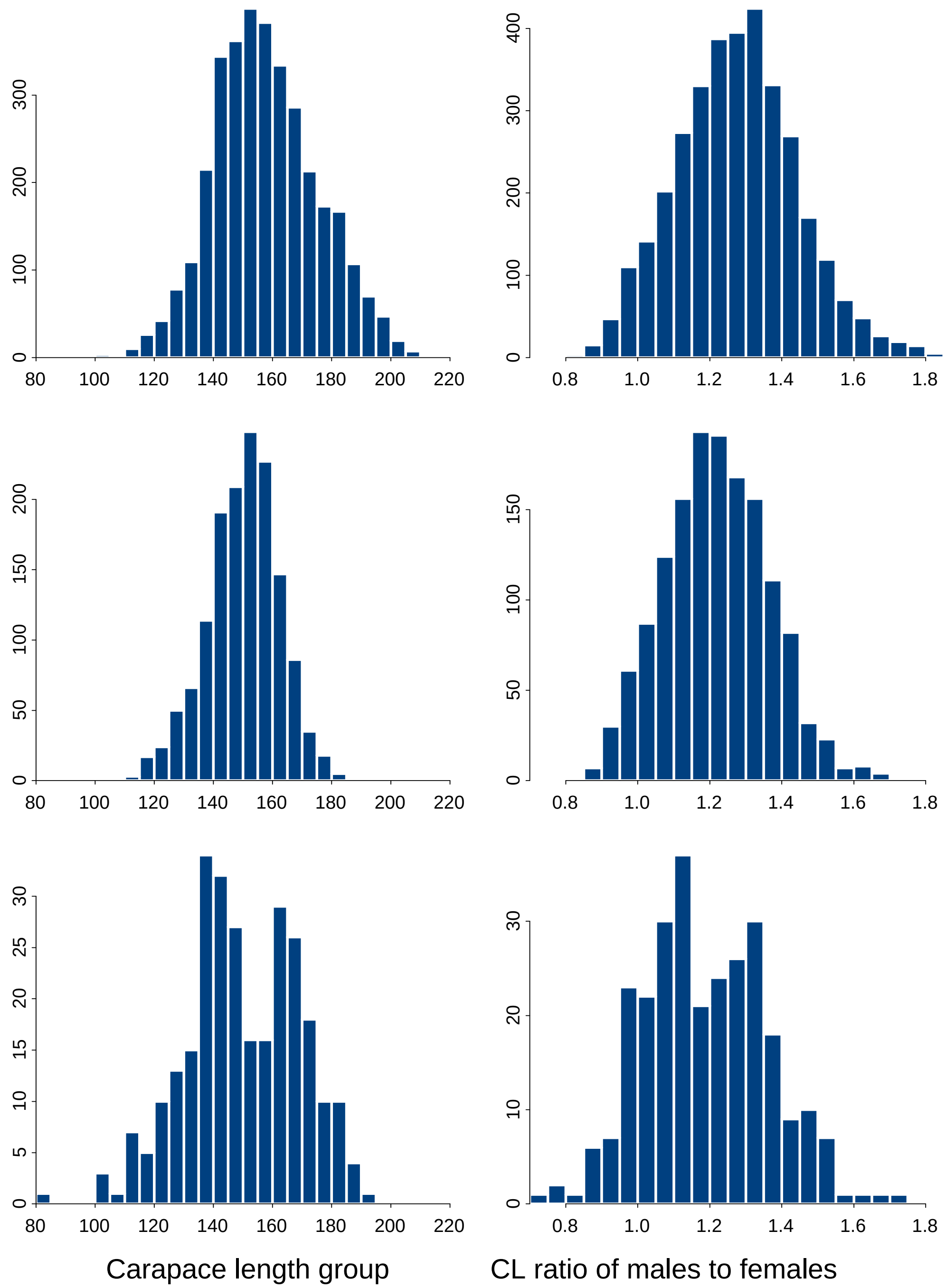
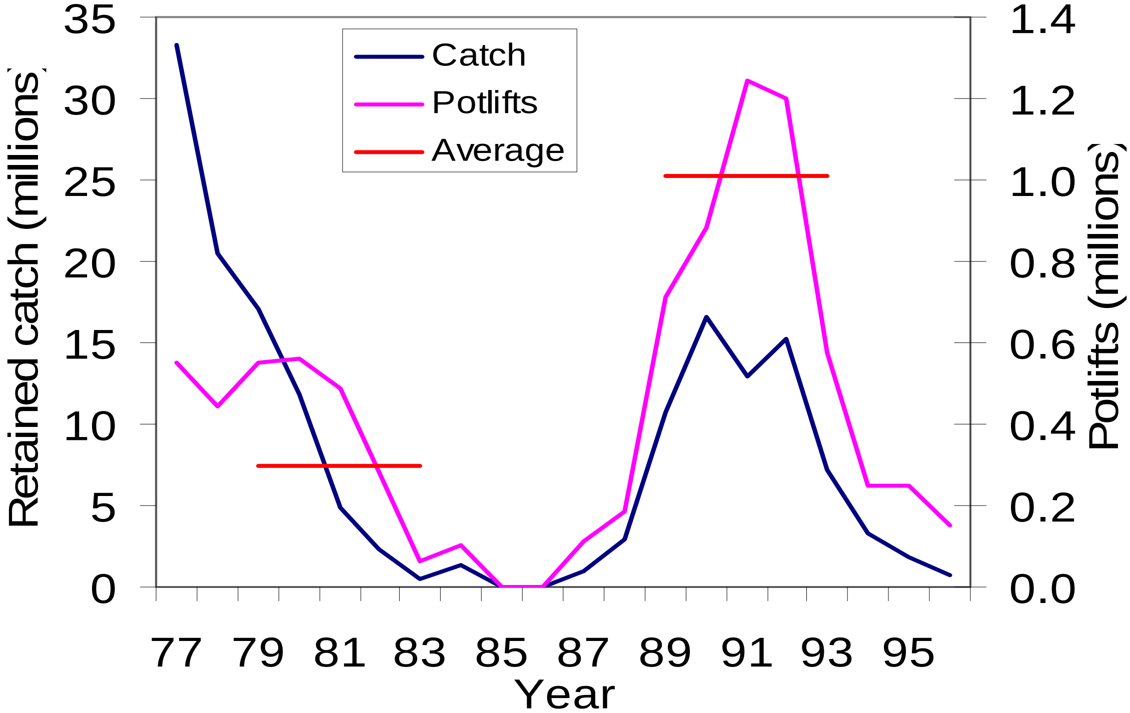


Figure A4. Histograms of carapace lengths (CL) and CL ratios of males to females for male shell ages ≤13 months of red king crab males in grasping pairs; Powell's Kodiak data. Upper plot: all locations and years pooled; middle plot: location 11; lower plot: locations 4 and 13. Sizes at maturity for Kodiak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



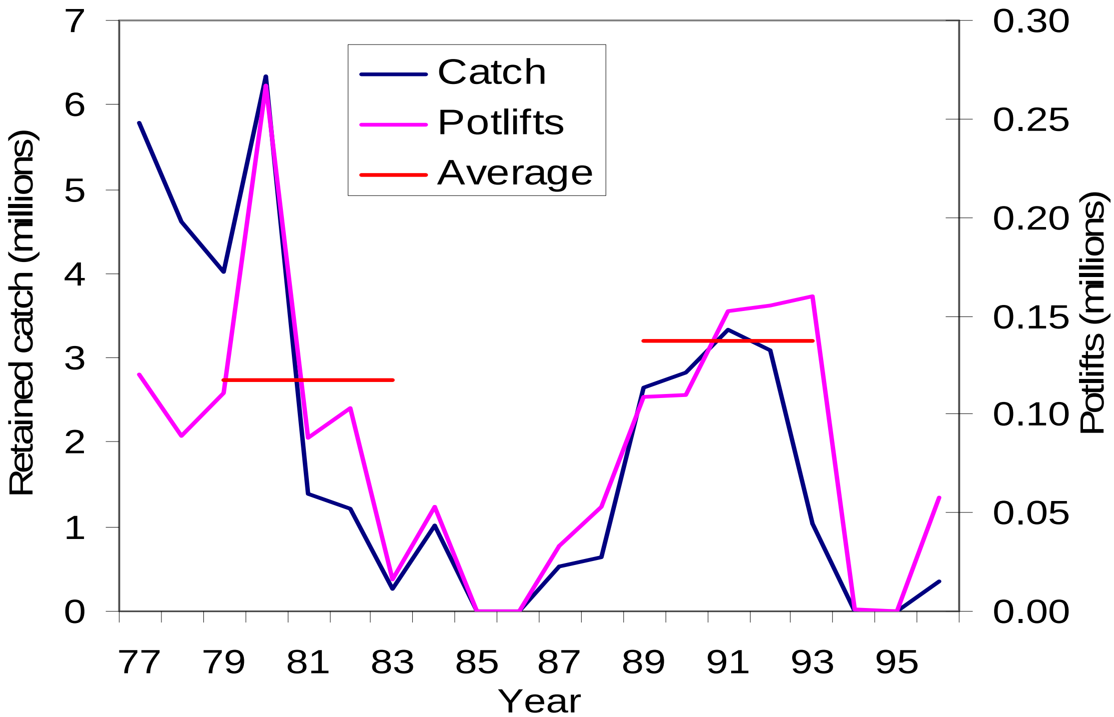


Figure A5. Retained catch and potlifts for total eastern Bering Sea Tanner crab fishery (upper plot) and the Tanner crab fishery east of 163° W (bottom).

