BRISTOL BAY RED KING CRAB STOCK ASSESSMENT IN SPRING 2014

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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 was about 7 million lbs (3,154 t) less in 2011/12 and 2012/13 than it was in 2010/11. 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 has increased during the last 25 years with mature females being 3.3 times more abundant in 2009 than in 1985 and mature males being 2.4 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 1984-2013, only in 1984, 1995, 2002 and 2005 was estimated recruitment above the historical average for 1969-2013. Estimated recruitment was extremely low during the last 7 years.
5. Management performance:

Status and catch specifications (1000 t) (Scenario 4):

Year	MSST	Biomass (MMB)	TAC	Retained Catch	Total Catch	OFL	ABC
2009/10	14.22[A]	40.37[A]	7.26	7.27	8.31	10.23	N/A
2010/11	13.63[B]	32.64[B]	6.73	6.76	7.71	10.66	N/A
2011/12	13.77[C]	30.88[C]	3.55	3.61	4.09	8.80	7.92
2012/13	13.19[D]	29.05[D]	3.56	3.62	3.90	7.96	7.17
2013/14		24.95[D]				7.07	6.36

The stock was above MSST in 2012/13 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
2009/10	31.3[A]	89.0[A]	16.00	16.03	18.32	22.56	N/A
2010/11	30.0[B]	72.0[B]	14.84	14.91	17.00	23.52	N/A
2011/12	30.4[C]	68.1[C]	7.83	7.95	9.01	19.39	17.46
2012/13	29.1[D]	64.0[D]	7.85	7.98	8.59	17.55	15.80
2013/14		55.0[D]				15.58	14.02

Notes:

A – Calculated from the assessment reviewed by the Crab Plan Team in September 2010
B – Calculated from the assessment reviewed by the Crab Plan Team in September 2011
C – Calculated from the assessment reviewed by the Crab Plan Team in September 2012
D – Calculated from the assessment reviewed by the Crab Plan Team in September 2013

6. Basis for the OFL: All table values are in 1000 t (Scenario 4).

Year	Tier	B_{MSY}	Current MMB	B/B_{MSY} (MMB)	F_{OFL}	Years to define B_{MSY}	Natural Mortality
2009/10	3a	31.1	43.2	1.39	0.32	1995–2009	0.18
2010/11	3a	28.4	37.7	1.33	0.32	1995-2010	0.18
2011/12	3a	27.3	29.8	1.09	0.32	1984-2011	0.18
2012/13	3a	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

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
2009/10	3a	68.5	95.2	1.39	0.32	1995–2009	0.18
2010/11	3a	62.7	83.1	1.33	0.32	1995-2010	0.18
2011/12	3a	60.1	65.6	1.09	0.32	1984-2011	0.18
2012/13	3a	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

Estimates of B35% were produced using estimated average recruitments during each of two periods: 1976-present, and 1984-present. 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 higher before vs. after 1984, which corresponds to the first brood years following 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. Biophysical connectivity likely favor larvae hatched in the southern Bristol Bay. Finally, stock productivity (recruitment/mature male biomass) was much higher before the 1976/1977 regime shift: the mean value was 3.753 during brood years 1968-1977 and 0.771 during 1978-2006. Two-tail t-tests with unequal variances show that ln(recruitment) and ln(recruitment/mature male biomass) between brood years 1968-1977 and 1978-2006 are strongly, statistically different (p <0.0001).

A. Summary of Major Changes

1. Change to management of the fishery: None.

2. Changes to the input data:

a. The same estimates of trawl survey results as those used in 2013 were used for scenarios 4 and 4b, and newly re-estimated trawl survey results provided by NMFS in 2014 were used for scenarios 4na, 4nb, 4nb0.5, 4nb2 and 4nb7.

3. Changes to the assessment methodology:

Seven model scenarios are evaluated in this report:

Scenario 4: base scenario used to set OFL in 2013. See Section E.3.a for details.

Scenario 4b: the same as scenario 4 except estimating trawl survey catchability.

Scenarios 4na and 4nb: the same as scenarios 4 and 4b except that the newly estimated time-series of trawl survey biomass, length/sex compositions and biomass CV provided by NMFS in 2014 are used.

Scenarios 4nb0.5 and 4nb2: the same as scenario 4nb except that the CV of trawl survey catchability is 0.5 and 2 times of the estimated value.

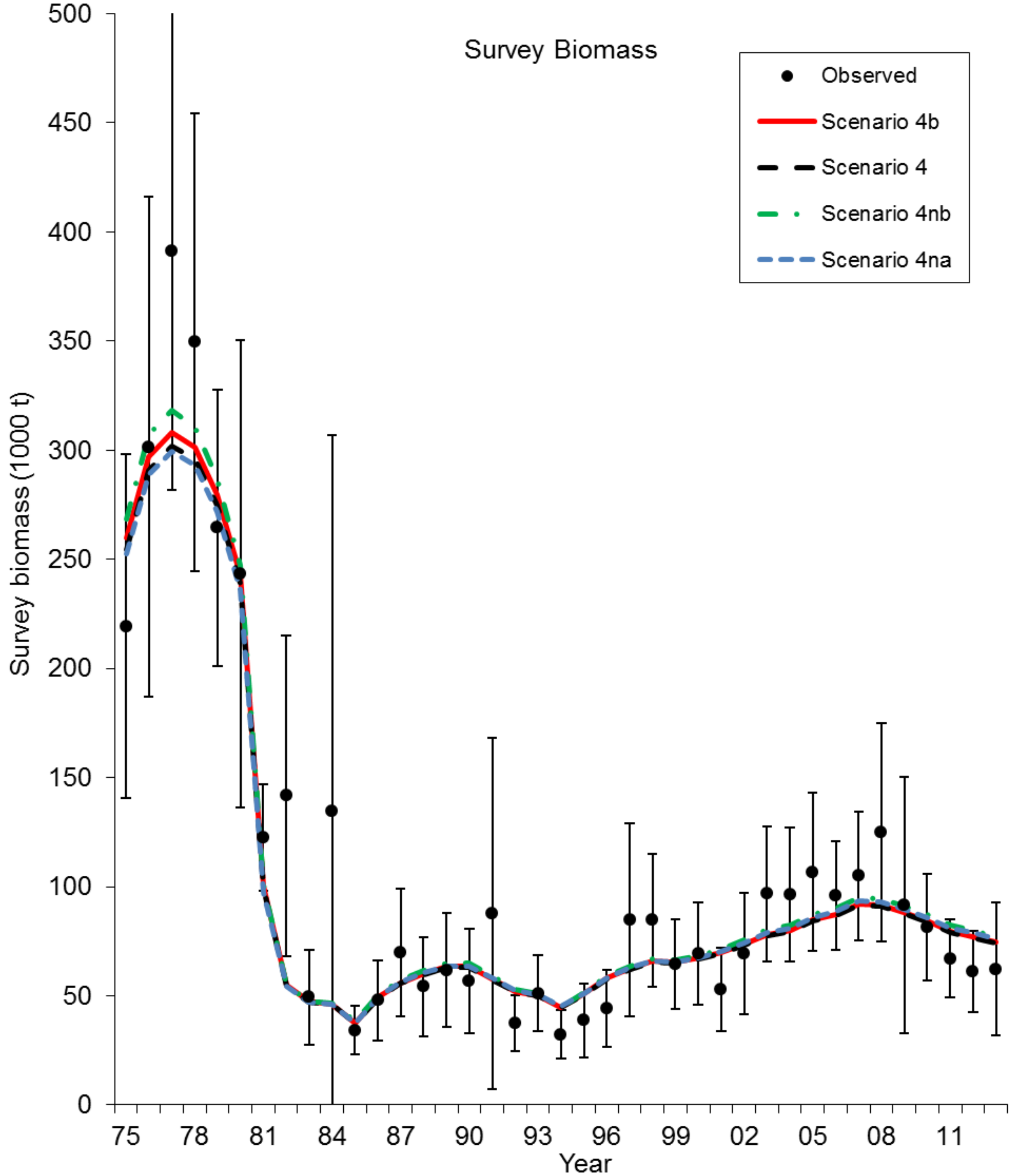
Scenario 4nb7: the same as scenario 4nb except estimating one additional natural mortality parameter for both males and females during 2006-2010.

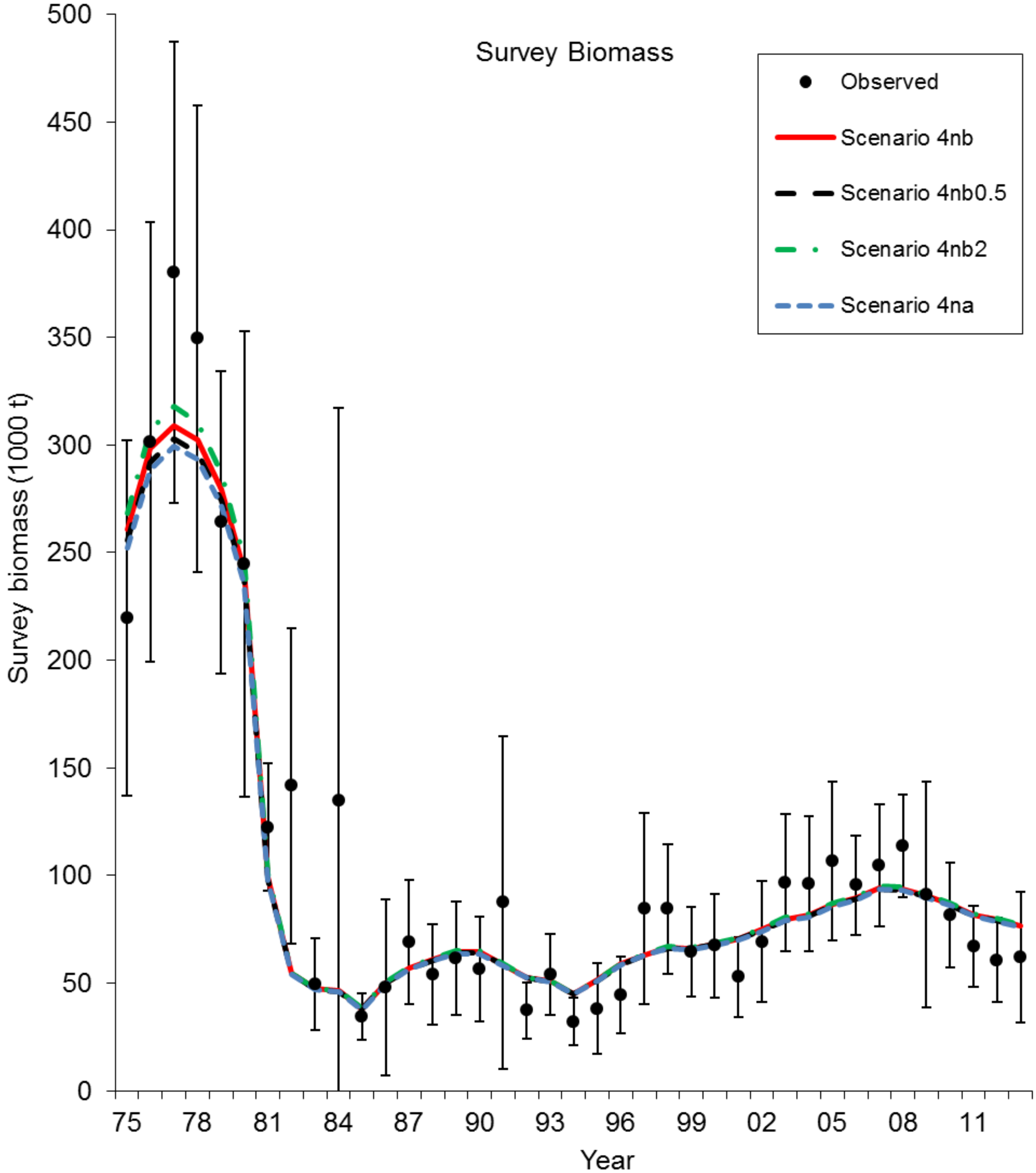
4. Changes to assessment results:

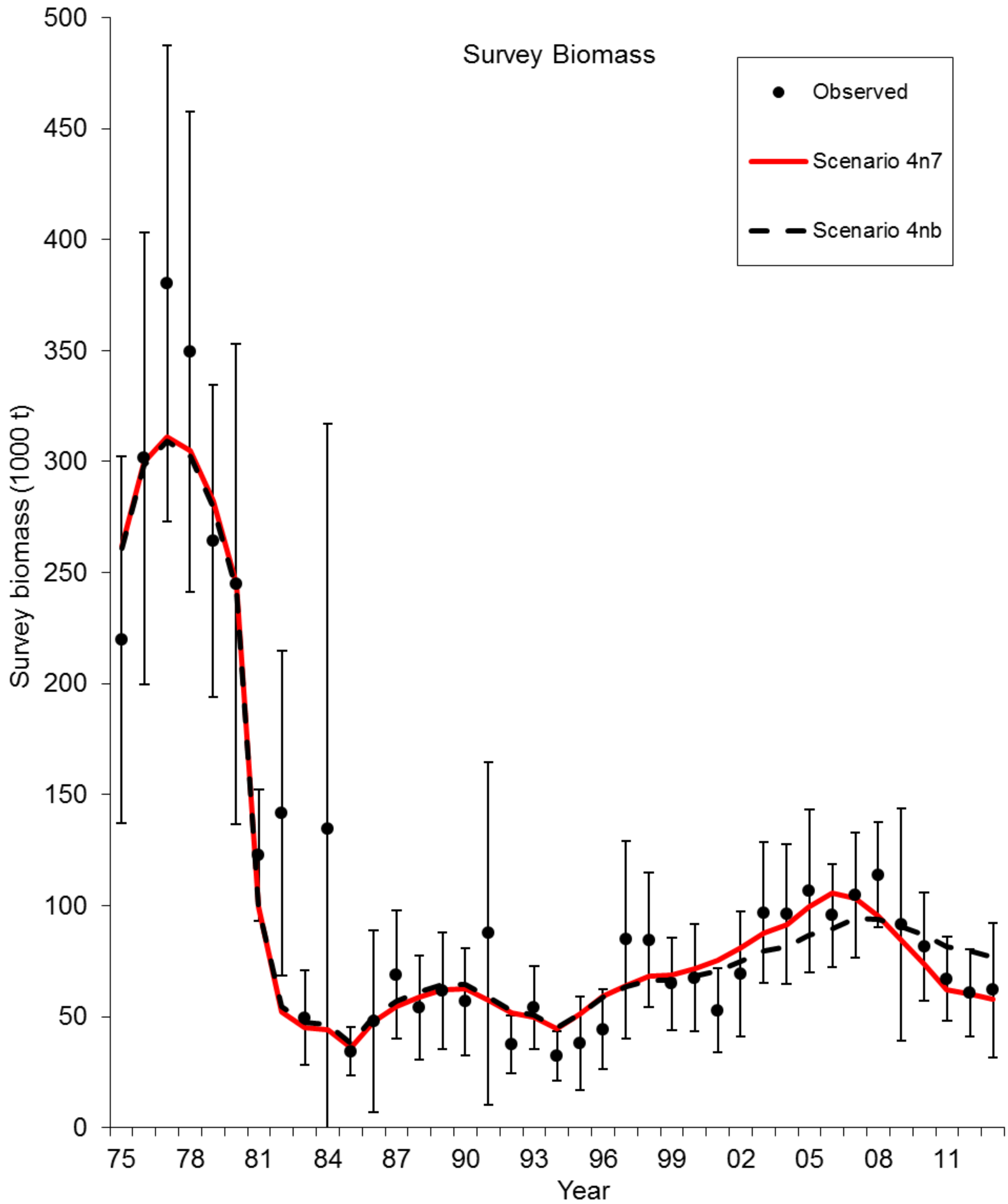
The following table summarizes the results for these scenarios.

	Scenario						
Negative log likelihood	4	4b	4na	4nb	4nb0.5	4nb2	4nb7
R-variation	73.60	73.53	72.37	72.33	72.36	72.23	74.62
Length-like-retained	-919.98	-919.86	-920.24	-920.32	-920.18	-921.20	-923.16
Length-like-discmale	-909.45	-909.32	-909.12	-908.91	-909.05	-908.65	-908.00
Length-like-discfemale	-2174.05	-2174.43	-2175.82	-2176.43	-2176.02	-2177.28	-2173.45
Length-like-survey	-43599.6	-43600.9	-43633.5	-43635.5	-43634.3	-43636.6	-43643.7
Length-like-disctrawl	-1836.07	-1835.58	-1834.08	-1833.13	-1833.82	-1831.44	-1831.59
Length-like-discTanner	-263.91	-263.95	-264.02	-264.10	-264.05	-264.21	-264.44
Length-like-bsfrfsurvey	-236.95	-236.97	-237.26	-237.28	-237.26	-237.31	-238.96
Catchbio_retained	47.88	48.04	47.47	47.79	47.57	48.14	44.88
Catchbio_discmale	217.24	217.11	217.27	217.06	217.20	216.76	209.93
Catchbio-discfemale	0.15	0.15	0.14	0.14	0.14	0.14	0.17
Catchbio-disctrawl	0.84	0.84	0.84	0.84	0.84	0.84	0.81
Biomass-trawl survey	83.11	81.93	79.29	77.45	78.56	76.22	71.45
Biomass-bsfrfsurvey	-5.01	-4.75	-5.16	-4.71	-5.01	-4.23	-6.71
Others	21.11	21.45	21.03	21.03	21.07	21.06	20.59
Total	-49501.1	-49502.3	-49540.8	-49542.6	-49541.4	-49544.3	-49565.6
Trawl Survey Q	0.896	0.919	0.896	0.934	0.909	0.974	0.945
B35 (t)	26382.2	26093.0	26508.8	26015.1	26334.2	25519.1	28396.1
F35	0.29	0.29	0.29	0.29	0.29	0.29	0.29
MMB2013 (t)	24952.3	24462.6	25526.9	24668.7	25225.5	23786.3	19392.7
F_OFL2013	0.27	0.27	0.28	0.27	0.28	0.27	0.19
OFL2013(t)	7066.41	6848.38	7392.85	7001.35	7255.57	6597.5	3630.56

The following figures compare the biomass estimates for different scenarios. The observed values in the first figure are for the time series used in 2013, whereas the observed values in the second and third figures are for the newly re-estimated times series provided by NMFS in 2014. Scenarios 4nb and 4na in the first figure are results through fitting the newly re-estimated times series provided by NMFS in 2014.


Survey Biomass
Observed
Scenario 4b
Scenario 4
Scenario 4nb
Scenario 4na
Survey biomass (1000 t)
500
450
400
350
300
250
200
150
100
50
0
75
78
81
84
87
90
93
96
99
02
05
08
11
Year


Survey Biomass
Observed
Scenario 4nb
Scenario 4nb0.5
Scenario 4nb2
Scenario 4na
Survey biomass (1000 t)
Year
500
450
400
350
300
250
200
150
100
50
0
75
78
81
84
87
90
93
96
99
02
05
08
11



Estimated abundance comparisons are in Figure 10.

In summary, the time series of area-swept abundance estimates as newly re-estimated by NMFS in 2014 is almost the same the time series that we used in 2013. The exception is for 2008, for which the new estimate computed by NMFS in 2014 has a lower estimate (9% lower) than the estimate used in 2013 (which was computed in 2010). CVs of area-swept estimated biomass are also very similar between those we used in 2013 and those provided by NMFS in 2014 with exceptions in 1986 and 2008. NMFS has a higher CV in 1986 and a lower CV in 2008.

Model estimated relative survey biomasses are very similar among different scenarios with the exception of 4nb7. Increasing natural mortality from 0.18 to 0.28 during 2006-2010 under scenario 4nb7 provided a better fit of trawl survey data during recent years, resulting in a much lower OFL. The estimated CV for the trawl survey catchability (*Q*) is about 0.03, and increasing CV resulted in higher estimated *Q* values. Scenario 4nb is recommended for overfishing determination this year. The full results for scenarios 4 and 4nb are presented in this report.

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 2013)

"The Terms of Reference should be followed as a rule, not an option."

If there are occasions where the Terms of Reference are not followed, please specify.

"The author should step-through all the changes between the base model and scenario 1 and present the key outputs after each change (trajectory of MMB, fit to survey, and likelihoods)."

Two scenarios, 01 and 02, were added to address this in September 2013.

"How the molt probabilities are estimated in scenario 1 should be described better."

Text has been revised to further clarify this.

"Model 3 had the poorest fit to the data, leading the CPT to wonder if there is a retrospective pattern in the recruitment estimates. The author should present a retrospective analysis of recruitment estimates in the next report."

Added plots of retrospective recruitment estimates for scenarios 1 and 4 in September 2013.

"In relation to scenario 4, the CPT was unsure whether catchability for the NMFS survey was estimated rather than being pre-specified."

The catchability for the NMFS survey was fixed at 0.896.

"The CPT would like to see more detail in both the SAFE and by presenting the likelihoods since what was provided to date made it difficult to know what was done.

All likelihood values have been summarized in a table and the equations to compute likelihoods are listed in the SAFE report.

"The model should be run to allow estimation of Q for the NMFS survey."

Scenarios 4b and 4nb estimate *Q* for the NMFS survey in May 2014.

"The rationale for the extra CV of 0.5 in scenario 4 should be given and the author should use the maximum likelihood estimate for the log CV term in equation 12."

We estimated the extra CV in the report.

"Scenarios 2, 3, 5 and 6 should not be considered further."

OK.

"Plots to validate sample sizes should be included in the assessment document."

Such plots are added.

"Along with presenting the base model in September 2013, the author should focus on scenario 1 which has a better retrospective pattern and fits the trawl survey better, and scenario 4 which includes almost all of the BSFRF survey information (but was incorrectly implemented for the May 2013 meeting)."

The complete likelihood for the BSFRF survey biomass was used and we presented the complete results for these three scenarios in September 2013.

Response to CPT Comments (from September 2013)

"Estimate catchability for the NMFS surveys while fixing it to 1 for the BSFRF surveys."

Scenarios 4b and 4nb estimate *Q* for the NMFS survey.

"Explore the implications in the new base model (Scenario 4) of an additional period of higher natural mortality in the mid-2000s as suggested by the Scenario 7 model results."

Scenario 4nb7 estimates an additional natural mortality during 2006-2010, which results in statistically better fits to the data.

Response to SSC Comments specific to this assessment (from June 2013)

"The SSC notes that the arbitrary time blocking to fix poor fits to the data is conditional on the initial model set up. ***Therefore the SSC requests that the authors explore a model that allows for interannual variations in M.*** *This could be accomplished with a random walk model for natural mortality or a model that allows independent deviations around the base M with the additional constraint that these deviations sum to 0. Results from this run could be used to explore objectively whether the time blocks selected for additional mortality were correctly specified. We recognize that there are tradeoffs with modeling M, survey Q, and survey selectivity; thus, we ask the authors to carefully consider which parameters should be fixed for this run to enable the desired temporal exploration of time varying M."*

We added a scenario of using a random walk to estimate annual *M* in September 2013. The time blocks used in the current models came from the results from the model first developed 19 years ago and that model did not include some small length groups the current models have. It is time to re-consider these blocks. The time blocks for females seem to match well with the results from the random walk approach. However, the blocks do not match very well for males.

Response to SSC Comments specific to this assessment (from October 2013)

"1. Shifts in the center of distribution of BBRKC can be a function of depletion of the stock, the crab closure area, shifts in larval drift, habitat selection, or fishing. The interpretation of which of these potential causes contributes to selection of a time period should be investigated."

The availability of adequate data to disentangle these causes is unlikely. There have been many studies on this issue and on the sharp decline of abundance in the early 1980s in the last 30 years, but the issue remains unresolved. We will attempt a more in-depth analysis of this issue and present the results in the September SAFE report.

"2. We suggest that the authors work with flatfish authors to come up with a consistent approach to treatment of biomass outside of the survey area."

The flatfish authors used a linear regression model to fill in the missing survey data. We feel that this approach does not apply to Bristol Bay red king crab. The area that is not surveyed for Bristol Bay red king crab is the shallow, nearshore area, where some juvenile red king crab may be found during the normal survey times. Presently, there are no surveys that can completely cover the area. Two recent nearshore surveys in 2011 and 2012, limited in spatial extent, found some red king crab in the unsurveyed area, but those surveys did not cover the untrawlable area. The abundance estimates of red king crab from those surveys varied greatly and are too limited to be useful for use for filling-in of any missing data. The current Bristol Bay red king crab model accounts for crab outside the survey area through the selectivity. The survey selectivity in the model includes both capture probability (gear selectivity) and availability to the survey. In the future, if we can find a way to completely survey this area, we will examine approaches to be better to deal with the availability problem.

"3. Further study of maturity is needed."

Currently, we use a step curve to model changes in female size-at-maturity over time (see Figure A3). It would be better to fit the data with a continuous curve over time. However, the reason for modeling the change is to improve estimation of growth increment per molt. There are very little growth increment data for females in the eastern Bering Sea. Limited availability of growth increment data is the main reason for using a simple step curve. In the future, we may examine the growth increment data from Kodiak female red king crab to see whether we can use them to construct growth functions for Bristol Bay female red king crab. Once we have better growth functions, we can improve methods of estimating variation in female size-at-maturity over time. Female biomass is not used for overfishing determination.

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. Based on the data of size of Kodiak red king crab males in mating pairs (see Figure A4) and the larger size-at-maturity of Kodiak red king crab females than of Bristol Bay red king crab females (Pengilly et al. 2002), the functional maturity sizes were estimated for Bristol Bay red king crab males. Sizes of males that can successfully mate with females in laboratory are much smaller than estimated 120+ mm functional maturity sizes.

"4. The SSC suggests a re-evaluation of predation pressure on BBRKC."

We would like to get some more detailed guidance from the SSC on how to investigate this issue. The main problem we have is that the diet data currently collected by NMFS do not reflect the predation of Bristol Bay red king crab by groundfish due to the timing (primarily summer) and spatial distribution of data collection. There is also a lack of information on groundfish abundance in the shallow, nearshore waters where small juvenile red king crab likely occur. At the CIE meeting in 2010 on Bristol Bay red king crab, a model was presented by a NMFS scientist to show how many juvenile king crab were consumed by groundfish. However, the juvenile king crab discussed were mainly St. Matthews blue king crab as very few small Bristol Bay juvenile red king crab were present in the diet data.

"5. The Plan Team should investigate the impact of dropping hotspots as per CIE review.
6. The Plan Team should investigate the impact of corner stations for hotspots as per CIE review.
7. The Plan Team should investigate the impact of re-tows as per CIE review."

The CPT has discussed these issues and made some decisions on use of the re-tow data. Any in-depth studies would be helpful.

With regard to the hotspots, we support the current approach by NMFS because it reduces the chance of overestimating abundance at terminal years due to a single, high-abundance tow.

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. RKC are found in several areas of the Aleutian Islands and eastern Bering Sea.

3. Stock Structure

The State of Alaska divides the Aleutian Islands and eastern Bering Sea into three management registration areas to manage RKC fisheries: Aleutian Islands, Bristol Bay, and Bering Sea (Alaska Department of Fish and Game (ADF&G 2012)). The Bristol Bay area includes all waters north of the latitude of Cape Sarichef (54^{o}36' N lat.), east of 168^{o}00' W long., and south of the latitude of Cape Newenham (58^{o}39' N lat.) and the fishery for red king crab in this area is managed separately from fisheries for red king crab 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 and fertilized in the spring and are held by females for about 11 months (Powell and Nickerson 1965). Fertilized eggs are hatched in spring, most during the April to June period (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 red king crab 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 through 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 to fish for Bristol Bay RKC in 1947, and 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 continued at low levels during the last two decades (Table 1). After the stock collapse in the early 1980s, 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%. An additional 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. In 2003, 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. The current harvest strategy is illustrated in Figure 1.

D. Data

1. Summary of New Information

(For September 2013) New data include commercial catch and bycatch in 2012/2013, the 2013 summer trawl survey, and updated summer trawl survey data from 1975 to 2013. The revised (2013) NMFS length-weight relationships are used.

2. Catch Data

Data on landings of Bristol Bay RKC by length and year and catch per unit effort were obtained from annual reports of the International North Pacific Fisheries Commission from 1960 to 1973 (Hoopes et al. 1972; Jackson 1974; Phinney 1975) and from the ADF&G from 1974 to 2012. 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 corresponds to what is reported for year 2003 in the NMFS database. Catch biomass is shown in Figure 2. Bycatch data for the cost-recovery fishery before 2006 were not available. In this report, pot fisheries mean directed or in-directed crab pot fisheries, and trawl fisheries mean 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 crabs per tan (a unit fishing effort for tanglenets) for the Japanese and Russian tanglenet fisheries and the number of retained crabs per potlift for the U.S. fishery (Table 3). Soak time, while an important factor influencing CPUE, is difficult to standardize. Furthermore, complete historical soak time data from the U.S. fishery are not available. Based on the approach of Balsiger (1974), all fishing effort from Japan, Russia, and U.S. were standardized to the Japanese tanglenet from 1960 to 1971, and the CPUE was standardized as crabs 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 seems pretty poor (Figure 3). Due to the difficulty in estimating commercial fishing catchability and the ready availability of 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, conduct this multispecies, crab-groundfish survey during the summer. Stations are 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 1975-2013 were provided by NMFS.

Abundance estimates by sex, carapace length, and shell condition were derived from survey data using an area-swept approach (Figures 4 and 5). Spatial distributions of crabs 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 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. If more than one tow was conducted in a station because of high RKC abundance (i.e., the station is a “hot spot”), NMFS regards the station as a separate stratum. Due to poor documentation, it is difficult to duplicate past NMFS post-stratifications. A “hot spot” was not surveyed with multiple tows during the early years. Two such “hot spots” affected the survey abundance estimates greatly: station H13 in 1984 (mostly juvenile crabs 75-90 mm CL) and station F06 in 1991 (mostly newshell legal males). The tow at station F06 was discarded in the older NMFS abundance estimates (Stevens et al. 1991). In this study, all tow data were used. NMFS re-estimated the historic area-swept by tow in 2008 using variable versus fixed net width and re-estimated area-swept abundance as well, using all tow data.

In addition to standard surveys, NMFS also conducted some surveys after the standard surveys to assess mature female abundance. In addition to the standard survey 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 tows (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 (Figure 6). 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 between the standard survey and resurvey (P=0.74, 0.74 and 0.95) based on paired t-tests of sample means. However, similar to 2006, area-swept estimates of mature females within the 32 resurvey stations in 2007 are significantly different between the standard survey and resurvey (P=0.03) based on the t-test. 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 abundance during these resurvey years.

4. Bering Sea Fisheries Research Foundation Survey Data

The BSFRF conducted trawl surveys for Bristol Bay red king crab in 2007 and 2008 with a small-mesh trawl net and 5-minute tows. The surveys occurred at similar times with the NMFS standard surveys and covered about 97% of the Bristol Bay area. Few Bristol Bay red king crab were outside of the BSFRF survey area. Because of small mesh size, the BSFRF surveys were expected to catch nearly all red king crabs 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 associated CVs of 0.0634 and 0.0765.

E. Analytic Approach

1. History of Modeling Approaches

To reduce annual measurement errors associated with abundance estimates derived from the area-swept method, the 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 2013.

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, catchabilities, 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 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) 1982-2013 based on modifications to the trawl gear used in the assessment survey.

   iii. Growth is a function of length and did not change over time for males. For females, three growth increments per molt as a function of length were estimated based on sizes at maturity (1975-1982, 1983-1993, and 1994-2013). Once mature, female red king crabs 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. Survey catchability (*Q*) was estimated to be 0.896, based on a trawl experiment by Weinberg et al. (2004) with a standard deviation of 0.025. *Q* was assumed to be constant over time. Some scenarios estimate *Q* 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. For summer trawl survey data, shell ages of newshell crabs were 12 months or less, and shell ages of oldshell and very oldshell crabs were more than 12 months.

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

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

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

3. Model Selection and Evaluation

a. Alternative model configurations:

Several scenarios were compared for this report:

Scenario 4: base scenario. Scenario 4 includes:

(1) Basic M = 0.18, and additional mortalities as one level (1980-1984) for males and two levels (1980-1984 and 76-79 & 85-93) for females.

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

(3) Assuming survey catchability to be 0.896 for all other years.

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

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

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

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

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

(7) Estimating initial year length compositions.

Scenario 4b: the same as scenario 4 except estimating trawl survey catchability.

Scenarios 4na and 4nb: the same as scenarios 4 and 4b except that newly revised NMFS estimates of time series of biomass, length/sex compositions and biomass CV of the trawl survey data are used.

Scenarios 4nb0.5 and 4nb2: the same as scenario 4nb except that the CV of trawl survey catchability is 0.5 and 2 times of the estimated value.

Scenario 4nb7: the same as scenario 4nb except estimating one additional natural mortality parameter for both males and females during 2006-2010.

Only the full results for scenarios 4 and 4nb are presented in this report. Each figure or table is indicated with a scenario. If not indicating scenario, it is for scenario 4.

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. Estimated sample sizes and effective sample sizes are summarized in tables.

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

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

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

i. Model evaluation is provided under Results, below.

4. Results

a. Effective sample sizes and weighting factors.

i. The effective sample sizes are:

(1) Trawl surveys: 200 for males and females except for females: 184 in 1986, 180 in 1992 and 133 in 1994.
(2) Retained catch: 100.
(3) Pot male discard: 100 except 87 in 1990 and 23 in 1996.
(4) Pot female discard: 50 except 38 in 1991, 1 in 1996, 4 in 1999, and 30 in 2002.
(5) Trawl bycatch: 50 for males and females except for males 28 in 2003, 14 in 2004, 19 in 2005, 22 in 2006, 24 in 2011 and 14 in 2012, and for females 31 in 2003, 12 in 2004, 12 in 2005, 17 in 2006, 22 in 2011 and 13 in 2012.
(6) BSFRF survey: 200 for the BSFRF survey males and females.

For scenario 4, effective sample sizes are illustrated in Figure 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 is estimated to be 0.896 with a standard deviation of 0.025 (CV about 0.03) based on the double-bag experiment results.

b. Tables of estimates.

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

ii. Abundance and biomass time series are provided in Table 6 for scenarios 4 and 4nb.

iii. Recruitment time series for scenarios 4 and 4nb are provided in Table 6.

iv. Time series of catch/biomass are provided in Table 1.

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

c. Graphs of estimates.

i. Selectivities and molting probabilities by length are provided in Figures 8 and 9 for scenarios 4 and 4nb.

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

For scenarios 4 and 4nb, estimated molting probabilities during 1975-2013 (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 crabs 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.

Estimated survey biomass, mature male and female abundances are similar among different scenarios (Figure 10a).

Although the model did not fit the mature crab abundance directly, trends in the mature abundance estimates agree well with observed survey values (Figure 10b). Estimated mature crab abundance increased dramatically in the mid 1970s then decreased precipitously in the early 1980s. Estimated mature crab abundance has increased during the last 27 years with mature females being 3.3 times more abundant in 2009 than in 1985 and mature males being 2.4 times more abundant in 2009 than in 1985 (Figure 10b). Mature abundances have declined since the late 2000s.

iii. Estimated recruitment time series are plotted in Figure 11 for scenarios 4 and 4nb.

iv. Estimated fishing mortaltiy rates are plotted against mature male biomass in Figure 12 for scenarios 4 and 4nb.

The average of estimated male recruits from 1984 to 2013 (Figure 11) 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 12). Estimated fishing mortalities in most years before the current harvest strategy was adopted in 1996 were above $F_{35\%}$ (Figure 12). Under the current harvest strategy, estimated fishing mortalities were at or above the $F_{35\%}$ limits in 1998, 2005, 2007-2010 but below the $F_{35\%}$ limits in the other post-1995 years.

Estimated full pot fishing mortalities ranged from 0.00 to 1.50 during 1968-2012, with estimated values over 0.40 during 1968-1981, 1985-1987, and 2008 (Table 5,

Figure 12). Estimated fishing mortalities for pot female bycatch and trawl bycatch were generally less than 0.06.

v. Estimated mature male biomass and recruitment are plotted to illustrate their relationships with scenario 4nb (Figure 13a). Annual stock productivities are illustrated in Figure 13b.

Stock productivity (recruitment/mature male biomass) was much higher before the 1976/1977 regime shift: the mean value was 3.753 during 1968-1977 and 0.771 during 1978-2013.

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 14). 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 14). The average clutch fullness was close for these two periods (Figure 14).

d. Graphic evaluation of the fit to the data.

i. Observed vs. estimated catches are plotted in Figure 15.

ii. Model fits to total survey biomass are shown in Figure 10 with a standardized residual plot in Figure 16.

iii. Model fits to catch and survey proportions by length are illustrated in Figures 17-24 and residual bubble plots are shown in Figures 25-27.

The model (scenarios 4 and 4nb) fit the fishery biomass data well and the survey biomass reasonably well (Figures 10 and 15). Because the model estimates annual fishing mortality for pot male catch, 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 17-24). It is surprising that the model 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 17 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 16). Standardized residuals of proportions of survey males appear to be random over length and year (Figures 25 and 26). There is an interesting pattern for residuals of proportions of survey females. Residuals were generally negative for large-sized mature females during 1975-1987 (Figure 27). 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. Further study for female growth and availability for survey gears due to different molting times may be needed.

e. Retrospective and historic analyses.

Two kinds of retrospective analyses were conducted for this report: (1) the 2013 model hindcast results and (2) historical results. The 2013 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 2013 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 2013 model includes sequentially excluding one-year of data. The model with scenarios 4 and 4nb performed reasonably well during 2008-2012 with a lower terminal year estimate in 2012 and higher estimates during 2008-2010 (Figure 28).

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

The model first fit the data from 1985 to 2004 in the terminal year of 2004. Thus, nine historical assessment results are available for comparison with the 2013 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 1000 for survey biomass, 2000 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 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 3000 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.

Overall, both historical results (historic analysis) and the 2013 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 4 and 4nb. 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 scenario 4nb using the mcmc approach; estimated *Q*s are generally less than 1.0. Probabilities for mature male biomass in 2013 are illustrated in Figure 31 for scenario 4 using the mcmc appproach. The confidence intervals are quite narrow.

iii. Sensitivity analysis for handling mortality rate was reported in the SAFE report in May 2010. The baseline handling mortality rate for the directed pot fishery was set at 0.2. A 50% reduction and 100% increase 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 2014), seven scenarios are compared and the results are summarized at the beginning of the report.

F. Calculation of the OFL and ABC

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

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

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

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

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

Where

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

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

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

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

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

Because trawl bycatch fishing mortality was not related to pot fishing mortality, average trawl bycatch fishing mortality during 2000 to 2012 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 1990-2012. Some discards of legal males occurred since the IFQ fishery started in 2005, but the discard rates were much lower during 2007-2012 than in 2005 after the fishing industry minimized discards of legal males. Thus, the average of retained selectivities and discard male selectivities during 2009-2012 were used to represent current trends for per recruit analysis and projections. Average molting probabilities during 2001-2012 were used for per recruit analysis and projections.

Average recruitments during three periods were used to estimate $B_{35\%}$: 1976-1983, 1976-2013, and 1984-2013 (Figure 11). 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 much higher before the 1976/1977 regime shift: the mean value was 4.054 during brood years 1968-1977 and 0.828 during 1978-2006 (Figure 13a-c). The two-tail t-tests with unequal variances show that ln(recruitment) and ln(recruitment/mature male biomass) between brood years 1968-1977 and 1978-2006 are strongly, statistically different ($p<0.0001$). There are several potential reasons for the recruitment and productivity differences between these two periods:

a. The 1976/77 regime shift created different environmental conditions before 1978 and after 1977. The PDO index matched crab recruitment strength very well (Figure 13d). The Aleutian Low index has the similar feature. Before 1978, the summer bottom temperatures in Bristol Bay were generally lower than those after 1977 (Figure 13d). Red king crab distributions changed greatly after the regime shift (Figure 13e). High recruitments during the late 1960s and 1970s (before brood year 1978) generally occurred when the spawning stock was primarily located in southern Bristol Bay while the current spawning stock is mainly in the middle of Bristol Bay. The current flows favor larvae hatched in southern Bristol Bay and these larvae settled within the juvenile nursery areas (Figure 13f). A proportion of the larvae hatched in central Bristol Bay may be carried away and settle outside of the juvenile nursery areas.

b. Predation on juvenile crabs may have increased after the 1976/77 regime shift. The biomass of the main crab predator, Pacific cod, increased greatly after the regime shift (Figure 13g). Yellowfin sole biomass also increased substantially during this period. The recruitment strength is statistically associated with the predator biomass (Figure 13h), but we lack stomach samples in shallow waters (juvenile habitat) to quantify the predation mortality.
c. Zheng and Kruse (2000) hypothesized that the strength of the Aleutian Low affects food availability for red king crab larvae. Strong Aleutian Lows may have effects on species composition of the spring bloom that are adverse for red king crab larvae. Diatoms such as *Thalassiosira* are important food for first-feeding red king crab larvae (Paul et al., 1989), and they predominate in the spring bloom in years of light winds when the water column is stable (Ziemann et al., 1991; Bienfang and Ziemann, 1995). Years of strong wind mixing associated with intensified Aleutian Lows may depress red king crab larval survival and subsequent recruitment. All strong year classes occurred before 1978 when the Aleutian Low was weak.

If we believe that the productivity differences and differences of 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 1984-2013 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 2013 is illustrated in Figure 30. The normal approximation is used to estimate the 49th percentile for the OFL in 2012 (Figure 31). Based the SSC suggestion in 2011, ABC = 0.9*OFL is used to estimate ABC.

Status and catch specifications (1000 t) (scenario 4):

Year	MSST	Biomass (MMB)	TAC	Retained Catch	Total Catch	OFL	ABC
2009/10	14.22^{A}	40.37^{A}	7.26	7.27	8.31	10.23	N/A
2010/11	13.63^{B}	32.64^{B}	6.73	6.76	7.71	10.66	N/A
2011/12	13.77^{C}	30.88^{C}	3.55	3.61	4.09	8.80	7.92
2012/13	13.19^{D}	29.05^{D}	3.56	3.62	3.90	7.96	7.17
2013/14		24.95^{D}				7.07	6.36

The stock was above MSST in 2012/13 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
2009/10	31.3[A]	89.0[A]	16.00	16.03	18.32	22.56	N/A
2010/11	30.0[B]	72.0[B]	14.84	14.91	17.00	23.52	N/A
2011/12	30.4[C]	68.1[C]	7.83	7.95	9.01	19.39	17.46
2012/13	29.1[D]	64.0[D]	7.85	7.98	8.59	17.55	15.80
2013/14		55.0[D]				15.58	14.02

Notes:

A – Calculated from the assessment reviewed by the Crab Plan Team in September 2010
B – Calculated from the assessment reviewed by the Crab Plan Team in September 2011
C – Calculated from the assessment reviewed by the Crab Plan Team in September 2012
D – Calculated from the assessment reviewed by the Crab Plan Team in September 2013

4. Based on the $B_{35\%}$ estimated from the average male recruitment during 1984-2013, the biological reference points and OFL were estimated as follows:

	Scenario 4na		Scenario 4nb		Scenario 4	
	1000t	Million lbs	1000t	Million lbs	1000t	Million lbs
$B_{35\%}$	26.509	58.442	26.015	57.353	26.382	58.163
$F_{35\%}$	0.29		0.29		0.29	
MMB_{2013}	25.527	56.277	24.669	54.385	24.952	55.010
OFL_{2013}	7.393	16.298	7.001	15.435	7.066	15.579
ABC_{2013}	6.654	14.669	6.301	13.892	6.360	14.021

5. Based on the 10% buffer rule used last year, ABC = 0.9*OFL. If P*=49% is used, the ABC would 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 1984-2013. Besides recruitment, the other major uncertainty for the projections is estimated abundance in 2013. The 2013 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 1000 times and projections made over 10 years beginning in 2013 (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 during 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 this year (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 in the 2012 or 2013 surveys. This singe tow is unlikely to be an indicator for a strong cohort. Due to lack of recruitment, mature and legal crabs 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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K. Literature Cited

Alaska Department of Fish and Game (ADF&G). 2012. Commercial king and Tanner crab fishing regulations, 2012-2013. Alaska Department of Fish and Game, Division of Commercial Fisheries, Juneau. 170 pp.

Balsiger, J.W. 1974. A computer simulation model for the eastern Bering Sea king crab. Ph.D. dissertation, Univ. Washington, Seattle, WA. 198 pp.

Bienfang, P.K., and D.A. Ziemann. 1995. APPRISE: a multi-year investigation of environmental variation and its effects on larval recruitment. In: Beamish, R.J. (Ed.), Climate Change and Northern Fish Populations, vol. 121. Canadian Special Publication of Fisheries and Aquatic Sciences, pp. 483–487.

Fitch, H., M. Deiman, J. Shaishnikoff, and K. Herring. 2012. Annual management report for the commercial shellfish fisheries of the Bering Sea, 2010/11. *In* Fitch, H. M. Schwenzfeier, B. Baechler, T. Hartill, M. Salmon, M. Deiman, E. Evans, E. Henry, L. Wald, J. Shaishnikoff, K. Herring, and J. Wilson. 2012. Annual management report for the commercial and subsistence fisheries of the Aleutian Islands, Bering Sea and the Westward Region's shellfish observer program, 2010/11. Alaska Dpeartment of Fihs and Game, Fishery Management report No. 12-22, Anchorage.

Gaeuman, W.G. 2013. Summary of the 2012/13 mandatory crab observer program database for the Bering Sea/Aleutian Islands commercial crab fisheries. Alaska Department of Fish and game, Fishery Data Series No. 13-54, Anchorage.

Gray, G.W. 1963. Growth of mature female king crab *Paralithodes camtschaticus* (Tilesius). Alaska Dept. Fish and Game, Inf. Leafl. 26. 4 pp.

Griffin, K. L., M. F. Eaton, and R. S. Otto. 1983. An observer program to gather in-season and post-season on-the-grounds red king crab catch data in the southeastern Bering Sea. Contract 82-2, North Pacific Fishery Management Council, 605 West 4th Avenue, Suite 306, Anchorage, Alaska 99501. 39 pp.

Haynes, E.B. 1968. Relation of fecundity and egg length to carapace length in the king crab, *Paralithodes camtschaticus*. Proc. Nat. Shellfish Assoc. 58: 60-62.

Hoopes, D.T., J.F. Karinen, and M. J. Pelto. 1972. King and Tanner crab research. Int. North Pac. Fish. Comm. Annu. Rep. 1970:110-120.

Ianelli, J.N., S. Barbeaux, G. Walters, and N. Williamson. 2003. Eastern Bering Sea walleye Pollock stock assessment. Pages 39-126 *In* Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands regions. North Pacific Fishery Management Council, Anchorage.

Jackson, P.B. 1974. King and Tanner crab fishery of the United States in the Eastern Bering Sea, 1972. Int. North Pac. Fish. Comm. Annu. Rep. 1972:90-102.

Loher, T., D.A. Armstrong, and B.G. Stevens. 2001. Growth of juvenile red king crab (*Paralithodes camtschaticus*) in Bristol Bay (Alaska) elucidated from field sampling and analysis of trawl-survey data. Fish. Bull. 99:572-587.

Matsuura, S., and K. Takeshita. 1990. Longevity of red king crab, *Paralithodes camtschaticus*, revealed by long-term rearing study. In Proceedings of the International Symposium on King and Tanner Crabs, pp. 181–188. University Alaska Fairbanks, Alaska Sea Grant College Program Report 90-04, Fairbanks. 633 pp.

McCaughran, D.A., and G.C. Powell. 1977. Growth model for Alaskan king crab (*Paralithodes camtschaticus*). J. Fish. Res. Board Can. 34:989-995.

North Pacific Fishery Management Council (NPFMC). 2007. Environmental assessment for proposed amendment 24 to the fishery management plan for Bering Sea and Aleutian Islands king and Tanner crabs to revise overfishing definitions. A review draft.

Otto, R.S. 1989. An overview of eastern Bering Sea king and Tanner crab fisheries. Pages 9–26 *In* Proceedings of the International Symposium on King and Tanner Crabs, Alaska Sea Grant Collecge Program Report No. 90-04.

Overland, J.E., J.M. Adams, and N.A. Bond. 1999. Decadal variability of the Aleutian Low and its relation to high-latitude circulation. J. Climate 12:1542-1548.

Parma, A.M. 1993. Retrospective catch-at-age analysis of Pacific halibut: implications on assessment of harvesting policies. Pages 247-266 *In* G. Kruse, D.M. Eggers, R.J. Marasco, C. Pautzke, and T.J. Quinn II (eds.). Proceedings of the international symposium on management strategies for exploited fish populations. University of Alaska Fairbanks, Alaska Sea Grant Rep. 90-04.

Paul, J.M., and A.J. Paul. 1990. Breeding success of sublegal size male red king crab *Paralithodes camtschaticus* (Tilesius, 1815) (Decapopa, Lithodidae). J. Shellfish Res. 9:29-32.

Paul, A.J., J.M. Paul, K.O. Coyle. 1989. Energy sources for first-feeding zoeae of king crab Paralithodes camtschatica (Tilesius). Journal of Experimental Marine Biology and Ecology 130, 55–69.

Paul, J.M., A.J. Paul, R.S. Otto, and R.A. MacIntosh. 1991. Spermatophore presence in relation to carapace length for eastern Bering Sea blue king crab (Paralithodes platypus, Brandt, 1850) and red king crab (P. camtschaticus, Tilesius, 1815). Journal of Shellfish research, Vol. 10, No. 1, 157-163.

Pengilly, D., S.F. Blau, and J.E. Blackburn. 2002. Size at maturity of Kodiak area female red king crab. Pages 213-224 *In* A.J. Paul, E.G. Dawe, R. Elner, G.S. Jamieson, G.H. Kruse, R.S. Otto, B. Sainte-Marie, T.C. Shirley, and D. Woodby (eds.). Crabs in Cold Water Regions: Biology, Management, and Economics. University of Alaska Sea Grant, AK-SG-02-01, Fairbanks.

Pengilly, D., and D. Schmidt. 1995. Harvest strategy for Kodiak and Bristol Bay red king crab and St. Matthew Island and Pribilof Islands blue king crab. Alaska Dep. Fish and Game, Comm. Fish. Manage. and Dev. Div., Special Publication 7. Juneau, AK. 10 pp.

Phinney, D.E. 1975. United States fishery for king and Tanner crabs in the eastern Bering Sea, 1973. Int. North Pac. Fish. Comm. Annu. Rep. 1973: 98-109.

Powell, G.C. 1967. Growth of king crabs in the vicinity of Kodiak, Alaska. Alaska Dept. Fish and Game, Inf. Leafl. 92. 106 pp.

Powell, G. C., and R.B. Nickerson. 1965. Aggregations among juvenile king crab (*Paralithodes camtschaticus*, Tilesius) Kodiak, Alaska. Animal Behavior 13: 374–380.

Schmidt, D., and D. Pengilly. 1990. Alternative red king crab fishery management practices: modeling the effects of varying size-sex restrictions and harvest rates, p.551-566. *In* Proc. Int. Symp. King & Tanner Crabs, Alaska Sea Grant Rep. 90-04.

Sparks, A.K., and J.F. Morado. 1985. A preliminary report on diseases of Alaska king crabs, p.333-340. *In* Proc. Int. Symp. King & Tanner Crabs, Alaska Sea Grant Rep. 85-12.

Stevens, B.G. 1990. Temperature-dependent growth of juvenile red king crab (*Paralithodes camtschaticus*), and its effects on size-at-age and subsequent recruitment in the eastern Bering Sea. Can. J. Fish. Aquat. Sci. 47: 1307-1317.

Stevens, B.G., R.A. MacIntosh, and J.A. Haaga. 1991. Report to industry on the 1991 eastern Bering Sea crab survey. Alaska Fisheries Science Center, Processed Rep. 91-17. 51 pp. NMFS, NOAA, 7600 Sand Point Way NE, Seattle, WA 99115.

Stevens, B.G., and K. Swiney. 2007. Hatch timing, incubation period, and reproductive cycle for primiparous and multiparous red king crab, *Paralithodes camtschaticus*. J. Crust. Bio. 27(1): 37-48.

Swiney, K. M., W.C. Long, G.L. Eckert, and G.H. Kruse. 2012. Red king crab, *Paralithodes camtschaticus*, size-fecundity relationship, and interannual and seasonal variability in fecundity. Journal of Shellfish Research, 31:4, 925-933.

Weber, D.D. 1967. Growth of the immature king crab *Paralithodes camtschaticus* (Tilesius). Int. North Pac. Fish. Comm. Bull. 21:21-53.

Weber, D.D., and T. Miyahara. 1962. Growth of the adult male king crab, *Paralithodes camtschaticus* (Tilesius). Fish. Bull. U.S. 62:53-75.

Weinberg, K.L., R.S. Otto, and D.A. Somerton. 2004. Capture probability of a survey trawl for red king crab (*Paralithodes camtschaticus*). Fish. Bull. 102:740-749.

Zheng, J. 2005. A review of natural mortality estimation for crab stocks: data-limited for every stock? Pages 595-612 *in* G.H. Kruse, V.F. Gallucci, D.E. Hay, R.I. Perry, R.M. Peterman, T.C. Shirley, P.D. Spencer, B. Wilson, and D. Woodby (eds.). Fisheries Assessment and Management in Data-limited Situation. Alaska Sea Grant College Program, AK-SG-05-02, Fairbanks.

Zheng, J., G.H. Kruse. 2000. Recruitment patterns of Alaskan crabs and relationships to decadal shifts in climate and physical oceanography. ICES Journal of Marine Science 57, 438–451.

Zheng, J., and G.H. Kruse. 2002. Retrospective length-based analysis of Bristol Bay red king crabs: model evaluation and management implications. Pages 475-494 *In* A.J. Paul, E.G. Dawe, R. Elner, G.S. Jamieson, G.H. Kruse, R.S. Otto, B. Sainte-Marie, T.C. Shirley, and D. Woodby (eds.). Crabs in Cold Water Regions: Biology, Management, and Economics. University of Alaska Sea Grant, AK-SG-02-01, Fairbanks.

Zheng, J., M.C. Murphy, and G.H. Kruse. 1995a. A length-based population model and stock-recruitment relationships for red king crab, *Paralithodes camtschaticus*, in Bristol Bay, Alaska. Can. J. Fish. Aquat. Sci. 52:1229-1246.

Zheng, J., M.C. Murphy, and G.H. Kruse. 1995b. Updated length-based population model and stock-recruitment relationships for red king crab, *Paralithodes camtschaticus,* in Bristol Bay, Alaska. Alaska Fish. Res. Bull. 2:114-124.

Zheng, J., M.C. Murphy, and G.H. Kruse. 1996. Overview of population estimation methods and recommended harvest strategy for red king crabs in Bristol Bay. Alaska Department of Fish and Game, Reg. Inf. Rep. 5J96-04, Juneau, Alaska. 37 pp.

Zheng, J., M.C. Murphy, and G.H. Kruse. 1997a. Analysis of the harvest strategies for red king crab, *Paralithodes camtschaticus*, in Bristol Bay, Alaska. Can. J. Fish. Aquat. Sci. 54:1121-1134.

Zheng, J., M.C. Murphy, and G.H. Kruse. 1997b. Alternative rebuilding strategies for the red king crab *Paralithodes camtschaticus* fishery in Bristol Bay, Alaska. J. Shellfish Res. 16:205-217.

Zheng, J., and M.S.M. Siddeek. 2010. Bristol Bay red king crab stock assessment in fall 2010. *In* Stock assessment and fishery evaluation report for the king and Tanner crab fisheries of the Bering Sea and Aleutian Islands regions. North Pacific Fishery Management Council, Anchorage.

Zheng, J., and M.S.M. Siddeek. 2011. Bristol Bay red king crab stock assessment in fall 2011. *In* Stock assessment and fishery evaluation report for the king and Tanner crab fisheries of the Bering Sea and Aleutian Islands regions. North Pacific Fishery Management Council, Anchorage.

Zheng, J., and M.S.M. Siddeek. 2012. Bristol Bay red king crab stock assessment in fall 2012. *In* Stock assessment and fishery evaluation report for the king and Tanner crab fisheries of the Bering Sea and Aleutian Islands regions. North Pacific Fishery Management Council, Anchorage.

Ziemann, D.A., L.D. Conquest, M. Olaizola, P.J. Bienfang. 1991. Interannual variability in the spring phytoplankton bloom in Auke Bay, Alaska. Marine Biology 109, 321–334.

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

Year	Retained Catch				Pot Bycatch		Trawl Bycatch	Total Catch
	U.S.	Cost-Recovery	Foreign	Total	Males	Females		
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			203.6	5371.8
1987	5574.2		0	5574.2			148.3	5722.5
1988	3351.1		0	3351.1			559.9	3910.9
1989	4656.0		0	4656.0			178.7	4834.7
1990	9236.2	36.6	0	9272.8	526.9	651.5	240.3	10691.4
1991	7791.8	93.4	0	7885.1	407.8	75.0	281.1	10080.3
1992	3648.2	33.6	0	3681.8	552.0	418.5	295.9	5405.0
1993	6635.4	24.1	0	6659.6	763.2	637.1	415.6	8671.5
1994	0.0	42.3	0	42.3	3.8	1.9	88.0	136.0
1995	0.0	36.4	0	36.4	3.3	1.6	115.4	156.6
1996	3812.7	49.0	0	3861.7	164.6	1.0	115.0	4142.3
1997	3971.9	70.2	0	4042.1	244.7	19.6	83.5	4389.9
1998	6693.8	85.4	0	6779.2	959.7	864.9	171.9	8775.7
1999	5293.5	84.3	0	5377.9	314.2	8.8	197.3	5898.1
2000	3698.8	39.1	0	3737.9	360.8	40.5	111.1	4250.3
2001	3811.5	54.6	0	3866.2	417.9	173.5	163.5	4621.0
2002	4340.9	43.6	0	4384.5	442.7	7.3	124.6	4959.1
2003	7120.0	15.3	0	7135.3	918.9	430.4	150.0	8634.6
2004	6915.2	91.4	0	7006.7	345.5	187.0	110.1	7649.4
2005	8305.0	94.7	0	8399.7	1359.5	498.3	159.1	10416.6
2006	7005.3	137.9	0	7143.2	563.8	37.0	101.7	7845.6
2007	9237.9	66.1	0	9303.9	1001.3	186.1	130.2	10621.6
2008	9216.1	0.0	0	9216.1	1165.5	148.4	165.3	10695.3
2009	7226.9	45.5	0	7272.5	888.1	85.2	105.0	8350.7
2010	6728.5	33.0	0	6761.5	797.5	122.6	89.0	7770.7
2011	3553.3	53.8	0.0	3607.1	395.0	24.0	76.4	4102.4
2012	3560.6	61.1	0.0	3621.7	205.2	12.3	57.1	3896.3

Table 2. Annual sample sizes (>64 mm CL) for catch by length and shell condition for retained catch and bycatch of Bristol Bay red king crab.

Year	Trawl Survey		Retained	Pot Bycatch		Trawl Bycatch	
	Males	Females	Catch	Males	Females	Males	Females
1968	3,684	2,165	18,044				
1969	6,144	4,992	22,812				
1970	1,546	1,216	3,394				
1971			10,340				
1972	1,106	767	15,046				
1973	1,783	1,888	11,848				
1974	2,505	1,800	27,067				
1975	2,943	2,139	29,570				
1976	4,724	2,956	26,450			2,327	676
1977	3,636	4,178	32,596			14,014	689
1978	4,132	3,948	27,529			8,983	1,456
1979	5,807	4,663	27,900			7,228	2,821
1980	2,412	1,387	34,747			47,463	39,689
1981	3,478	4,097	18,029			42,172	49,634
1982	2,063	2,051	11,466			84,240	47,229
1983	1,524	944	0			204,464	104,910
1984	2,679	1,942	4,404			357,981	147,134
1985	792	415	4,582			169,767	30,693
1986	1,962	367	5,773			62,023	20,800
1987	1,168	1,018	4,230			60,606	32,734
1988	1,834	546	9,833			102,037	57,564
1989	1,257	550	32,858			47,905	17,355
1990	858	603	7,218	873	699	5,876	2,665
1991	1,378	491	36,820	1,801	375	2,964	962
1992	513	360	23,552	3,248	2,389	1,157	2,678
1993	1,009	534	32,777	5,803	5,942		
1994	443	266	0	0	0	4,953	3,341
1995	2,154	1,718	0	0	0	1,729	6,006
1996	835	816	8,896	230	11	24,583	9,373
1997	1,282	707	15,747	4,102	906	9,035	5,759
1998	1,097	1,150	16,131	11,079	9,130	25,051	9,594
1999	764	540	17,666	1,048	36	16,653	5,187
2000	731	1,225	14,091	8,970	1,486	36,972	10,673
2001	611	743	12,854	9,102	4,567	56,070	32,745
2002	1,032	896	15,932	9,943	302	27,705	25,425
2003	1,669	1,311	16,212	17,998	10,327	281	307
2004	2,871	1,599	20,038	8,258	4,112	137	120
2005	1,283	1,682	21,938	55,019	26,775	186	124
2006	1,171	2,672	18,027	32,252	3,980	217	168
2007	1,219	2,499	22,387	59,769	12,661	1,981	2,880
2008	1,221	3,352	14,567	49,315	8,488	1,013	673
2009	830	1,857	16,708	52,359	6,041	1,110	827
2010	705	1,633	20,137	36,654	6,868	898	863
2011	525	994	10,706	20,629	1,920	238	220
2012	580	707	8,956	7,206	561	142	129
2013	752	587					

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

Year	Japanese Tanglenet		Russian Tanglenet		U.S. Pot/Trawl		Standardized Crabs/tan
	Catch	Crabs/tan	Catch	Crabs/tan	Catch	Crabs/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	

Table 4(4). Summary of statistics for the model (Scenario 4).

Parameter counts

Fixed growth parameters	9
Fixed recruitment parameters	2
Fixed length-weight relationship parameters	6
Fixed mortality parameters	4
Fixed survey catchability parameter	2
Fixed high grading parameters	8
Total number of fixed parameters	31
Free growth parameters	6
Initial abundance (1975)	1
Recruitment-distribution parameters	2
Mean recruitment parameters	1
Male recruitment deviations	39
Female recruitment deviations	39
Natural and fishing mortality parameters	4
Pot male fishing mortality deviations	40
Bycatch mortality from the Tanner crab fishery	6
Pot female bycatch fishing mortality deviations	25
Trawl bycatch fishing mortality deviations	39
Initial (1975) length compositions	35
Free selectivity parameters	22
Total number of free parameters	259
Total number of fixed and free parameters	290

Negative log likelihood components (see the table in Section A.4)

Length compositions---retained catch
Length compositions---pot male discard
Length compositions---pot female discard
Length compositions---survey
Length compositions---trawl discard
Length compositions---Tanner crab discards
Pot discard male biomass
Retained catch biomass
Pot discard female biomass
Trawl discard
Survey biomass
Recruitment variation
Others
Total

Table 4(4nb). Summary of statistics for the model (Scenario 4nb).

Parameter counts

Fixed growth parameters	9
Fixed recruitment parameters	2
Fixed length-weight relationship parameters	6
Fixed mortality parameters	4
Fixed survey catchability parameter	1
Fixed high grading parameters	8
Total number of fixed parameters	30
Free survey catchability parameter	1
Free growth parameters	6
Initial abundance (1975)	1
Recruitment-distribution parameters	2
Mean recruitment parameters	1
Male recruitment deviations	39
Female recruitment deviations	39
Natural and fishing mortality parameters	4
Pot male fishing mortality deviations	40
Bycatch mortality from the Tanner crab fishery	6
Pot female bycatch fishing mortality deviations	25
Trawl bycatch fishing mortality deviations	39
Initial (1975) length compositions	35
Free selectivity parameters	22
Total number of free parameters	260
Total number of fixed and free parameters	290

Negative log likelihood components (see the table in Section A.4)

Length compositions---retained catch
Length compositions---pot male discard
Length compositions---pot female discard
Length compositions---survey
Length compositions---trawl discard
Length compositions---Tanner crab discards
Pot discard male biomass
Retained catch biomass
Pot discard female biomass
Trawl discard
Survey biomass
Recruitment variation
Others
Total

Table 5(4). Summary of model parameter estimates (scenario 4) for Bristol Bay red king crab. Estimated values and standard deviations (SD). All values are on a log scale. Male recruit is exp(mean+males), and female recruit is exp(mean+males+females).

	Recruits				F for Directed Pot Fishery				F for Trawl	
Year	Females	SD	Males	SD	Males	SD	Females	SD	Estimate	SD
Mean	15.967	0.021	15.967	0.021	-2.021	0.033	0.011	0.001	-5.182	0.065
Limits↑	13,18		13,18		-4.0,0.0		.001,0.1		-8.5,-1.0	
Limits↓	-15,15		-15,15		-15,2.43		-6.0,3.5		-10,10	
1975					1.122	0.100				
1976	-0.413	0.305	0.759	0.130	1.148	0.070			0.201	0.107
1977	0.683	0.132	0.698	0.093	1.178	0.060			0.729	0.105
1978	0.575	0.112	0.902	0.078	1.410	0.053			0.723	0.104
1979	0.281	0.110	1.079	0.074	1.665	0.047			0.747	0.104
1980	0.288	0.105	1.287	0.073	2.425	0.011			0.769	0.104
1981	0.440	0.117	0.645	0.093	2.425	0.007			0.339	0.104
1982	-0.113	0.048	2.248	0.043	0.532	0.046			2.065	0.106
1983	0.002	0.073	1.369	0.050	-10.147	0.653			1.946	0.105
1984	0.359	0.062	1.243	0.044	0.962	0.056			2.935	0.104
1985	0.151	0.159	-0.596	0.102	1.036	0.063			1.874	0.105
1986	0.442	0.058	0.627	0.045	1.487	0.059			0.811	0.105
1987	-0.105	0.135	-0.272	0.071	1.089	0.054			0.249	0.104
1988	0.342	0.166	-1.028	0.107	0.187	0.049			1.382	0.102
1989	0.067	0.144	-0.760	0.082	0.315	0.046			0.062	0.102
1990	-0.076	0.068	0.307	0.045	0.922	0.042	2.084	0.104	0.290	0.102
1991	-0.244	0.100	-0.130	0.054	0.895	0.044	-0.066	0.104	0.528	0.103
1992	-0.662	0.387	-1.803	0.159	0.377	0.045	2.236	0.104	0.688	0.103
1993	-0.256	0.096	-0.347	0.054	1.023	0.047	2.138	0.104	1.049	0.102
1994	-0.155	0.393	-2.128	0.184	-4.112	0.047	1.495	0.131	-0.393	0.104
1995	0.032	0.039	1.187	0.035	-4.442	0.044	1.609	0.135	-0.276	0.103
1996	-0.646	0.237	-0.605	0.107	0.103	0.042	-3.674	0.151	-0.394	0.103
1997	-0.817	0.386	-1.444	0.156	0.213	0.042	-0.963	0.105	-0.719	0.103
1998	-0.213	0.116	-0.252	0.067	0.910	0.043	2.133	0.103	-0.037	0.102
1999	0.020	0.060	0.573	0.042	0.466	0.042	-2.003	0.108	0.102	0.102
2000	-0.037	0.133	-0.370	0.079	0.101	0.041	-0.231	0.103	-0.533	0.102
2001	0.779	0.163	-0.947	0.128	0.126	0.041	1.147	0.103	-0.196	0.102
2002	0.242	0.056	0.975	0.041	0.233	0.041	-2.186	0.109	-0.500	0.102
2003	0.017	0.210	-0.584	0.127	0.756	0.040	1.184	0.103	-0.353	0.102
2004	-0.067	0.139	0.047	0.081	0.620	0.041	0.413	0.102	-0.636	0.102
2005	0.365	0.061	0.897	0.047	1.045	0.042	0.939	0.103	-0.291	0.102
2006	-0.701	0.164	0.289	0.066	0.772	0.042	-1.512	0.104	-0.728	0.102
2007	-0.336	0.157	-0.264	0.084	1.101	0.044	-0.263	0.103	-0.532	0.102
2008	0.029	0.164	-0.741	0.103	1.198	0.048	-0.563	0.104	-0.291	0.103
2009	0.118	0.156	-0.783	0.101	0.908	0.051	-0.788	0.105	-0.750	0.104
2010	-0.120	0.120	-0.267	0.075	0.775	0.055	-0.246	0.105	-0.944	0.106
2011	-0.026	0.117	-0.192	0.077	0.107	0.057	-1.171	0.107	-1.089	0.107
2012	0.129	0.167	-0.638	0.111	0.012	0.060	-1.711	0.110	-1.391	0.108
2013	-0.374	0.315	-0.982	0.167						

Table 5(4) (continued). Summary of model parameter estimates for Bristol Bay red king crab (scenario 4). Estimated values and standard deviations. For initial year length composition deviations, the first 20 length groups are for males and the last 16 length groups are for females.

				Initial Length Composition 1975			
Parameter	Value	SD	Limits	Length	Value	SD	Limits
Mm80-84	0.475	0.016	0.184, 1.00	68	1.225	0.095	-5, 5
Mf80-84	0.802	0.020	0.276, 1.50	73	1.266	0.087	-5, 5
Mf76-79,85-93	0.073	0.006	0.0, 0.082	78	0.484	0.111	-5, 5
log_betal, females	0.171	0.054	-0.67, 1.32	83	0.457	0.097	-5, 5
log_betal, males	0.531	0.084	-0.67, 1.32	88	0.416	0.090	-5, 5
log_betar, females	-0.707	0.064	-1.14, 0.50	93	0.107	0.102	-5, 5
log_betar, males	-0.646	0.048	-1.14, 0.50	98	0.133	0.099	-5, 5
Bsfrf_CV	0.066	0.067	0.00, 0.40	103	-0.100	0.114	-5, 5
moltp_slope, 75-79	0.137	0.021	0.01, 0.168	108	-0.044	0.114	-5, 5
moltp_slope, 80-12	0.100	0.004	0.01, 0.168	113	0.071	0.112	-5, 5
log_moltp_L50, 75-79	4.964	0.011	4.47, 5.52	118	-0.080	0.130	-5, 5
log_moltp_L50, 80-12	4.943	0.003	4.47, 5.52	123	-0.094	0.139	-5, 5
log_N75	20.049	0.031	15.0, 21.00	128	-0.080	0.148	-5, 5
log_avg_L50_ret	4.921	0.002	4.78, 5.05	133	-0.130	0.161	-5, 5
ret_fish_slope	0.530	0.032	0.05, 0.70	138	-0.218	0.145	-5, 5
pot disc.males, φ	-0.329	0.015	-0.40, 0.00	143	-0.317	0.146	-5, 5
pot disc.males, κ	0.004	0.000	0.0, 0.005	148	-0.471	0.156	-5, 5
pot disc.males, γ	-0.015	0.001	-0.025, 0.0	153	-0.829	0.190	-5, 5
pot disc.fema., slope	0.577	0.203	0.05, 0.69	158	-1.321	0.255	-5, 5
log_pot disc.fema., L50	4.386	0.009	4.24, 4.61	163	-1.347	0.268	-5, 5
trawl disc slope	0.056	0.003	0.01, 0.20	68	1.658	0.096	-5, 5
log_trawl disc L50	5.037	0.044	4.40, 5.20	73	1.588	0.095	-5, 5
log_srv_L50, m, bsfrf	4.387	0.045	3.59, 5.49	78	1.405	0.094	-5, 5
srv_slope, f, bsfrf	0.013	0.006	0.01, 0.435	83	1.159	0.097	-5, 5
log_srv_L50, f, bsfrf	5.166	0.478	4.09, 5.54	88	1.156	0.088	-5, 5
log_srv_L50, m, 75-81	4.326	0.011	4.09, 5.54	93	0.764	0.100	-5, 5
srv_slope, f, 75-81	0.067	0.004	0.01, 0.33	98	0.484	0.114	-5, 5
log_srv_L50, f, 75-81	4.443	0.018	4.09, 4.70	103	0.403	0.116	-5, 5
log_srv_L50, m, 82-12	4.482	0.008	4.09, 5.10	108	0.206	0.129	-5, 5
srv_slope, f, 82-12	0.058	0.002	0.01, 0.30	113	0.027	0.144	-5, 5
log_srv_L50, f, 82-12	4.525	0.012	4.09, 4.90	118	-0.490	0.210	-5, 5
TC_slope, females	0.290	0.122	0.02, 0.40	123	-0.683	0.256	-5, 5
log_TC_L50, females	4.558	0.019	4.24, 4.90	128	-1.102	0.378	-5, 5
TC_slope, males	0.177	0.066	0.05, 0.90	133	-1.877	0.757	-5, 5
log_TC_L50, males	4.606	0.029	4.25, 5.14	138	-2.349	1.259	-5, 5
log_TC_F, males, 91	-4.148	0.083	-7.0, 1.00	143	NA	NA	
log_TC_F, males, 92	-5.275	0.086	-7.0, 1.00				
log_TC_F, males, 93	-6.565	0.088	-7.0, 1.00				
log_TC_F, females, 91	-2.871	0.087	-7.0, 1.00				
log_TC_F, females, 92	-4.022	0.088	-7.0, 1.00				
log_TC_F, females, 93	-4.617	0.087	-7.0, 1.00				

Table 5(4nb). Summary of model parameter estimates (scenario 4nb) for Bristol Bay red king crab. Estimated values and standard deviations. All values are on a log scale. Male recruit is exp(mean+males), and female recruit is exp(mean+males+females).

Year	Recruits				F for Directed Pot Fishery				F for Trawl	
	Females	SD	Males	SD	Males	SD	Females	SD	Estimate	SD
Mean	15.948	0.024	15.948	0.024	-1.994	0.043	0.011	0.001	-5.157	0.070
Limits↑	13,18		13,18		-4.0,0.0		.001,0.1		-8.5,-1.0	
Limits↓	-15,15		-15,15		-15,2.43		-6.0,3.5		-10,10	
1975					1.114	0.103				
1976	-0.399	0.302	0.733	0.134	1.135	0.072			0.188	0.108
1977	0.710	0.133	0.663	0.097	1.161	0.063			0.714	0.105
1978	0.581	0.112	0.884	0.079	1.392	0.058			0.708	0.105
1979	0.296	0.111	1.044	0.076	1.646	0.054			0.734	0.105
1980	0.300	0.106	1.248	0.075	2.420	0.057			0.759	0.105
1981	0.441	0.117	0.609	0.094	2.425	0.007			0.349	0.104
1982	-0.127	0.049	2.225	0.044	0.550	0.047			2.088	0.106
1983	-0.003	0.073	1.354	0.050	-10.150	0.680			1.964	0.106
1984	0.372	0.062	1.243	0.045	0.961	0.057			2.941	0.105
1985	0.166	0.157	-0.593	0.103	1.034	0.064			1.874	0.105
1986	0.435	0.058	0.636	0.045	1.488	0.059			0.809	0.105
1987	-0.134	0.137	-0.268	0.072	1.091	0.055			0.248	0.104
1988	0.319	0.167	-1.027	0.108	0.187	0.049			1.381	0.102
1989	0.089	0.141	-0.754	0.083	0.313	0.047			0.059	0.102
1990	-0.084	0.068	0.309	0.045	0.923	0.043	2.097	0.104	0.287	0.102
1991	-0.161	0.095	-0.139	0.055	0.900	0.045	-0.060	0.104	0.528	0.103
1992	-0.507	0.360	-1.804	0.159	0.385	0.046	2.234	0.104	0.694	0.103
1993	-0.300	0.098	-0.357	0.055	1.037	0.048	2.130	0.105	1.058	0.103
1994	-0.146	0.382	-2.136	0.186	-4.100	0.048	1.491	0.131	-0.381	0.104
1995	-0.004	0.039	1.188	0.035	-4.436	0.045	1.614	0.135	-0.268	0.103
1996	-0.677	0.235	-0.600	0.107	0.110	0.043	-3.664	0.152	-0.389	0.103
1997	-0.775	0.370	-1.440	0.157	0.221	0.043	-0.955	0.105	-0.712	0.103
1998	-0.258	0.118	-0.242	0.067	0.921	0.044	2.141	0.103	-0.030	0.102
1999	0.082	0.059	0.586	0.042	0.478	0.043	-1.999	0.108	0.110	0.102
2000	-0.086	0.137	-0.362	0.079	0.109	0.042	-0.237	0.104	-0.527	0.102
2001	0.735	0.165	-0.934	0.129	0.132	0.042	1.138	0.103	-0.192	0.102
2002	0.215	0.056	0.993	0.042	0.238	0.042	-2.192	0.109	-0.497	0.102
2003	0.014	0.210	-0.588	0.130	0.757	0.042	1.181	0.103	-0.353	0.102
2004	-0.071	0.139	0.048	0.082	0.621	0.042	0.411	0.102	-0.637	0.102
2005	0.351	0.061	0.903	0.048	1.048	0.043	0.935	0.103	-0.293	0.102
2006	-0.711	0.159	0.326	0.065	0.773	0.043	-1.514	0.104	-0.731	0.102
2007	-0.330	0.154	-0.235	0.084	1.103	0.045	-0.268	0.103	-0.536	0.102
2008	0.002	0.165	-0.724	0.104	1.199	0.049	-0.569	0.104	-0.295	0.103
2009	0.098	0.156	-0.766	0.102	0.908	0.052	-0.793	0.105	-0.755	0.104
2010	-0.133	0.119	-0.249	0.075	0.770	0.056	-0.247	0.105	-0.952	0.106
2011	-0.054	0.117	-0.176	0.077	0.098	0.059	-1.168	0.107	-1.098	0.107
2012	0.089	0.169	-0.626	0.112	0.001	0.061	-1.704	0.110	-1.402	0.109
2013	-0.335	0.305	-0.972	0.169						

Table 5(4nb) (continued). Summary of model parameter estimates for Bristol Bay red king crab (scenario 4nb). Estimated values and standard deviations. For initial year length composition deviations, the first 20 length groups are for males and the last 16 length groups are for females.

				Initial Length Composition 1975			
Parameter	Value	SD	Limits	Length	Value	SD	Limits
Mm80-84	0.467	0.016	0.184, 1.0	68	1.241	0.094	-5, 5
Mf80-84	0.815	0.020	0.276, 1.5	73	1.278	0.086	-5, 5
Mf76-79,85-93	0.075	0.006	0.0, 0.082	78	0.493	0.111	-5, 5
log_betal, females	0.173	0.054	-0.67, 1.32	83	0.467	0.097	-5, 5
log_betal, males	0.549	0.084	-0.67, 1.32	88	0.426	0.090	-5, 5
log_betar, females	-0.721	0.063	-1.14, 0.5	93	0.119	0.102	-5, 5
log_betar, males	-0.648	0.048	-1.14, 0.5	98	0.144	0.100	-5, 5
Bsfrf_CV	0.080	0.074	0.00, 0.40	103	-0.088	0.114	-5, 5
moltp_slope, 75-78	0.139	0.024	0.01, 0.207	108	-0.031	0.114	-5, 5
moltp_slope, 79-13	0.101	0.004	0.01, 0.207	113	0.084	0.112	-5, 5
log_moltp_L50, 75-78	4.967	0.014	4.47, 5.62	118	-0.068	0.129	-5, 5
log_moltp_L50, 79-13	4.945	0.004	4.47, 5.62	123	-0.084	0.138	-5, 5
log_N75	20.031	0.034	15.0, 21.0	128	-0.070	0.148	-5, 5
log_avg_L50_ret	4.921	0.002	4.78, 5.05	133	-0.124	0.161	-5, 5
ret_fish_slope	0.529	0.032	0.05, 0.70	138	-0.213	0.146	-5, 5
pot disc.males, φ	-0.326	0.015	-0.40, 0.00	143	-0.311	0.147	-5, 5
pot disc.males, κ	0.004	0.000	0.0, 0.005	148	-0.467	0.157	-5, 5
pot disc.males, γ	-0.015	0.001	-0.025, 0.0	153	-0.825	0.192	-5, 5
pot disc.fema., slope	0.564	0.198	0.05, 0.69	158	-1.320	0.258	-5, 5
log_pot disc.fema., L50	4.387	0.009	4.24, 4.61	163	-1.346	0.271	-5, 5
trawl disc slope	0.056	0.003	0.01, 0.20	68	1.650	0.096	-5, 5
log_trawl disc L50	5.033	0.044	4.40, 5.20	73	1.583	0.095	-5, 5
log_srv_L50, m, bsfrf	4.392	0.044	3.59, 5.49	78	1.401	0.094	-5, 5
srv_slope, f, bsfrf	0.013	0.006	0.01, 0.435	83	1.157	0.097	-5, 5
log_srv_L50, f, bsfrf	5.127	0.469	4.09, 5.54	88	1.150	0.088	-5, 5
log_srv_L50, m, 75-81	4.325	0.011	4.09, 5.54	93	0.761	0.101	-5, 5
srv_slope, f, 75-81	0.066	0.004	0.01, 0.33	98	0.478	0.115	-5, 5
log_srv_L50, f, 75-81	4.441	0.018	4.09, 4.70	103	0.397	0.117	-5, 5
log_srv_L50, m, 82-12	4.482	0.009	4.09, 5.10	108	0.203	0.130	-5, 5
srv_slope, f, 82-12	0.062	0.002	0.01, 0.30	113	0.028	0.145	-5, 5
log_srv_L50, f, 82-12	4.510	0.011	4.09, 4.90	118	-0.510	0.214	-5, 5
TC_slope, females	0.291	0.120	0.02, 0.40	123	-0.695	0.260	-5, 5
log_TC_L50, females	4.560	0.019	4.24, 4.90	128	-1.117	0.387	-5, 5
TC_slope, males	0.175	0.065	0.05, 0.90	133	-1.923	0.797	-5, 5
log_TC_L50, males	4.608	0.029	4.25, 5.14	138	-2.350	1.269	-5, 5
log_TC_F, males, 91	-4.115	0.089	-7.0, 1.00	143	NA	NA	
log_TC_F, males, 92	-5.241	0.092	-7.0, 1.00				
log_TC_F, males, 93	-6.526	0.095	-7.0, 1.00	Q	0.934	0.021	0.6, 1.2
log_TC_F, females, 91	-2.821	0.090	-7.0, 1.00				
log_TC_F, females, 92	-3.972	0.091	-7.0, 1.00				
log_TC_F, females, 93	-4.572	0.091	-7.0, 1.00				

Table 6(4). Annual abundance estimates (million crabs), mature male biomass (MMB, 1000 t), and total survey biomass estimates (1000 t) for red king crab in Bristol Bay estimated by length-based analysis (scenario 4) from 1975-2013. Mature male biomass for year *t* is on Feb. 15, year *t*+1. Size measurements are mm CL.

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	55.408	29.648	82.387	5.225	89.783		254.465	219.344
1976	59.896	35.392	89.842	4.382	122.321	30.516	290.827	301.530
1977	61.521	37.271	91.818	3.672	151.873	51.506	301.914	391.066
1978	69.830	38.211	96.645	3.045	145.703	58.869	295.928	349.495
1979	67.849	41.092	85.275	2.561	129.770	58.822	274.571	264.389
1980	49.089	34.934	26.105	0.945	118.433	72.679	239.106	243.299
1981	15.527	8.900	9.151	0.403	51.432	41.862	99.487	122.497
1982	7.814	3.385	8.727	0.361	24.137	154.219	54.593	141.612
1983	6.812	3.202	8.868	0.348	15.827	67.715	47.251	49.322
1984	6.557	3.130	6.793	0.340	16.122	72.499	45.936	134.594
1985	8.420	2.659	11.907	0.508	13.609	10.255	37.305	34.285
1986	13.510	5.397	17.712	0.744	19.457	41.173	49.093	47.901
1987	16.466	7.697	23.973	0.901	23.308	12.451	55.645	69.759
1988	17.003	9.890	29.459	0.981	28.442	7.411	59.752	54.224
1989	18.567	11.538	33.101	1.018	26.402	8.328	62.909	61.835
1990	18.780	12.568	30.989	1.024	22.936	22.526	62.994	56.892
1991	15.254	11.333	25.882	0.994	20.952	13.469	57.481	87.572
1992	12.107	9.150	23.545	0.944	20.768	2.149	51.785	37.671
1993	12.639	8.259	20.939	0.909	18.472	10.786	49.962	51.022
1994	12.453	7.627	26.383	0.921	15.290	1.901	44.493	32.357
1995	12.864	9.426	29.092	0.892	14.971	57.280	50.659	38.656
1996	12.895	10.032	27.005	0.845	20.270	7.161	57.885	44.338
1997	12.077	9.084	25.015	0.804	29.841	2.928	62.267	84.836
1998	16.434	8.732	27.333	0.857	27.840	12.089	65.499	84.572
1999	18.059	10.352	31.881	0.940	24.394	30.819	65.076	64.609
2000	16.029	11.740	31.570	0.932	26.496	11.660	66.875	69.314
2001	14.884	11.193	30.197	0.897	30.360	10.607	69.197	52.816
2002	16.440	10.629	31.872	0.894	30.293	51.865	73.281	69.327
2003	17.075	11.370	30.351	0.889	35.833	9.670	77.667	96.814
2004	15.154	10.747	28.003	0.858	43.369	17.446	79.333	96.297
2005	17.290	10.099	27.905	0.876	41.852	51.453	84.089	106.600
2006	17.482	10.511	29.656	0.935	45.834	17.186	86.881	95.743
2007	16.971	11.014	26.893	0.975	52.900	11.331	91.501	104.993
2008	18.425	10.220	27.776	1.128	49.315	8.322	91.011	124.971
2009	19.315	10.878	31.027	1.354	44.415	8.357	87.614	91.692
2010	18.125	11.892	30.809	1.514	40.150	12.434	83.894	81.527
2011	15.485	11.386	30.610	1.586	36.983	14.023	79.039	67.159
2012	13.904	10.820	29.054	1.605	35.284	9.713	76.809	61.106
2013	13.288	9.951	24.952	1.280	33.983	5.438	74.218	62.254

Table 6(4nb). Annual abundance estimates (million crabs), mature male biomass (MMB, 1000 t), and total survey biomass estimates (1000 t) for red king crab in Bristol Bay estimated by length-based analysis (scenario 4nb) from 1975-2013. Mature male biomass for year *t* is on Feb. 15, year *t*+1. Size measurements are mm CL.

Year (t)	Males				Females	Total Recruits	Trawl Survey Biomass	
	Mature (>119 mm)	Legal (>134 mm)	MMB (>119 mm)	SD MMB	Mature (>89 mm)		Model Est. (>64 mm)	Area-Swept
1975	54.681	29.194	80.925	5.744	87.424		260.936	219.637
1976	59.139	34.961	88.461	4.788	119.219	29.339	298.224	301.454
1977	60.731	36.839	90.477	3.960	147.772	49.653	309.169	380.194
1978	68.906	37.764	95.206	3.263	141.375	56.937	302.331	349.437
1979	66.802	40.606	83.770	2.706	125.585	56.177	279.510	264.248
1980	47.981	34.401	25.178	1.015	114.271	69.054	241.917	244.793
1981	14.985	8.621	8.715	0.495	48.871	39.642	99.185	122.499
1982	7.514	3.251	8.380	0.451	22.602	146.705	54.564	141.610
1983	6.578	3.097	8.605	0.423	14.642	65.220	47.347	49.322
1984	6.380	3.053	6.607	0.395	14.890	71.643	46.489	134.594
1985	8.232	2.603	11.598	0.590	12.758	10.168	38.050	34.281
1986	13.216	5.283	17.206	0.869	18.596	40.556	50.210	47.804
1987	16.104	7.517	23.306	1.072	22.459	12.096	56.977	68.935
1988	16.627	9.658	28.711	1.178	27.503	7.178	61.192	54.056
1989	18.178	11.283	32.299	1.234	25.461	8.303	64.426	61.499
1990	18.392	12.298	30.146	1.251	22.082	22.053	64.453	56.730
1991	14.886	11.054	25.035	1.223	20.179	13.586	58.677	87.499
1992	11.757	8.872	22.721	1.165	20.088	2.224	52.726	37.410
1993	12.272	7.990	20.088	1.132	18.024	10.276	50.791	53.898
1994	12.047	7.351	25.466	1.154	14.892	1.857	45.056	32.099
1995	12.464	9.132	28.167	1.119	14.502	55.230	51.353	38.116
1996	12.498	9.734	26.078	1.061	19.449	6.978	58.812	44.323
1997	11.689	8.783	24.097	1.011	28.491	2.920	63.293	84.653
1998	15.961	8.434	26.305	1.088	26.586	11.737	66.572	84.554
1999	17.551	10.019	30.759	1.191	23.274	31.595	66.163	64.745
2000	15.559	11.382	30.484	1.176	25.646	11.266	68.187	67.490
2001	14.459	10.844	29.179	1.127	29.930	10.235	70.767	52.801
2002	16.038	10.306	30.905	1.116	29.757	50.980	75.094	69.273
2003	16.702	11.075	29.458	1.096	34.993	9.438	79.801	96.781
2004	14.824	10.478	27.198	1.050	42.280	17.087	81.636	96.230
2005	16.982	9.858	27.159	1.062	40.794	50.383	86.579	106.558
2006	17.180	10.292	28.938	1.114	44.644	17.424	89.531	95.457
2007	16.641	10.799	26.143	1.143	51.581	11.458	94.405	104.590
2008	18.037	9.979	26.970	1.297	48.204	8.185	93.928	113.698
2009	18.986	10.622	30.278	1.524	43.485	8.244	90.467	91.321
2010	17.888	11.672	30.213	1.675	39.298	12.331	86.668	81.568
2011	15.298	11.217	30.131	1.730	36.196	13.775	81.672	66.947
2012	13.745	10.685	28.653	1.730	34.527	9.435	79.393	60.801
2013	13.146	9.835	24.669	1.382	33.193	5.474	76.729	61.954

Table 7(4). 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 2013-2022. Parameter estimates with scenario 4 are used for the projection.