Appendix B. Recruitment Breakpoint Analysis

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 were 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,

$$\hat{y}_t = \alpha_1 + \beta_1 \cdot MMB \qquad t < b,$$
$$\hat{y}_t = \alpha_2 + \beta_2 \cdot MMB \qquad t \geq b, \qquad (1)$$

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,

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

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

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

where Ω contains observation and process error as

$$\mathbf{\Omega} = \mathbf{O} + \mathbf{P}, \qquad (4)$$

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) was 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 was 5 years. Each brood year from 1980 to 2005 was 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 was also evaluated. Models with different breakpoints were then ranked using AICc (AIC corrected for small sample size; Burnham and Anderson 2004),

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

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

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

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 with 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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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

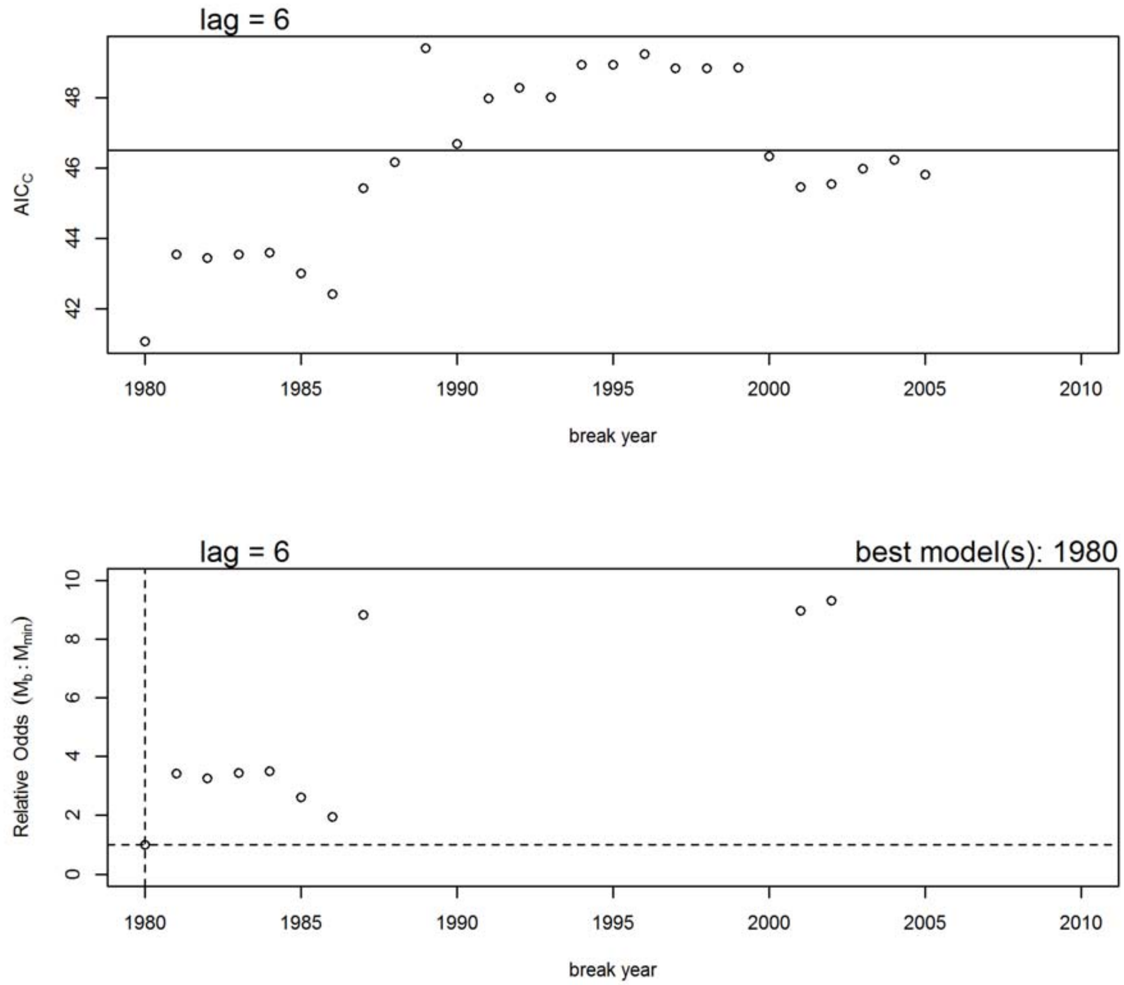


Figure B1. Results from the Ricker stock-recruit breakpoint analysis. Upper graph: AICc vs. year of breakpoint for the 1-breakpoint models (circles) and AICc for the model with no breakpoint (horizontal line). Lower graph: probabilistic odds for all 1-breakpoint models (circles) and the no breakpoint 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.

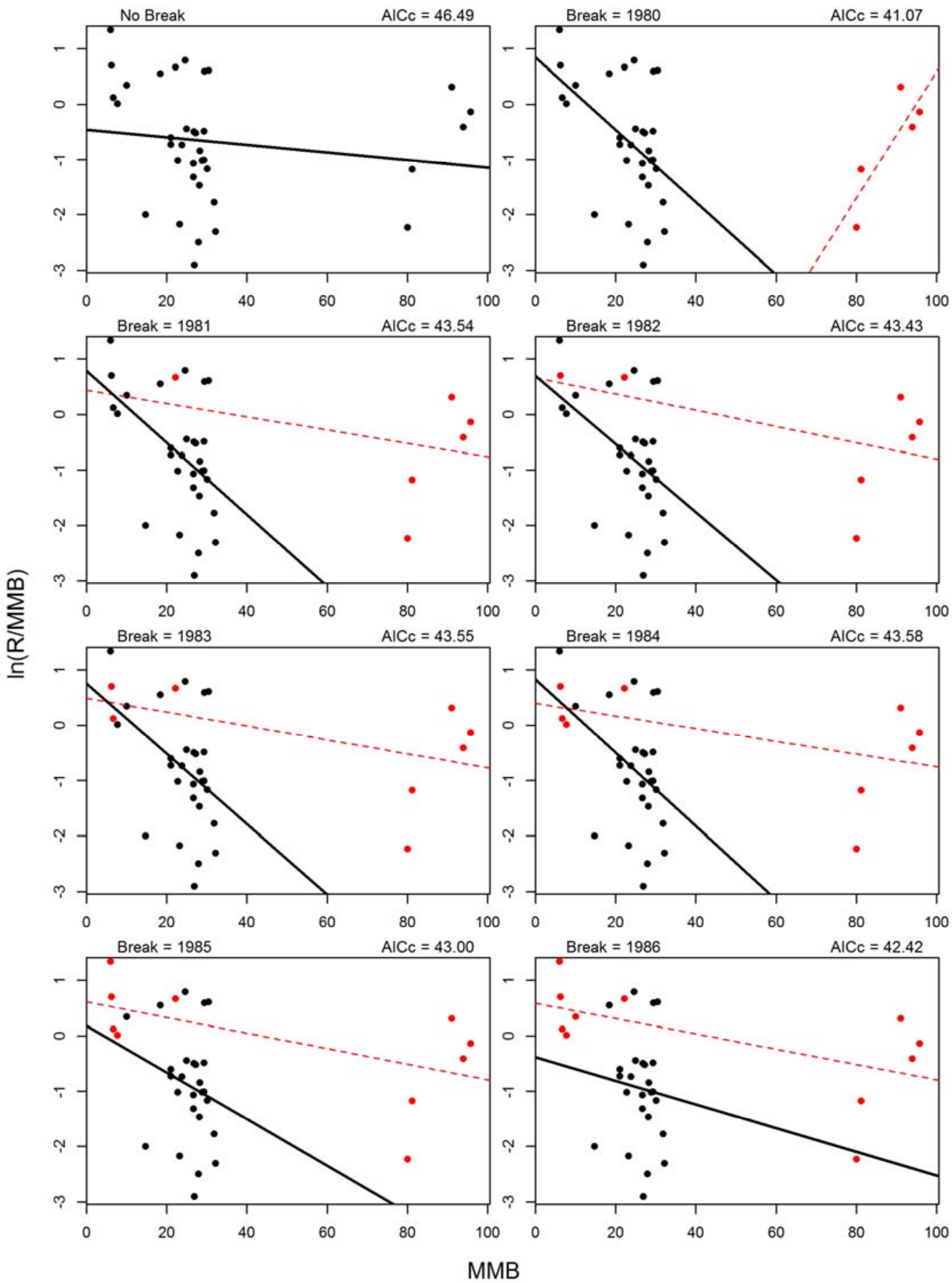
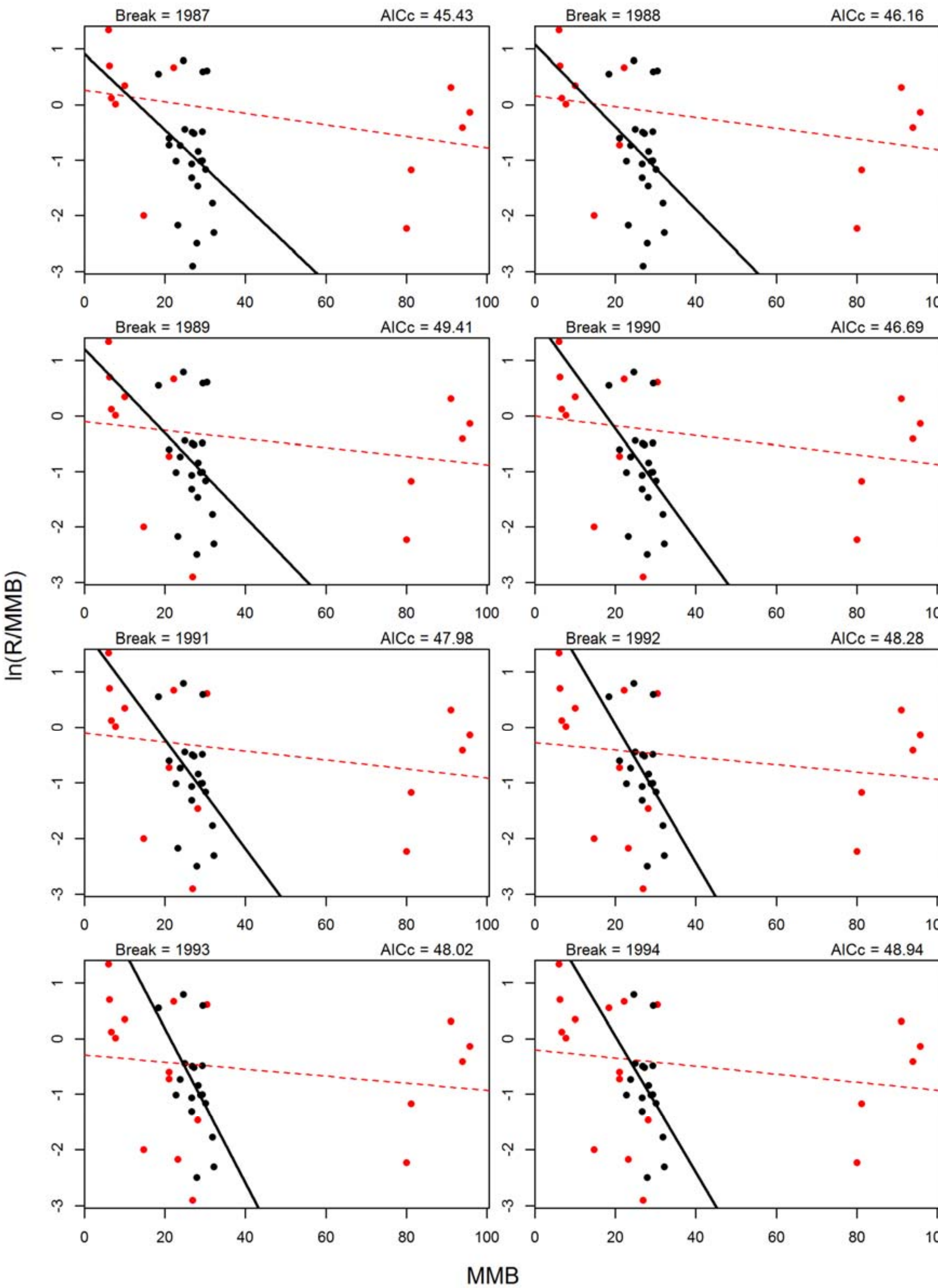


Figure B2. Fits for Ricker models with no breakpoint (upper left graph) and with 1-breakpoint for break years 1975-2005. For 1-breakpoint models, the pre-break data (circles) and model fit (line) are shown in red, whereas the post-break data and fit are shown in black.



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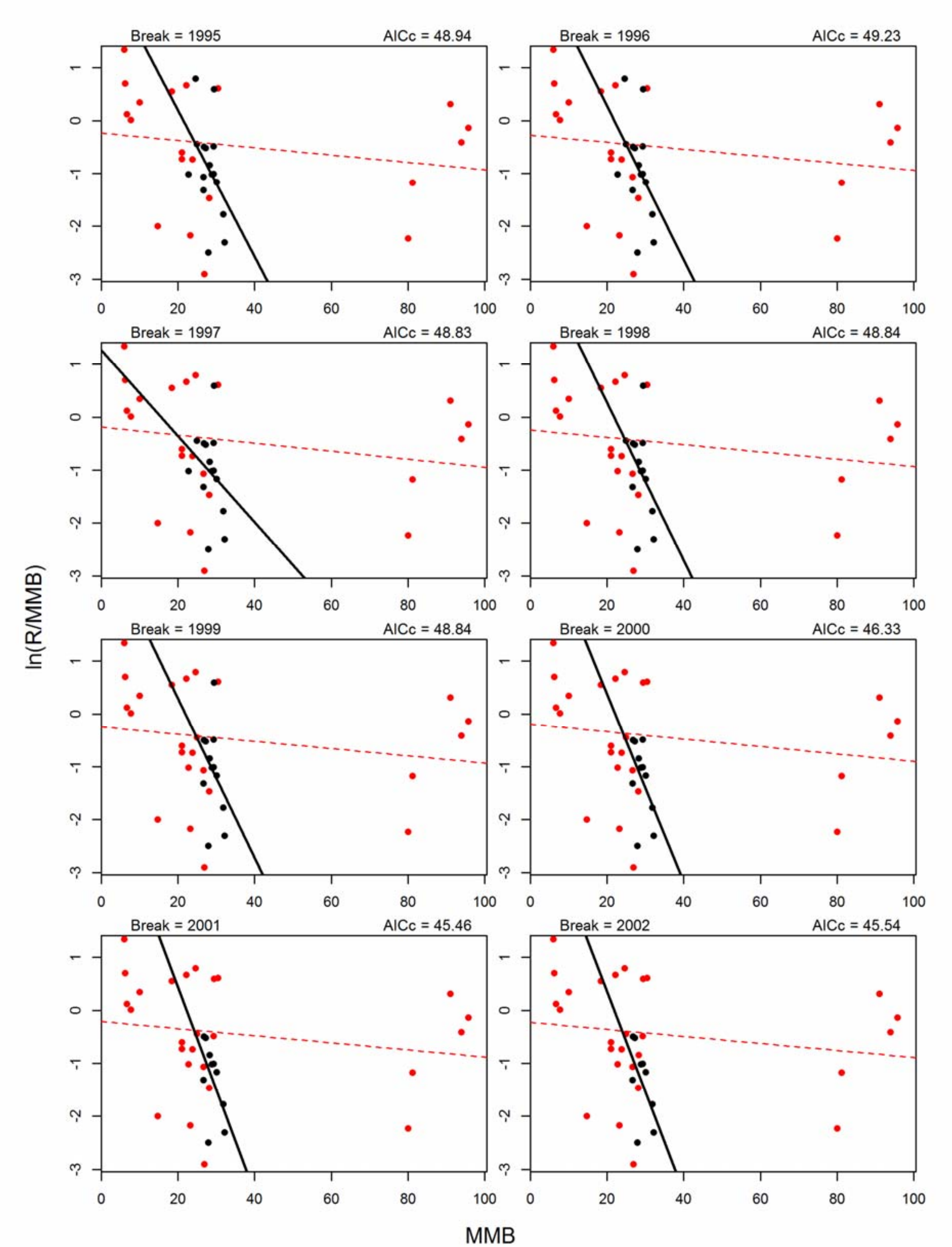

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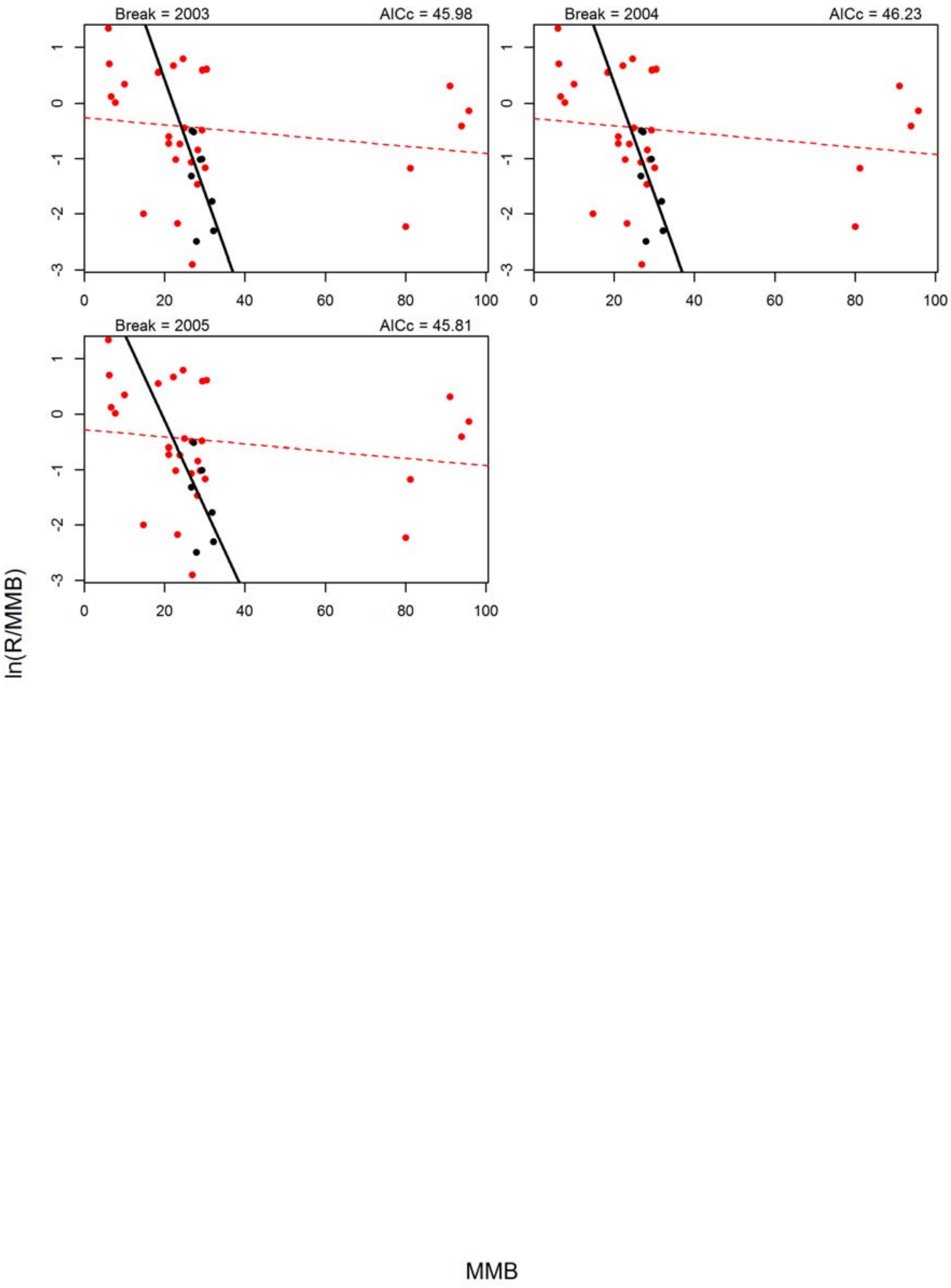