			No Directed Fishery			
Year	MMB	95% LCI	95% UCI	Catch	95% LCI	95% UCI
2013	31.321	28.507	33.978	0.000	0.000	0.000
2014	34.110	31.046	37.004	0.000	0.000	0.000
2015	36.059	32.819	39.118	0.000	0.000	0.000
2016	36.747	33.489	40.040	0.000	0.000	0.000
2017	38.754	33.583	48.693	0.000	0.000	0.000
2018	42.600	33.300	62.014	0.000	0.000	0.000
2019	47.017	32.882	72.705	0.000	0.000	0.000
2020	51.241	33.377	80.642	0.000	0.000	0.000
2021	55.053	33.750	86.096	0.000	0.000	0.000
2022	58.479	34.458	90.913	0.000	0.000	0.000
			$F_{40\%}$			
2013	25.813	23.852	27.834	5.646	4.772	6.298
2014	24.390	22.765	26.003	4.749	4.085	5.455
2015	23.130	21.721	24.489	4.219	3.686	4.763
2016	21.582	20.233	22.961	3.717	3.280	4.175
2017	21.841	18.697	29.870	3.509	2.840	4.651
2018	23.871	17.294	38.308	3.733	2.397	5.945
2019	26.119	16.689	43.706	4.263	2.182	7.588
2020	27.876	16.674	47.663	4.801	2.092	8.671
2021	29.099	17.073	48.907	5.220	2.133	9.395
2022	29.982	17.477	50.225	5.507	2.208	9.633
			$F_{35\%}$			
2013	24.980	23.161	26.720	6.497	5.480	7.437
2014	23.203	21.735	24.578	5.169	4.480	5.850
2015	21.794	20.533	22.959	4.472	3.936	4.990
2016	20.215	18.999	21.458	3.879	3.442	4.319
2017	20.444	17.455	28.008	3.671	2.940	5.142
2018	22.361	16.100	35.855	3.963	2.459	6.596
2019	24.404	15.586	41.141	4.579	2.241	8.378
2020	25.913	15.579	44.250	5.164	2.144	9.580
2021	26.890	16.047	45.384	5.600	2.211	10.305
2022	27.569	16.445	45.759	5.867	2.301	10.605

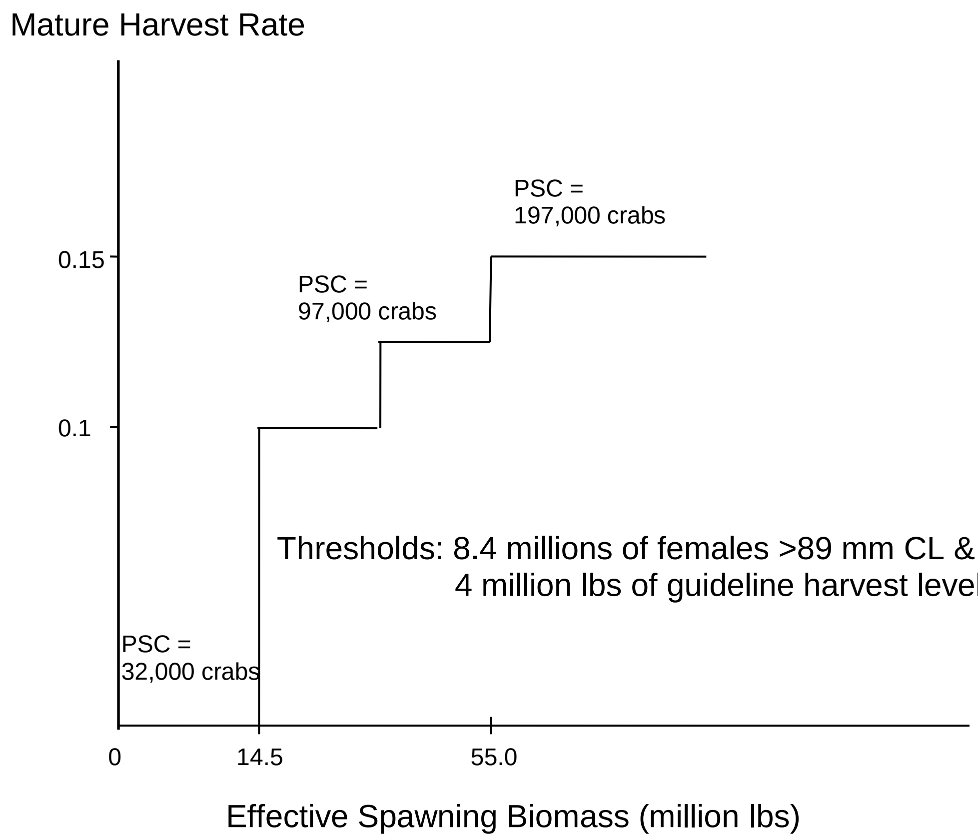


Figure 1. Current harvest rate strategy (line) for the Bristol Bay red king crab fishery and annual prohibited species catch (PSC) limits (numbers of crabs) of Bristol Bay red king crabs in the groundfish fisheries in zone 1 in the eastern Bering Sea. Harvest rates are based on current-year estimates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

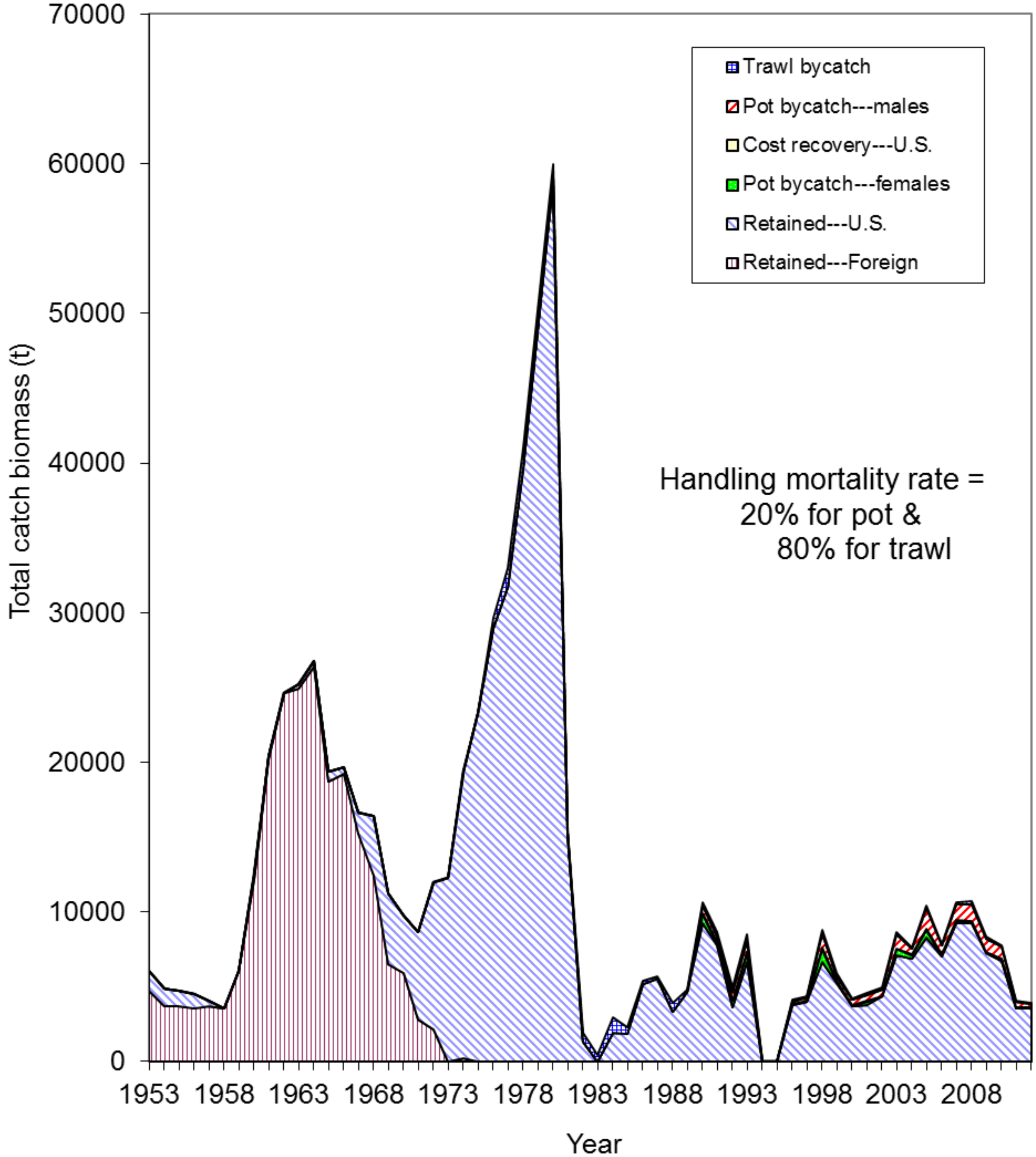


Figure 2. Retained catch biomass and bycatch mortality biomass (t) for Bristol Bay red king crab from 1953 to 2012. Handling mortality rates were assumed to be 0.2 for the directed pot fishery and 0.8 for the trawl fisheries.

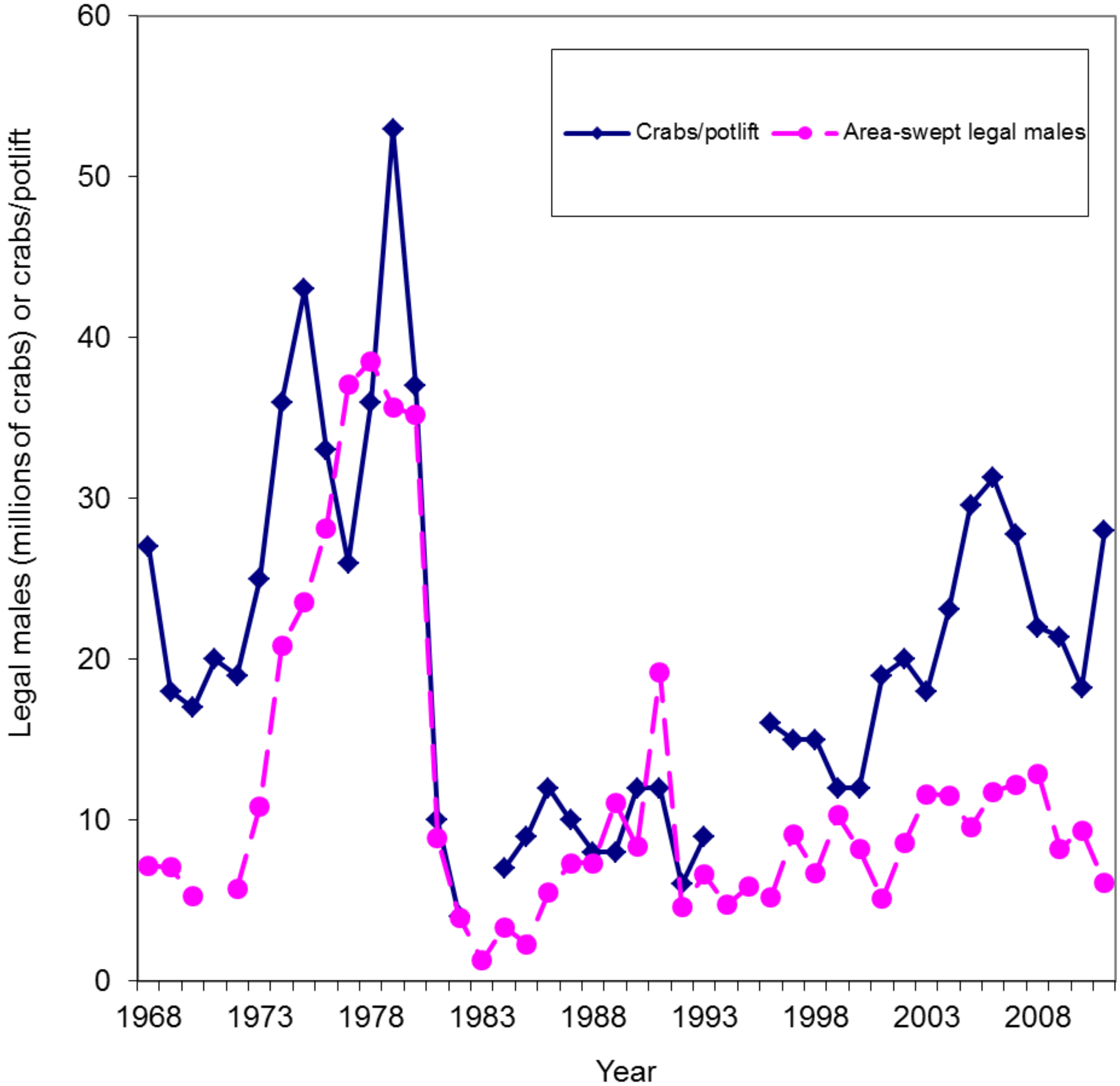


Figure 3. Comparison of survey legal male abundances and catches per unit effort for Bristol Bay red king crab from 1968 to 2011.

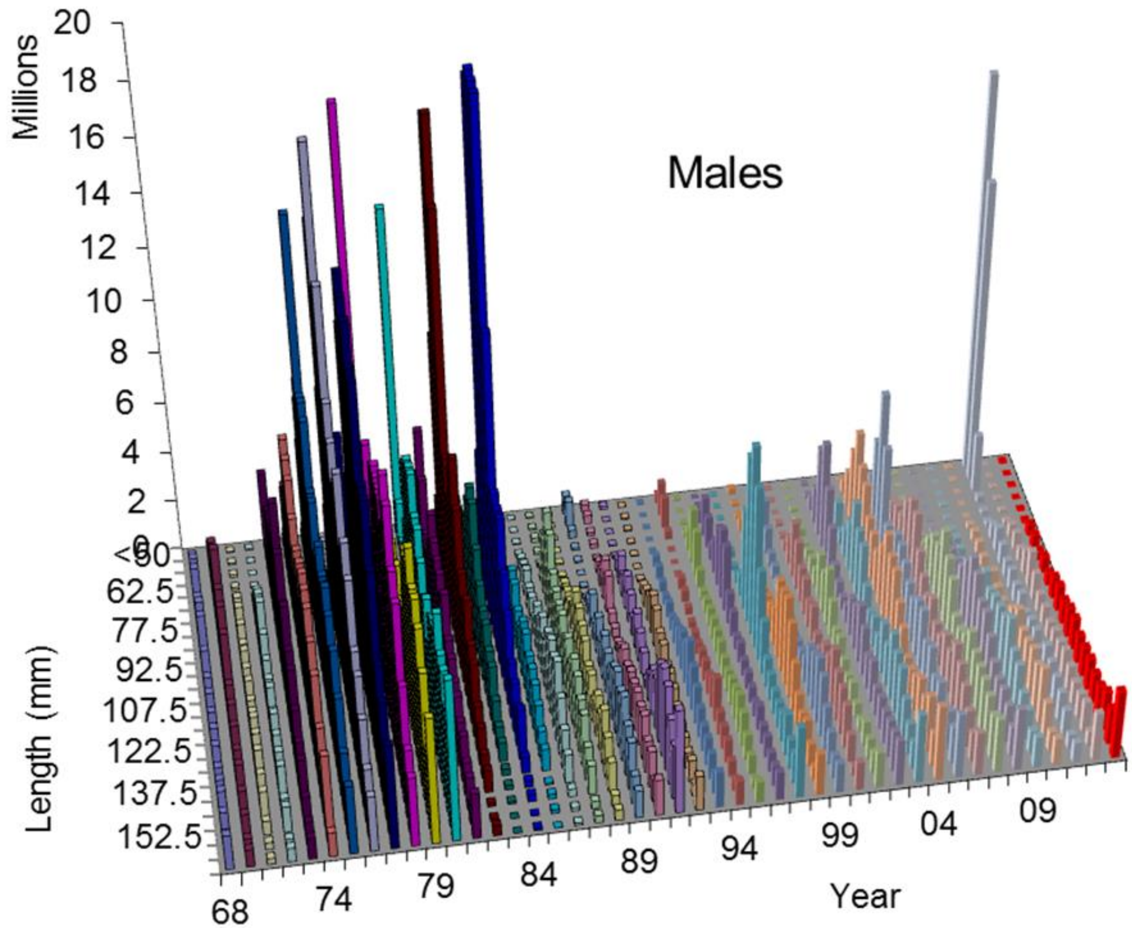


Figure 4. Survey abundances by 5-mm carapace length bin for male Bristol Bay red king crabs from 1968 to 2013.

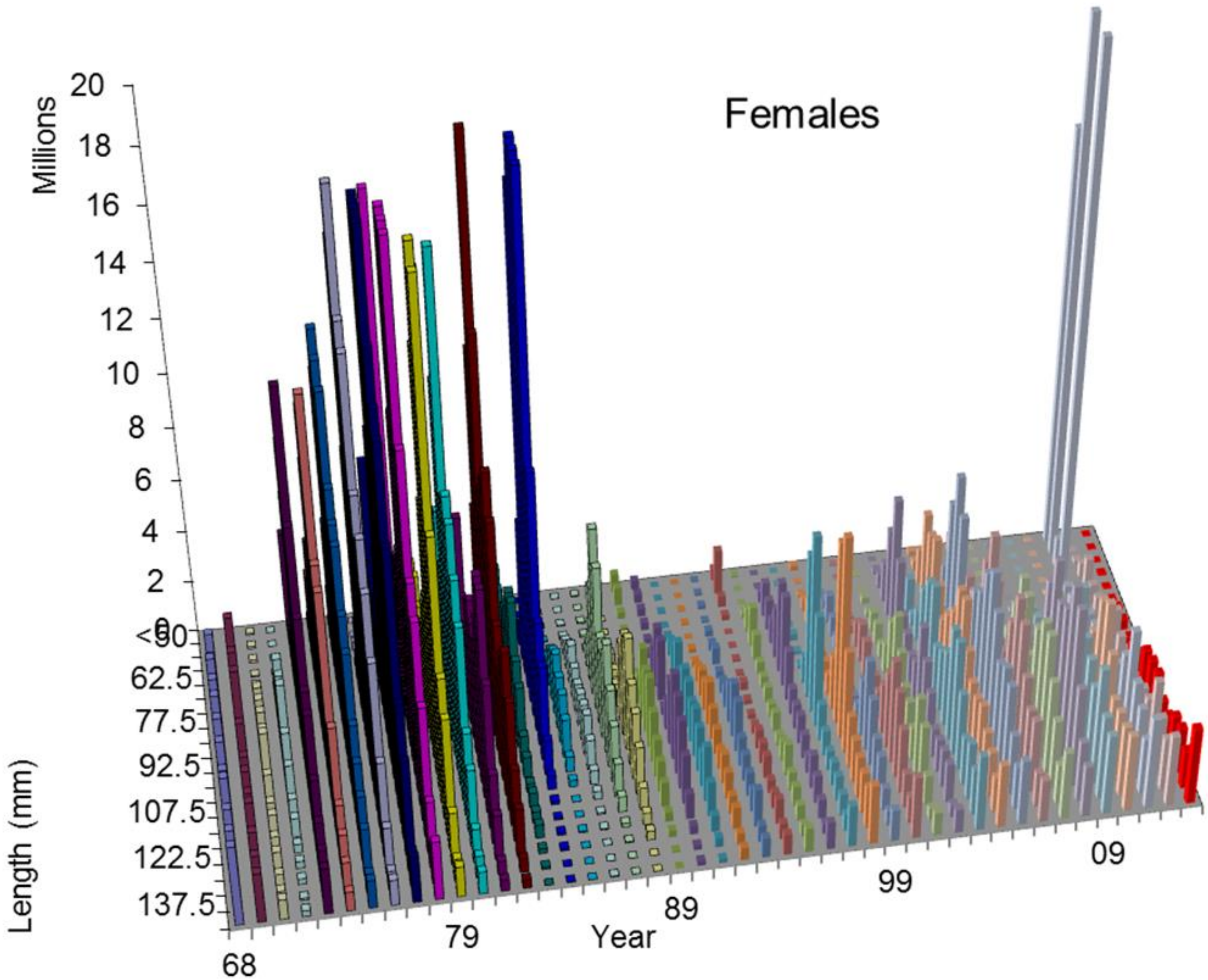


Figure 5. Survey abundances by 5 mm. carapace length bin for female Bristol Bay red king crabs from 1968 to 2013.

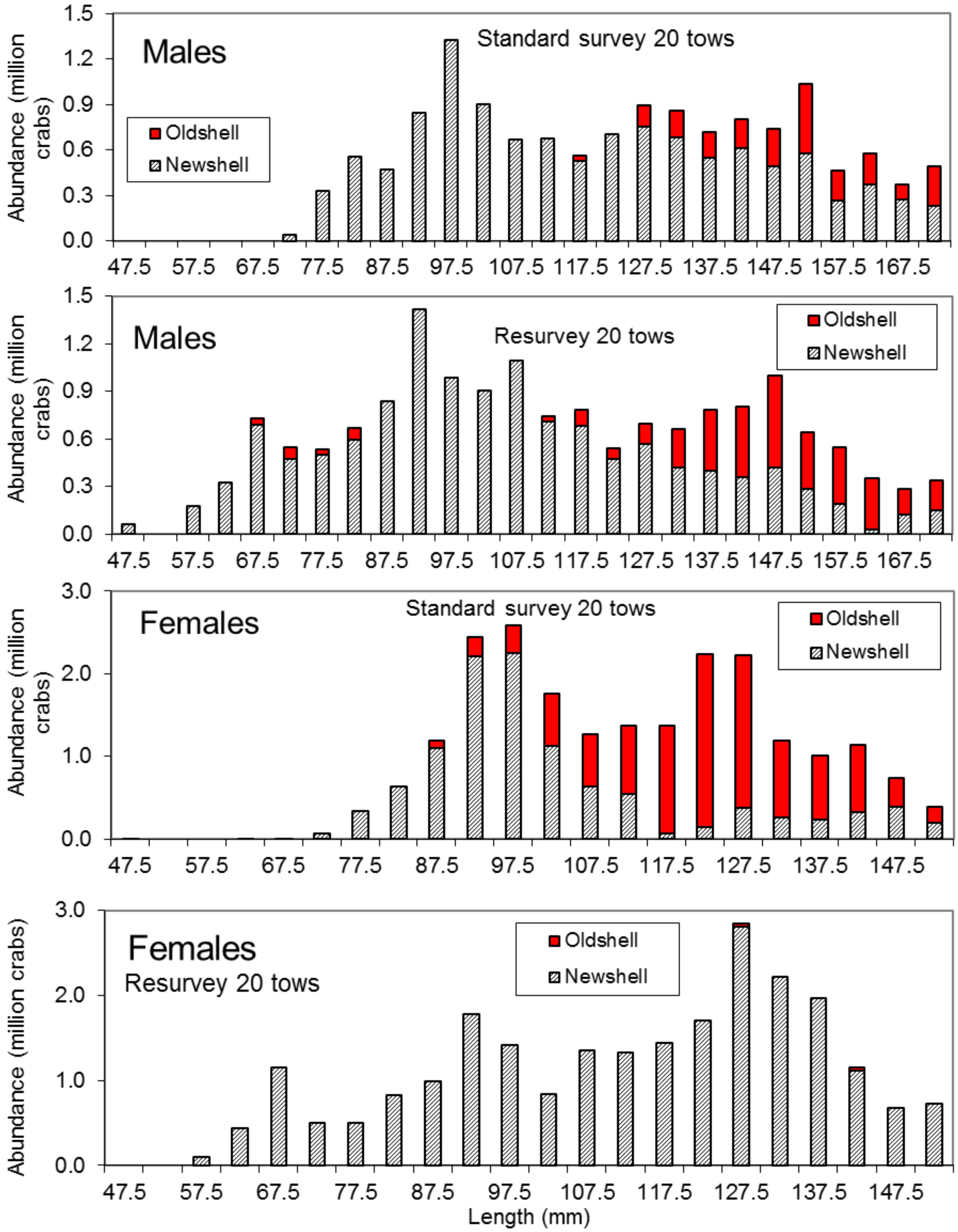


Figure 6. Comparison of area-swept estimates of abundance in 20 stations from the standard trawl survey and resurvey in 2012.

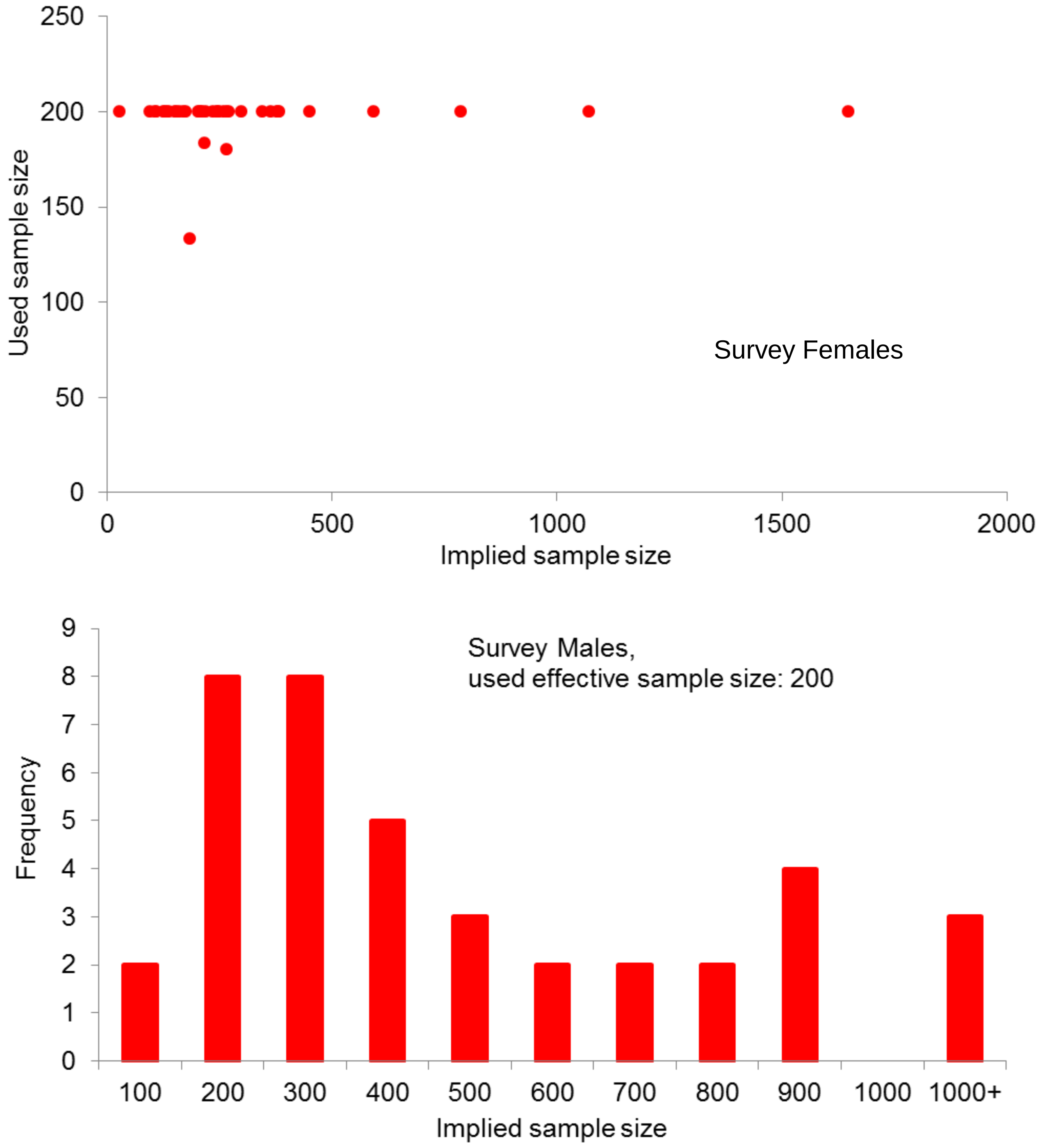


Figure 7b(4). Relationship between implied effective sample sizes (section 3(a)(5)(i)) and used effective sample sizes (see effective sample sizes for scenario 4) for length/sex composition data with scenario 4: trawl survey data.

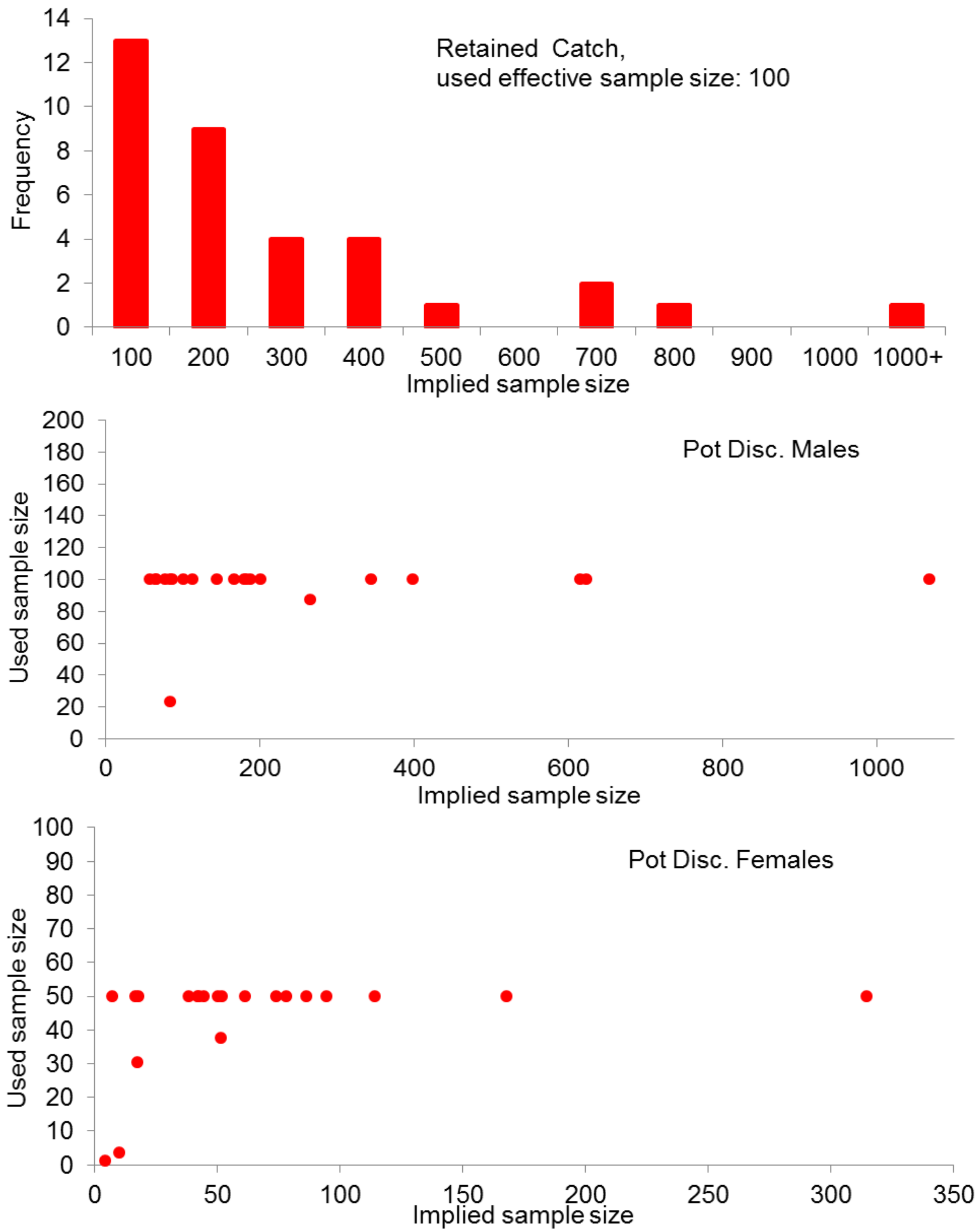


Figure 7b(4). Relationship between implied effective sample sizes (section 3(a)(5)(i)) and used effective sample sizes (see effective sample sizes for scenario 4) for length/sex composition data with scenario 4: directed pot fishery data.

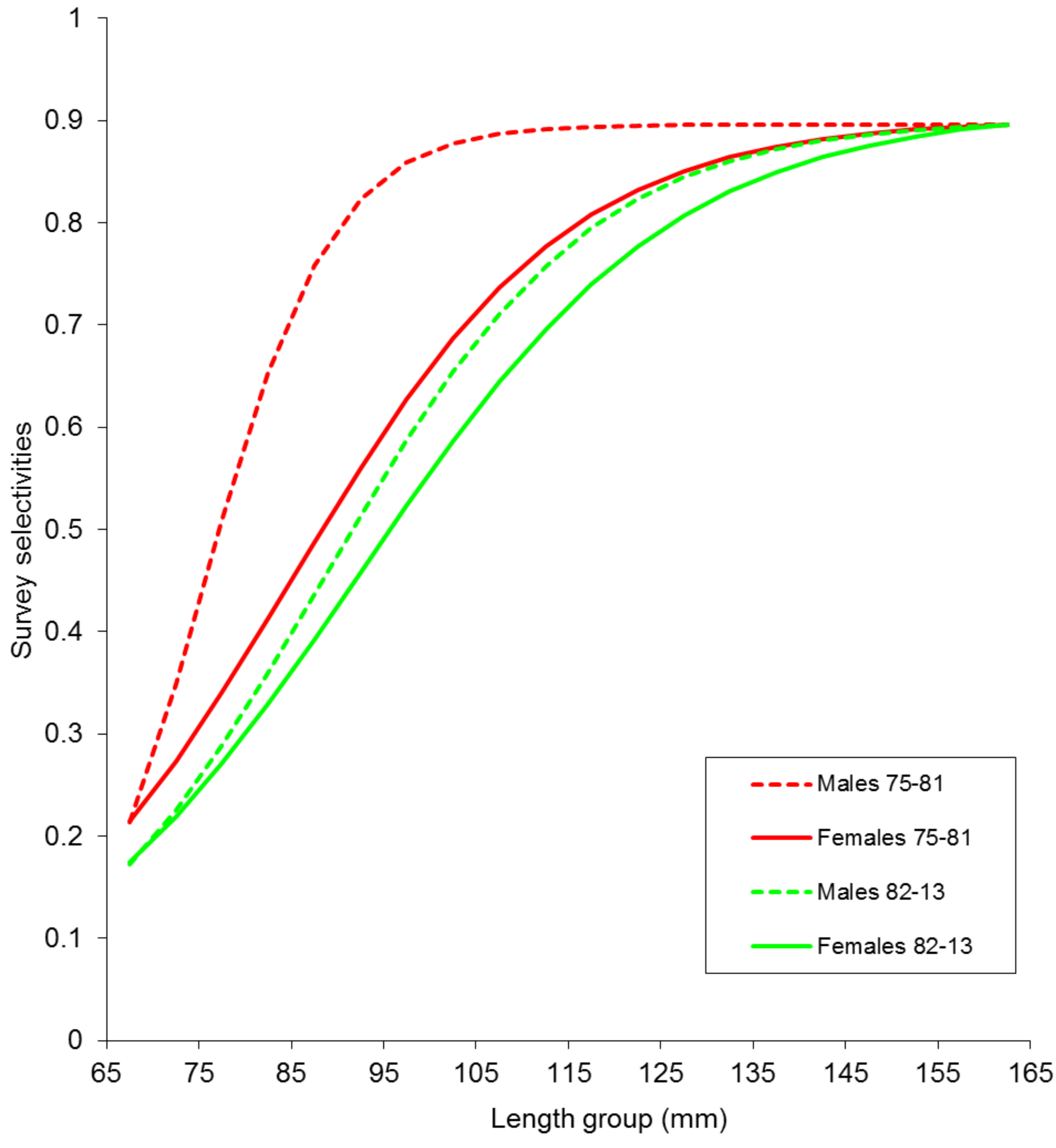


Figure 8a(4). Estimated trawl survey selectivities under scenario 4. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

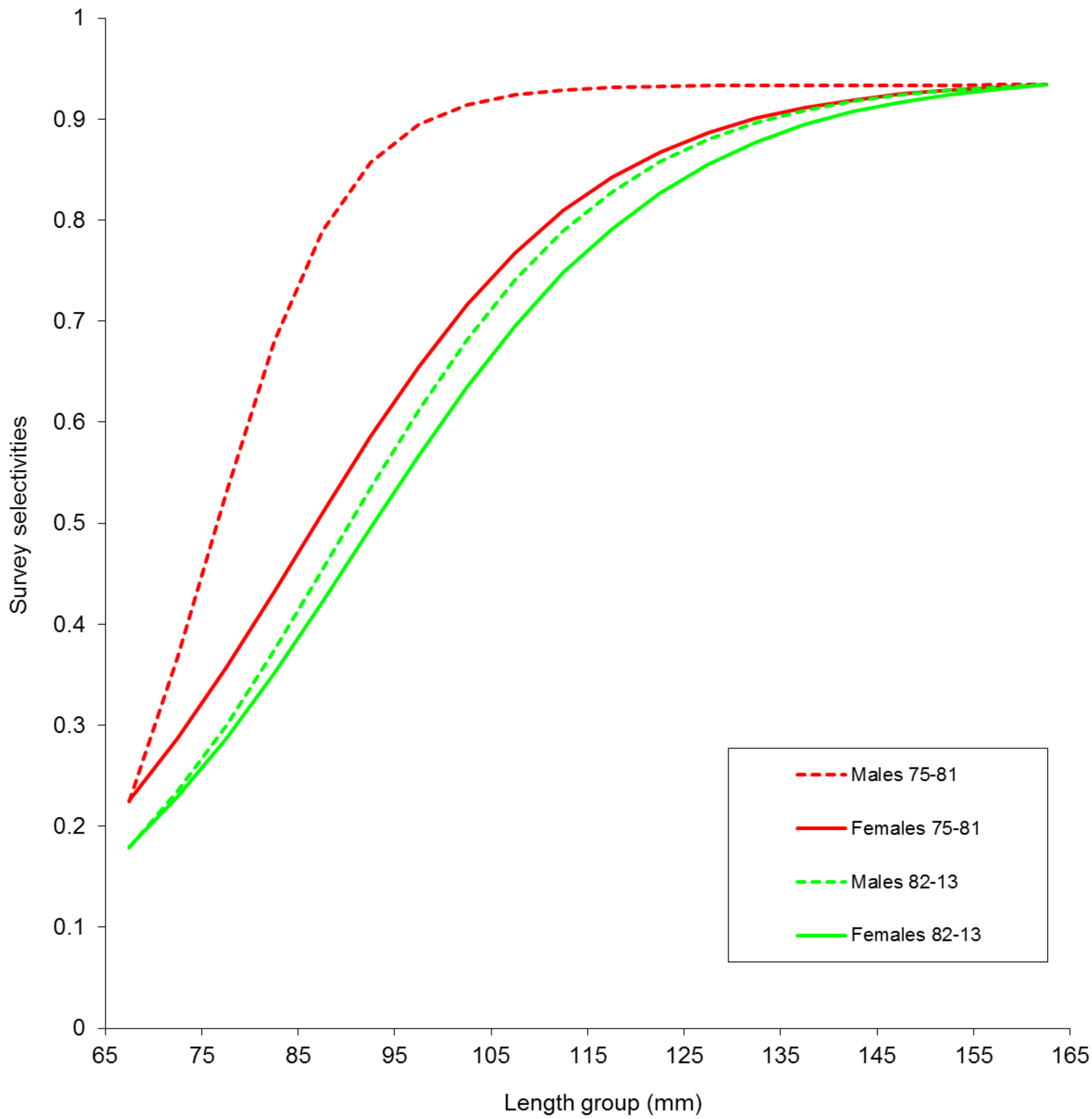
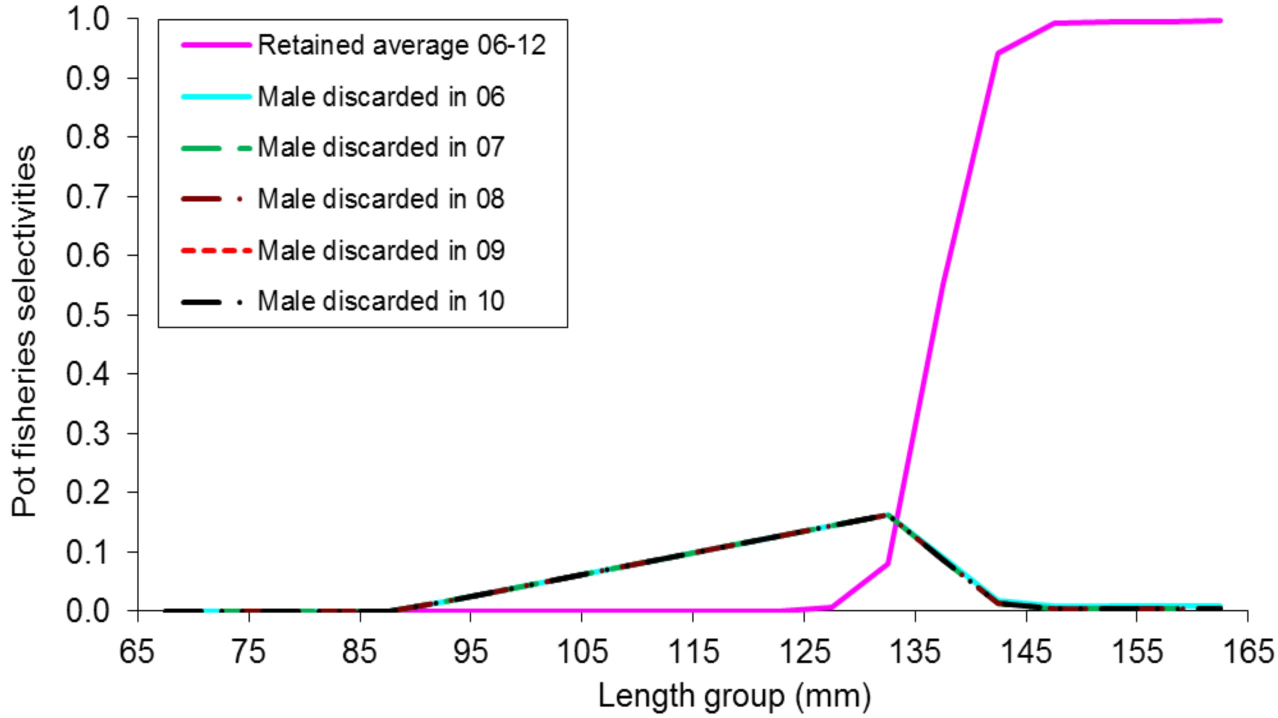


Figure 8a(4nb). Estimated trawl survey selectivities under scenario 4nb. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.