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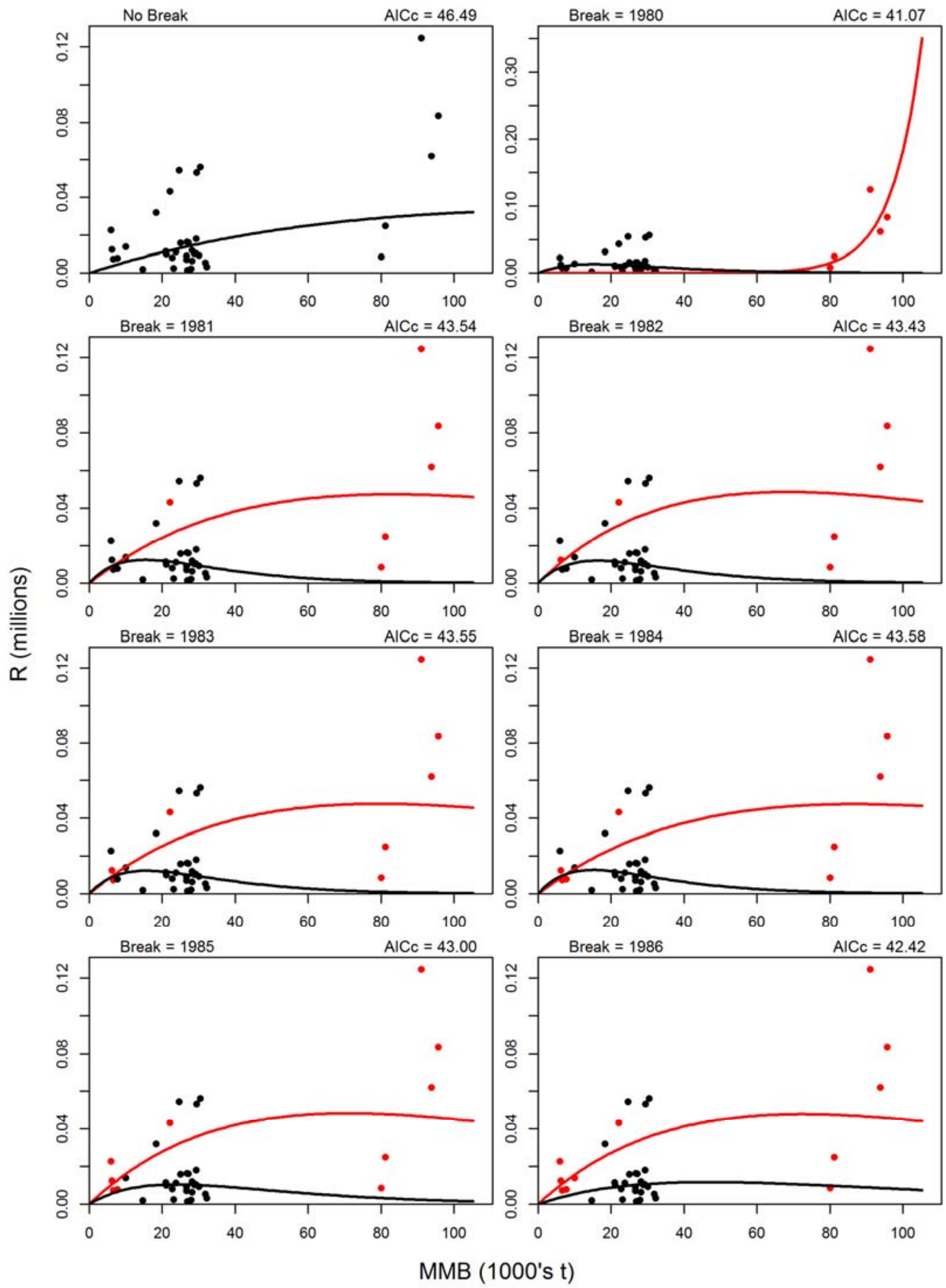
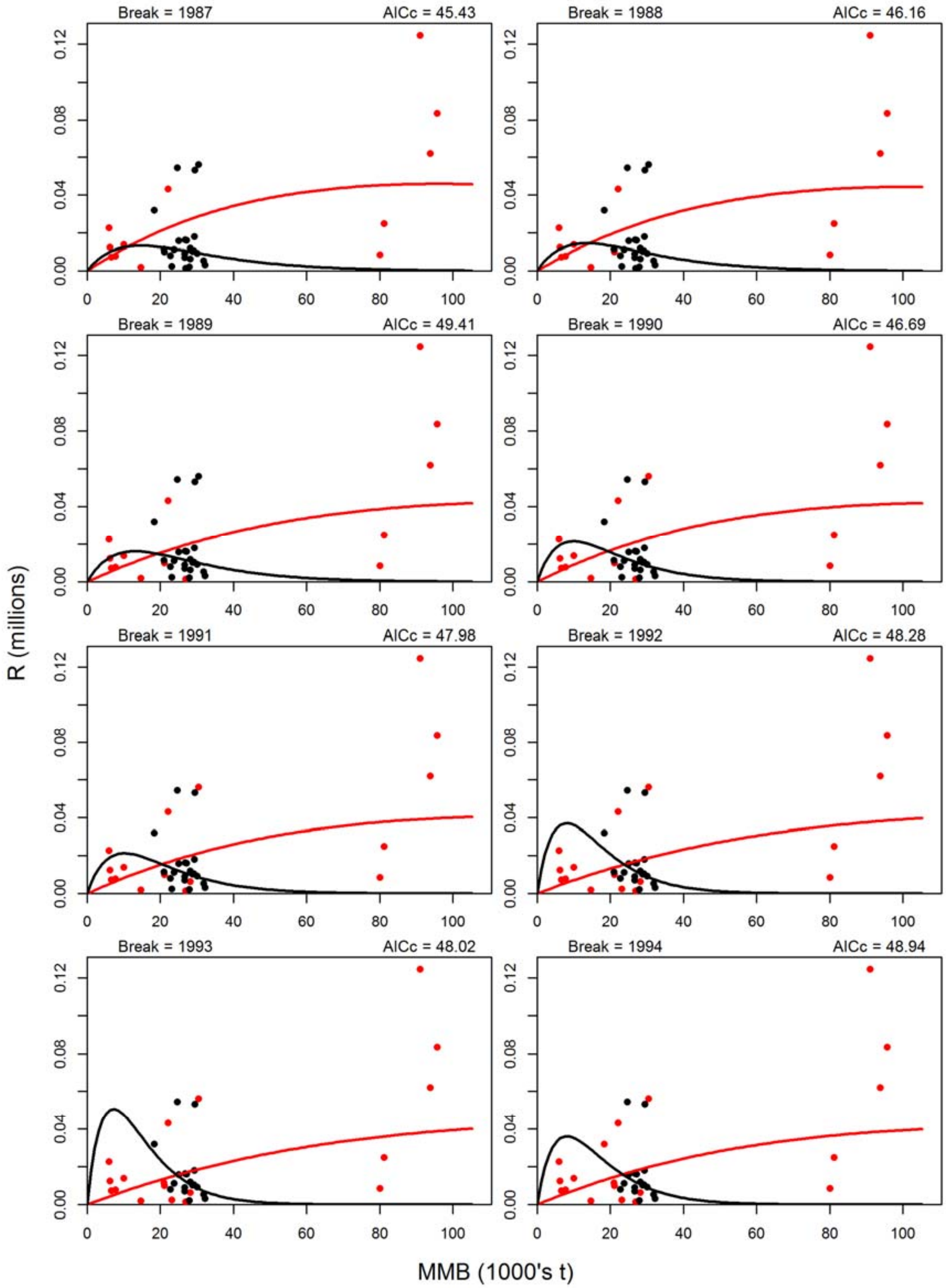


Figure B3. Fits on the arithmetic scale for Ricker models with no breakpoint (upper left graph) and with 1-breakpoint for break years 1975-2005. For 1-breakpoint models, the pre-break data (circles) and model fit (line) are shown in red, whereas the post-break data and fit are shown in black.



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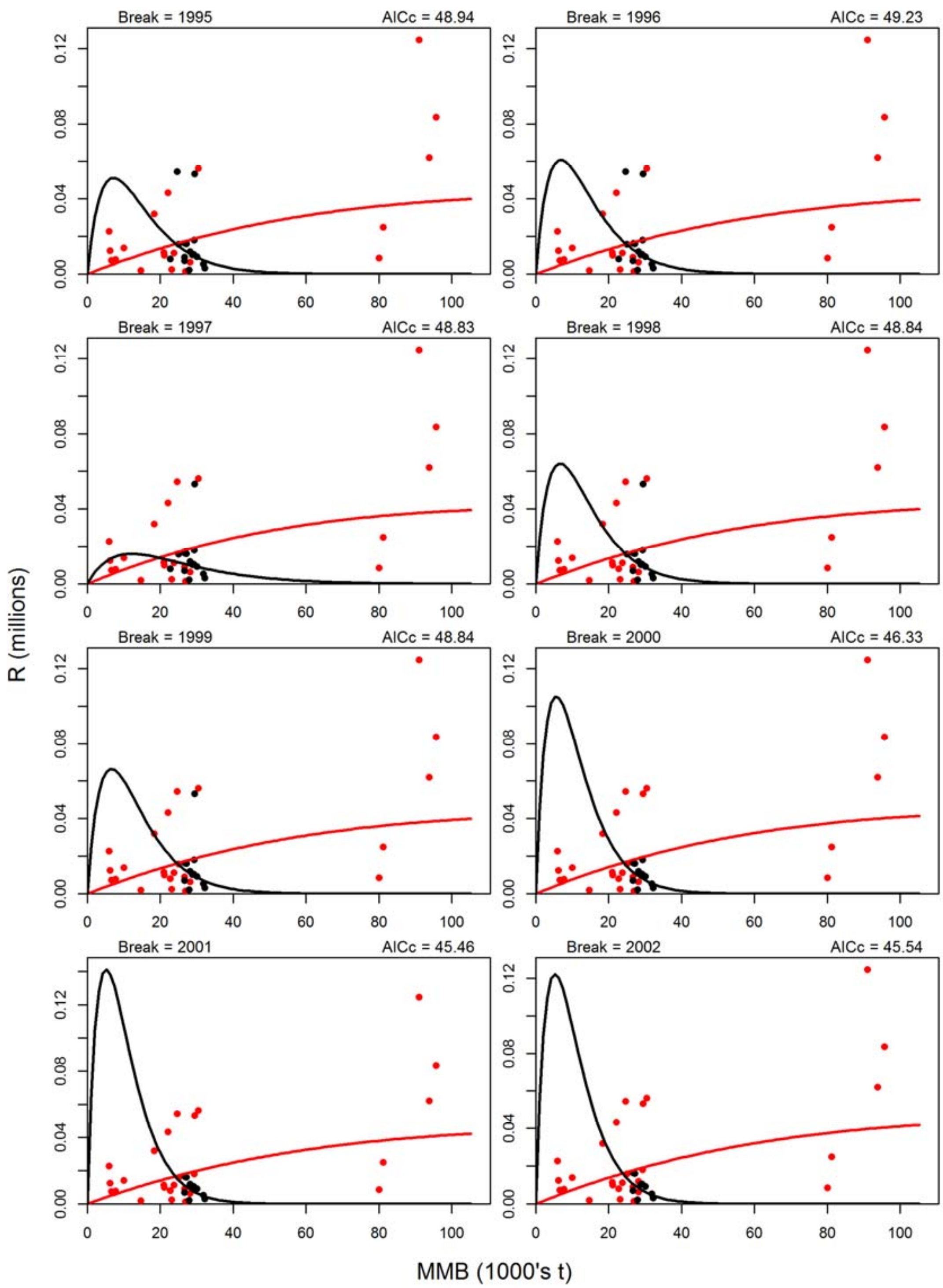

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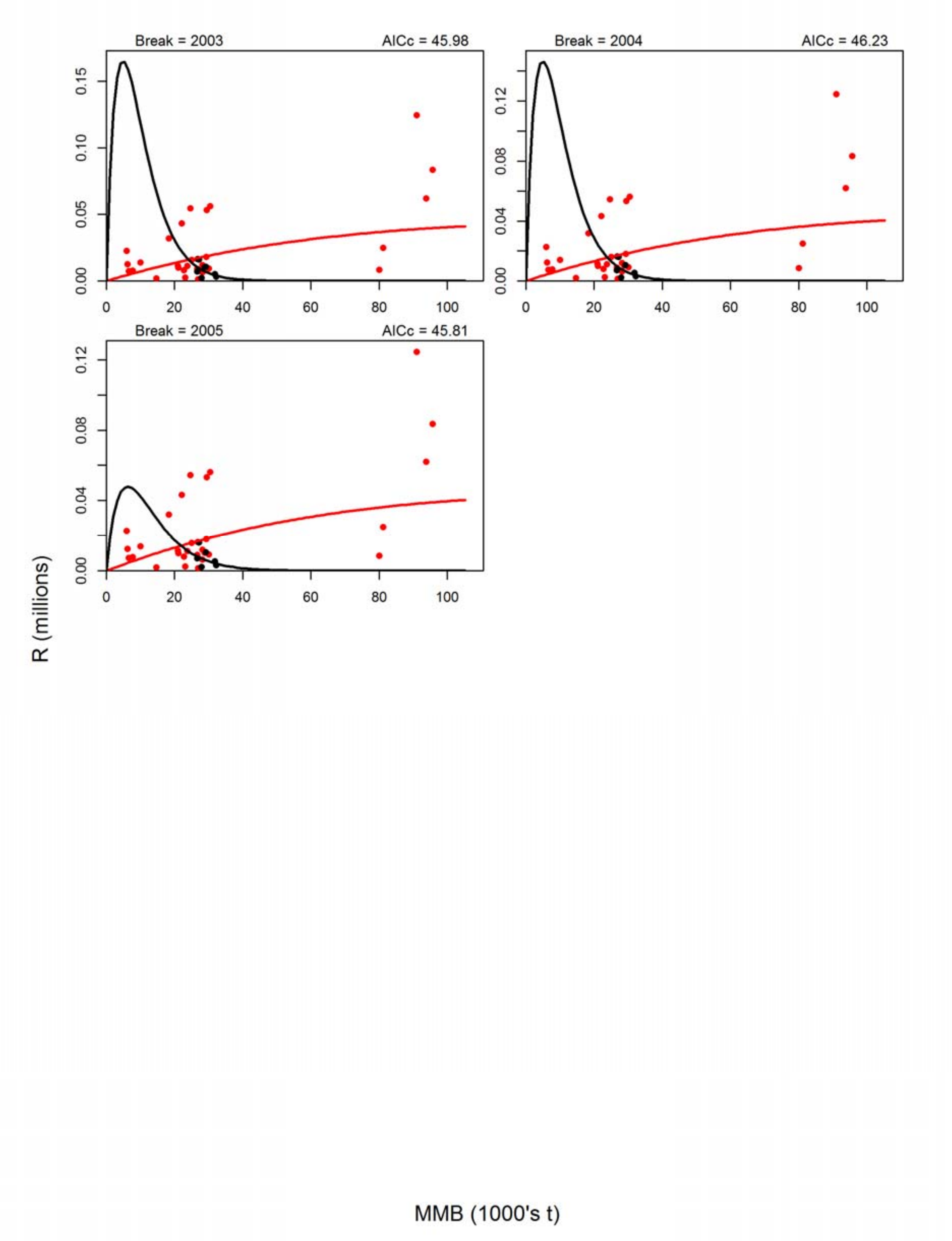

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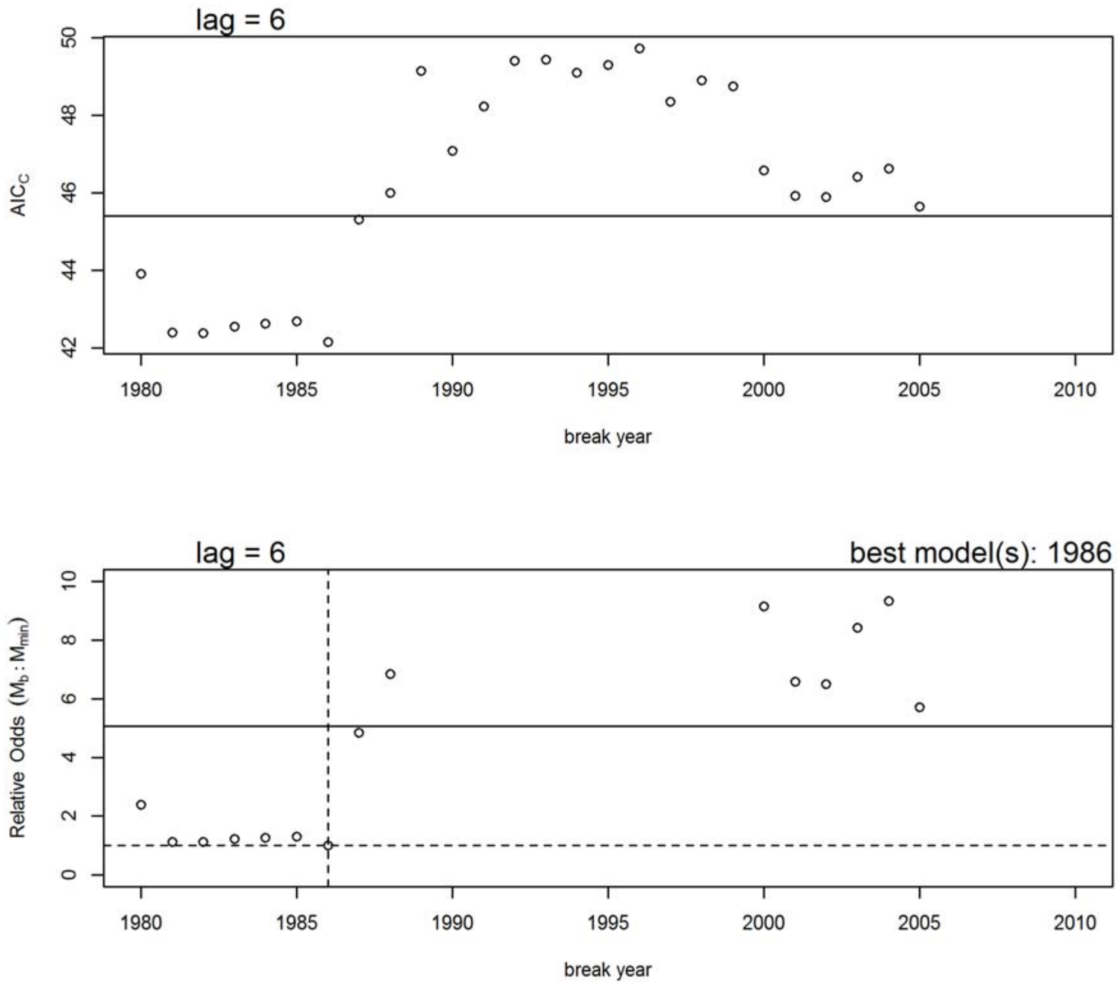


Figure B4. Results from the B-H stock-recruit breakpoint analysis. Upper graph: AICc vs. year of breakpoint for the 1-breakpoint models (circles) and AICc for the model with no breakpoint (horizontal line). Lower graph: probabilistic odds for all 1-breakpoint models (circles) and the no breakpoint model (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.