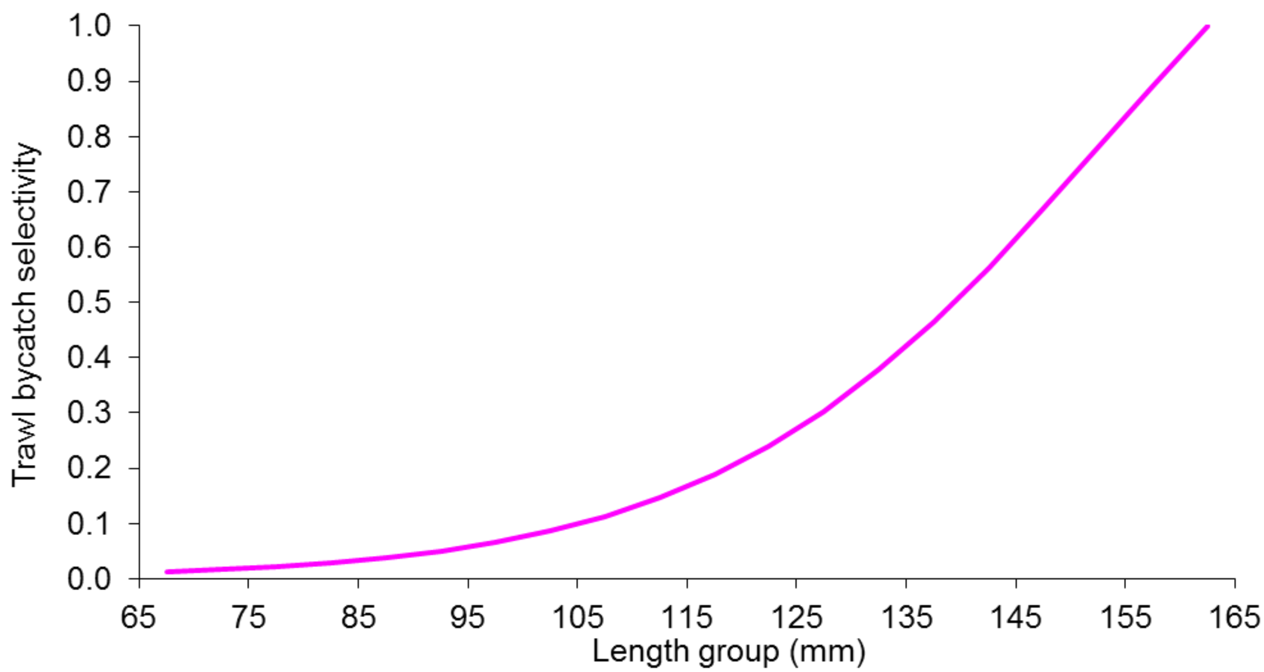


Figure 8b. Estimated pot fishery selectivities and groundfish trawl bycatch selectivities under scenario 4nb. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

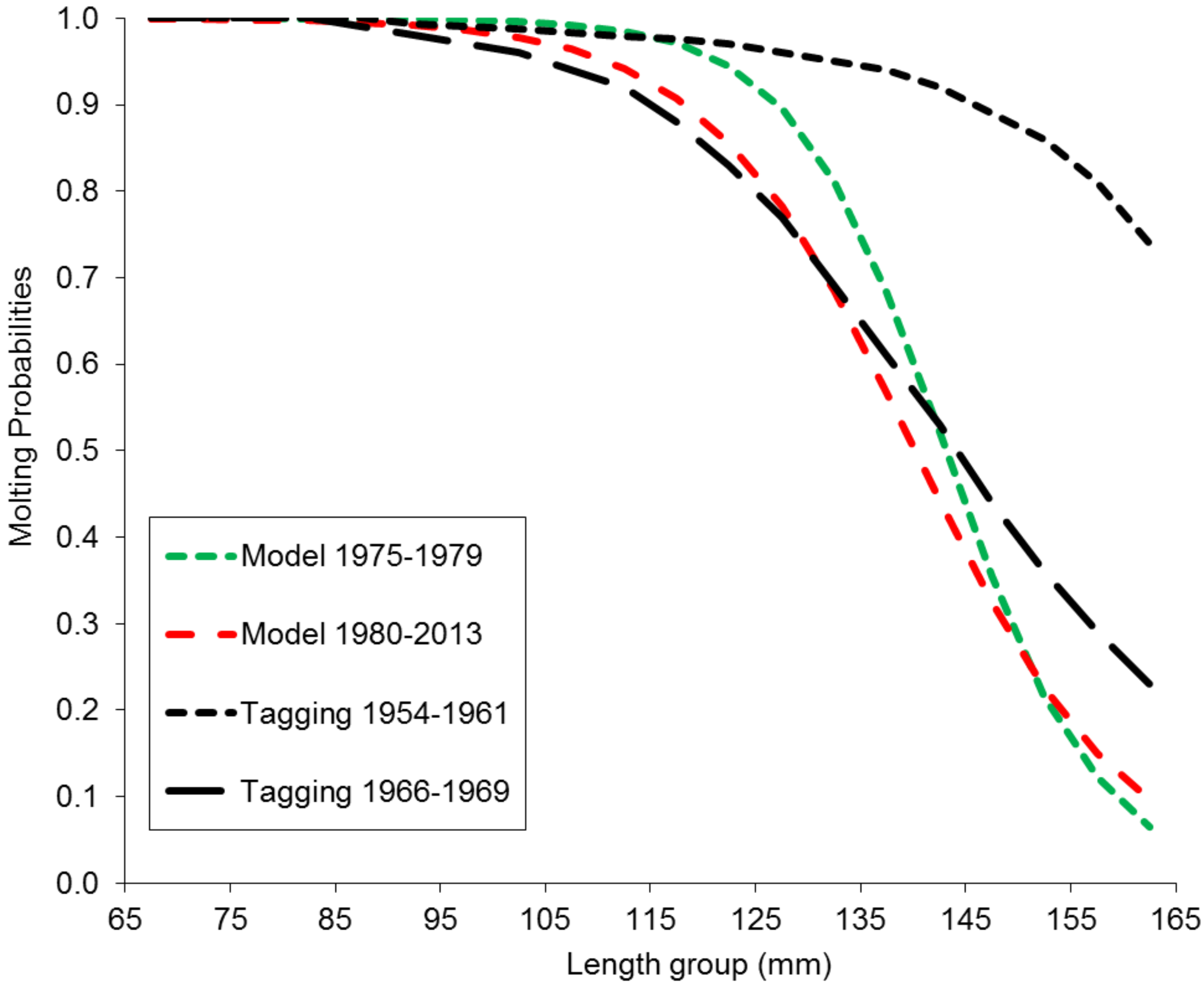


Figure 9(4). Comparison of estimated probabilities of molting of male red king crabs in Bristol Bay for different periods. Molting probabilities for periods 1954-1961 and 1966-1969 were estimated by Balsiger (1974) from tagging data. Molting probabilities for 1975-2013 were estimated with a length-based model with a pot handling mortality rate of 0.2 under scenario 4.

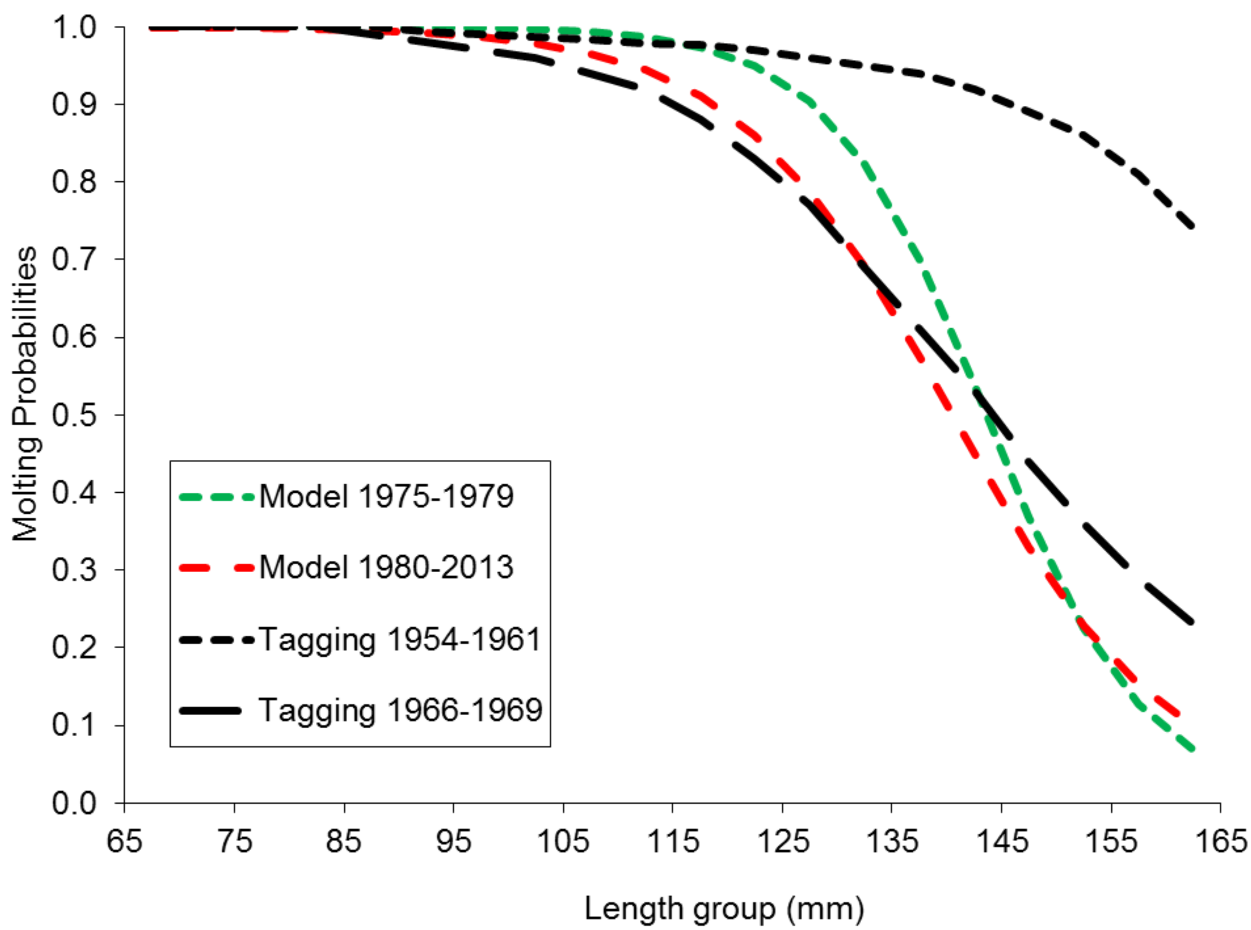


Figure 9(4nb). Comparison of estimated probabilities of molting of male red king crabs in Bristol Bay for different periods. Molting probabilities for periods 1954-1961 and 1966-1969 were estimated by Balsiger (1974) from tagging data. Molting probabilities for 1975-2013 were estimated with a length-based model with pot handling mortality rate to be 0.2 under scenario 4nb.

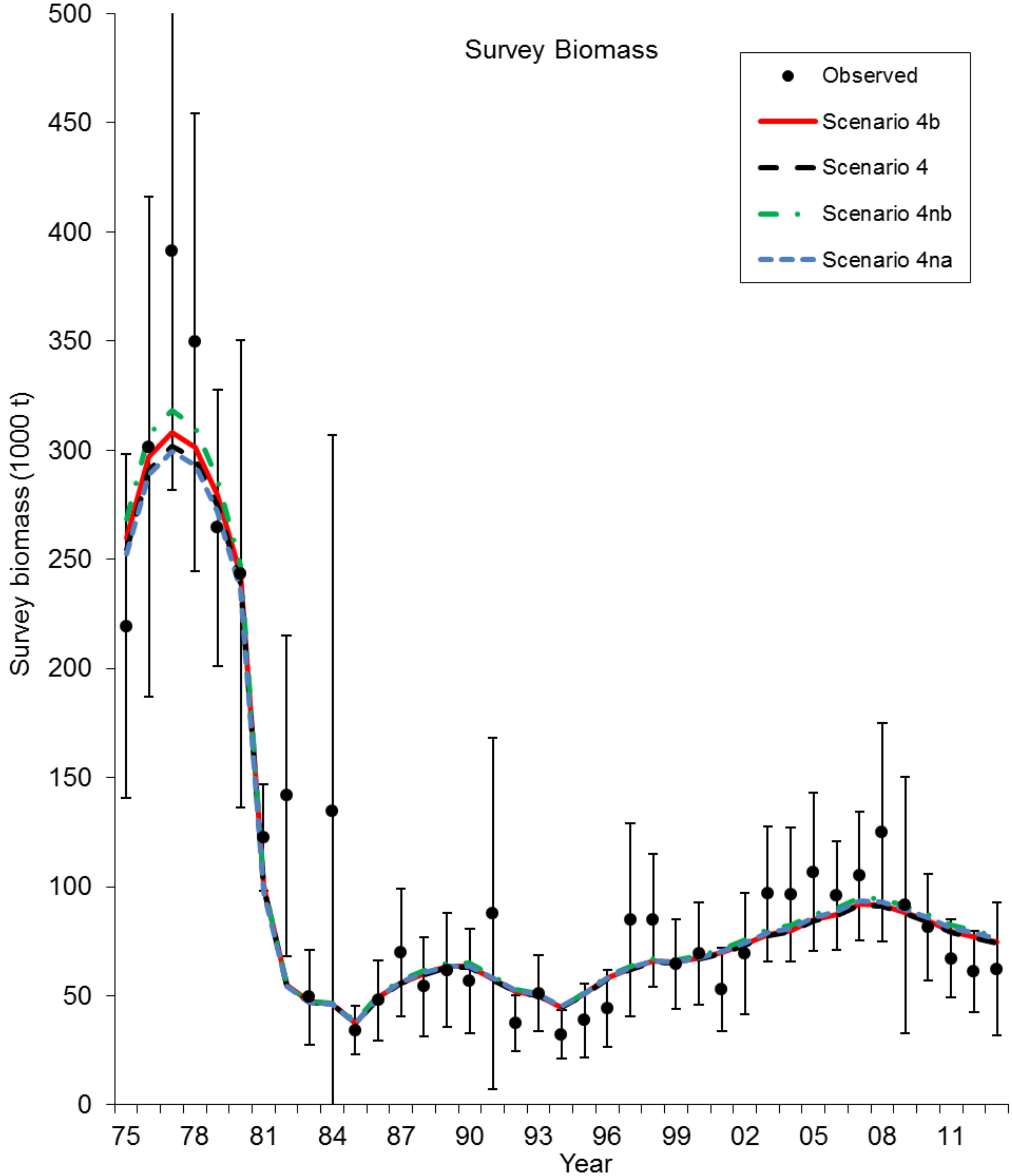


Figure 10a(4). Comparisons of area-swept estimates of total survey biomass and model prediction for model estimates in 2013 under scenarios 4, 4b, 4na and 4nb. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively. The error bars are plus and minus 2 standard deviations. Note that scenarios 4nb and 4na do not fit to these data.

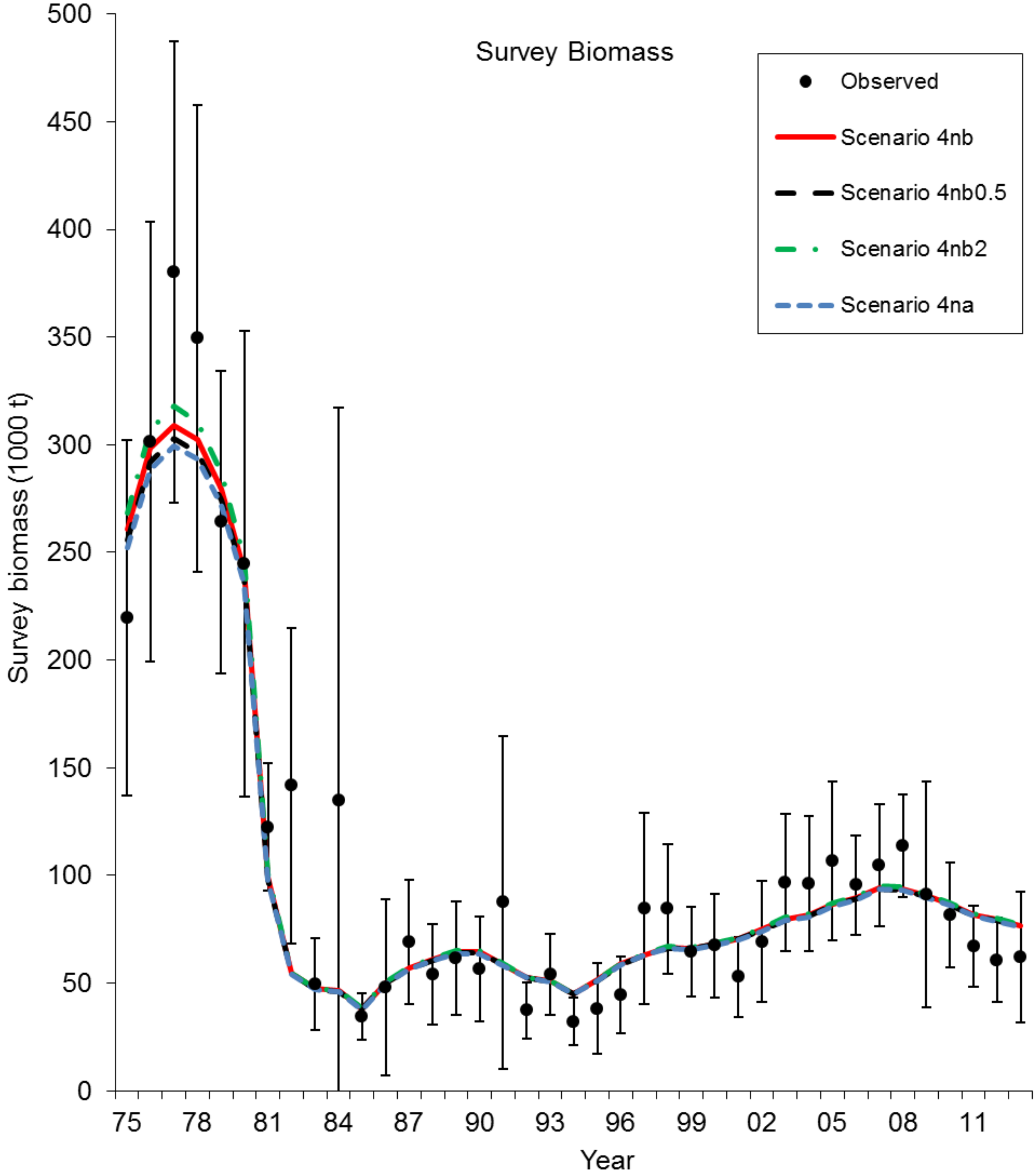


Figure 10a(4nb). Comparisons of area-swept estimates of total survey biomass and model prediction for model estimates in 2013 under scenarios 4nb, 4nb0.5, 4nb2 and 4na. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively. The error bars are plus and minus 2 standard deviations.

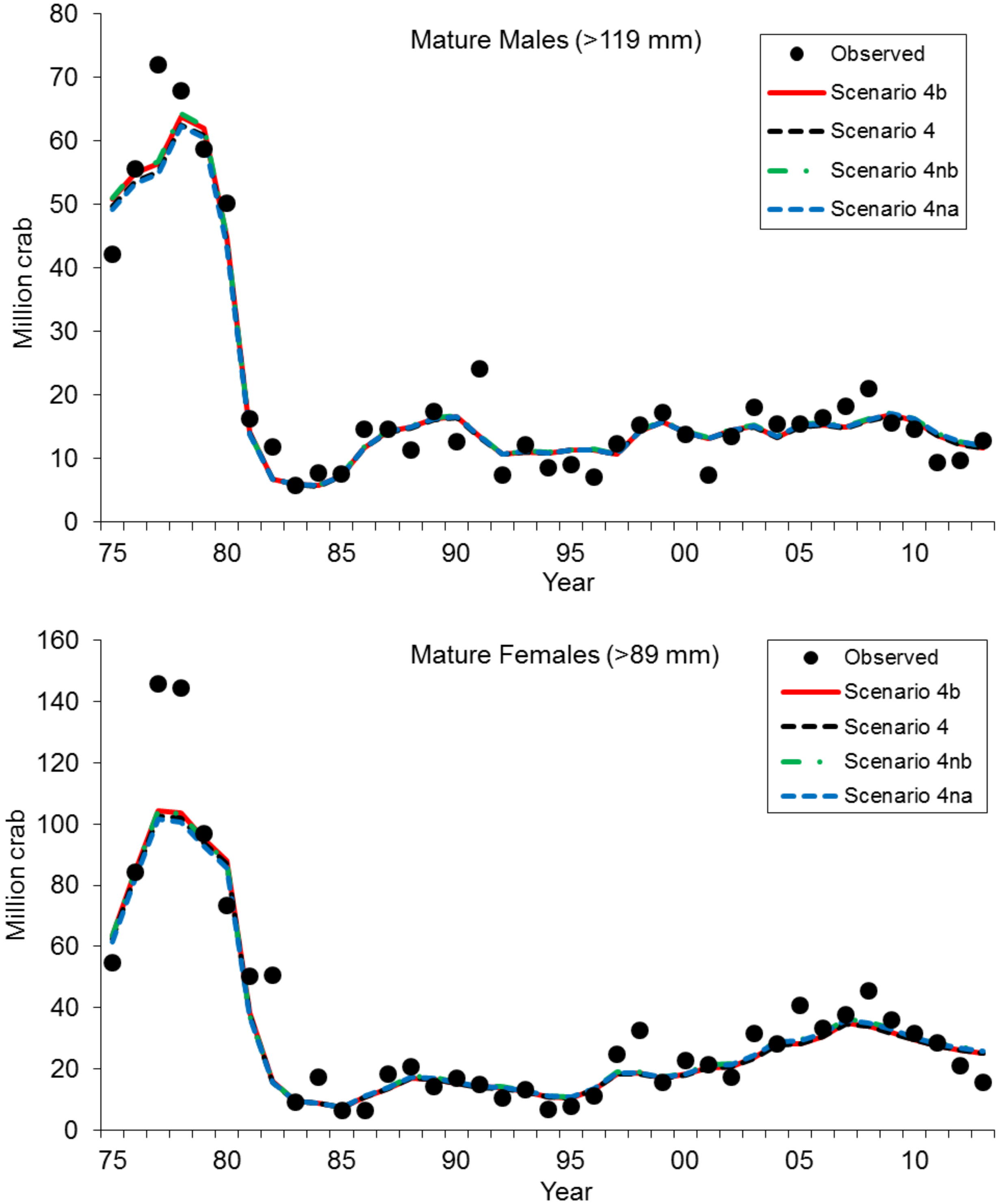


Figure 10b(4). Comparisons of area-swept estimates of mature male (>119 mm) and female (>89 mm) abundance and model prediction for model estimates in 2013 under scenarios 4, 4b, 4na and 4nb. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively. Note that scenarios 4nb and 4na do not fit to these data.

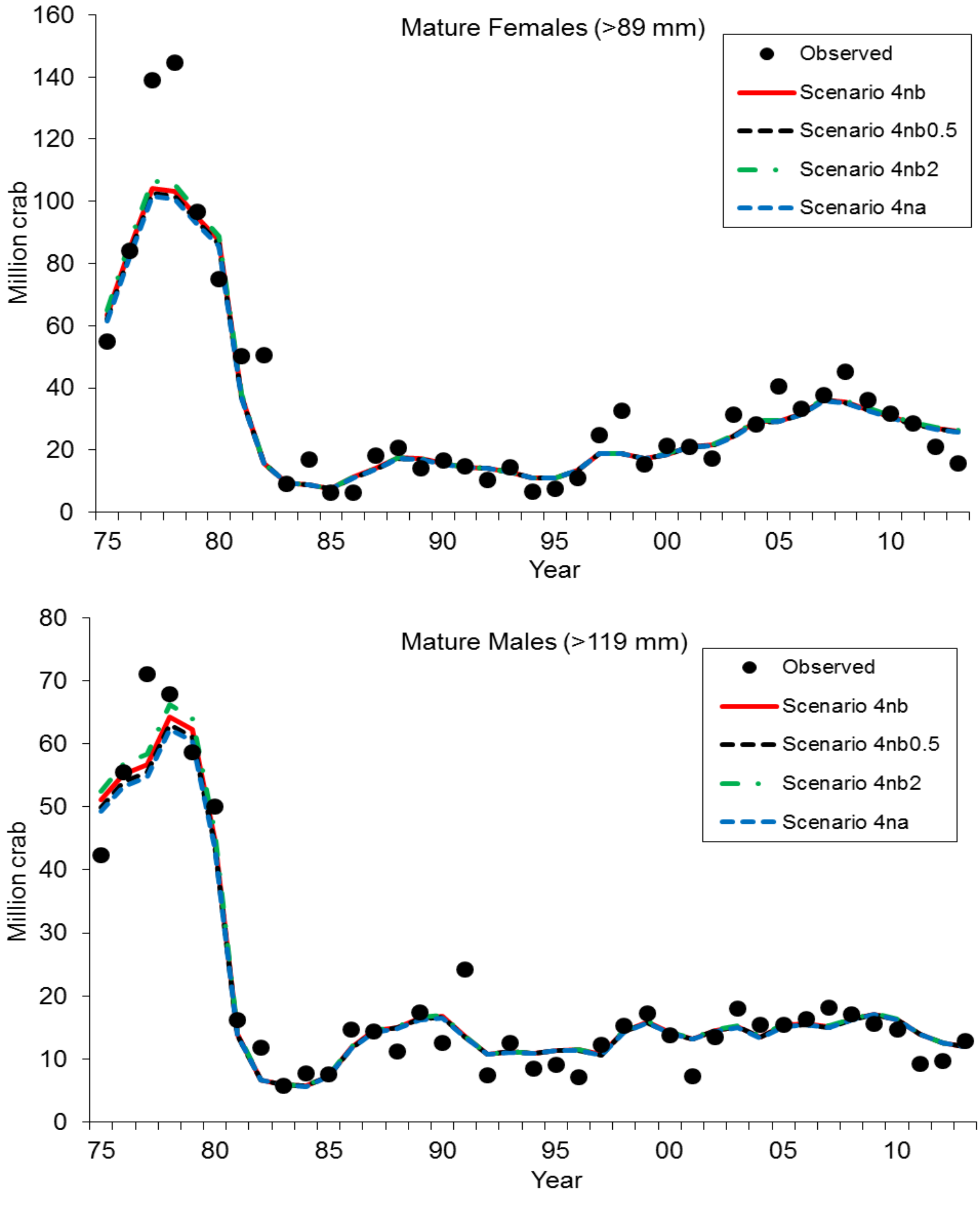


Figure 10b(4nb). Comparisons of area-swept estimates of mature male (>119 mm) and female (>89 mm) abundance and model prediction for model estimates in 2013 under scenarios 4nb, 4nb0.5, 4nb2 and 4na. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

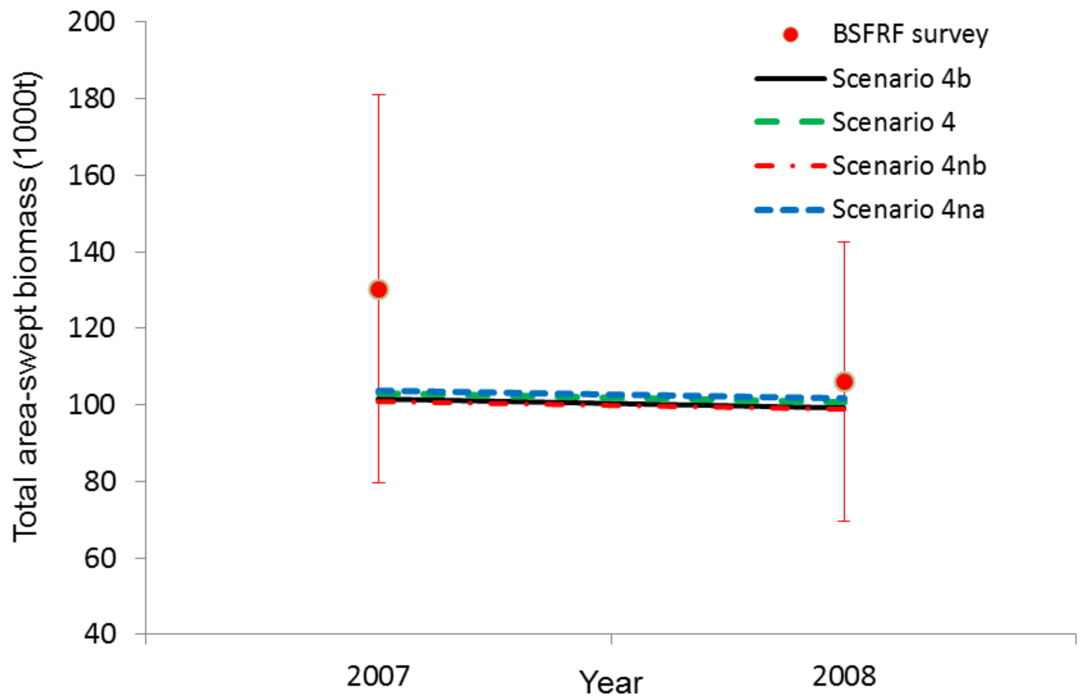


Figure 10c(4). Comparisons of total survey biomass estimates by the BSFRF survey and the model for model estimates in 2013 (scenarios 4, 4b, 4nb and 4na). The error bars are plus and minus 2 standard deviations.

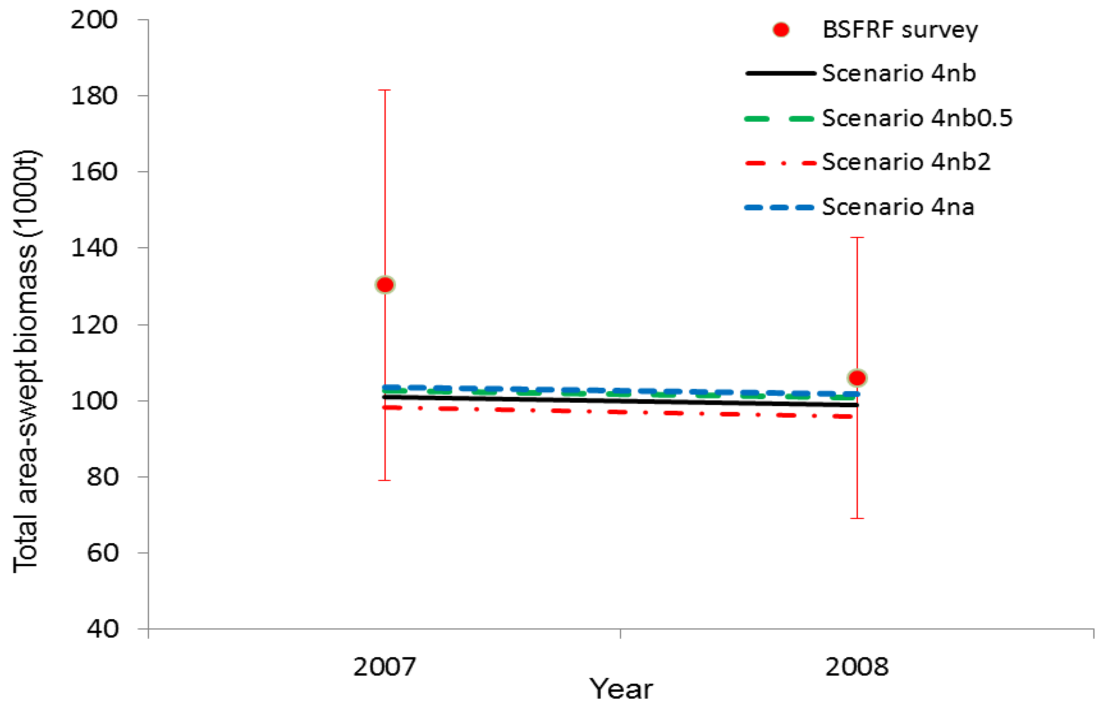


Figure 10c(4nb). Comparisons of total mature male abundance estimates by the BSFRF survey and the model for model estimates in 2013 (scenarios 4nb, 4nb0.5, 4nb2 and 4na). The error bars are plus and minus 2 standard deviations.

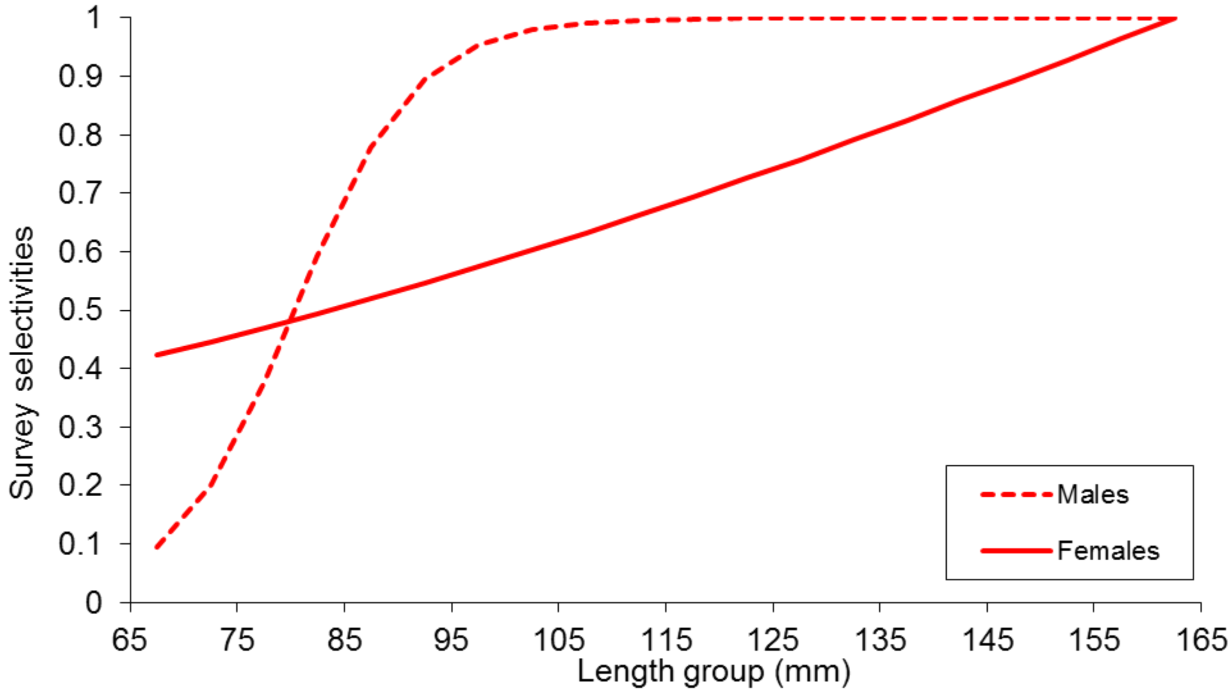


Figure 10d(4). Estimated BSFRF survey selectivities with scenario 4. The catchability is assumed to be 1.0.

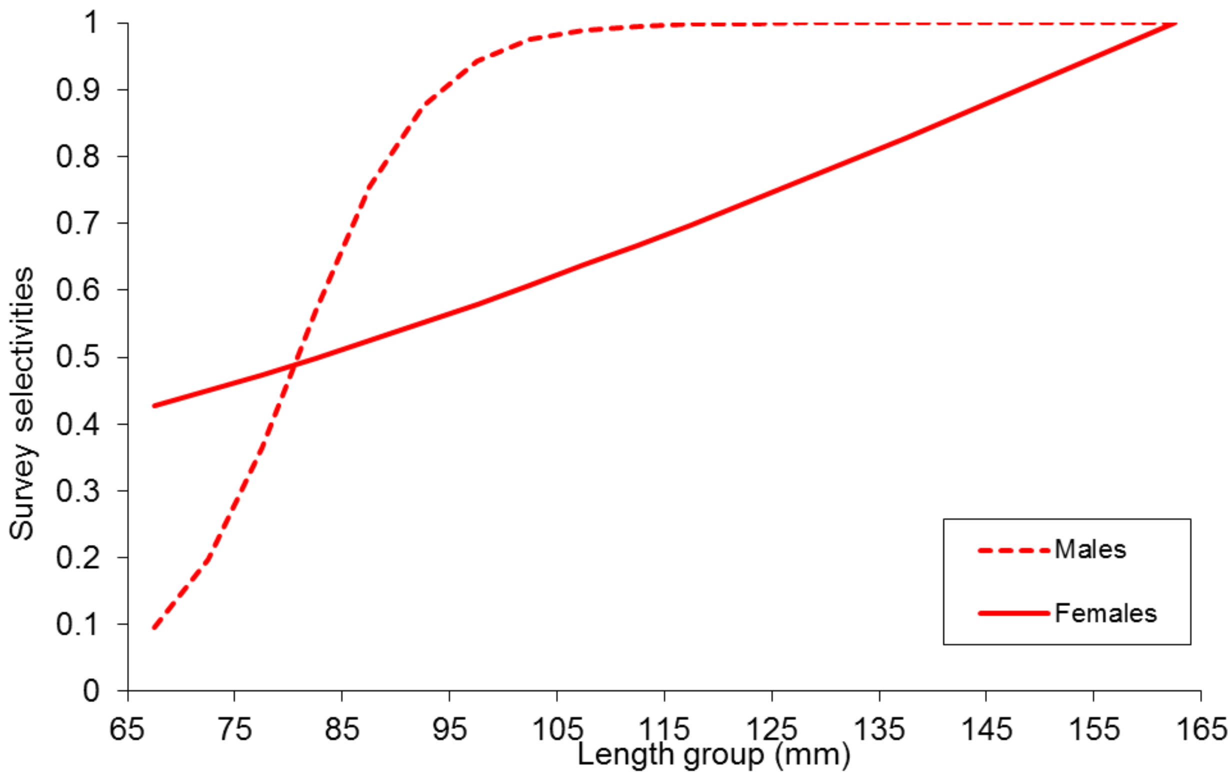


Figure 10d(4nb). Estimated BSFRF survey selectivities with scenario 4nb. The catchability is assumed to be 1.0.

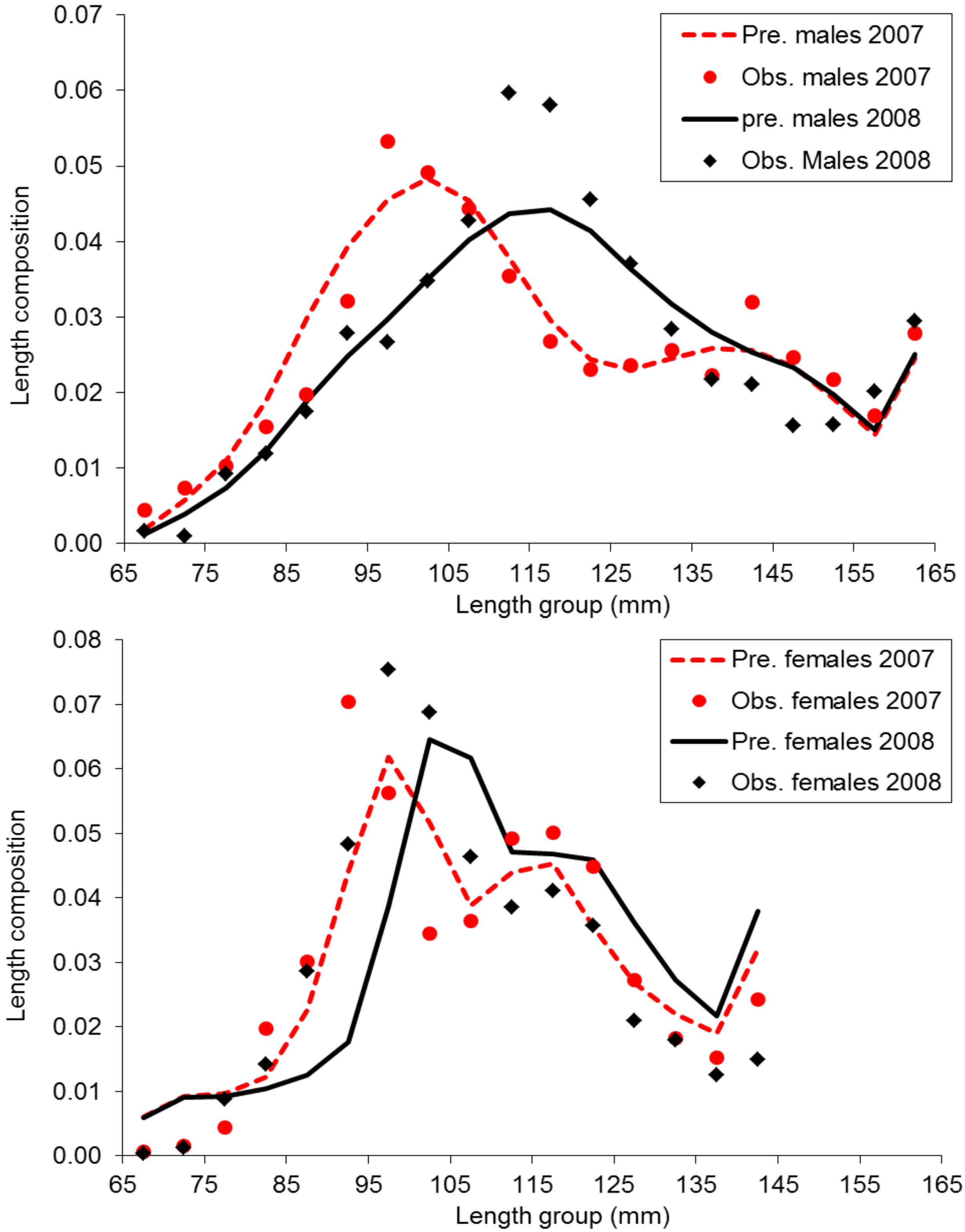


Figure 10e(4). Comparisons of length compositions by the BSFRF survey and the model estimates in 2007 and 2008 with scenario 4.

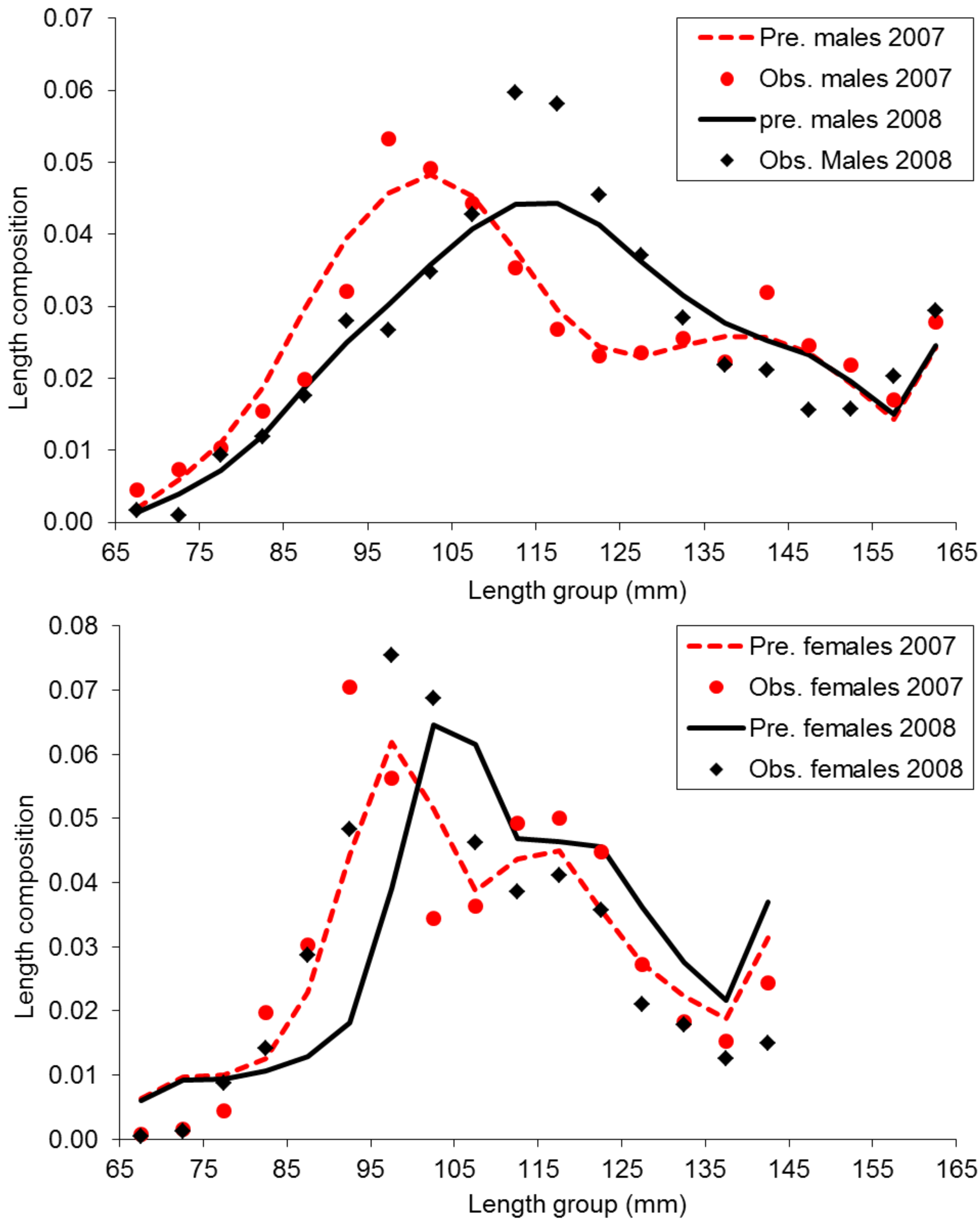


Figure 10e(4nb). Comparisons of length compositions by the BSFRF survey and the model estimates in 2007 and 2008 with scenario 4nb.

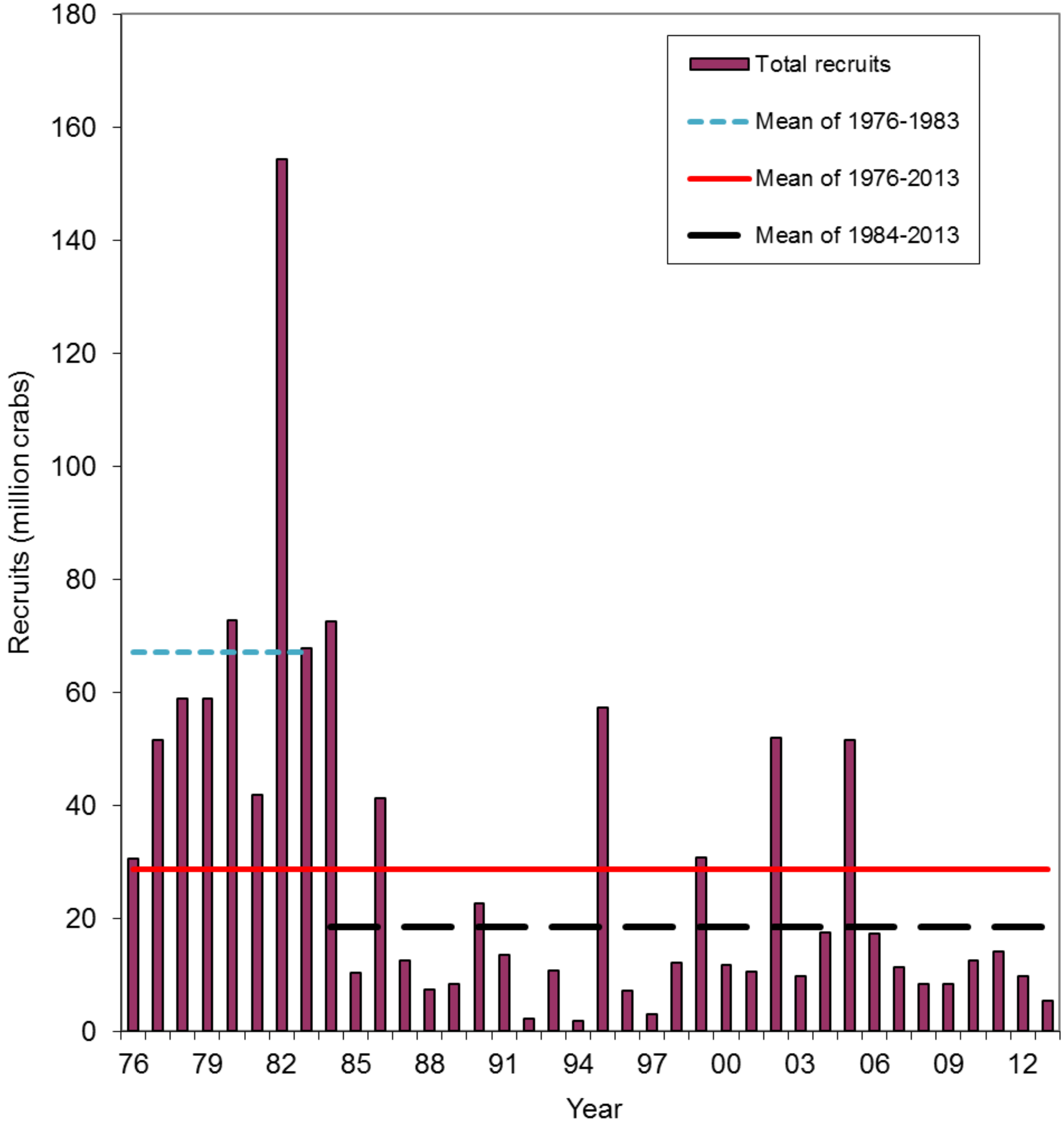


Figure 11(4). Estimated recruitment time series during 1976-2013 (occurred year) with scenario 4. Mean male recruits during 1984-2013 was used to estimate $B_{35\%}$.

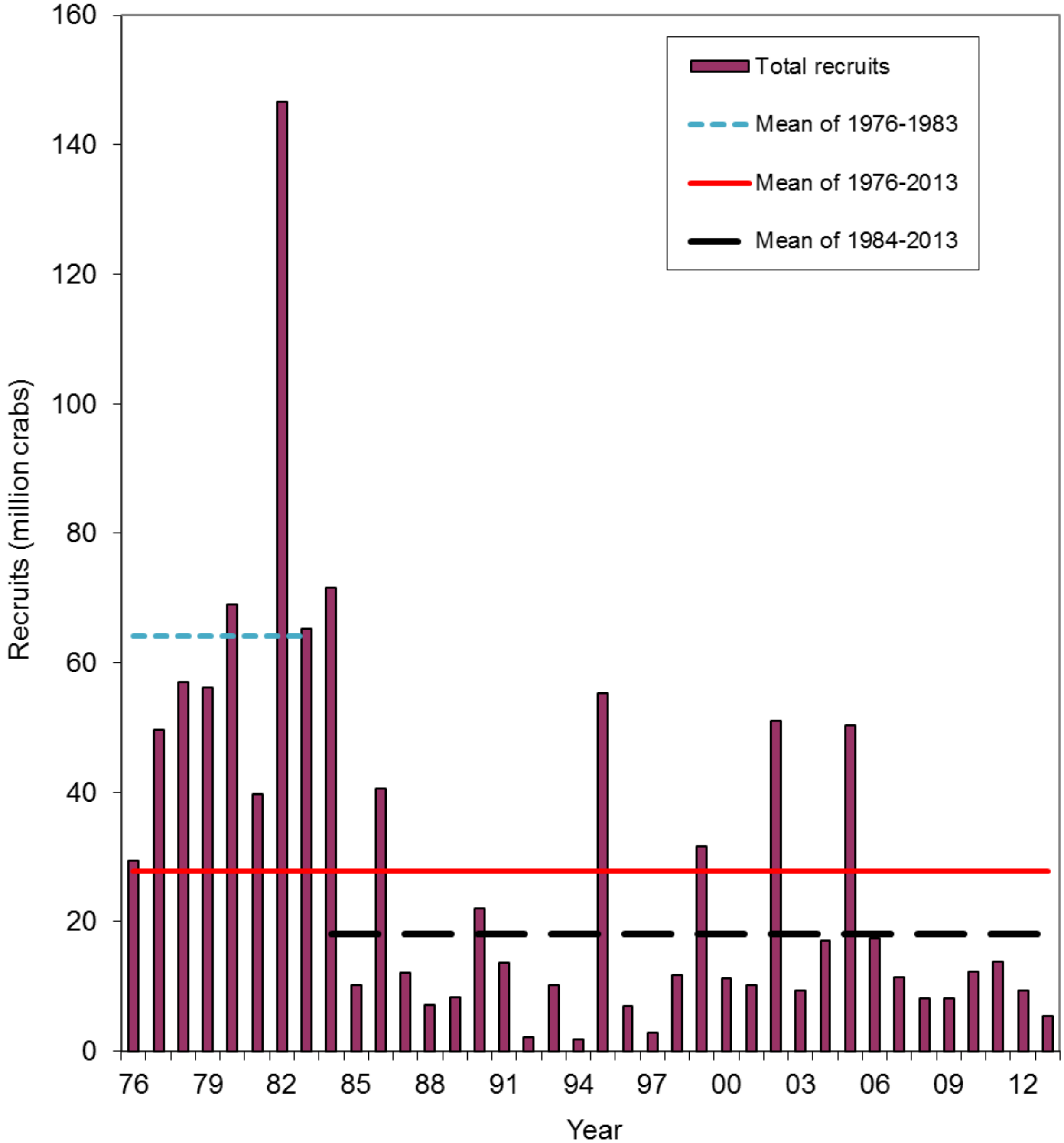


Figure 11(4nb). Estimated recruitment time series during 1976-2013 (occurred year) with scenario 4nb. Mean male recruits during 1984-2013 was used to estimate $B_{35\%}$.

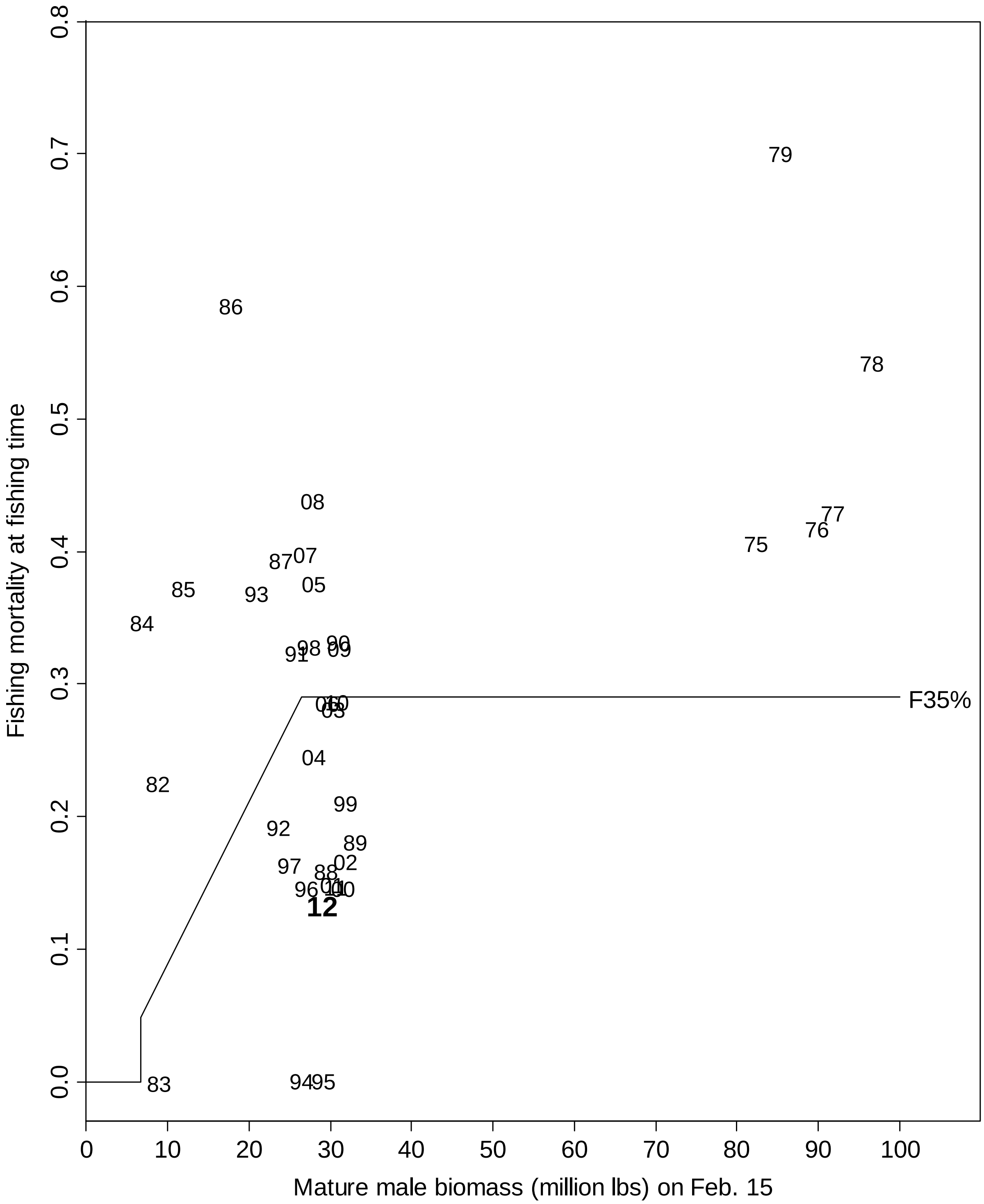


Figure 12(4). Relationships between full fishing mortalities for the directed pot fishery and mature male biomass on Feb. 15 during 1975-2012 under scenario 4. Average of recruitment from 1984 to 2013 was used to estimate B_{MSY}. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

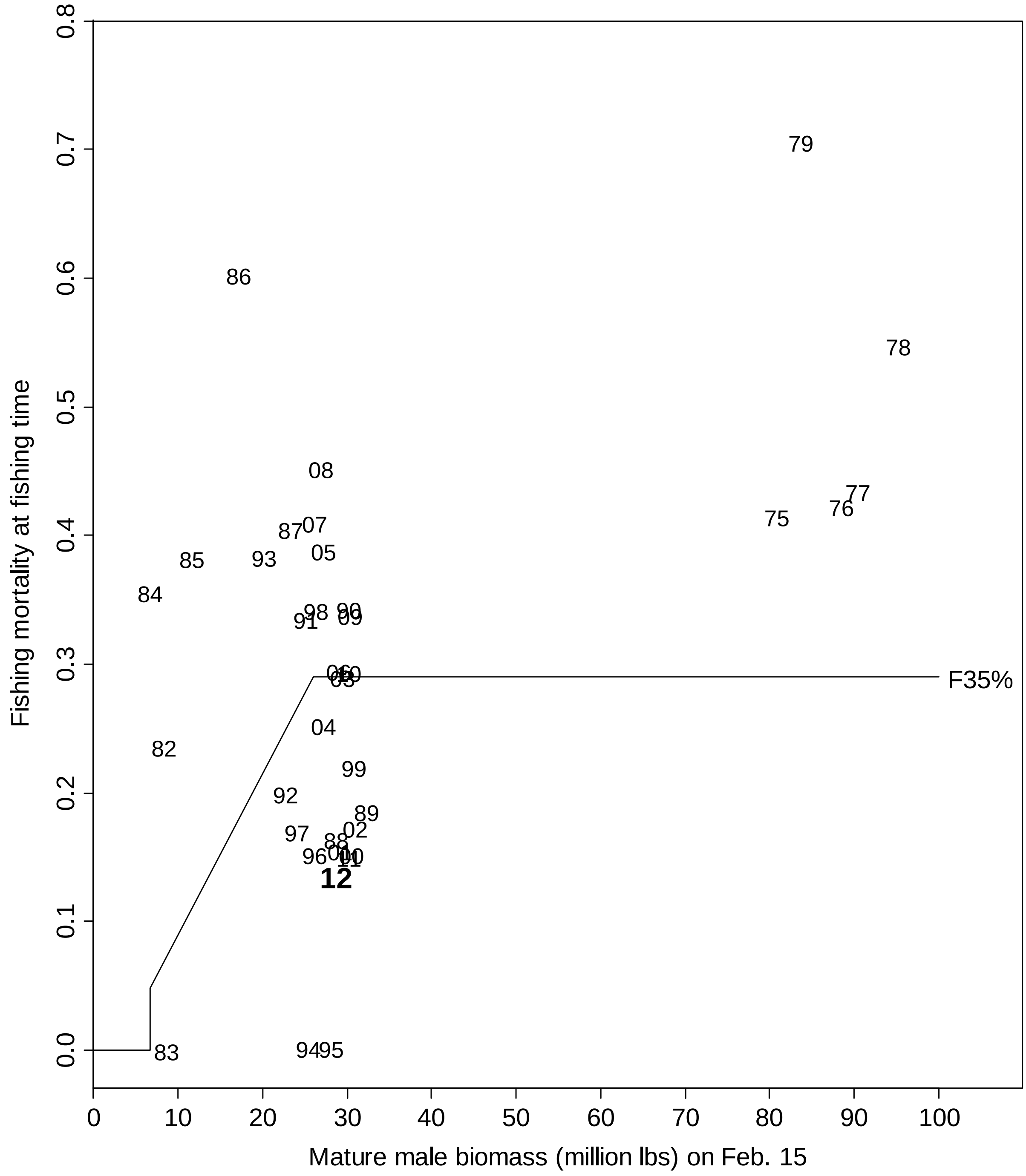


Figure 12(4nb). Relationships between full fishing mortalities for the directed pot fishery and mature male biomass on Feb. 15 during 1975-2012 under scenario 4nb. Average of recruitment from 1984 to 2013 was used to estimate B_{MSY}. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

(Figure 13a is not updated for this report)

Figure 13a. 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 to be 0.2 under scenario 4nb. 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 2013.

(Figure 13b is not updated for this report)

Figure 13b. 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 to be 0.2 under scenario 4nb. Numerical labels are years of mating, and the dotted line is the regression line for data of 1978-2008.

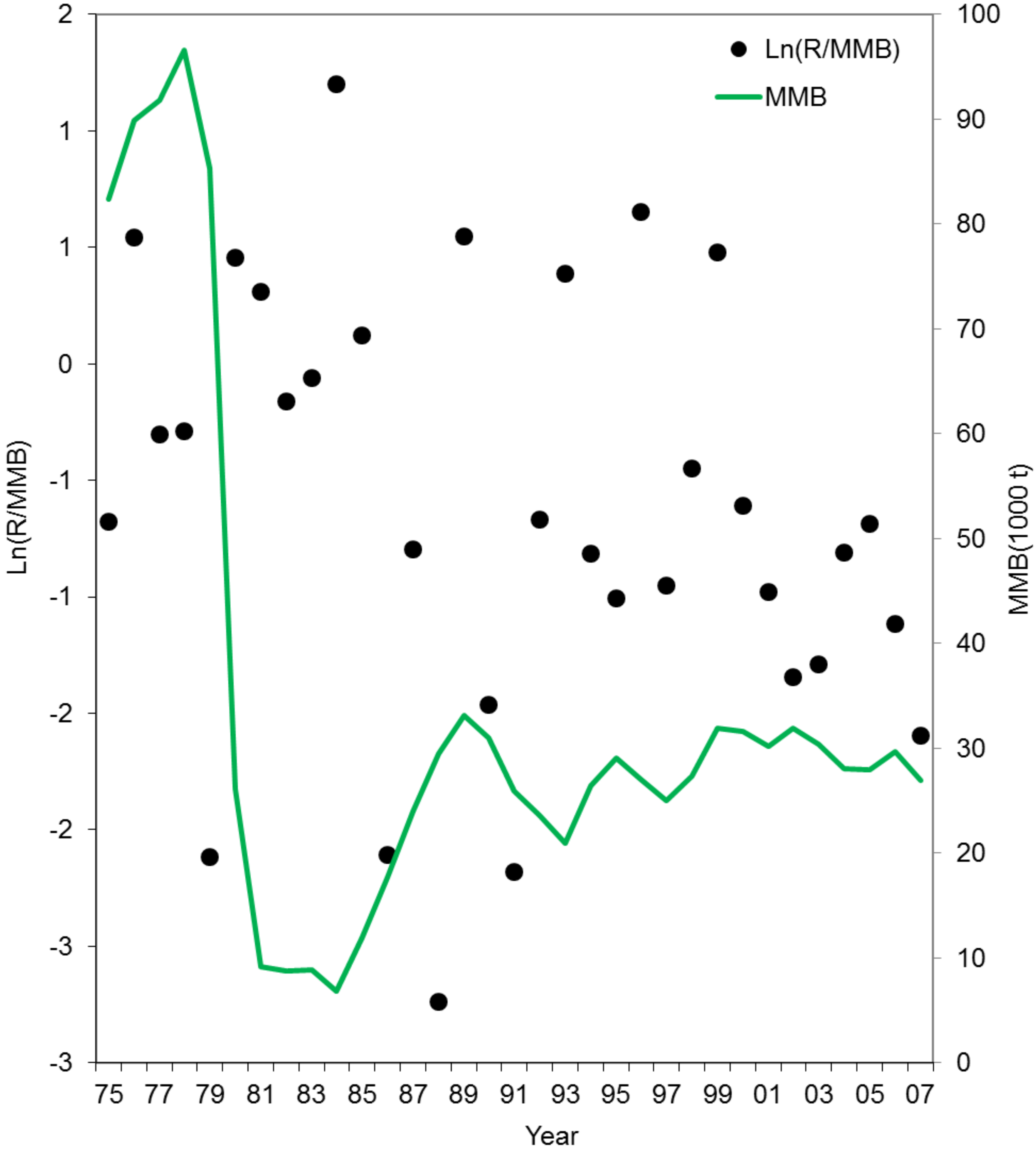


Figure 13c(4). Time series of log recruitment per mature male biomass and mature male biomass on Feb. 15 for Bristol Bay red king crab with pot handling mortality rate to be 0.2 under scenario 4.

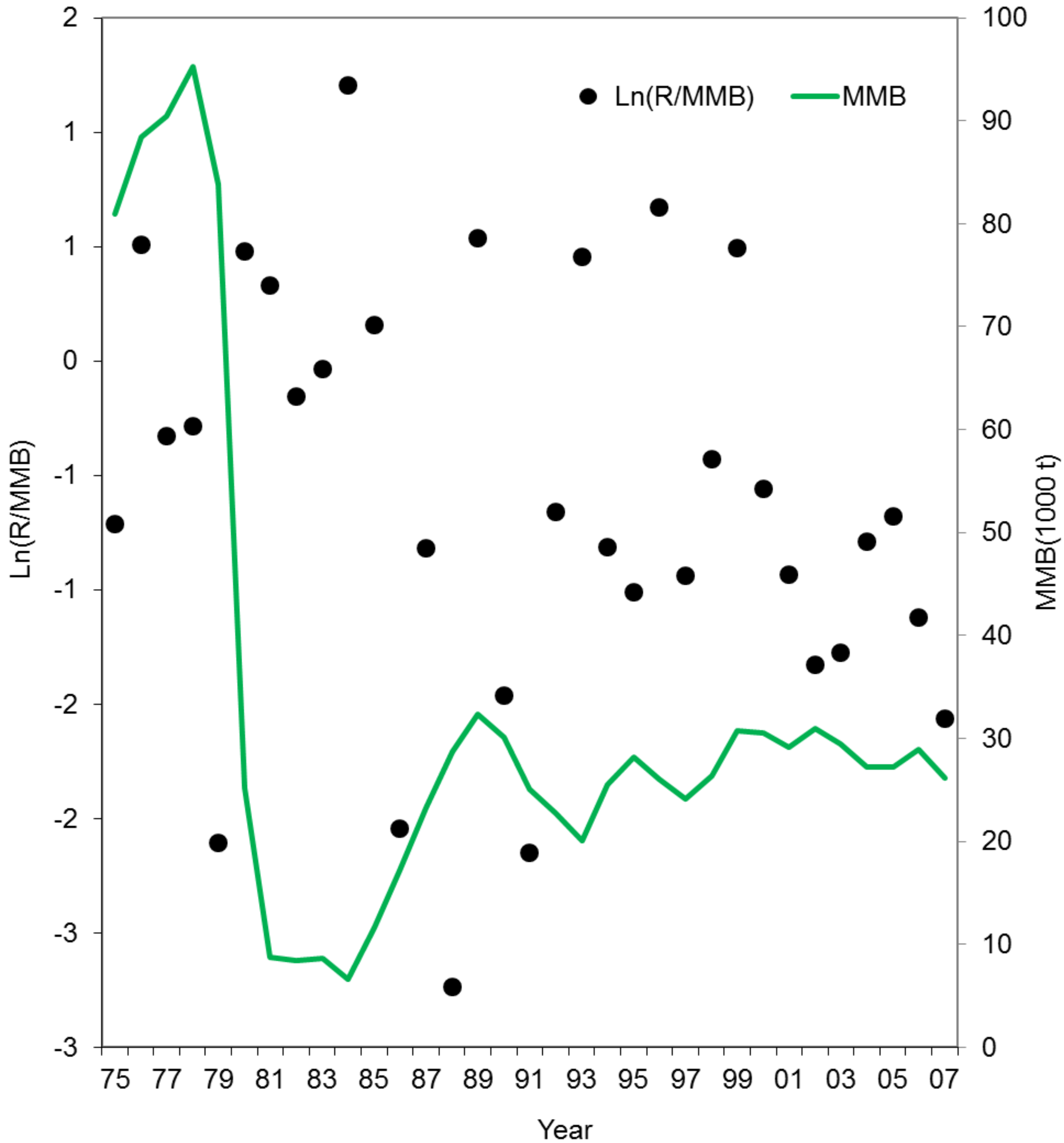


Figure 13c(4nb). Time series of log recruitment per mature male biomass and mature male biomass on Feb. 15 for Bristol Bay red king crab with pot handling mortality rate to be 0.2 under scenario 4nb.

Figures 13d, 13e, 13f, 13g and 13h are not updated and shown here to reduce file size. Please see previous SAFE reports for these figures.

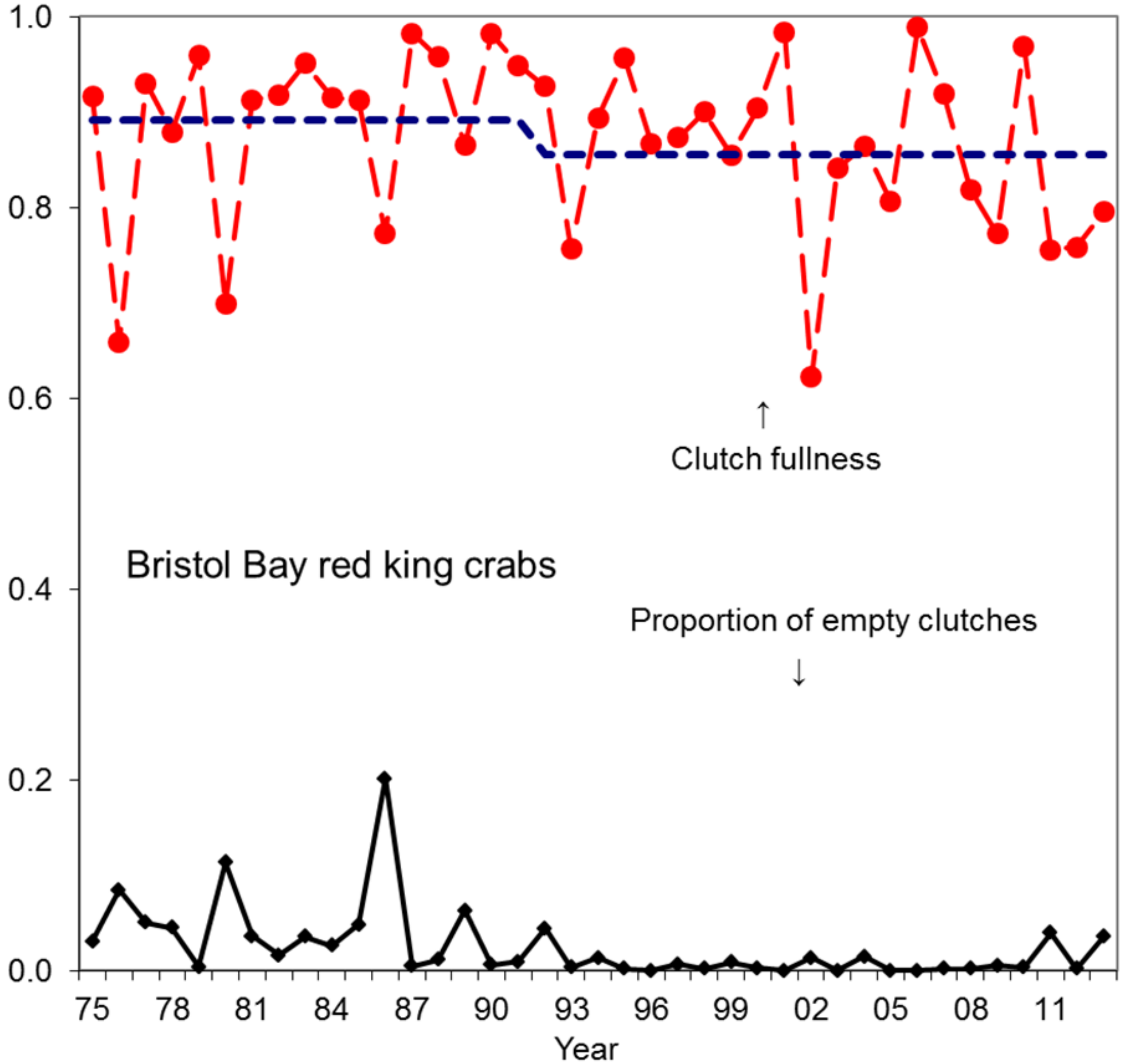


Figure 14. Average clutch fullness and proportion of empty clutches of newshell (shell conditions 1 and 2) mature female crabs >89 mm CL from 1975 to 2013 from survey data. Oldshell females were excluded.

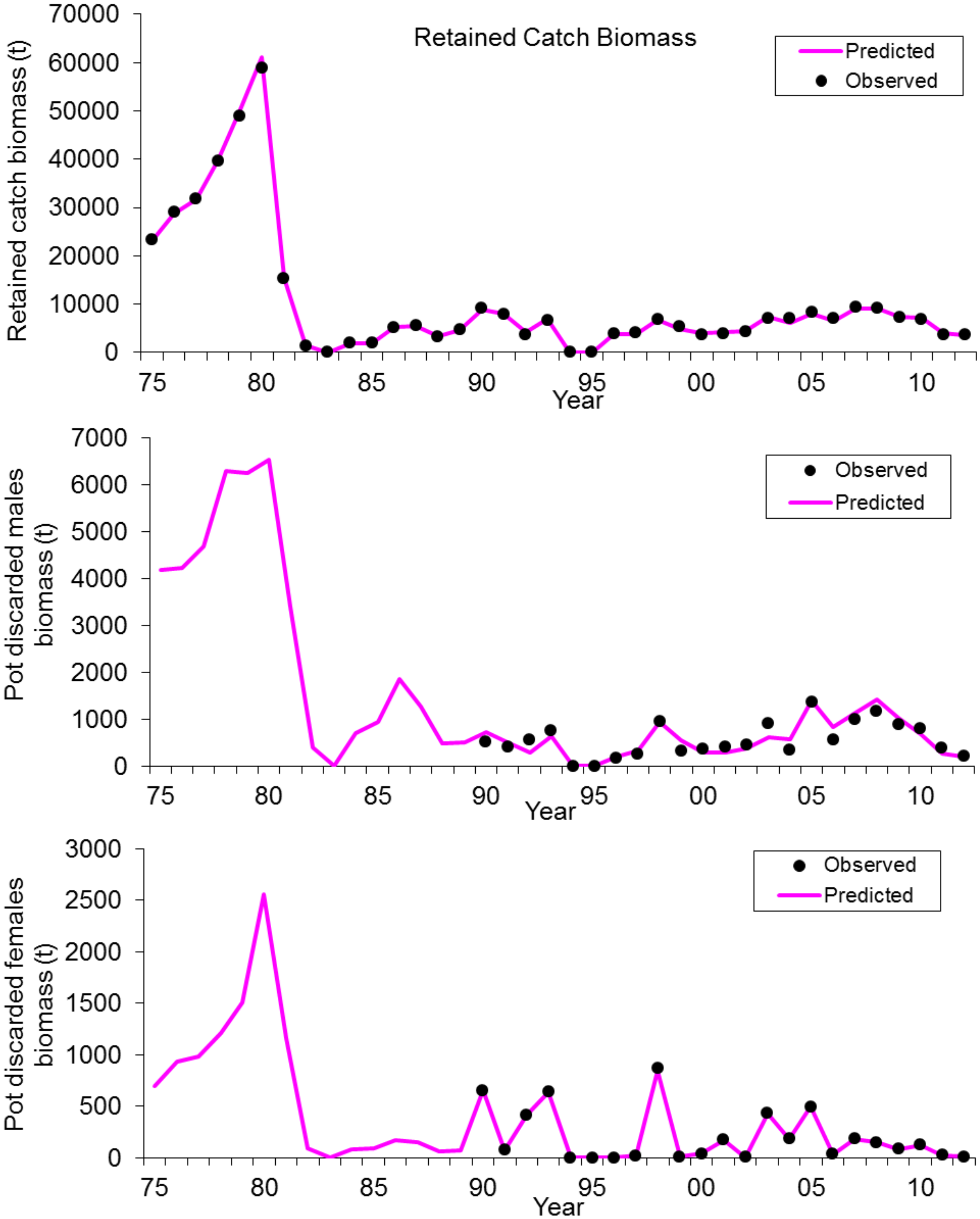


Figure 15a(4). Observed and predicted catch mortality biomass under scenario 4. Mortality biomass is equal to caught biomass times a handling mortality rate. Pot handling mortality rate is 0.2.

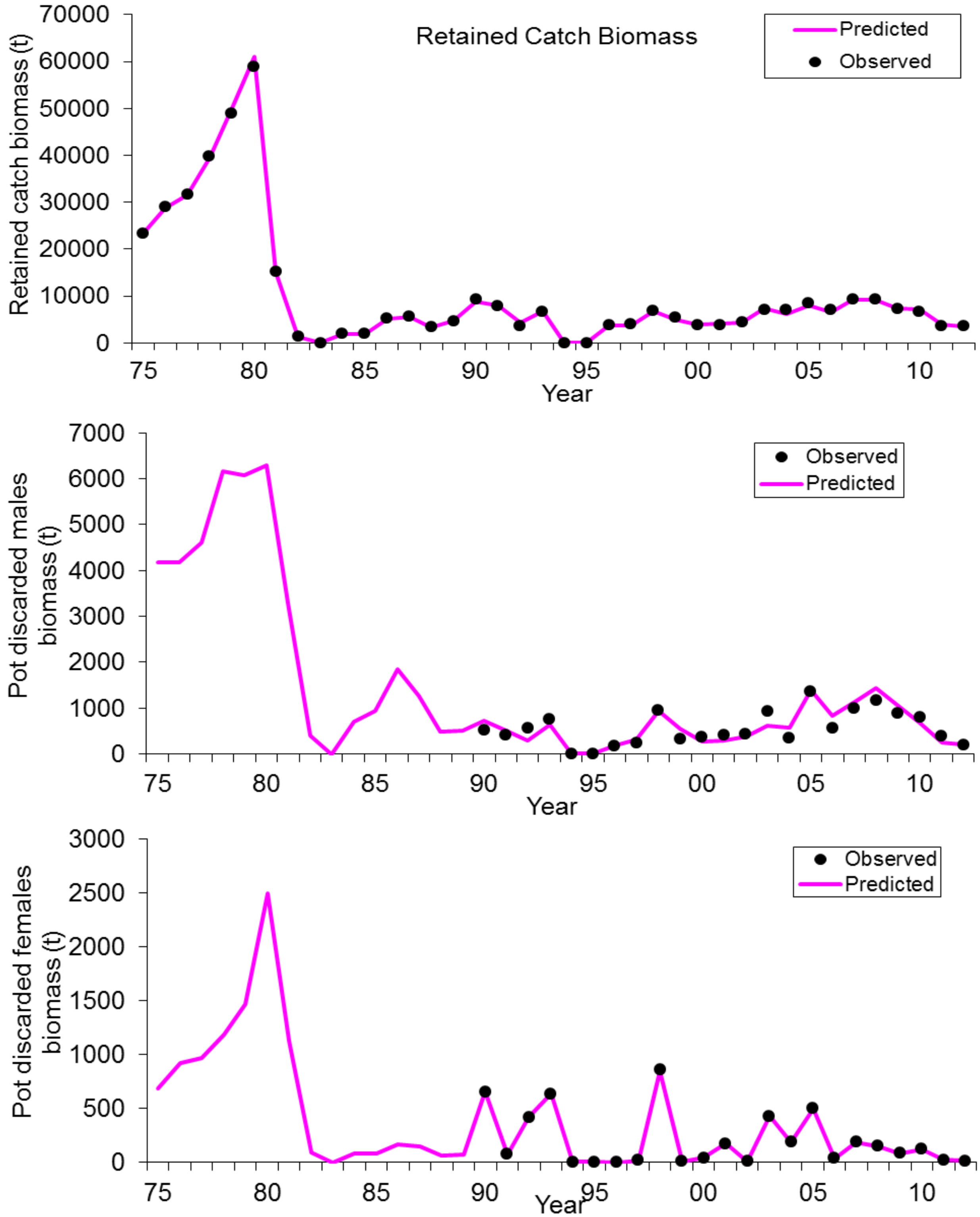
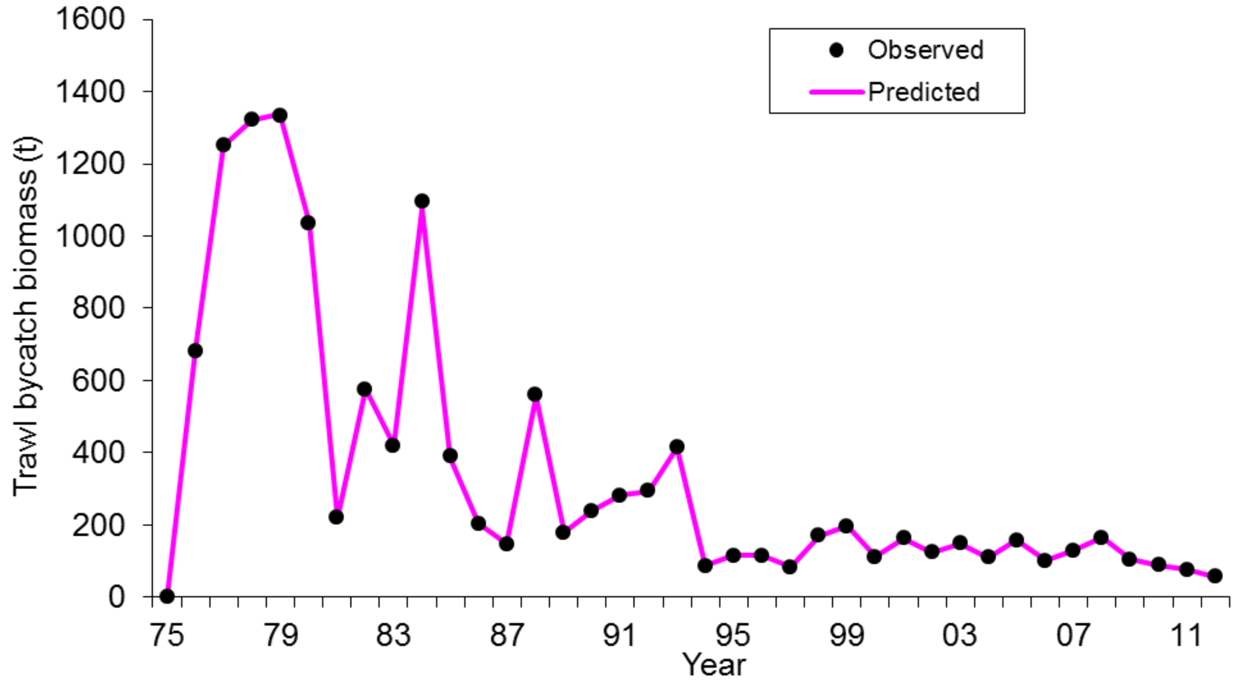


Figure 15a(4nb). Observed and predicted catch mortality biomass under scenario 4nb. Mortality biomass is equal to caught biomass times a handling mortality rate. Pot handling mortality rate is 0.2.



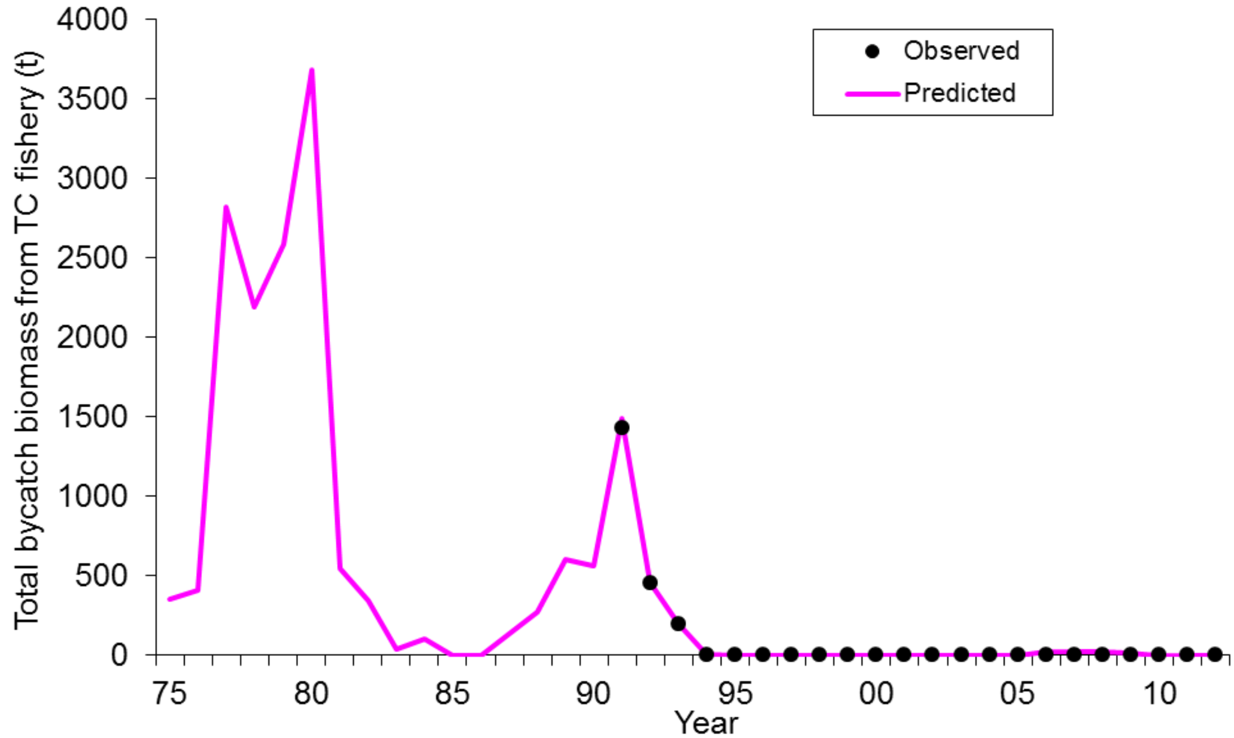
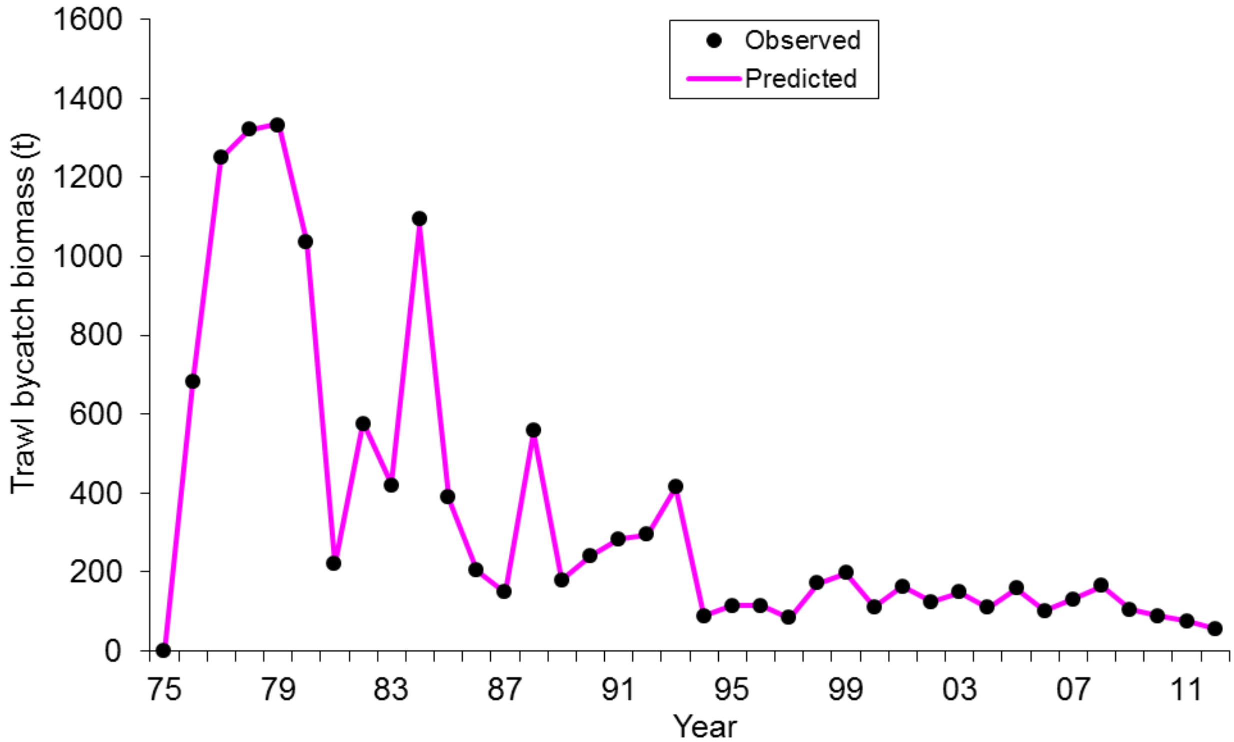


Figure 15b(4). Observed and predicted bycatch mortality biomass from trawl fisheries and Tanner crab fishery under scenario 4. Mortality biomass is equal to caught biomass times a handling mortality rate. Trawl handling mortality rate is 0.8, and Tanner crab pot handling mortality is 0.25. Trawl bycatch biomass was 0 before 1976.