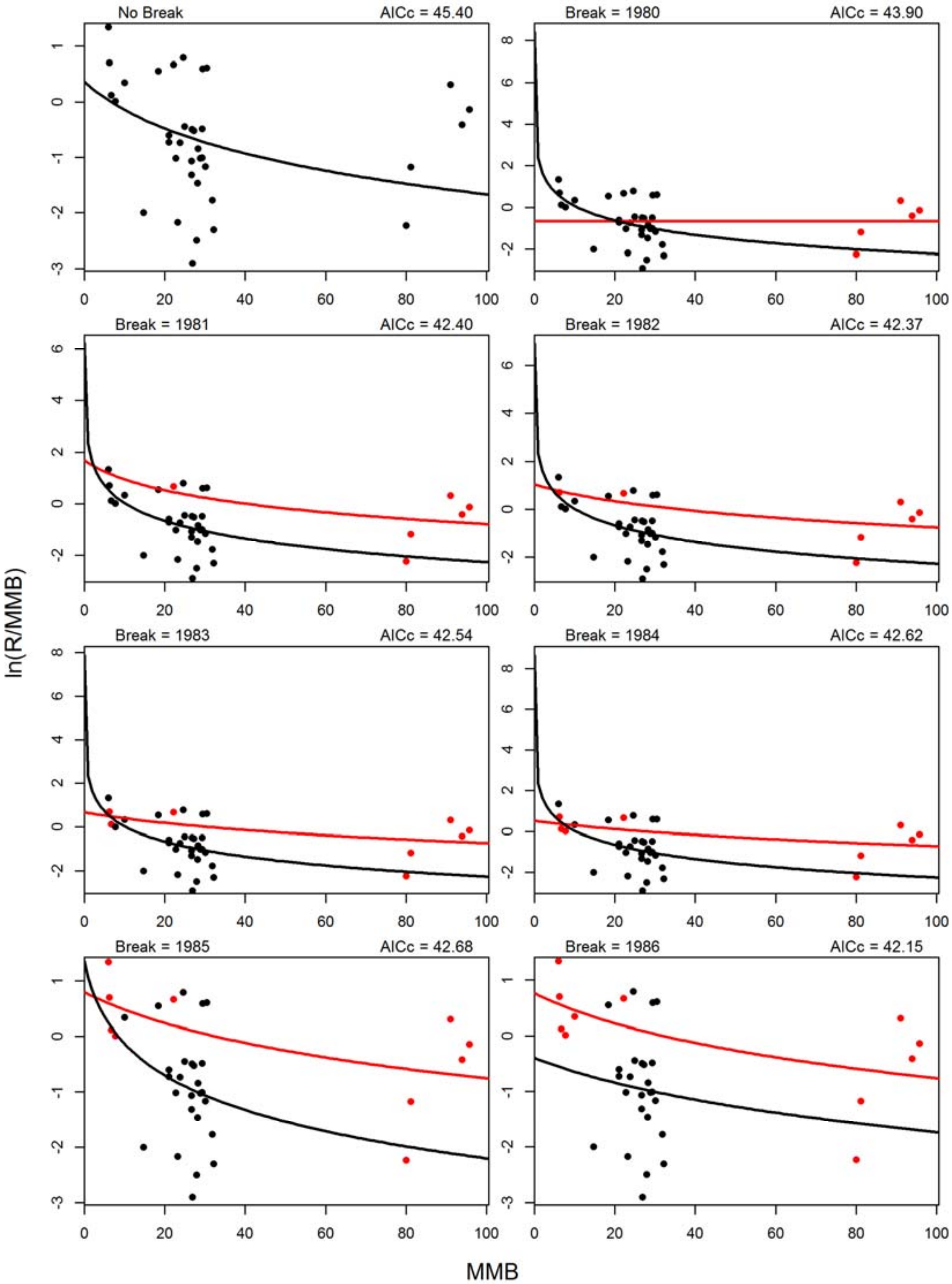
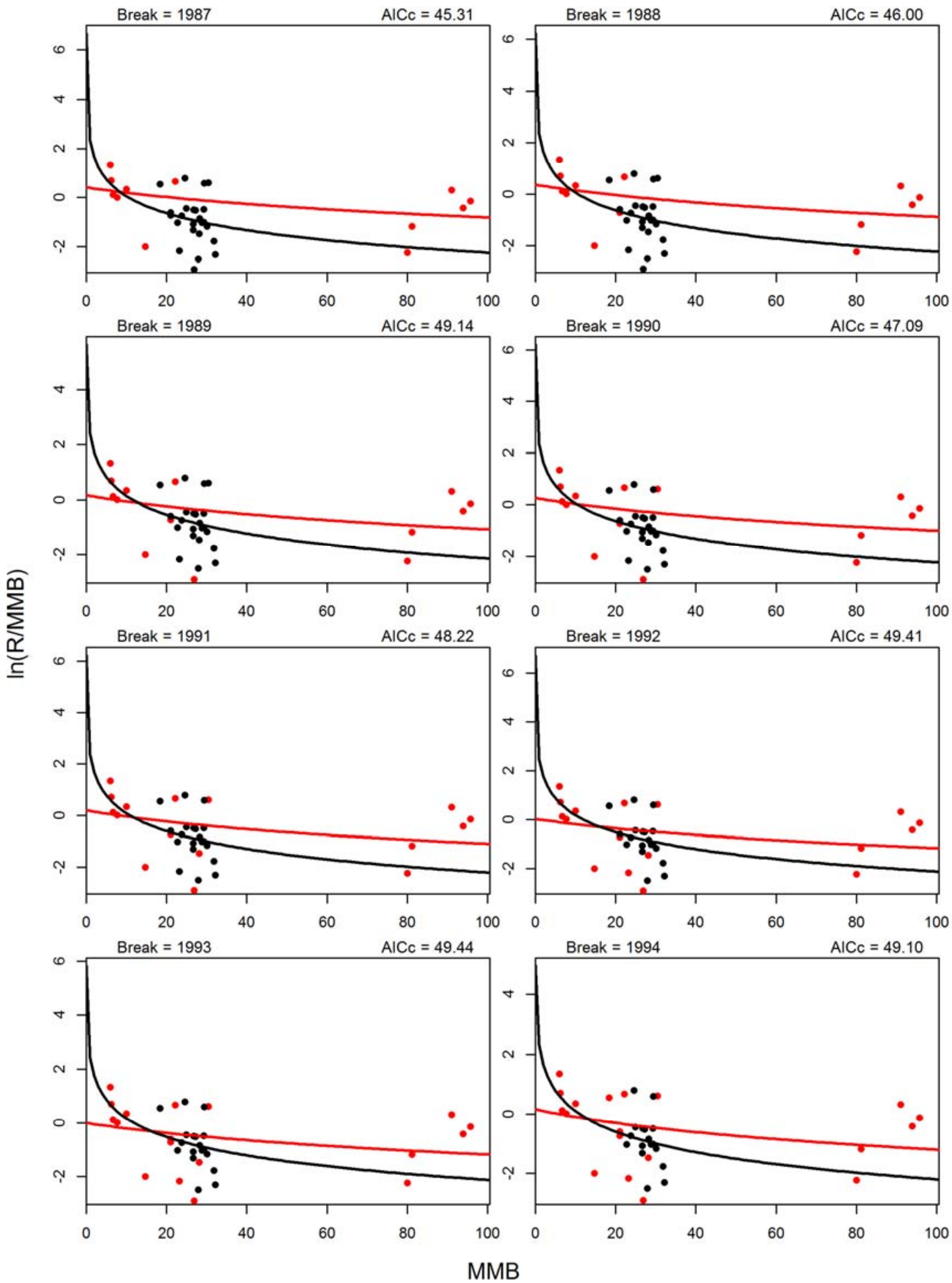


Figure B5. Fits for B-H models with no breakpoint (upper left graph) and with 1-breakpoint for break years 1975-2005. For 1-breakpoint models, the pre-break data (circles) and model fit (line) are shown in red, whereas the post-break data and fit are shown in black.



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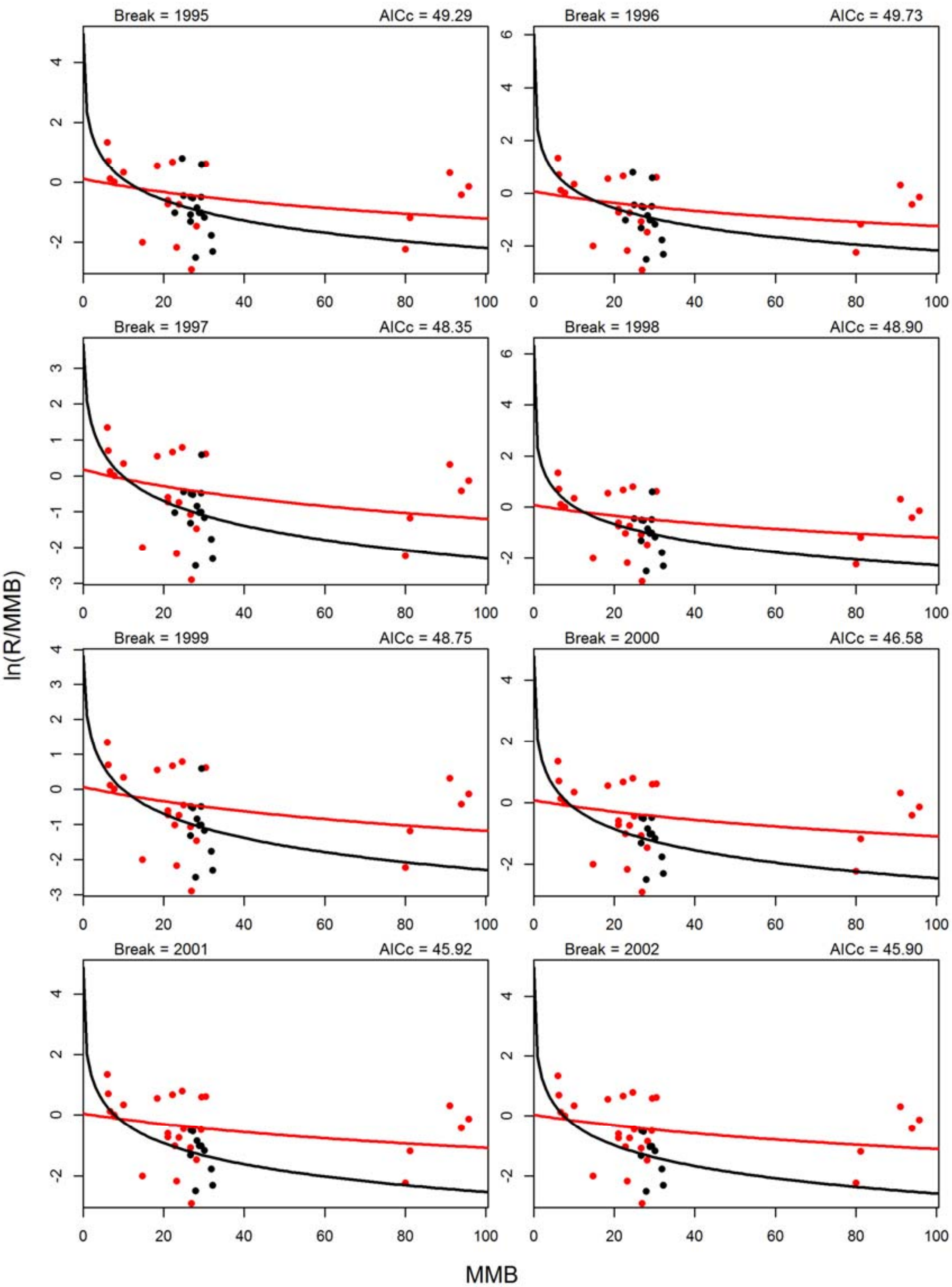