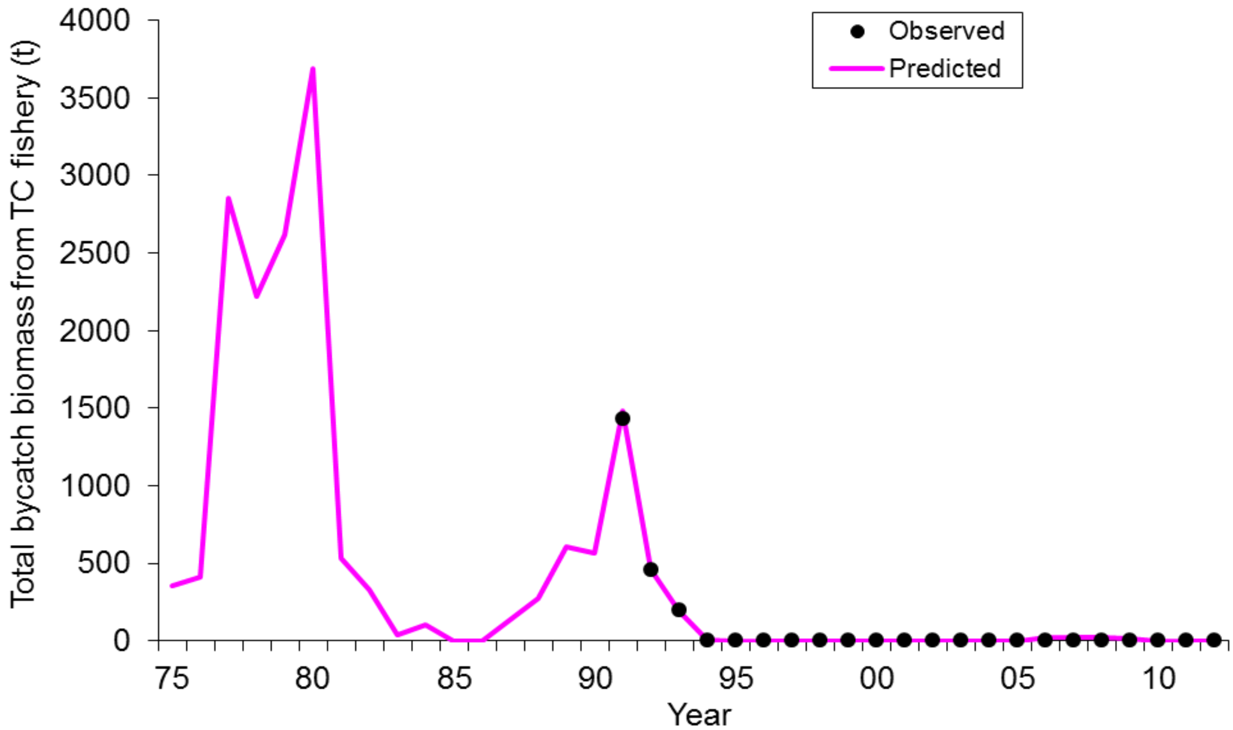


Figure 15b(4nb). Observed and predicted bycatch mortality biomass from trawl fisheries and Tanner crab fishery under scenario 4nb. Mortality biomass is equal to caught biomass times a handling mortality rate. Trawl handling mortality rate is 0.8, and Tanner crab pot handling mortality is 0.25. Trawl bycatch biomass was 0 before 1976.

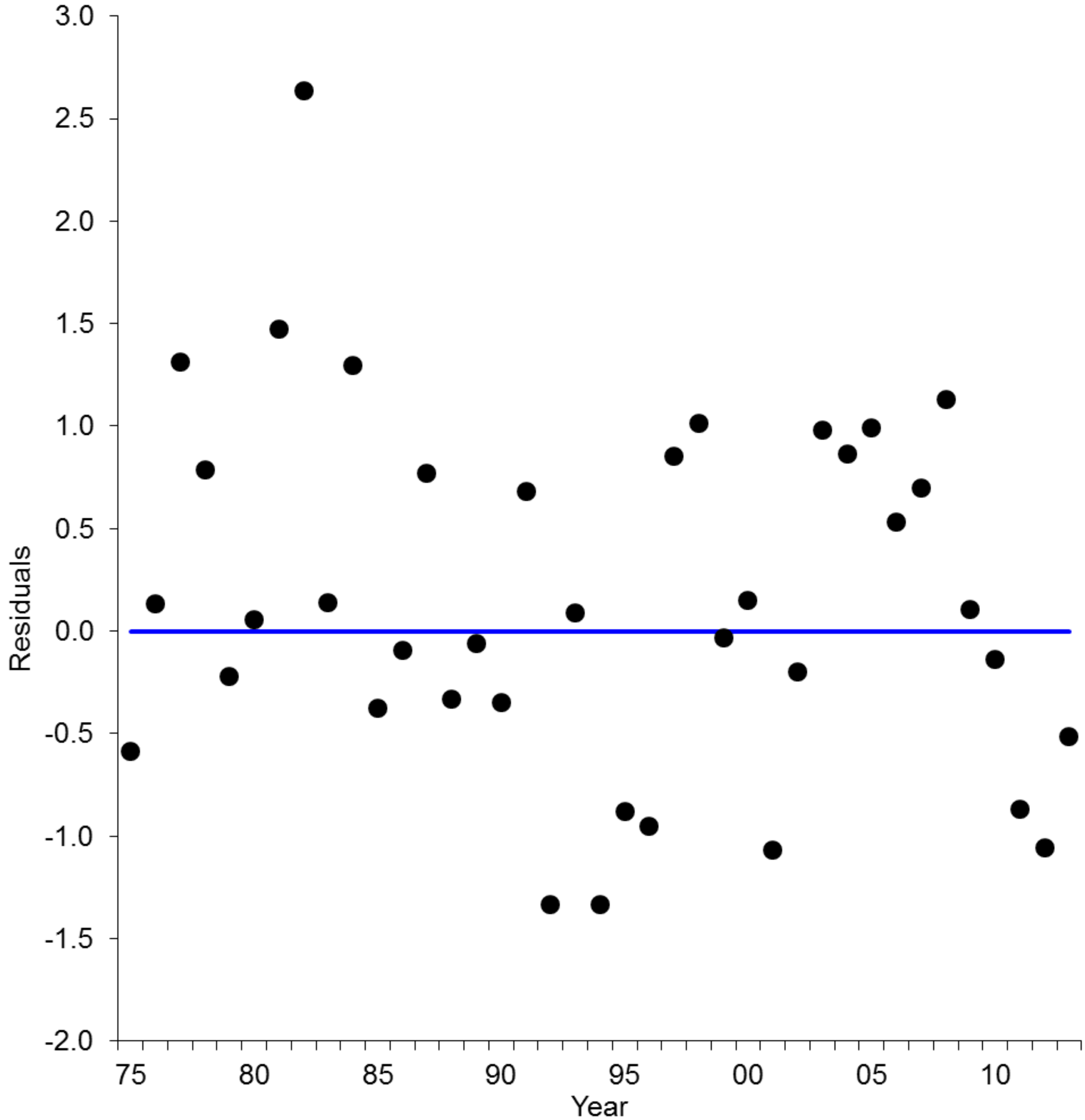


Figure 16(4). Standardized residuals of total survey biomass under scenario 4. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

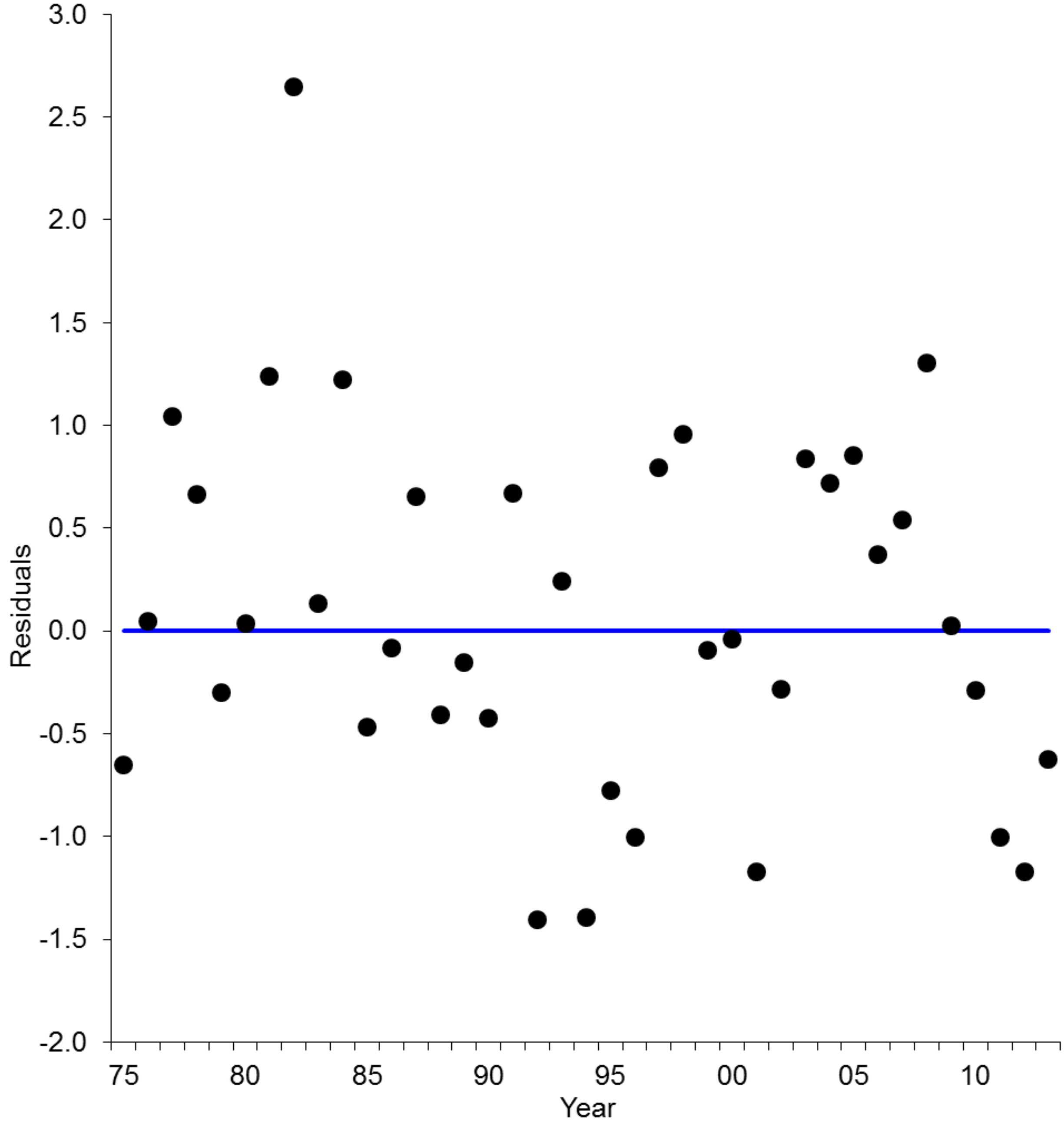


Figure 16(4nb). Standardized residuals of total survey biomass under scenario 4nb. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

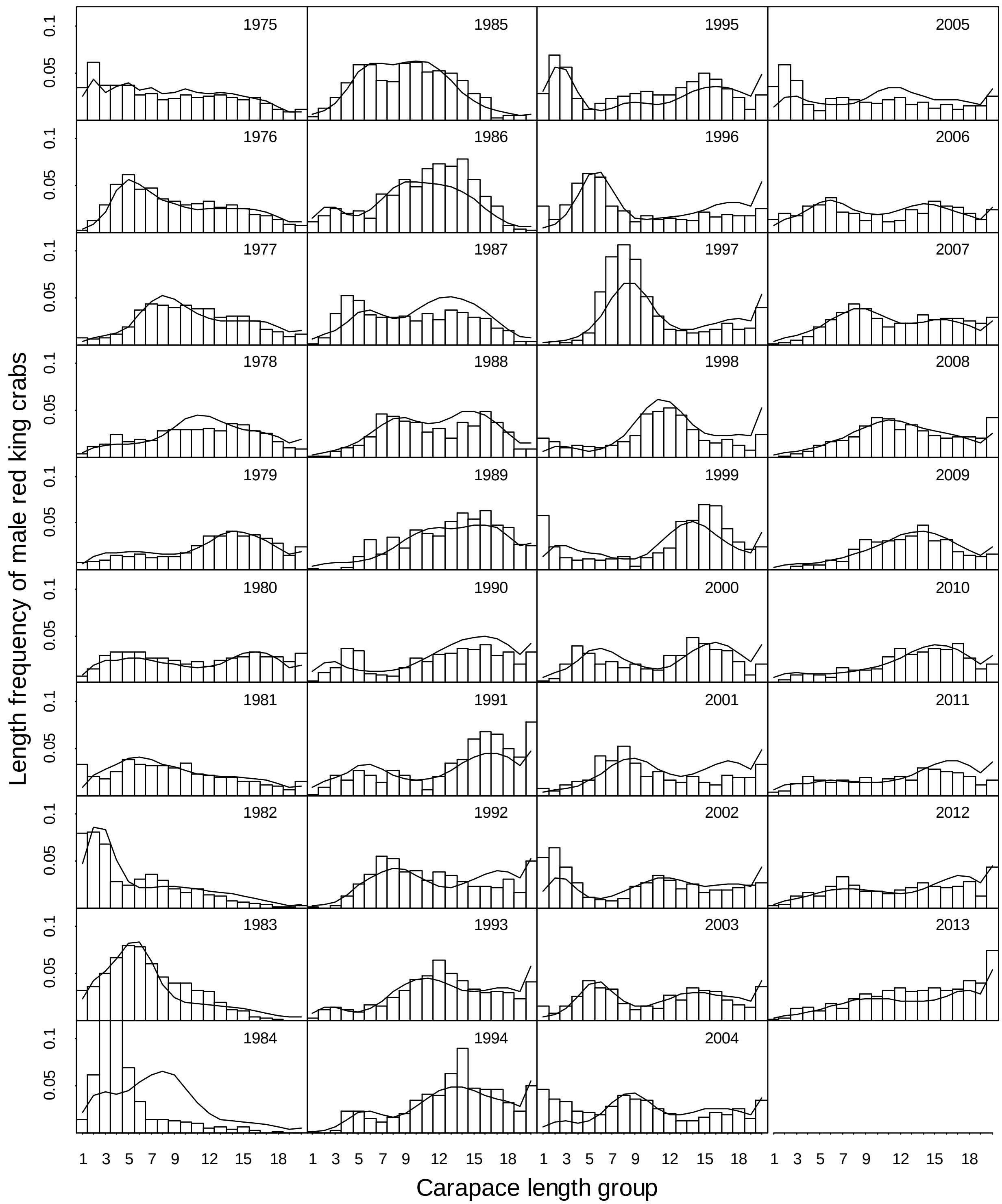


Figure 17(4). Comparison of area-swept and model estimated survey length frequencies of Bristol Bay male red king crabs by year under scenario 4. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, and the first length group is 67.5 mm.

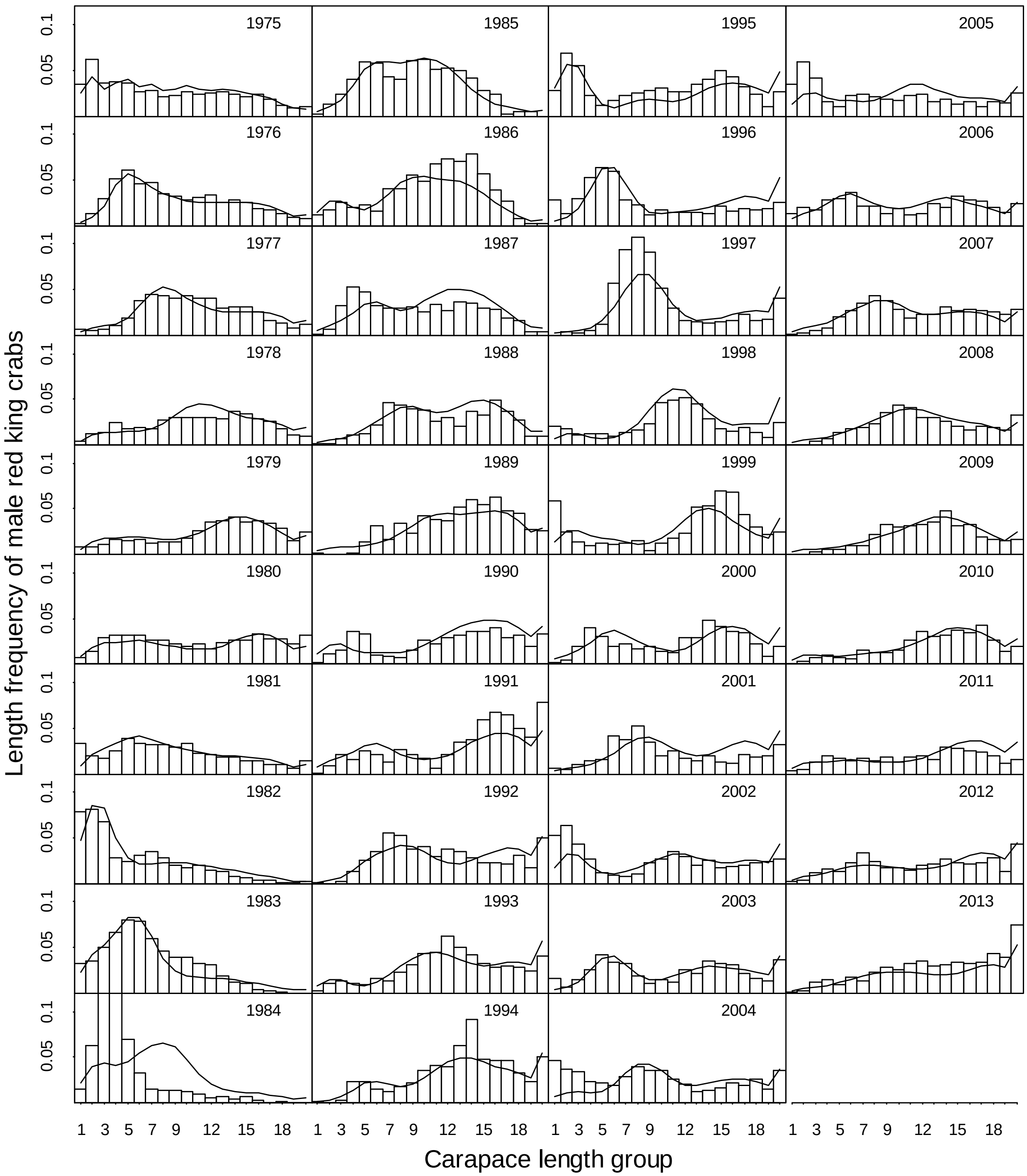


Figure 18(4nb). Comparison of area-swept and model estimated survey length frequencies of Bristol Bay male red king crabs by year under scenario 4nb. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively, and the first length group is 67.5 mm.

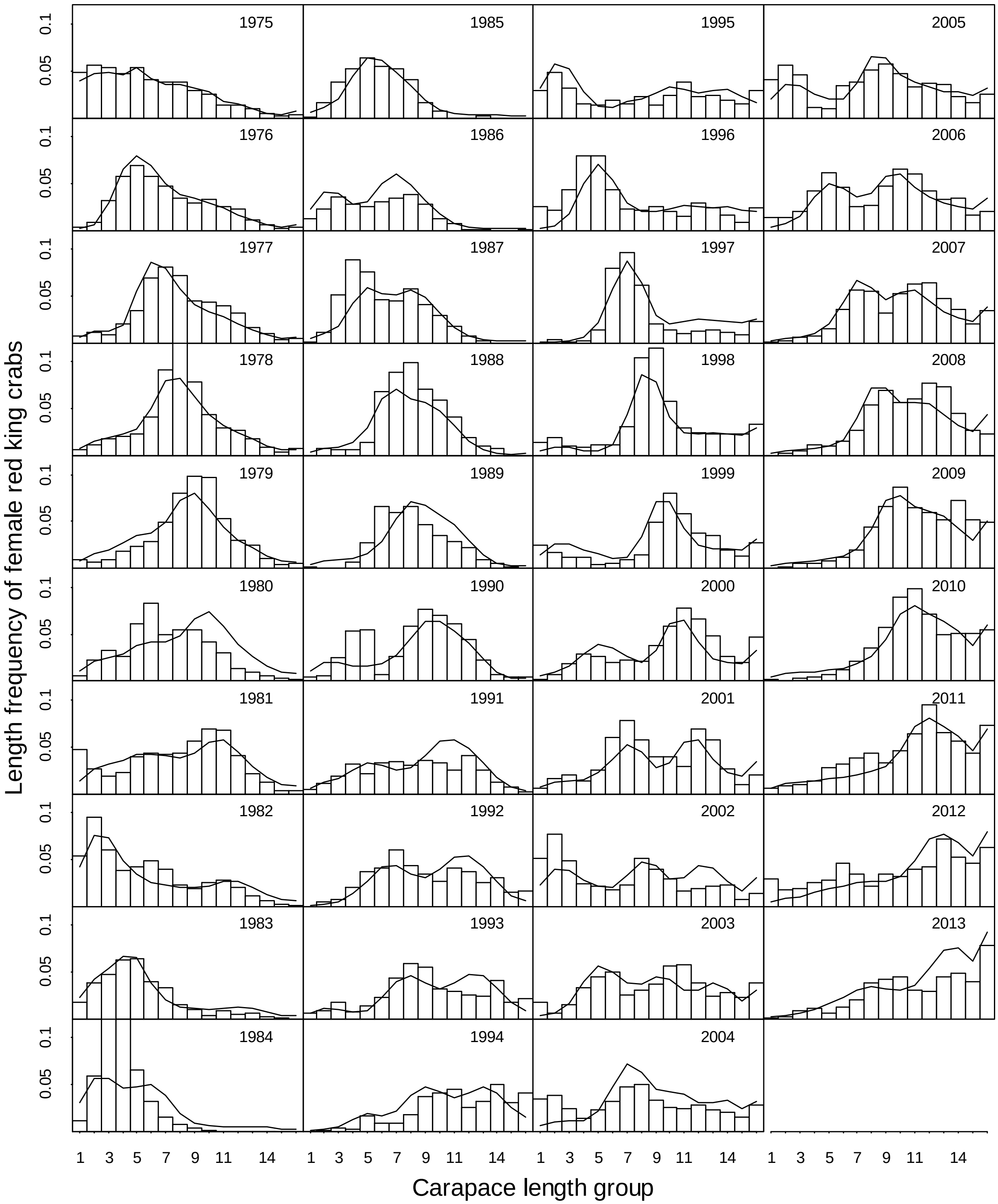


Figure 19(4). Comparison of area-swept and model estimated survey length frequencies of Bristol Bay female red king crabs by year under scenario 4. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively, and the first length group is 67.5 mm.

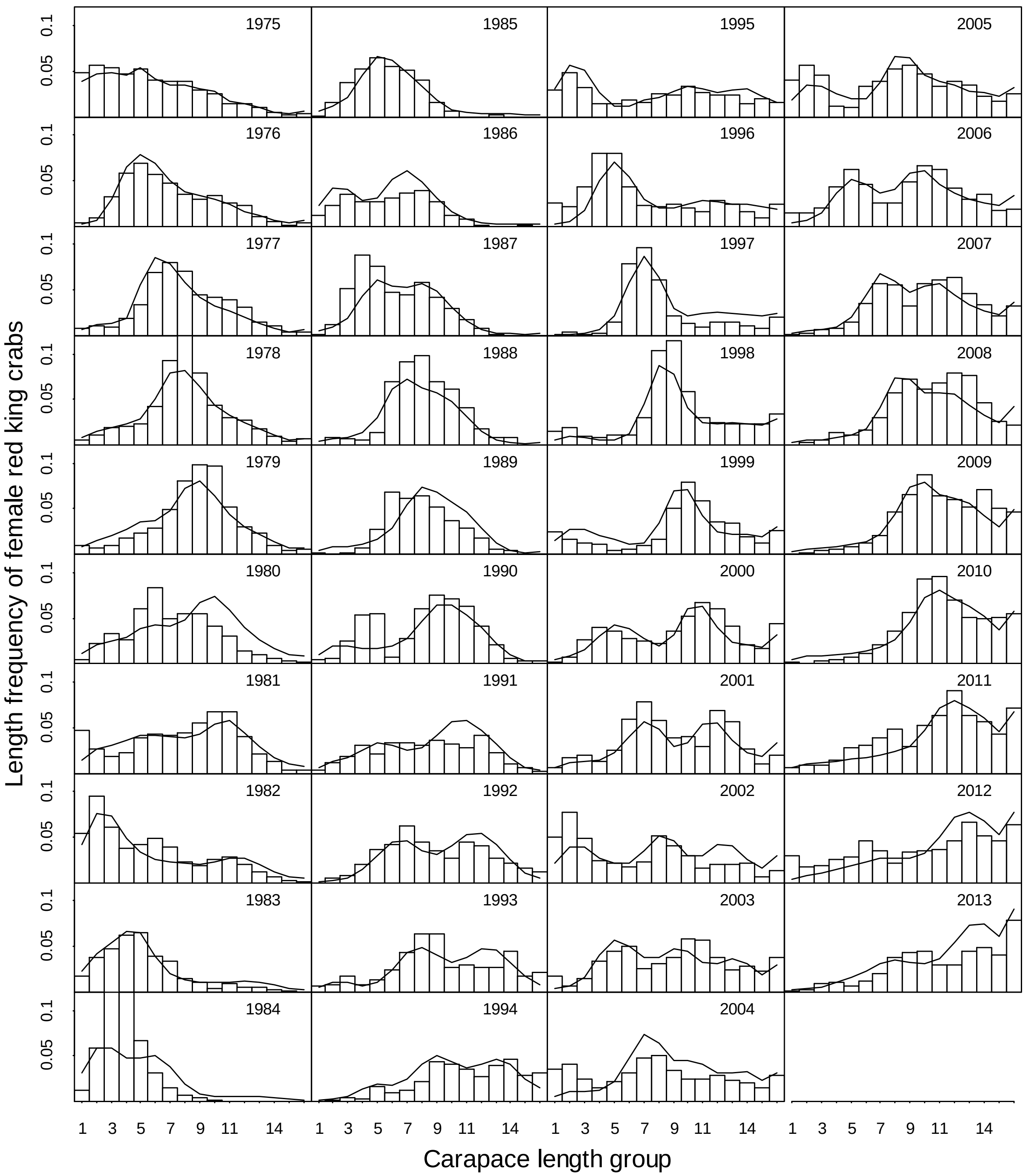


Figure 19(4nb). Comparison of area-swept and model estimated survey length frequencies of Bristol Bay female red king crabs by year under scenario 4nb. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively, and the first length group is 67.5 mm.

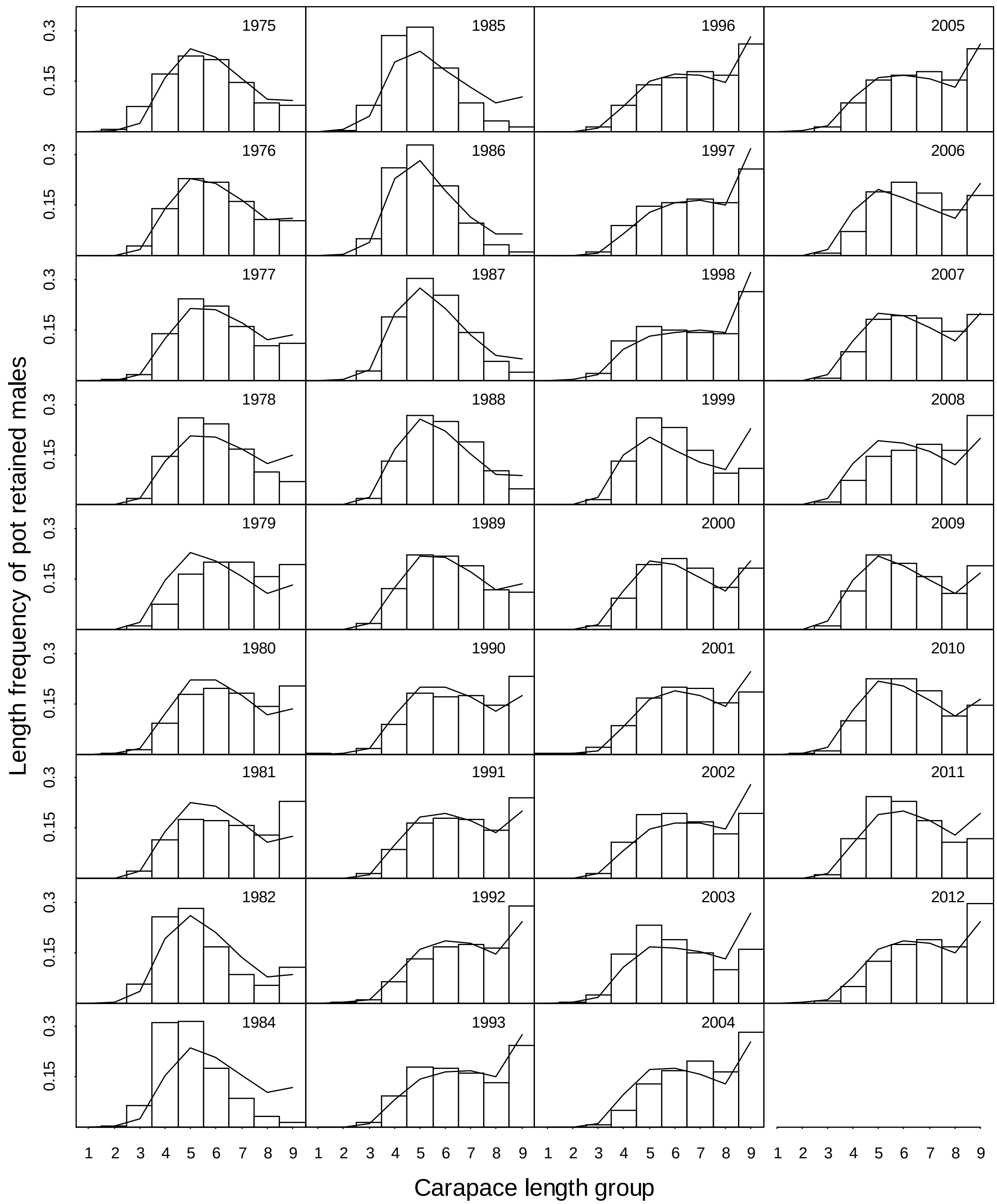


Figure 20(4). Comparison of observed and model estimated retained length frequencies of Bristol Bay male red king crabs by year in the directed pot fishery under scenario 4. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively, and the first length group is 122.5 mm.

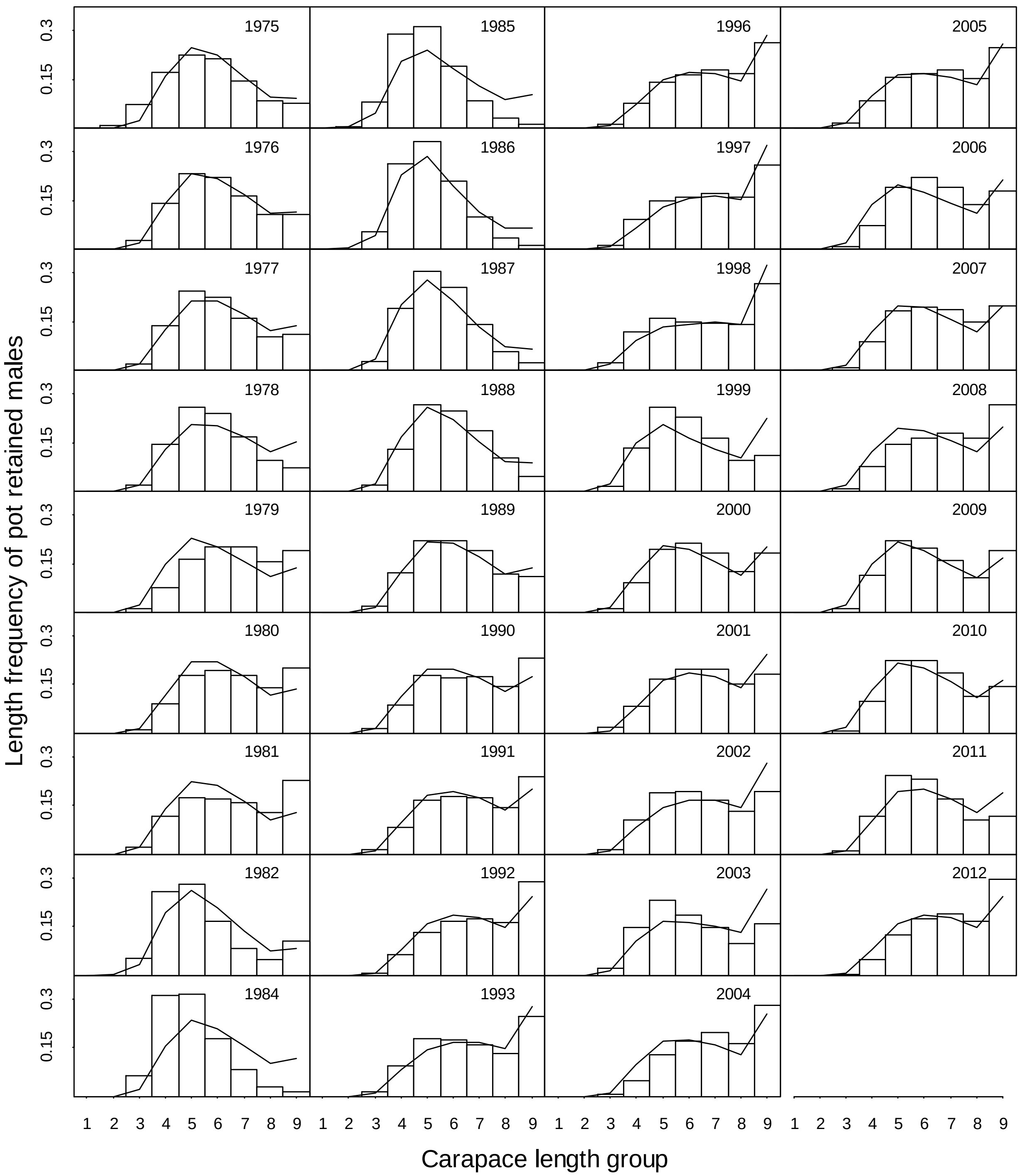


Figure 20(4nb). Comparison of observed and model estimated retained length frequencies of Bristol Bay male red king crabs by year in the directed pot fishery under scenario 4nb. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively, and the first length group is 122.5 mm.

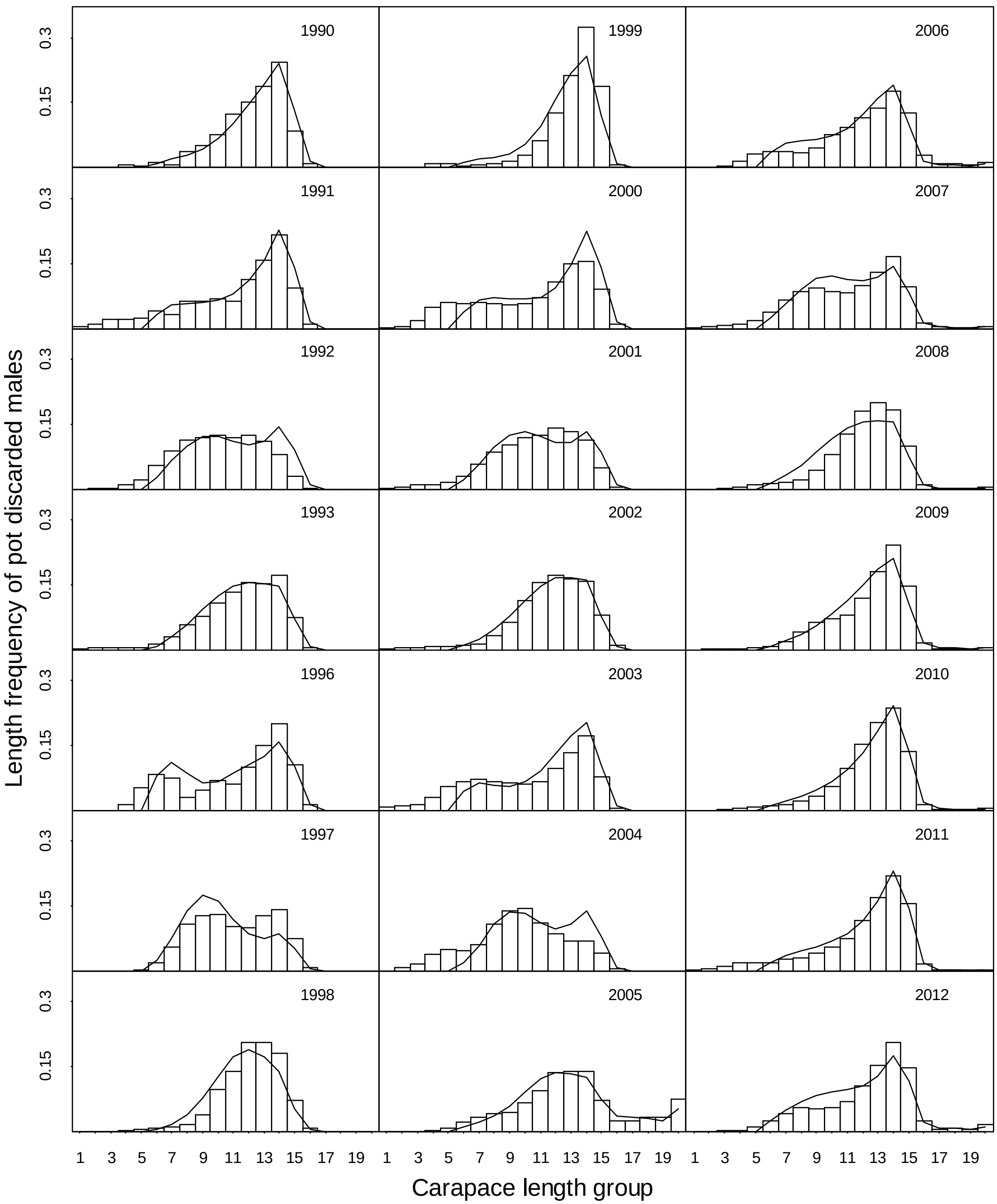


Figure 21(4). Comparison of observer and model estimated discarded length frequencies of Bristol Bay male red king crabs by year in the directed pot fishery under scenario 4. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively, and the first length group is 67.5 mm.

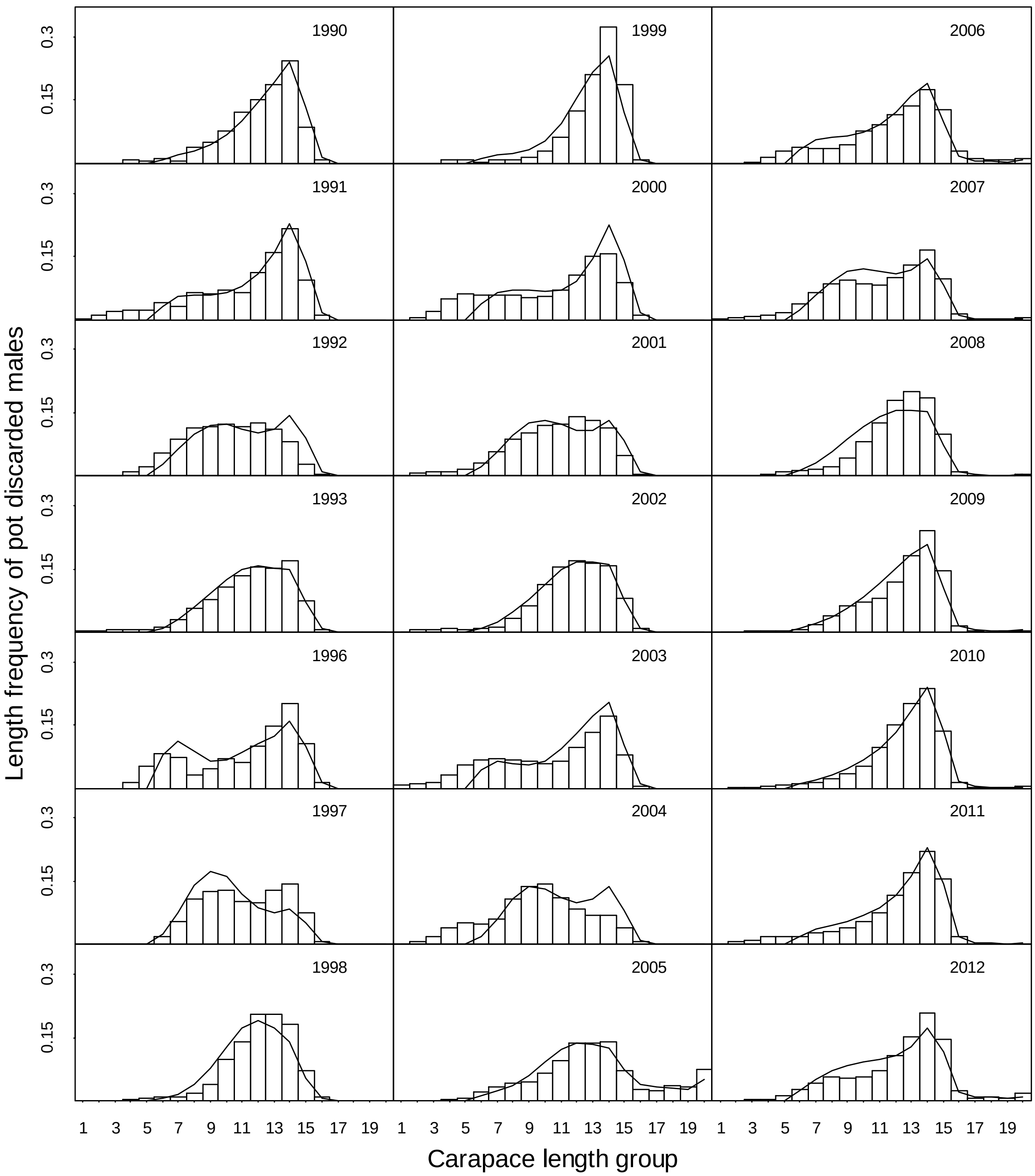


Figure 21(4nb). Comparison of observer and model estimated discarded length frequencies of Bristol Bay male red king crabs by year in the directed pot fishery under scenario 4nb. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively, and the first length group is 67.5 mm.

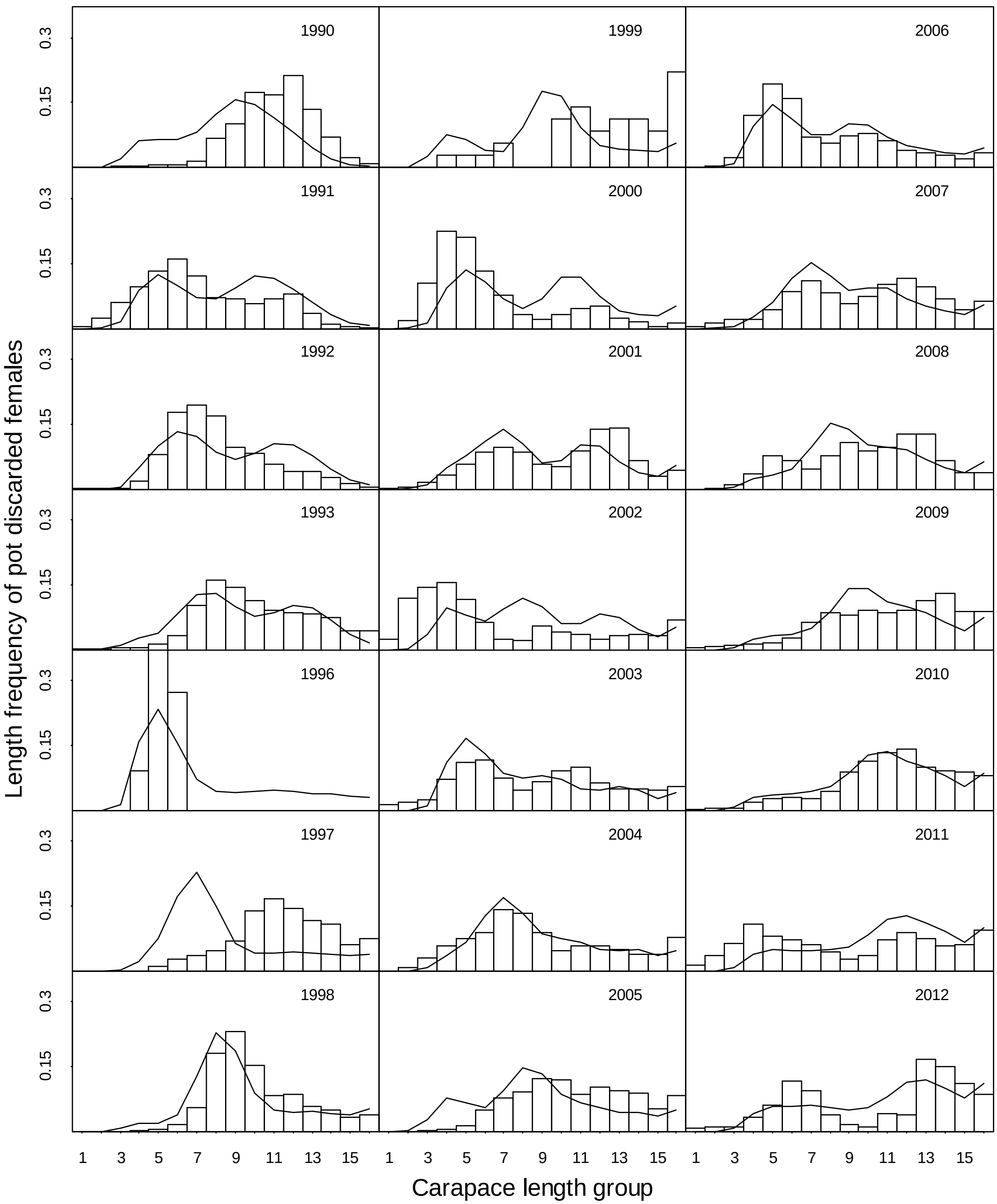


Figure 22(4). Comparison of observer and model estimated discarded length frequencies of Bristol Bay female red king crabs by year in the directed pot fishery under scenario 4. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively, and the first length group is 67.5 mm.

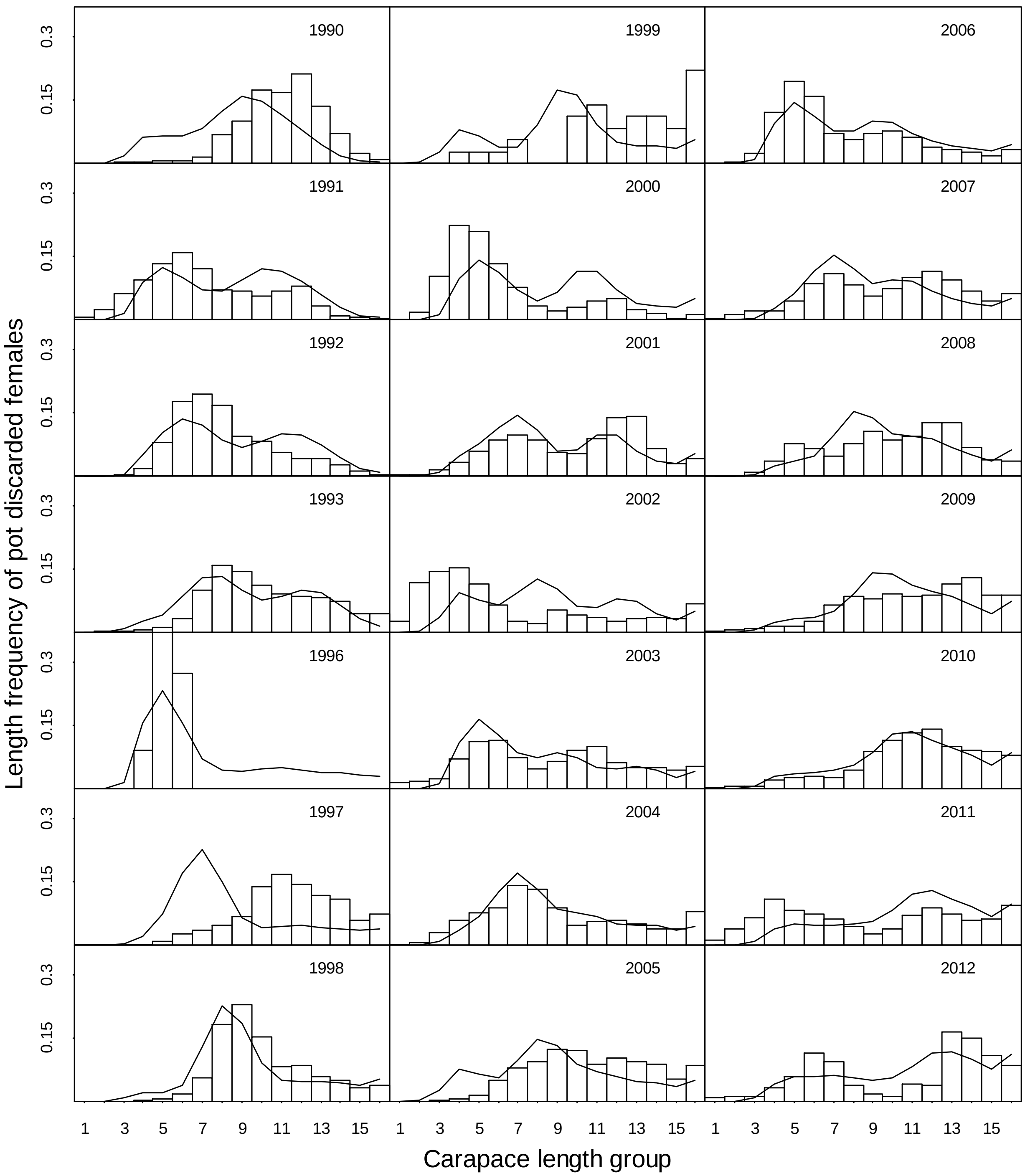


Figure 22(4nb). Comparison of observer and model estimated discarded length frequencies of Bristol Bay female red king crabs by year in the directed pot fishery under scenario 4nb. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively, and the first length group is 67.5 mm.

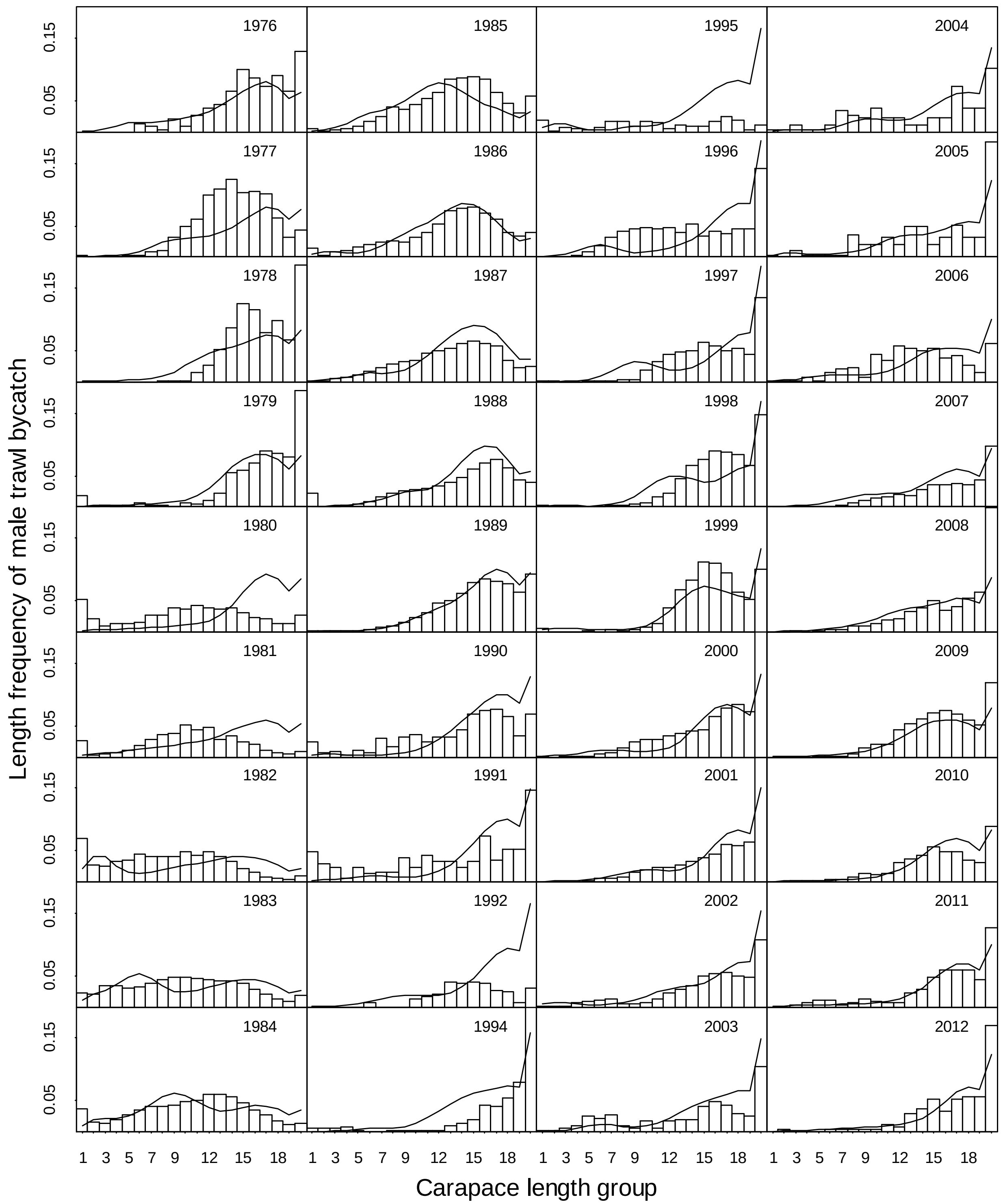


Figure 23(4). Comparison of observer and model estimated discarded length frequencies of Bristol Bay male red king crabs by year in the groundfish trawl fisheries under scenario 4. Pot handling mortality rate is 0.2, trawl bycatch mortality rate is 0.8, and the first length group is 67.5 mm.

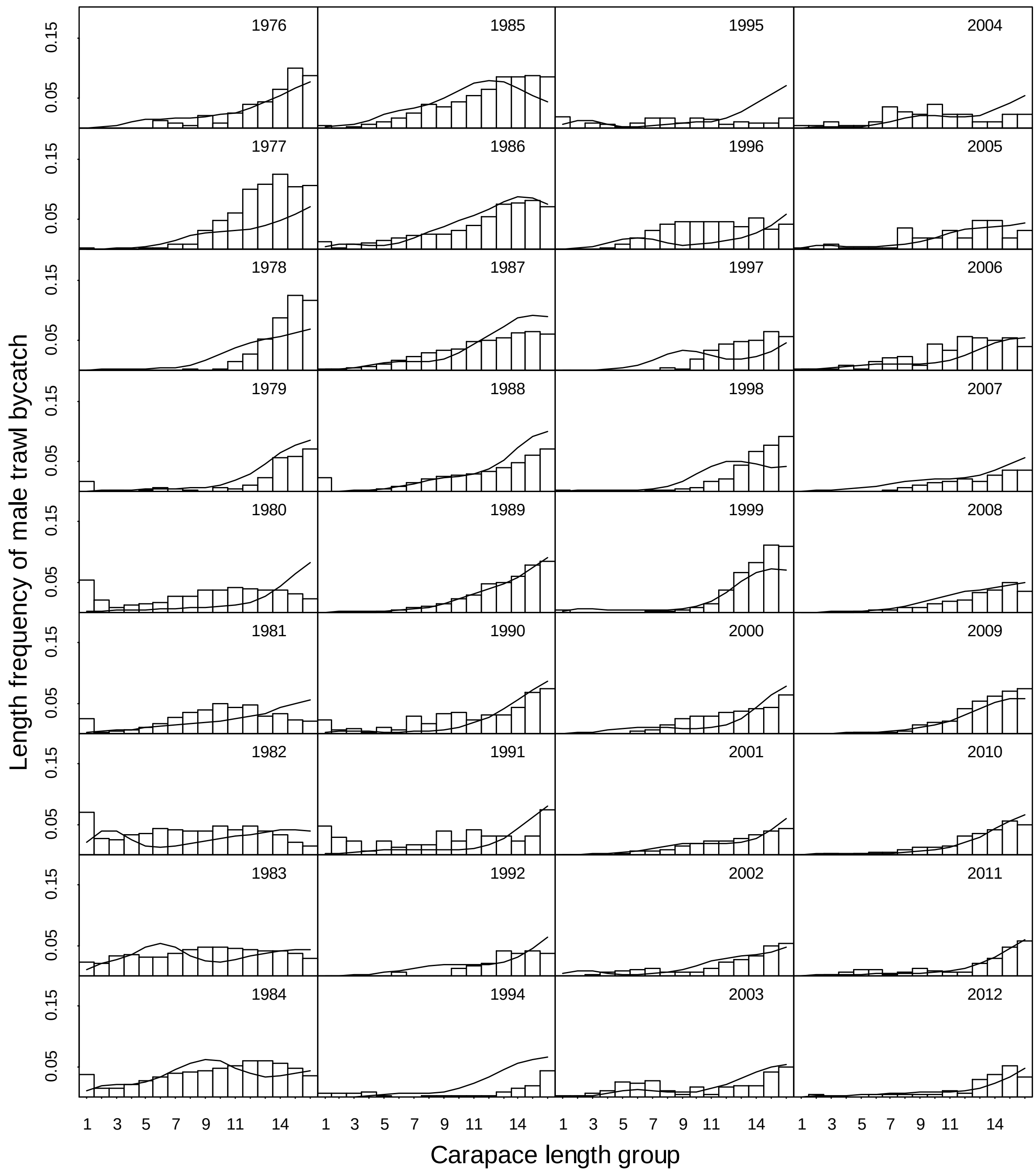


Figure 23(4nb). Comparison of observer and model estimated discarded length frequencies of Bristol Bay male red king crabs by year in the groundfish trawl fisheries under scenario 4nb. Pot handling mortality rate is 0.2, trawl bycatch mortality rate is 0.8, and the first length group is 67.5 mm.

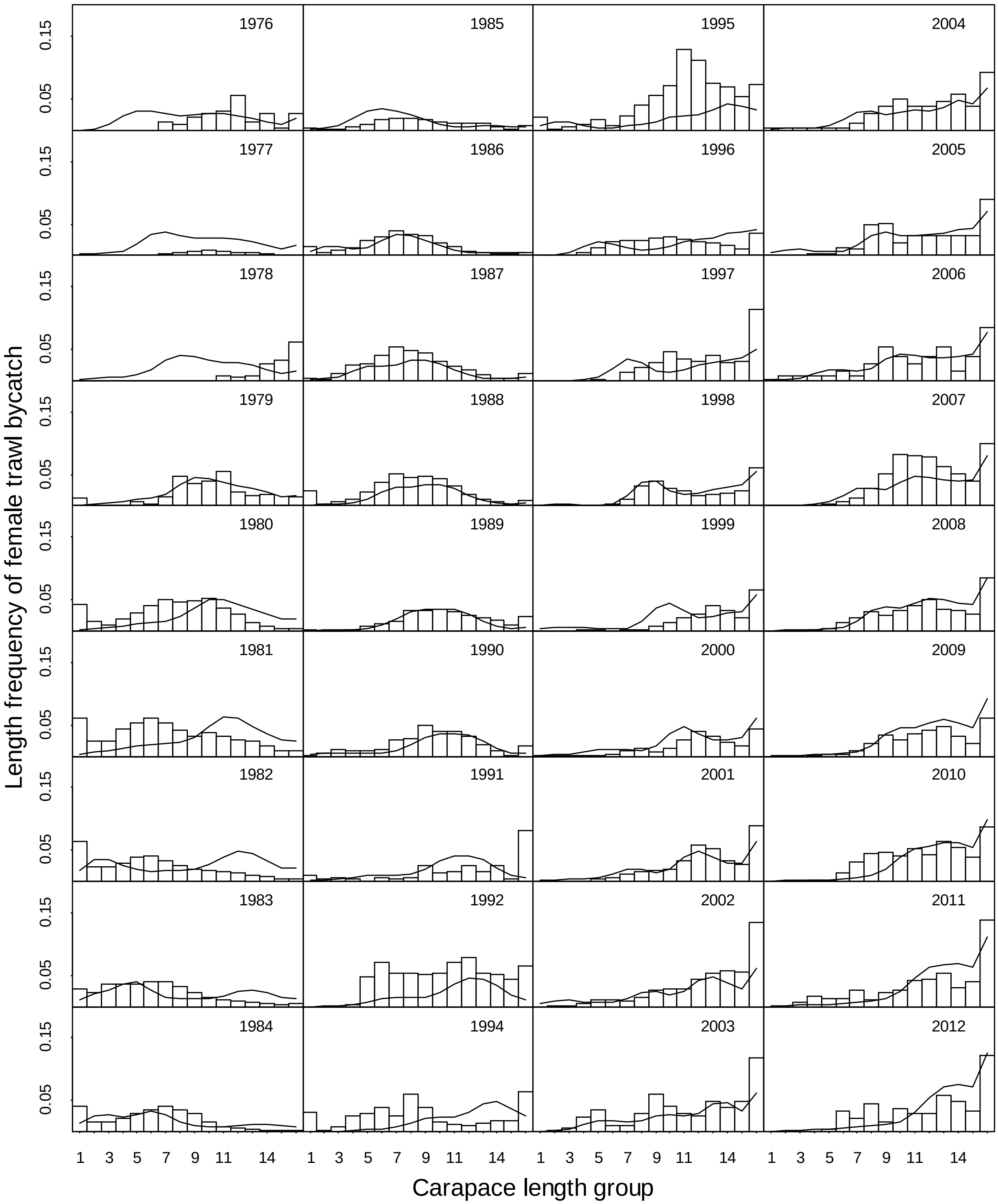


Figure 24(4). Comparison of observer and model estimated discarded length frequencies of Bristol Bay female red king crabs by year in the groundfish trawl fisheries under scenario 4. Pot handling mortality rate is 0.2, trawl bycatch mortality rate is 0.8, and the first length group is 67.5 mm.

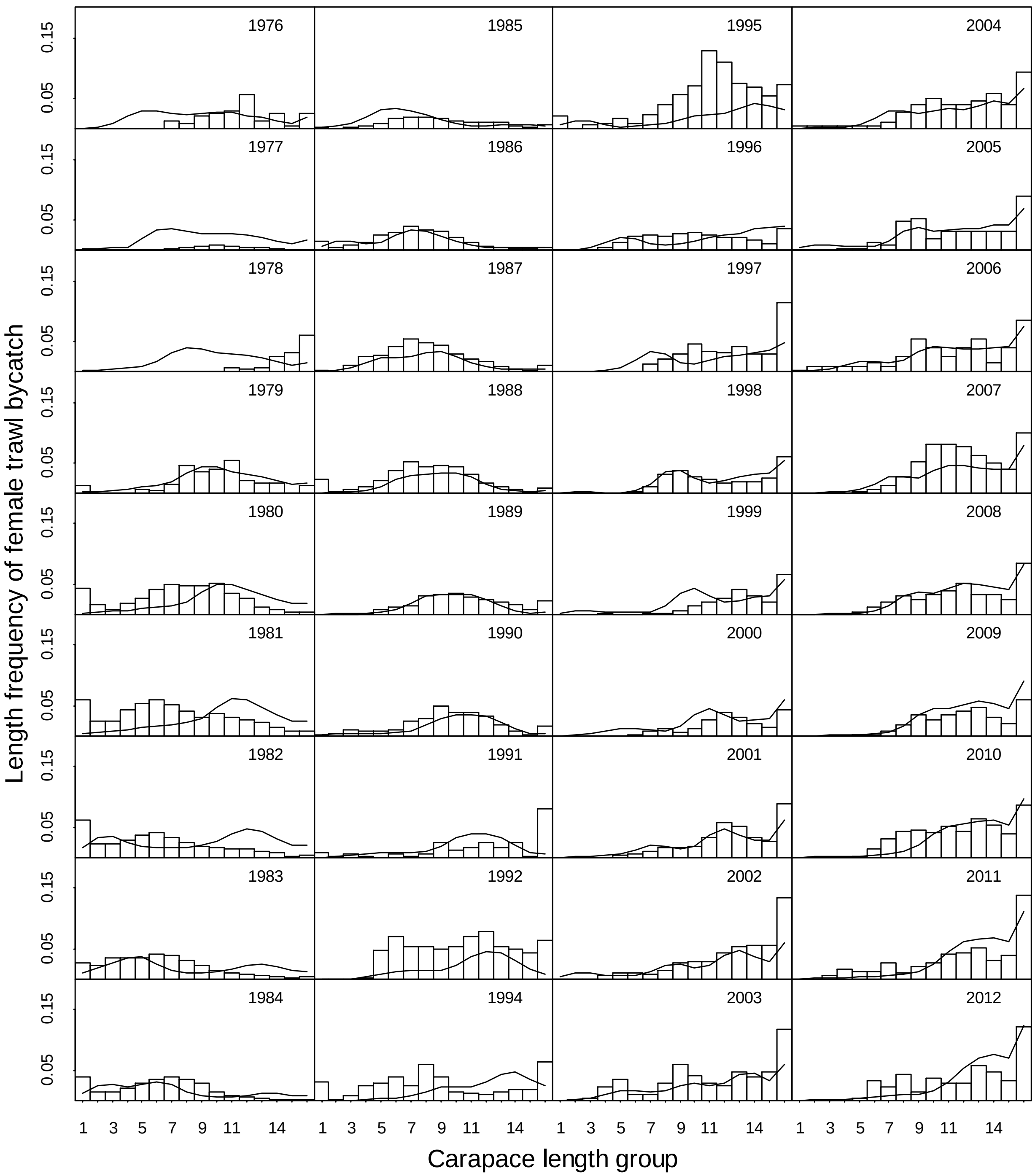


Figure 24(4nb). Comparison of observer and model estimated discarded length frequencies of Bristol Bay female red king crabs by year in the groundfish trawl fisheries under scenario 4nb. Pot handling mortality rate is 0.2, trawl bycatch mortality rate is 0.8, and the first length group is 67.5 mm.

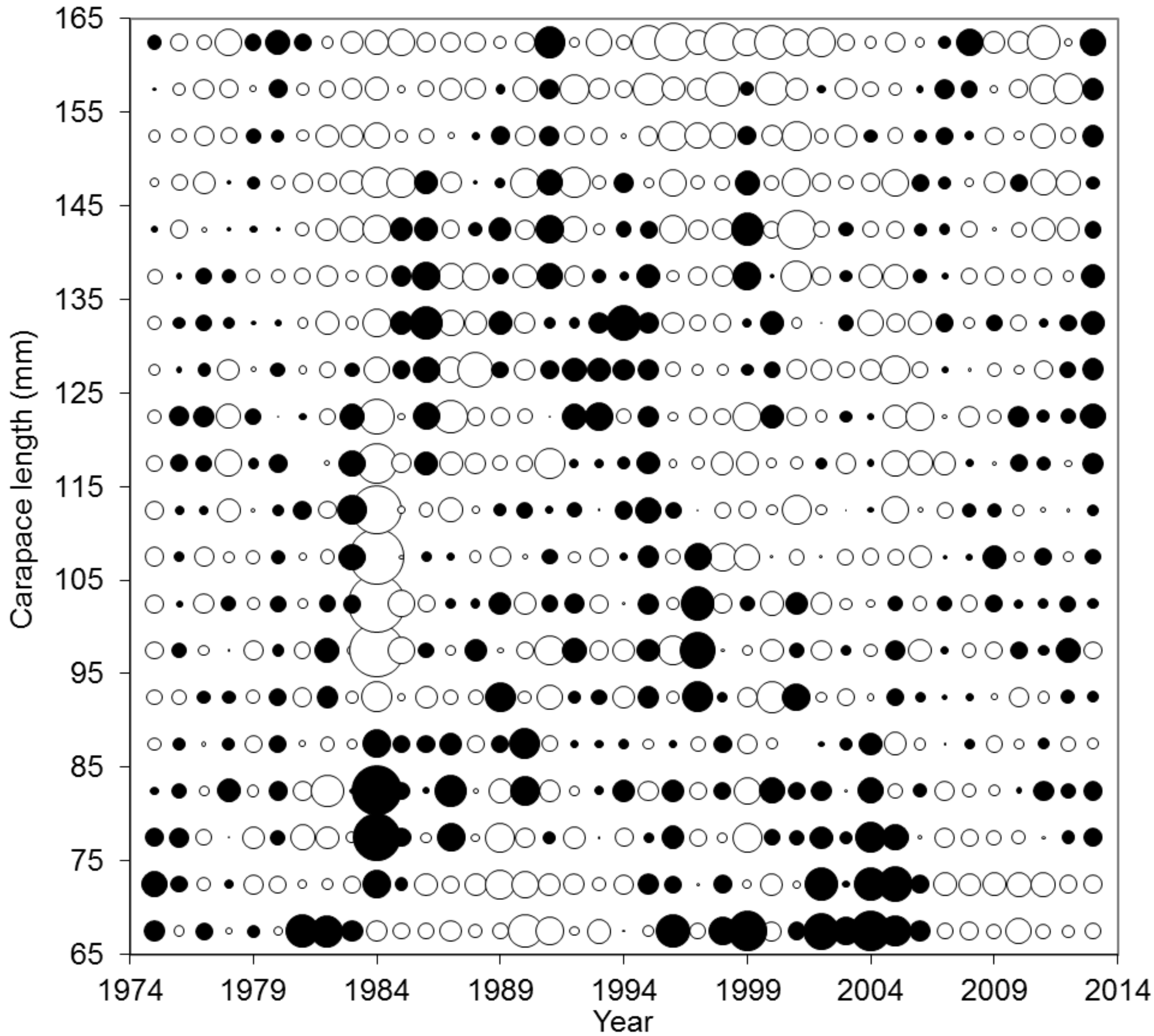


Figure 25. Standardized residuals of proportions of survey male red king crabs under scenario 4. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

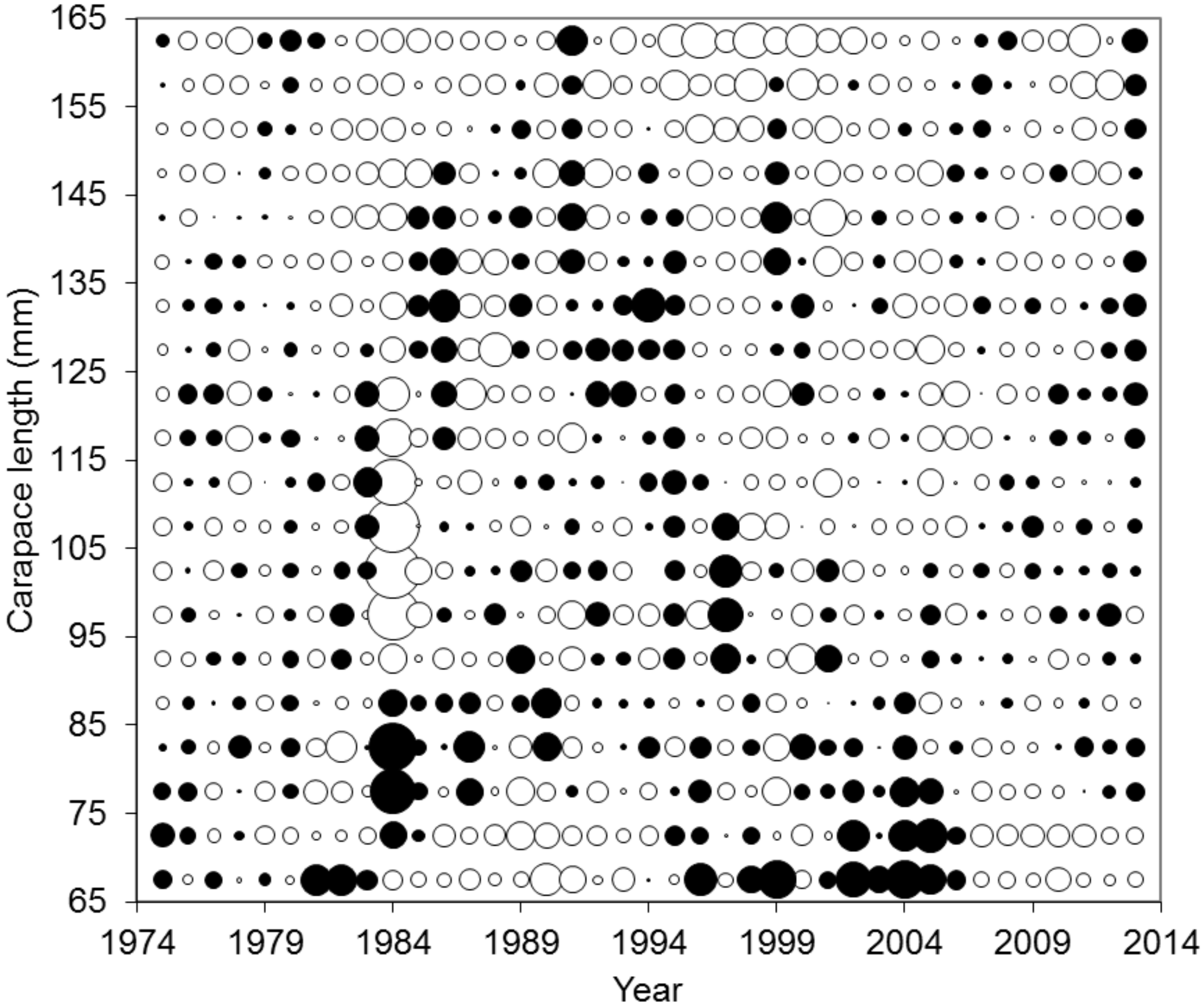


Figure 26. Standardized residuals of proportions of survey male red king crabs under scenario 4nb. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

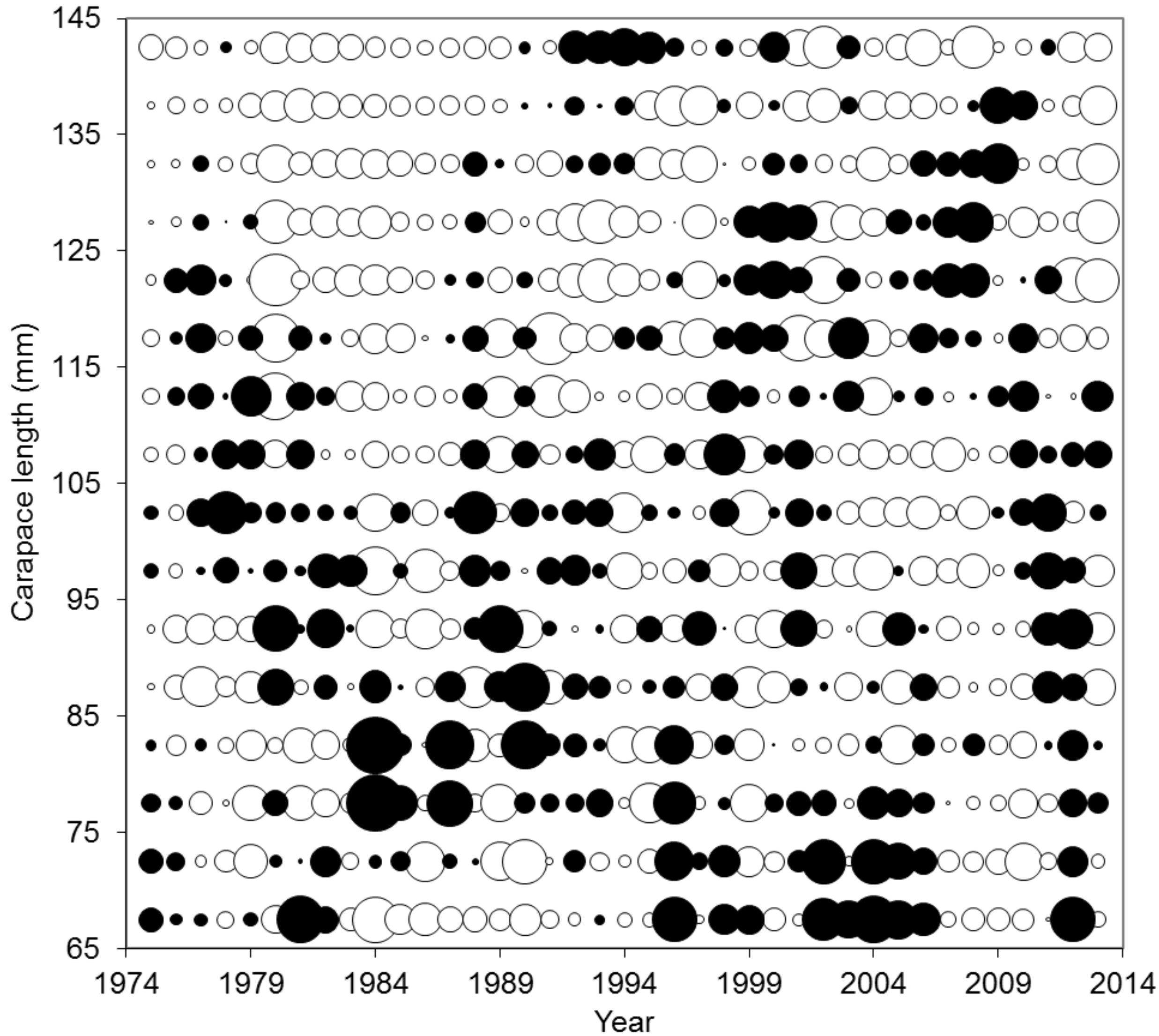


Figure 27(4). Standardized residuals of proportions of survey female red king crabs under scenario 4. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

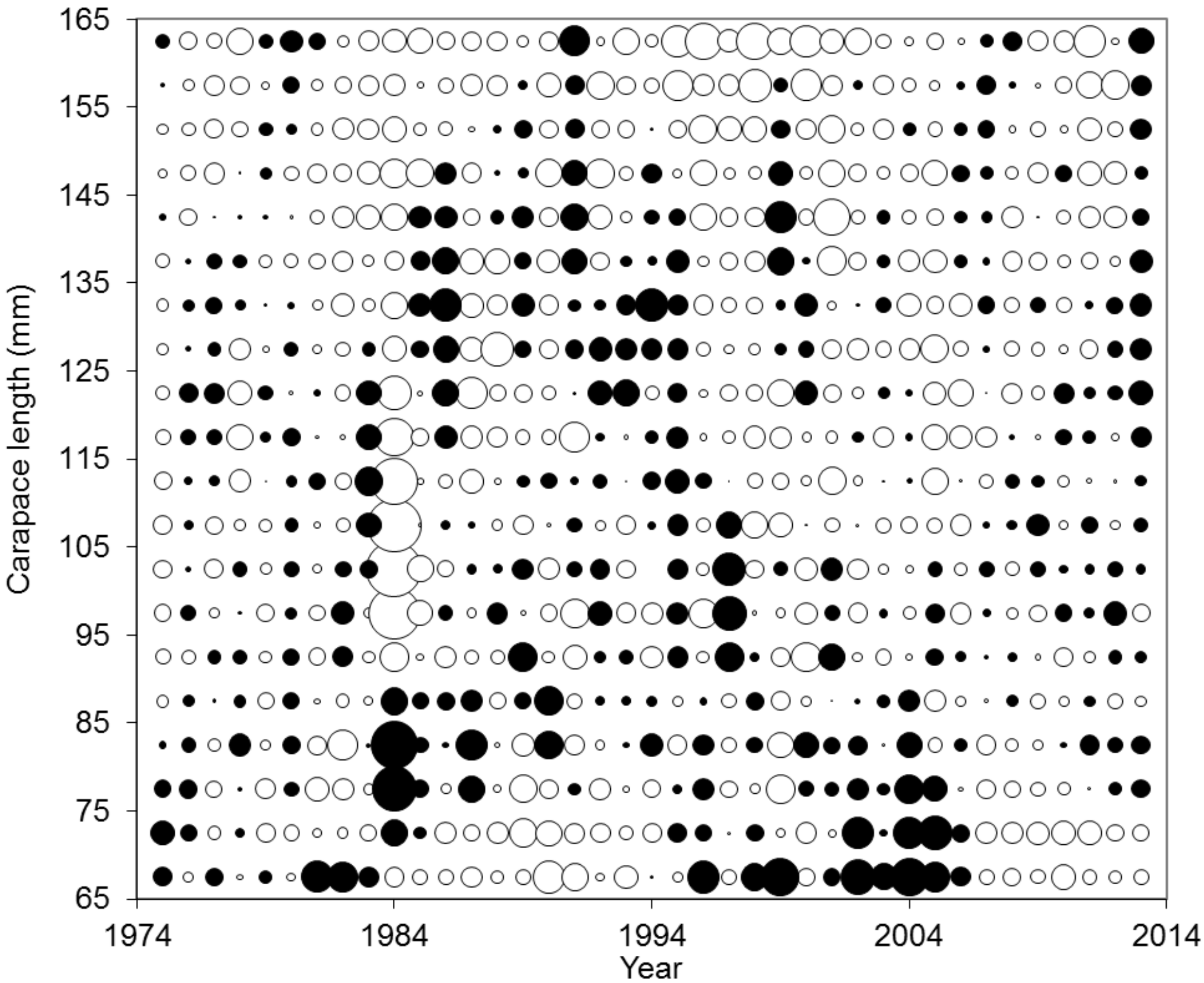


Figure 27(4nb). Standardized residuals of proportions of survey female red king crabs under scenario 4nb. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

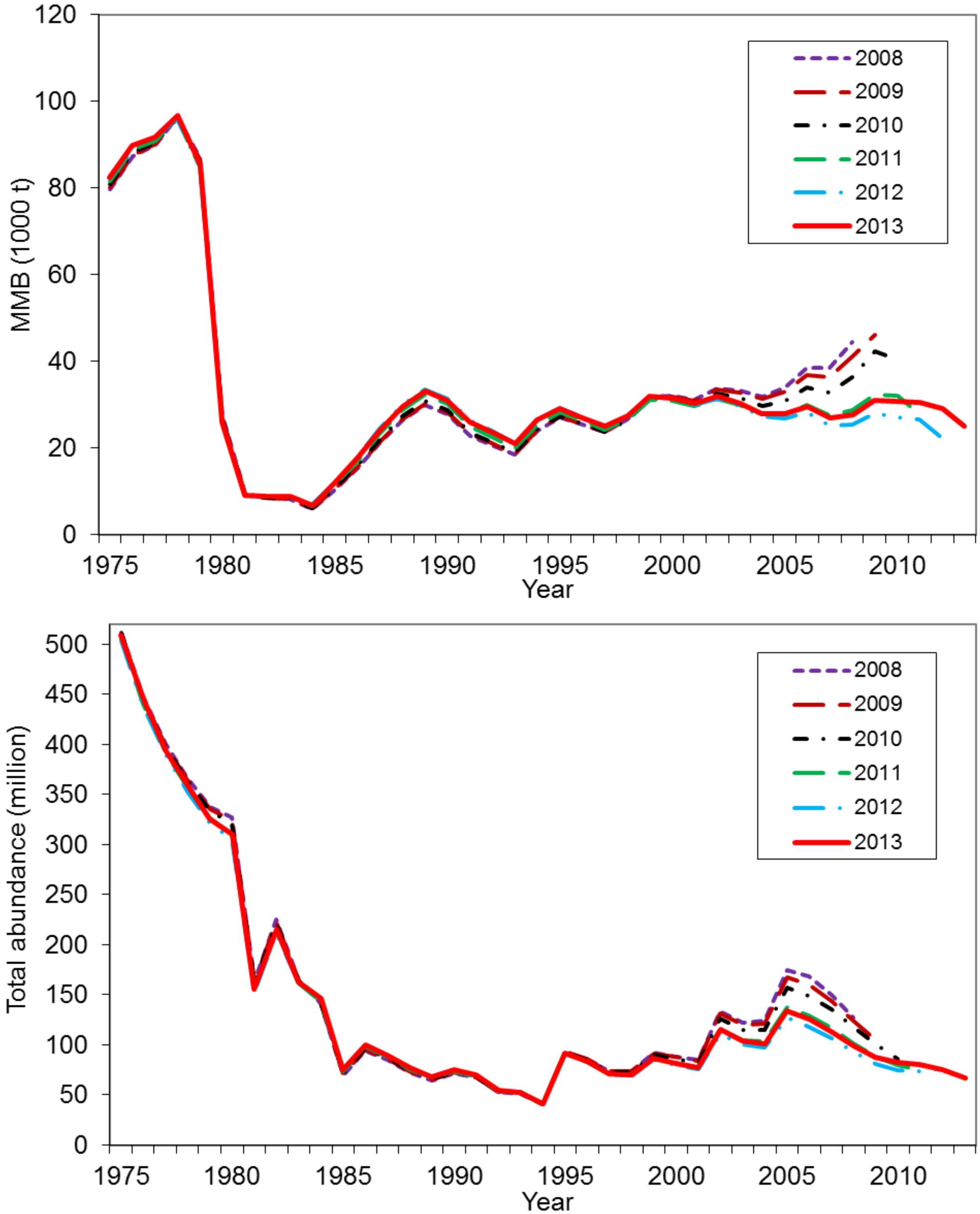


Figure 28(4). Comparison of estimates of mature male biomass on Feb. 15 (top) and total abundance (bottom) of Bristol Bay red king crab from 1975 to 2013 made with terminal years 2008-2013 with scenario 4. These are results of the 2013 model. Legend shows the terminal year. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

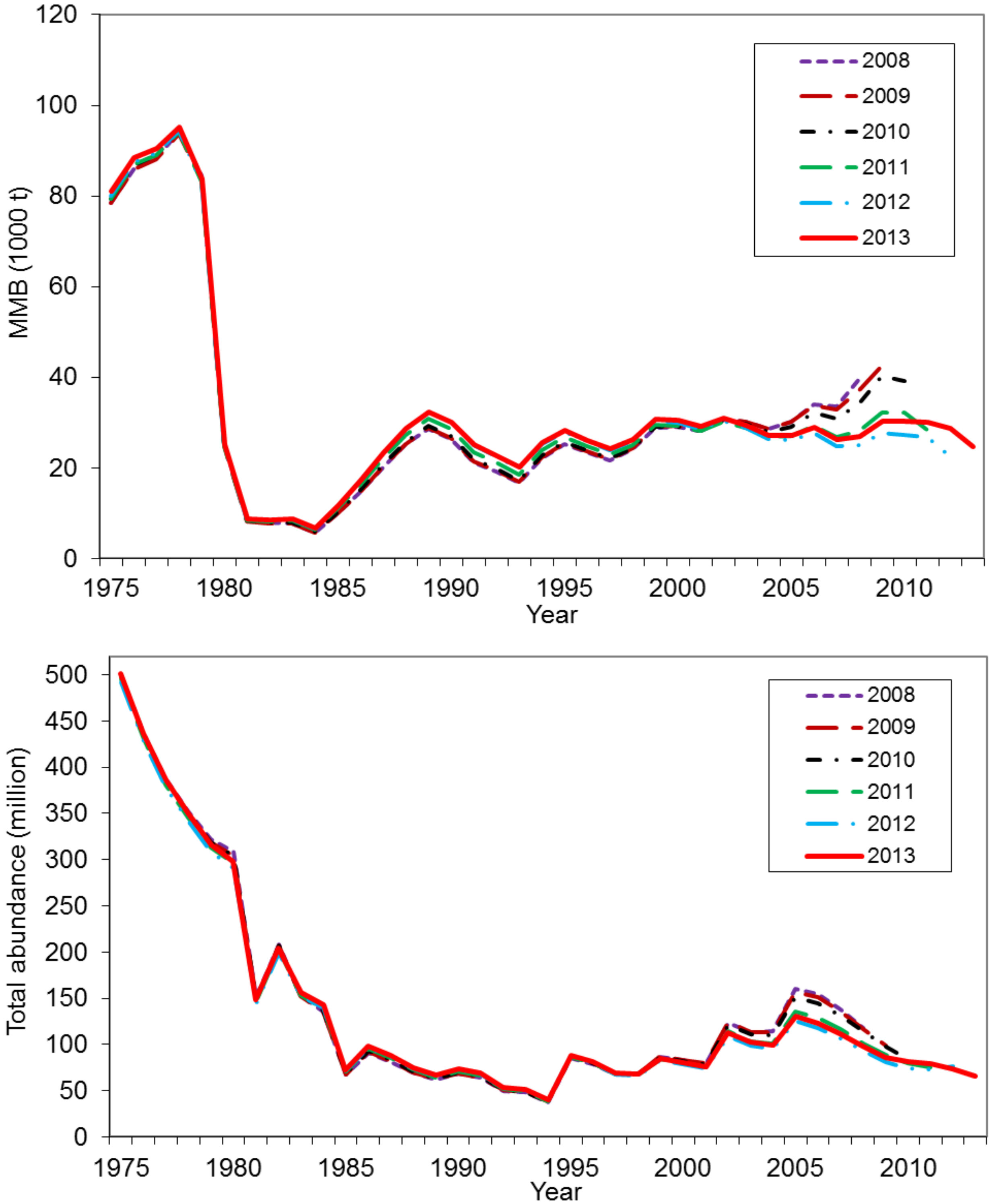
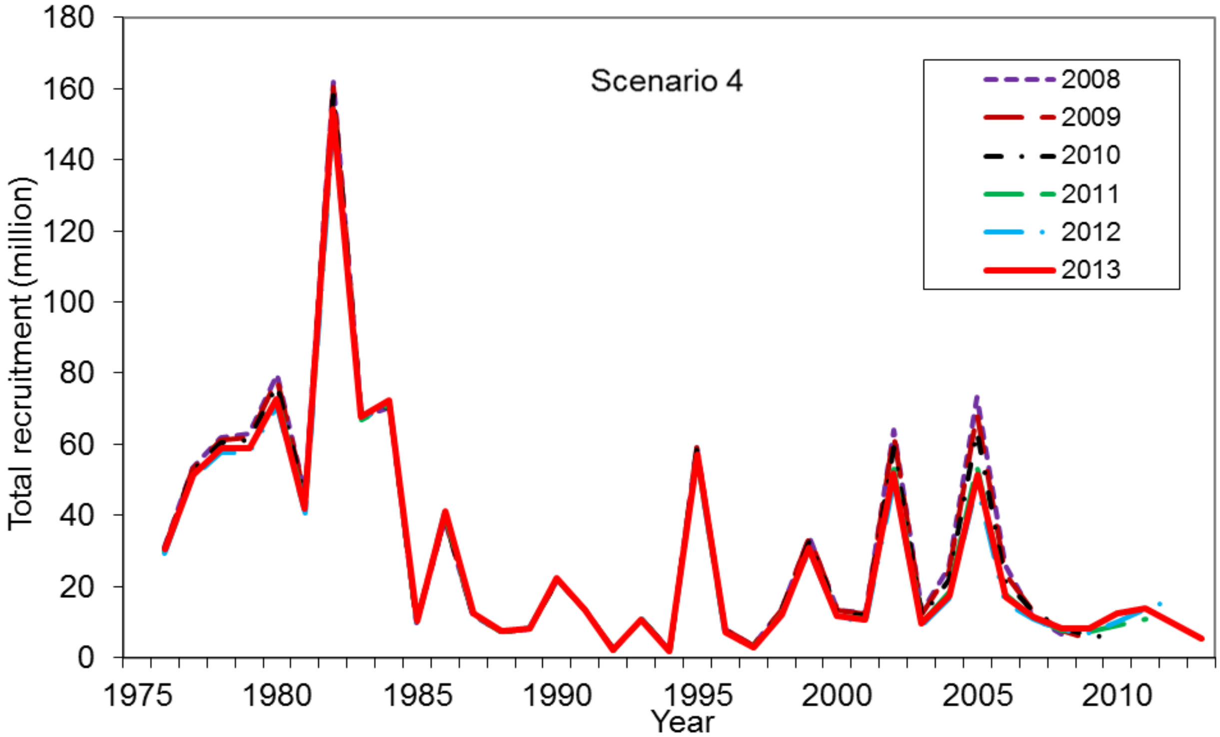


Figure 28(4nb). Comparison of estimates of mature male biomass on Feb. 15 (top) and total abundance (bottom) of Bristol Bay red king crab from 1975 to 2013 made with terminal years 2008-2013 with scenario 4nb. These are results of the 2013 model. Legend shows the terminal year. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.