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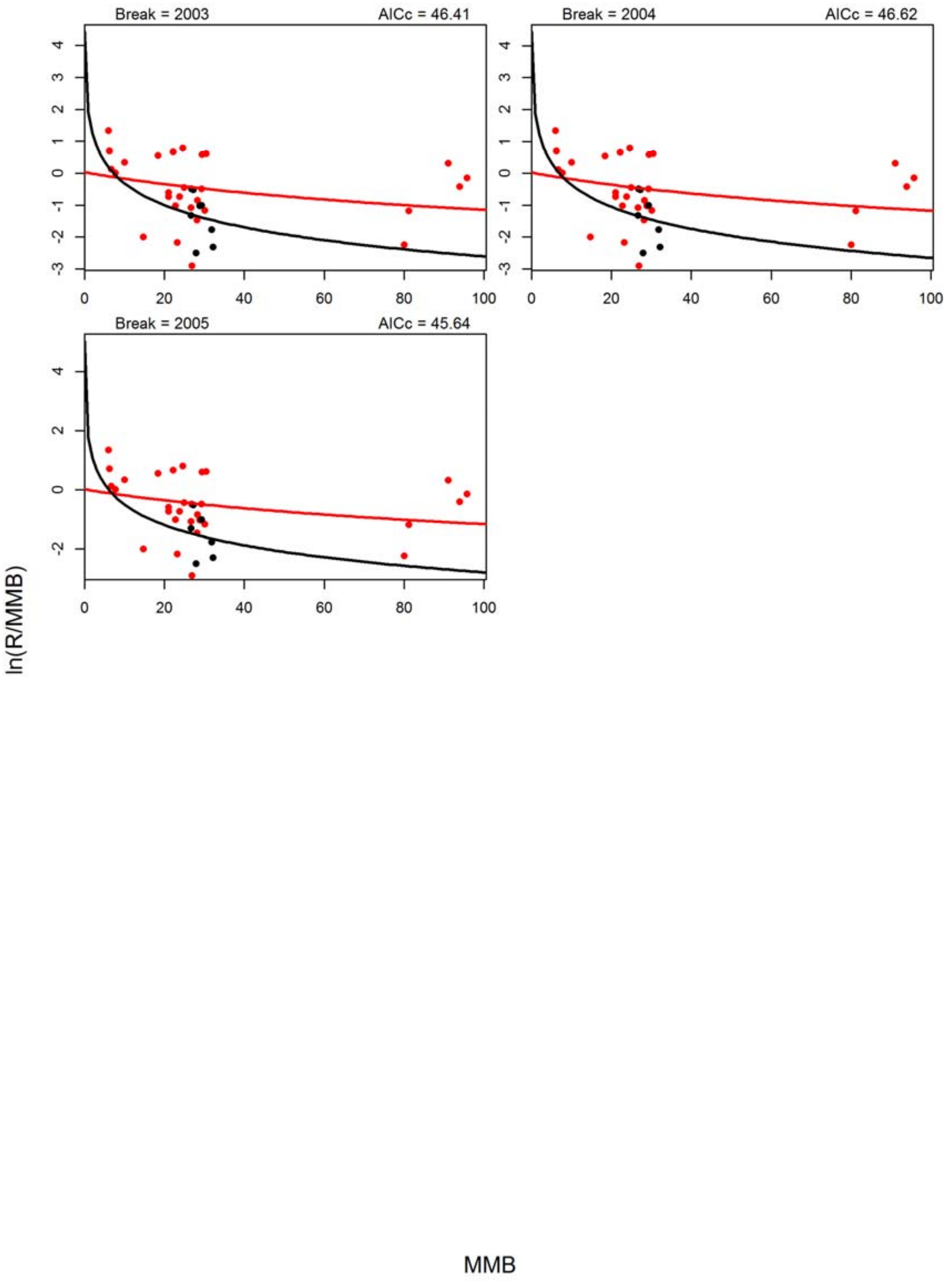

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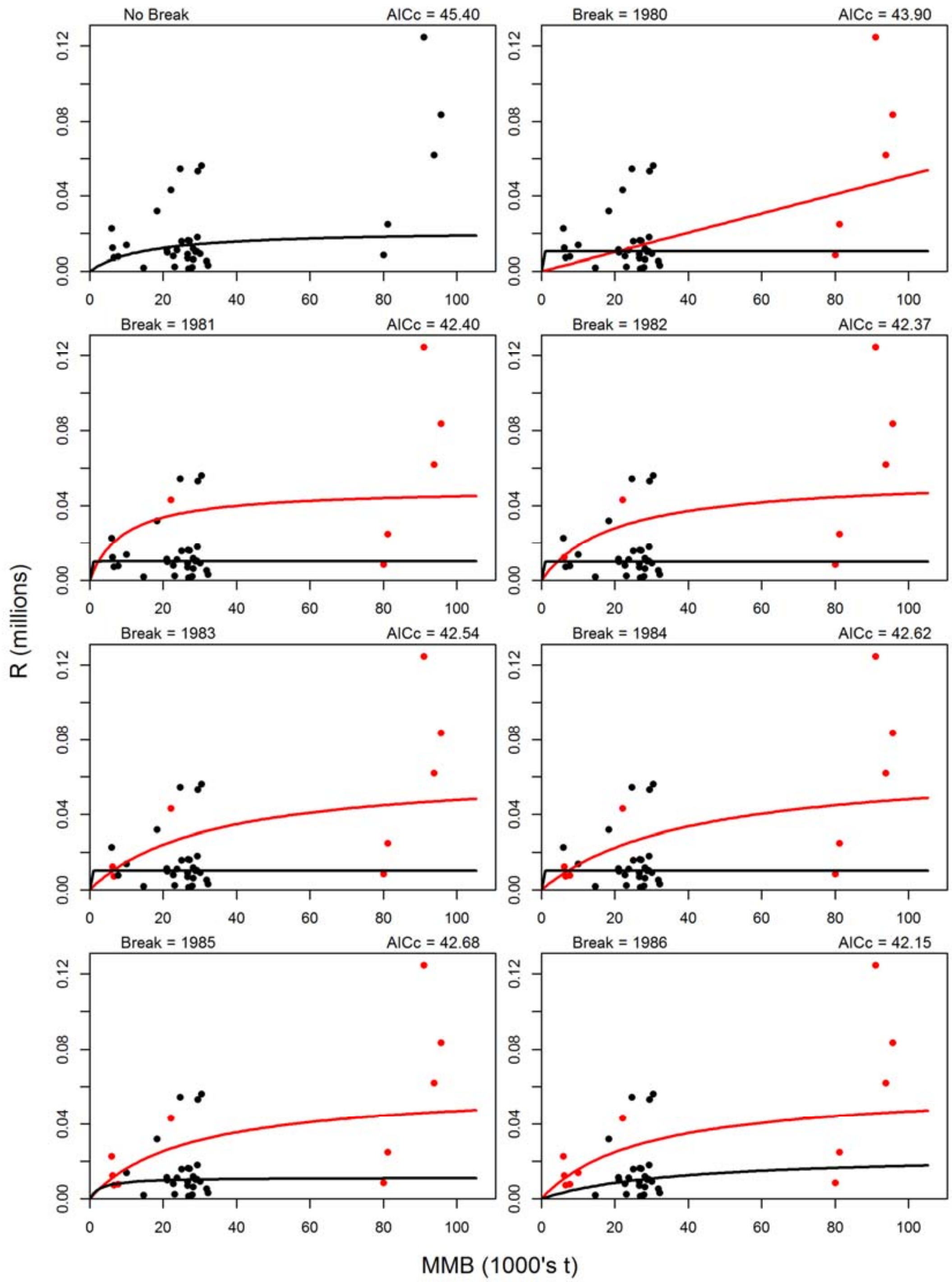
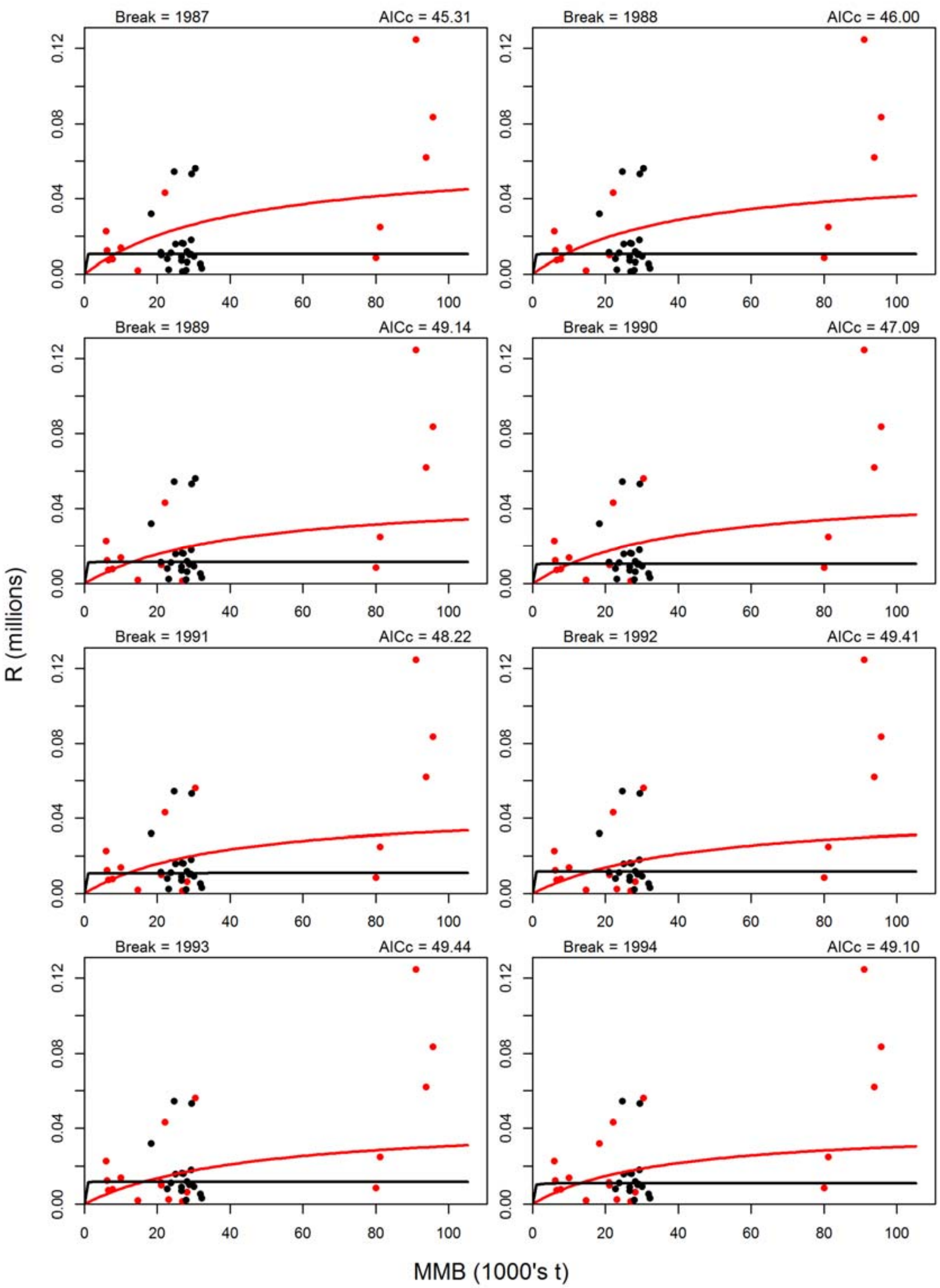


Figure B6. Fits on the arithmetic scale for B-H models with no breakpoint (upper left graph) and with 1-breakpoint for break years 1975-2005. For 1-breakpoint models, the pre-break data (circles) and model fit (line) are shown in red, whereas the post-break data and fit are shown in black.



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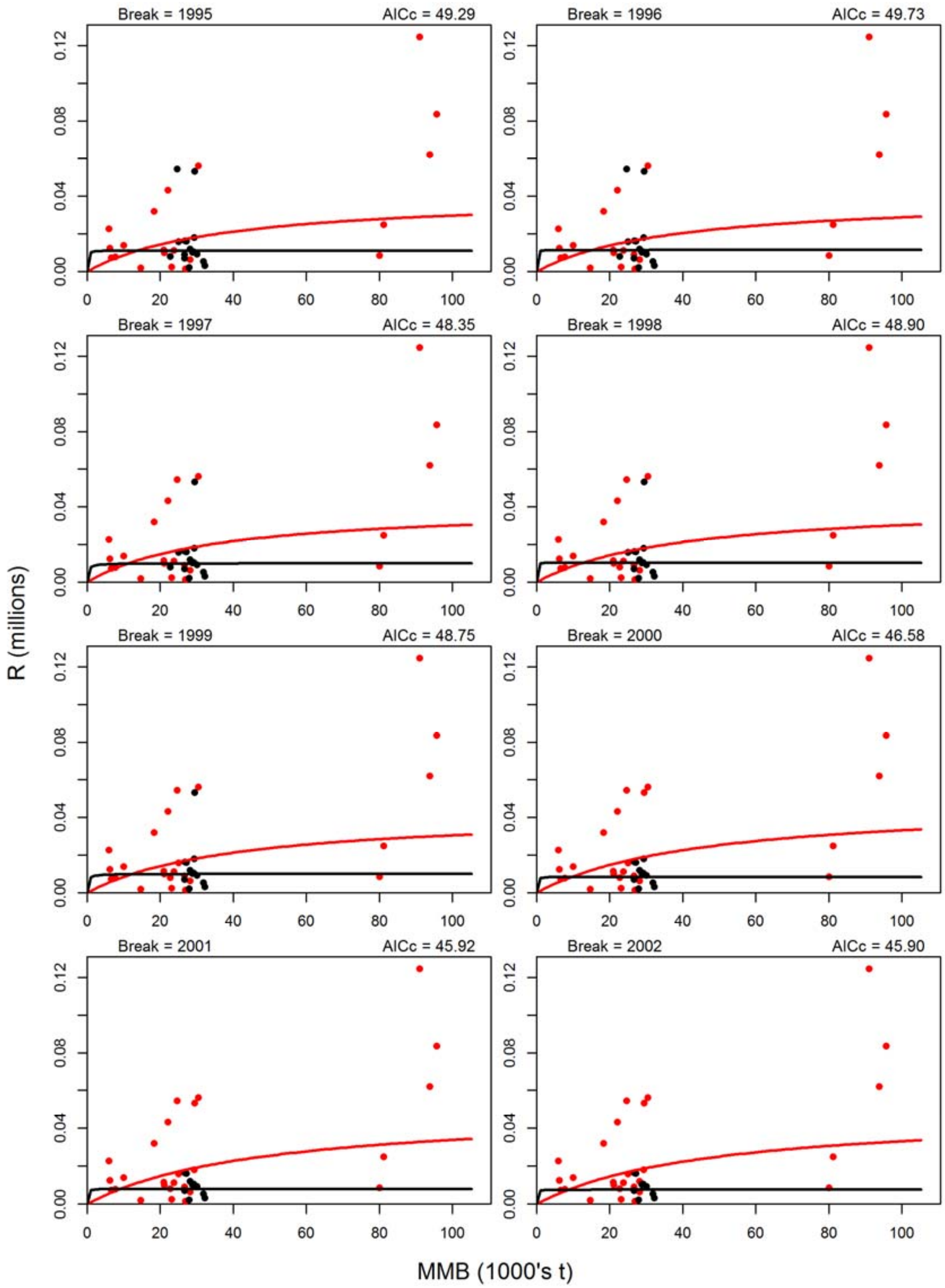

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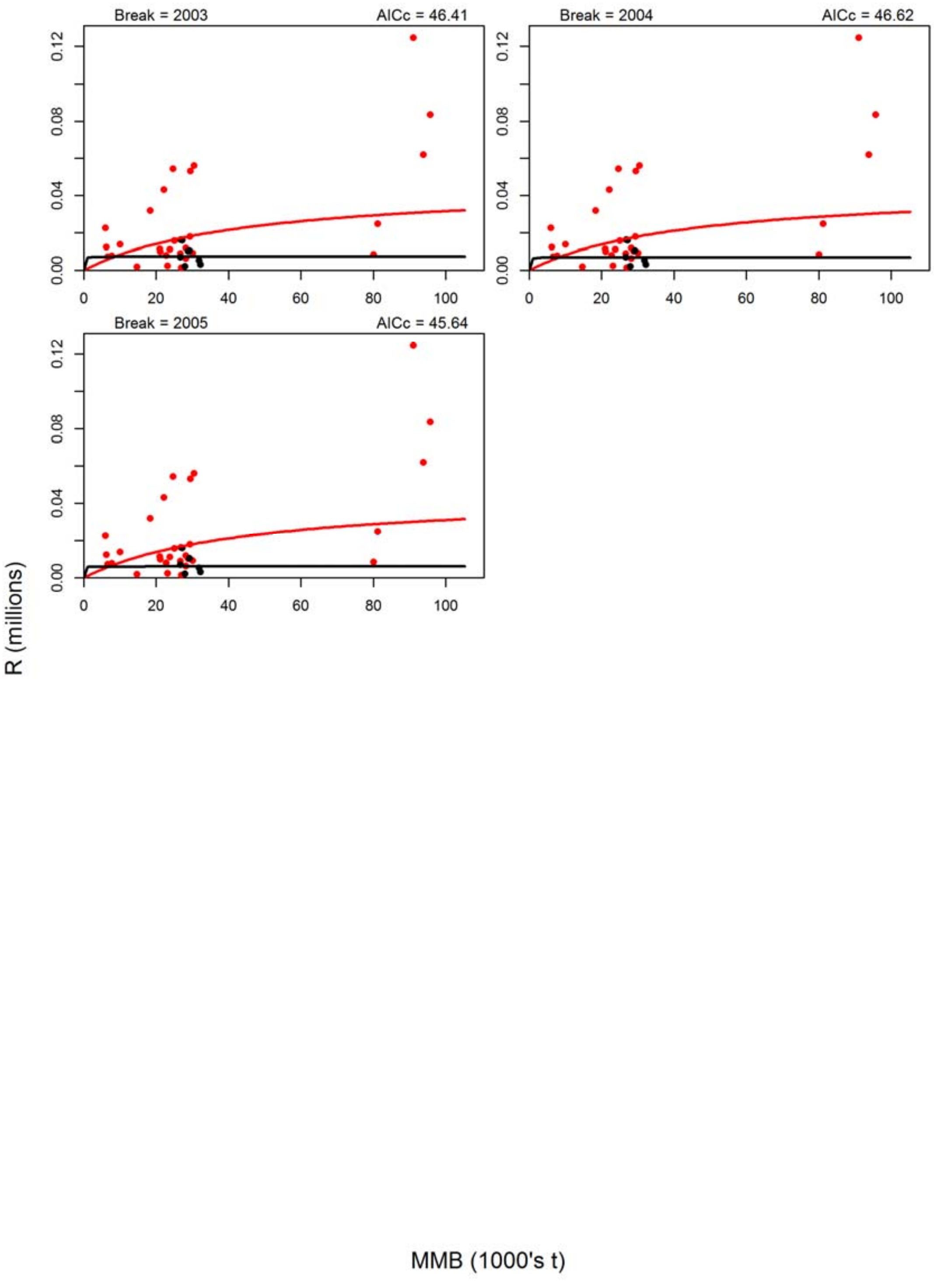

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