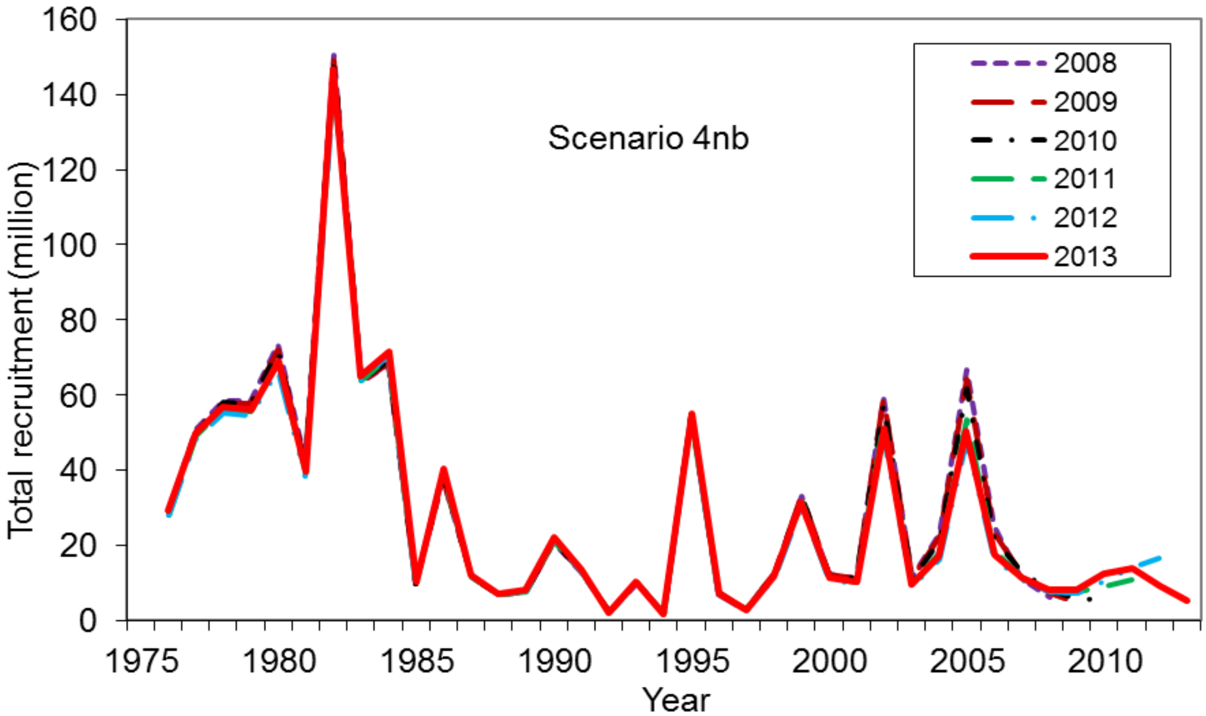
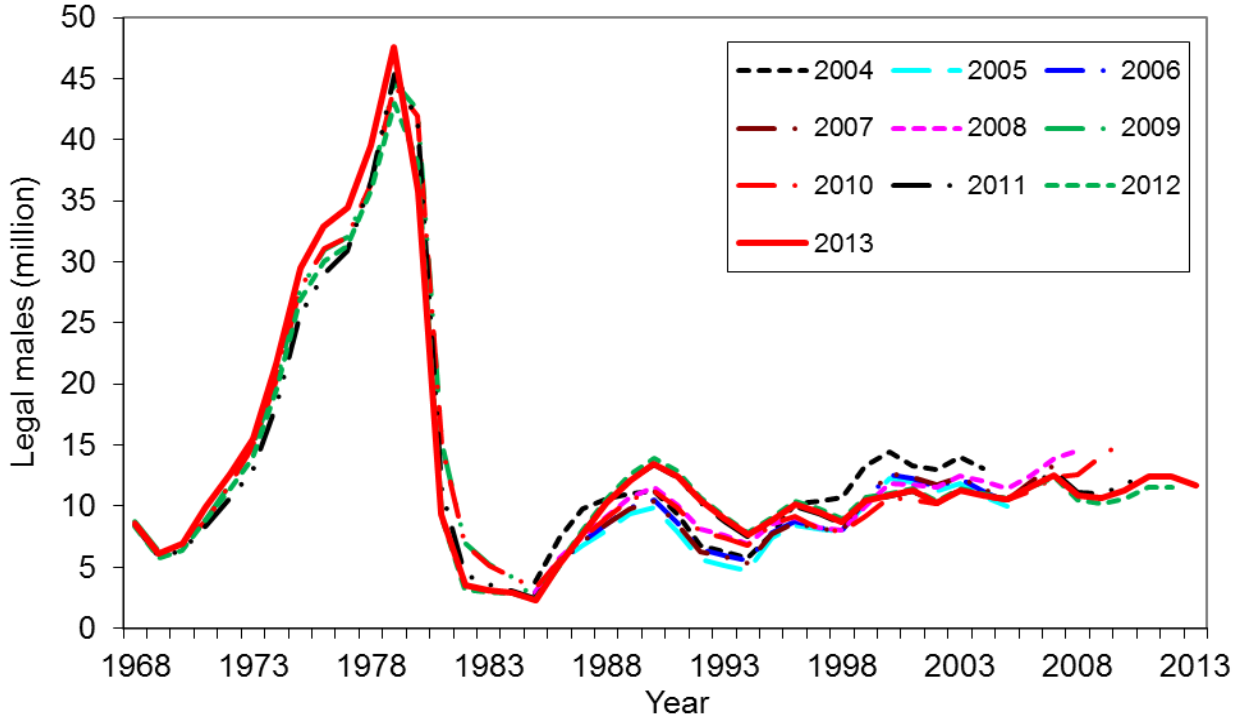


Figure 28(4&4nb). Comparison of estimates of total recruitment for scenario 4 (top) and scenario 4nb (bottom) of Bristol Bay red king crab from 1976 to 2013 made with terminal years 2008-2013. These are results of the 2013 model. Legend shows the terminal year. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.



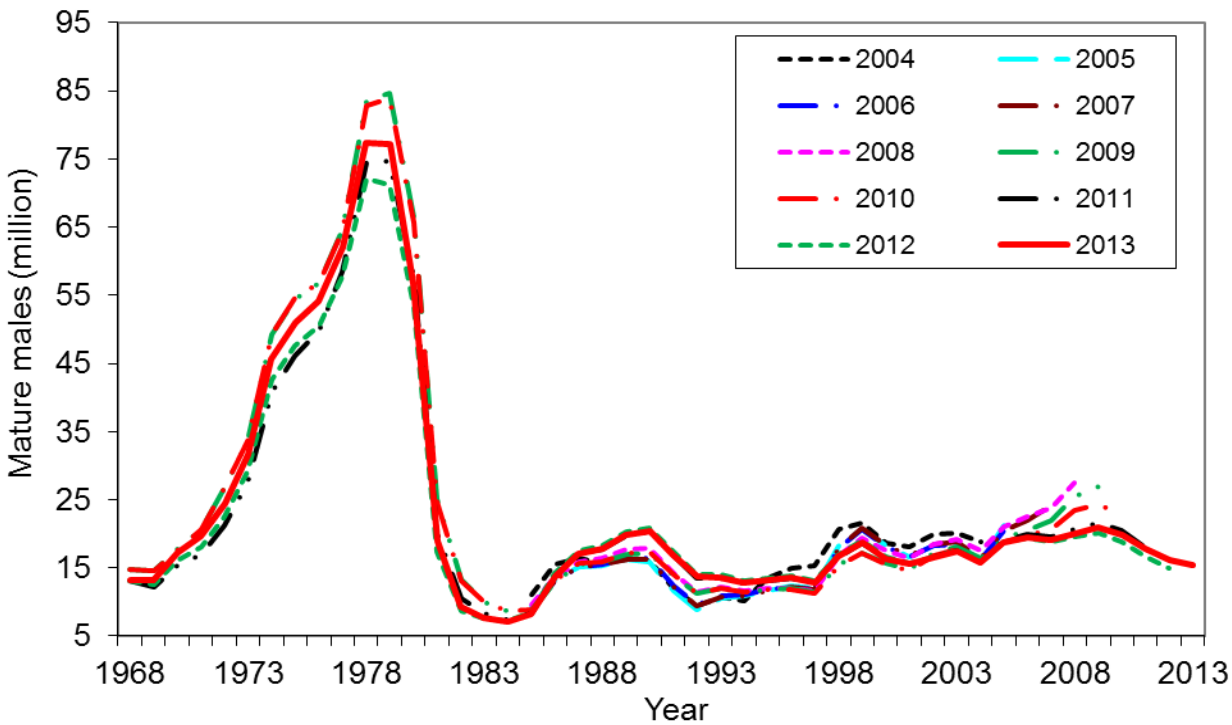


Figure 29. Comparison of estimates of legal male abundance (top) and mature males (bottom) of Bristol Bay red king crab from 1968 to 2013 made with terminal years 2004-2013 with the base scenarios. These are results of historical assessments. Legend shows the year in which the assessment was conducted. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

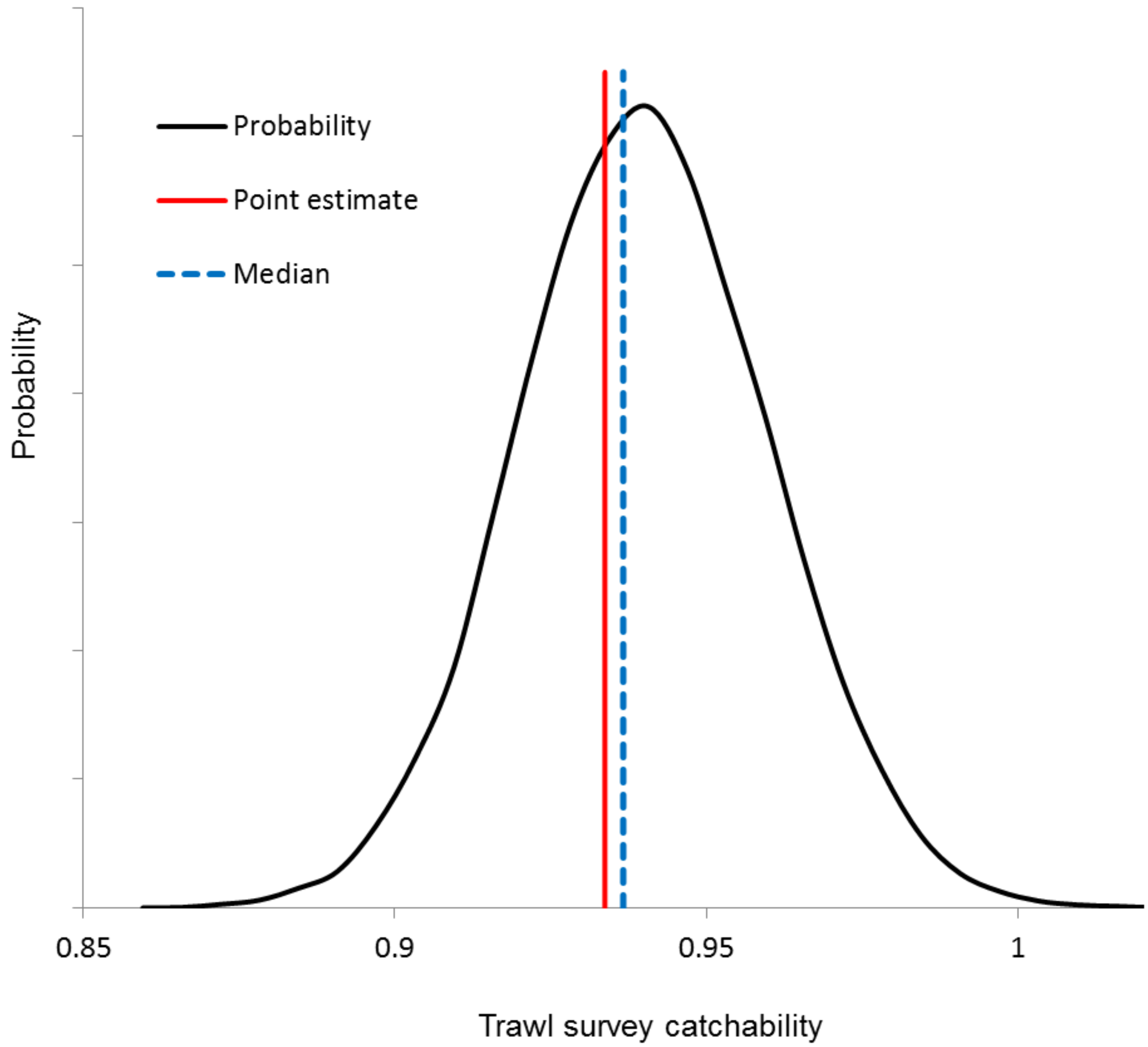


Figure 30. Probability distributions of estimated trawl survey catchability (*Q*) under scenario 4nb with the mcmc approach. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

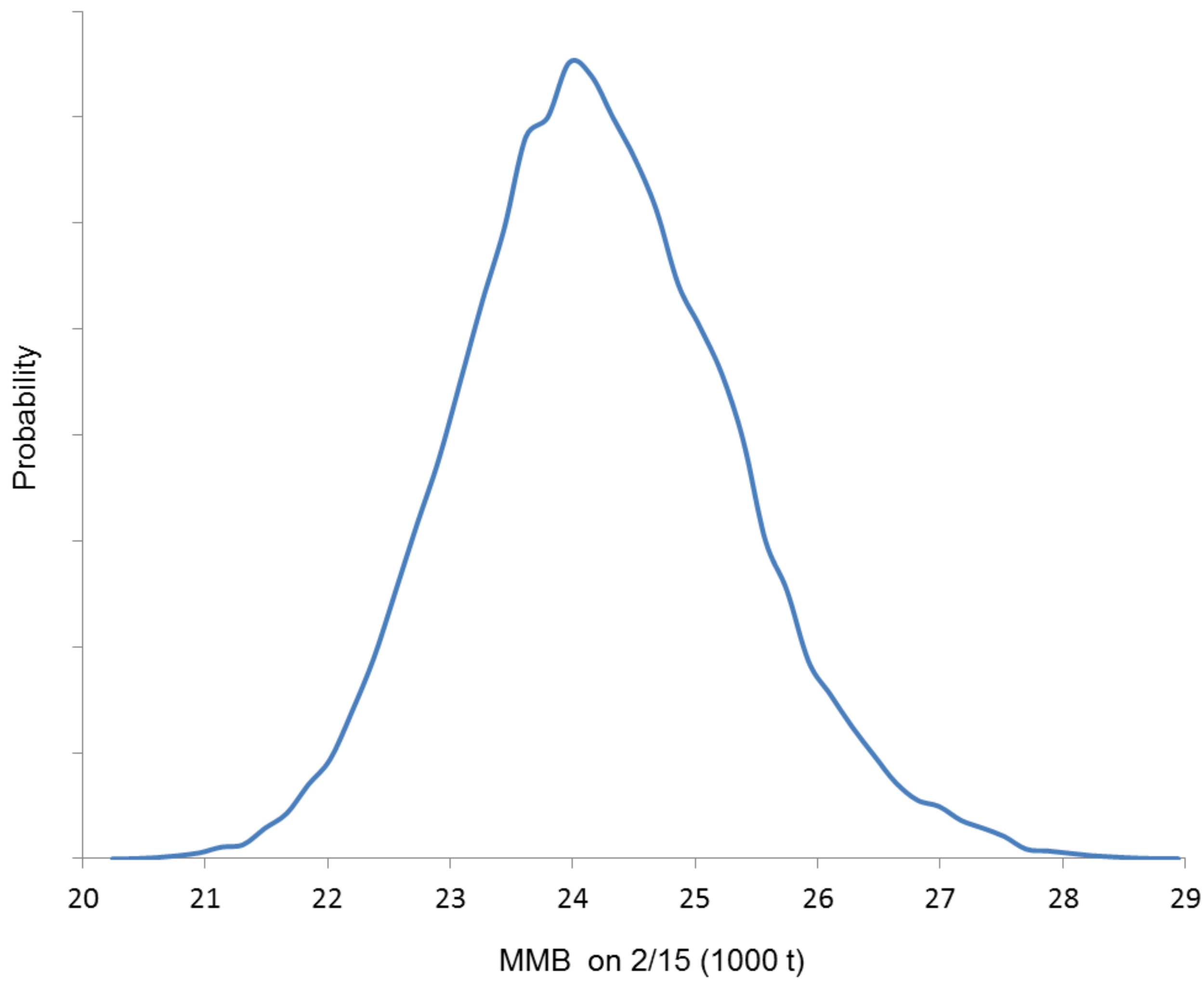


Figure 31a. Probability distributions of estimated mature male biomass on Feb. 15, 2014 with $F_{35\%}$ under scenario 4 with the mcmc approach. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

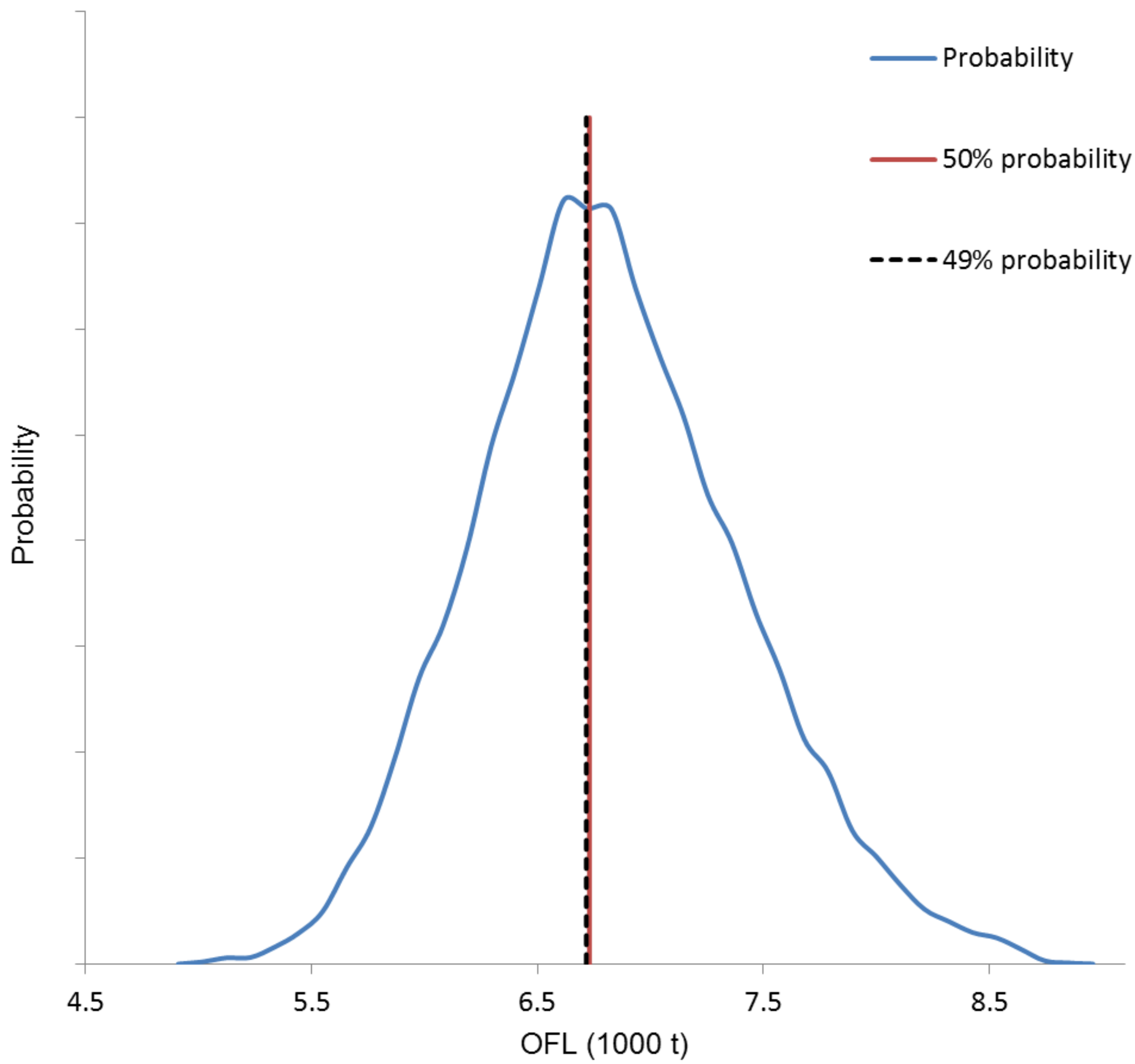


Figure 31b. Probability distributions of the 2013 estimated OFL with scenario 4 with the mcmc approach. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

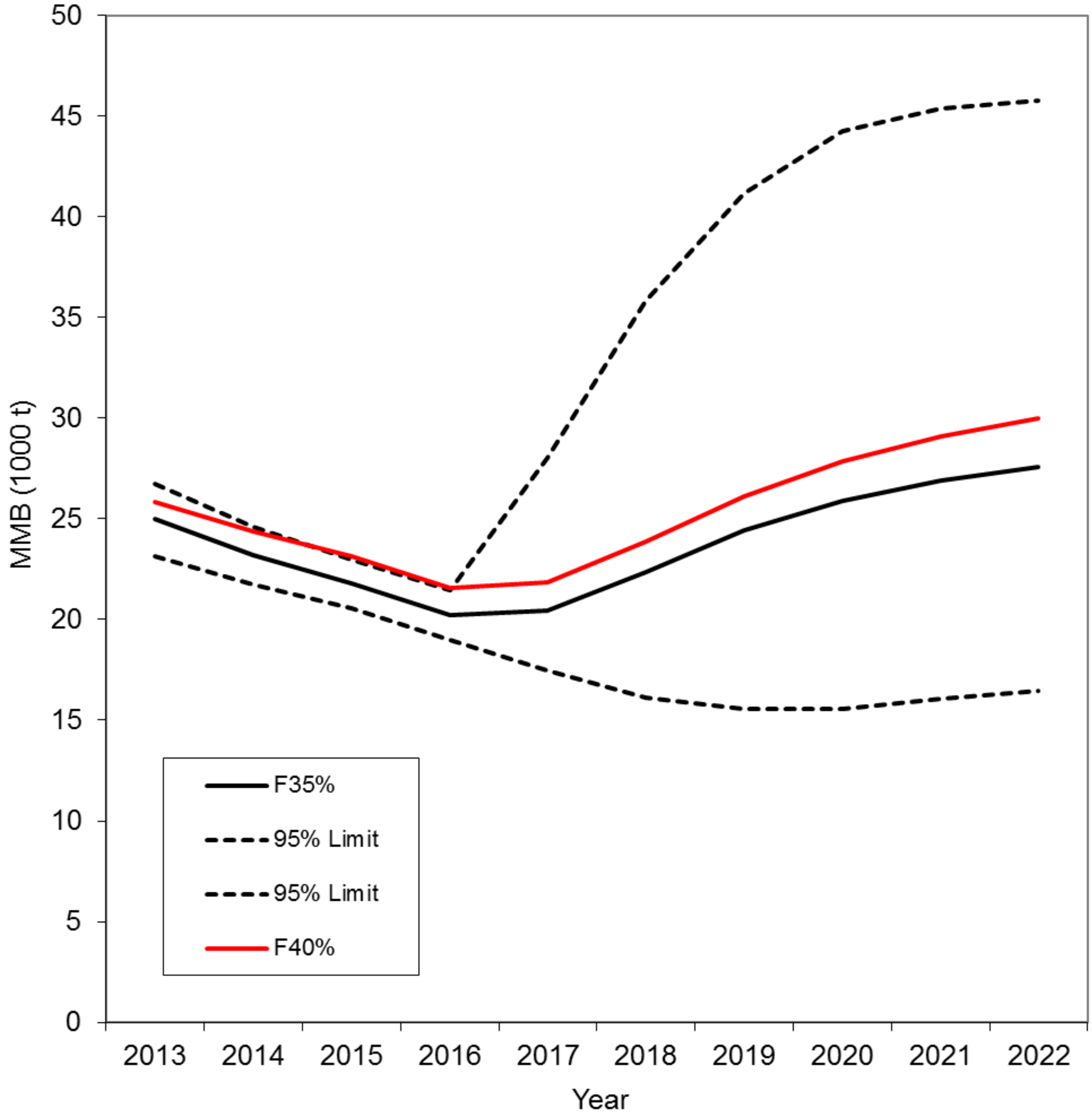


Figure 32. Projected mature male biomass on Feb. 15 with $F_{40\%}$ and $F_{35\%}$ harvest strategy during 2013-2022. Input parameter estimates are based on scenario 4. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively, and the confidence limits are for the $F_{35\%}$ harvest strategy.

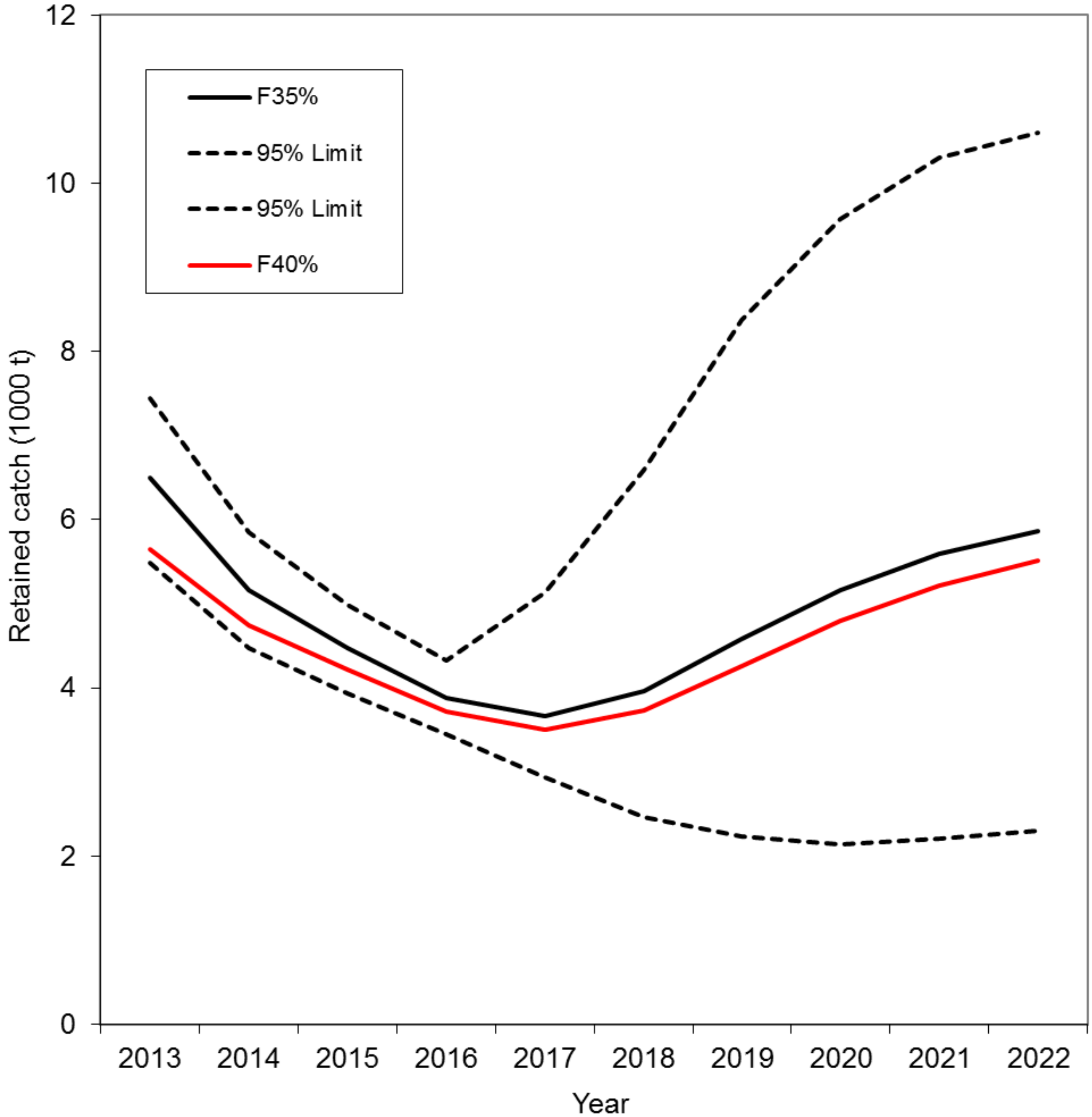


Figure 33. Projected retained catch biomass with $F_{40\%}$ and $F_{35\%}$ harvest strategy during 2013-2122. Input parameter estimates are based on scenario 4. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively, and the confidence limits are for the $F_{35\%}$ harvest strategy.

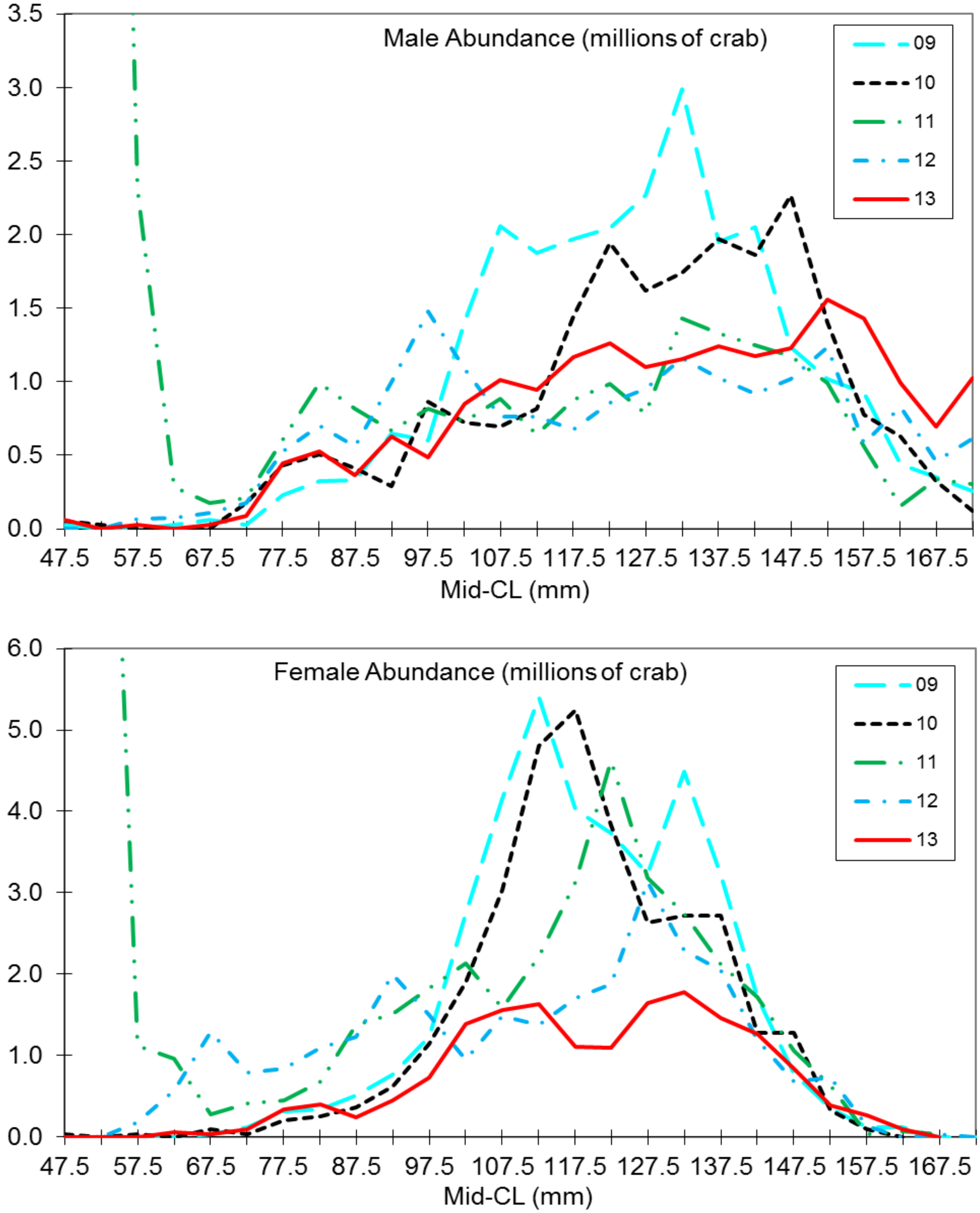


Figure 34. Length frequency distributions of male (top panel) and female (bottom panel) red king crabs in Bristol Bay from NMFS trawl surveys during 2009-2013. For purposes of these graphs, abundance estimates are based on area-swept methods.

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). Male 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:

$$N_{l+1,t+1} = \sum_{l'=1}^{l'=l+1} \{P_{l',l+1}[(N_{l',t} + O_{l',t})\, e^{-M_t} - (C_{l',t} + D_{l',t})\, e^{(y_t-1)M_t} - T_{l,t}e^{(j_t-1)M_t}]\, m_{l',t}\} + R_{l+1,t+1}\,,$$
$$O_{l+1,t+1} = [(N_{l+1,t} + O_{l+1,t})\, e^{-M_t} - (C_{l+1,t} + D_{l+1,t})\, e^{(y_t-1)M_t} - T_{l+1,t}e^{(j_t-1)M_t}](1 - m_{l+1,t}), \qquad (1)$$

where

- $N_{l,t}$ is newshell crab abundance in length class *l* and year *t*,
- $O_{l,t}$ is oldshell crab abundances in length class *l* and year *t*,
- M is the instantaneous natural mortality,
- $m_{l,t}$ is the molting probability for length class *l* and year *t*,
- $R_{l,t}$ is recruitment into length class *l* in year *t*,
- y_t is the lag in years between the assessment survey and the mid fishery time in year *t*,
- j_t is the lag in years between the assessment survey and the mid Tanner crab fishery time in year *t*,
- $P_{l',l}$ is the proportion of molting crabs growing from length class *l'* to *l* after one molt,
- $C_{l,t}$ is the retained catch of length class *l* in year *t*, and
- $D_{l,t}$ is the discarded mortality catch of length class *l* in year *t*, including directed pot and trawl bycatch,
- $T_{l,t}$ is the discarded mortality catch of length class *l* in year *t* from the Tanner crab fishery.

The minimum carapace length for males is set at 65 mm, and crab abundance is modeled with a length-class interval of 5 mm. The last length class includes all crabs ≥160-mm CL. There are 20 length classes/groups. $P_{l',l}$, m_l, $R_{l,t}$, $C_{l,t}$, and $D_{l,t}$ are computed as follows:

Mean growth increment per molt is assumed to be a linear function of pre-molt length:

$$G_l = a + b\,\iota, \qquad (2)$$

where *a* and *b* are constants. Growth increment per molt is assumed to follow a gamma distribution:

$$g(x\,|\,\alpha_l,\beta) = x^{\alpha_l-1}\ e^{-x/\beta}/[\beta^{\alpha_l}\ \Gamma(\alpha_l)]. \qquad (3)$$

The expected proportion of molting individuals growing from length class l_1 to length class l_2 after one molt is equal to the sum of probabilities within length range [ι_1, ι_2) of the receiving length class l_2 at the beginning of the next year:

$$P_{l_1,l_2} = \int_{\iota_1-\iota}^{\iota_2-\iota} g(x\,|\,\alpha_l,\beta)dx, \qquad (4)$$

where ι is the mid-length of length class l_1. For the last length class L, $P_{L,L} = 1$.

The molting probability for a given length class l is modeled by an inverse logistic function:

$$m_{l,t} = 1 - \frac{1}{1+e^{-\beta\ (l-L_{50})}}, \qquad (5)$$

where

β, L_{50} are parameters with three sets of values for three levels of molting probabilities, and ι is the mid-length of length class l.

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, and size-dependent variables, U_l, representing the proportion of recruits belonging to each length class. R_t is assumed to consist of crabs at the recruiting age with different lengths and thus represents year class strength for year t. $R_{l,t}$ is computed as

$$R_{l,t} = R_t U_l, \qquad (6)$$

where U_l is described by a gamma distribution similar to equations (3) and (4) with a set of parameters α_r and β_r. Because of different growth rates, recruitment was estimated separately for males and females under a constraint of approximately equal sex ratios of recruitment over time.

Before 1990, no observed bycatch data were available in the directed pot fishery; the crabs 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^{o} 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. For bycatch, all fishery catch and discard mortality bycatch are estimated as:

$$C_{l,t}\ or\ D_{l,t} = (N_{l,t} + O_{l,t})\ e^{-y_t M_t}(1-e^{-s_l F_t}) \qquad (7)$$

where

s_l is selectivity for retained, pot or trawl discarded mortality catch of length class *l*, and

F_t is full fishing mortality of retained, pot or trawl discarded mortality catch in year *t*.

For discarded mortality bycatch from the Tanner crab fishery, y_t is replaced by j_t in the right side of equation (7).

The female crab model is the same as the male crab model except that the retained catch equals zero, molting probability equals 1.0 to reflect annual molting (Powell 1967), and growth matrix, *P*, changes over time due to change in size at maturity for females. The minimum carapace length for females is set at 65 mm, and the last length class includes all crabs ≥140-mm CL, resulting in length groups 1-16. Three sets of growth increments per molt are used for females due to changes in sizes at maturity over time (Figures A2 and A3).

ii. Fisheries Selectivities

Retained selectivity, female pot bycatch selectivity, and both male and female trawl bycatch selectivity are estimated as a function of length:

$$s_l = \frac{1}{1+e^{-\beta\ (\iota - L_{50})}}, \tag{8}$$

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. Because some catches were from the foreign fisheries during 1968-1972, a different set of parameters (β, L_{50}) are estimated for retained males for this period and a third parameter, sel_62.5mm, is used to explain the high proportion of catches in the last length group.

Male pot bycatch selectivity is modeled by two linear functions:

$$\begin{aligned} s_l &= \varphi + \kappa\,\iota, \quad if\ \ \iota < 135\,\text{mm CL}, \\ s_l &= s_{l-1} + 5\gamma, \quad if\ \ \iota > 134\,\text{mm CL} \end{aligned} \tag{9}$$

Where

φ, κ, γ are parameters.

During 2005-2012, a portion of legal males were also discarded in the pot fishery. The selectivity for this high grading was estimated to be the retained selectivity in each year times a high grading parameter, hg_t.

iii. Trawl Survey Selectivities/Catchability

Trawl survey selectivities/catchability are estimated as

$$s_l = \frac{Q}{1 + e^{-\beta\ (l - L_{50})}}, \tag{10}$$

with different sets of parameters (β, L_{50}) estimated for males and females as well as two different periods (1975-81 and 1982-13). 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 crabs 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 crabs are likely in the shallow water areas that are not accessible for the trawl survey, NMFS survey catchability/selectivity consists of capture probability and crab availability.

b. Software Used: AD Model Builder (Otter Research Ltd. 1994).

c. Likelihood Components

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

$$Rf = \prod_{l=1}^{L}\prod_{t=1}^{T}\prod_{s=1}^{2}\prod_{sh=1}^{2}\frac{\left\{\exp\left[-\frac{(p_{l,t,s,sh}-\hat{p}_{l,t,s,sh})^2}{2\sigma^2}\right]+0.01\right\}}{\sqrt{2\pi\sigma^2}}, \tag{11}$$

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

where

L is the number of length groups,

T is the number of years, and

n is 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:

$$
\begin{aligned}
&\textit{Length compositions}: \quad -\sum \ln(Rf_i)\ , \\
&\textit{Biomasses other than survey}: \quad \lambda_j \sum \left[\ln(C_t / \hat{C}_t)^2\right], \\
&\textit{NMFS survey biomass}: \quad \sum \left[\ln(B_t / \hat{B}_t)^2 / (2\ln(CV_t^2+1))\right], \\
&\textit{BSFRF mature males}: \quad \sum [\ln(\ln(CV_t^2+1))^{0.5} + \ln(N_t / \hat{N}_t)^2 / (2\ln(CV_t^2+1))], \\
&\textit{R variation}: \quad \lambda_R \sum [\ln(R_t / \overline{R})^2]\ , \\
&\textit{R sex ratio}: \quad \lambda_s [\ln(\overline{R}_M / \overline{R}_F)^2]\ , \\
&\textit{Trawl bycatch fishing mortalities}: \lambda_t [\ln(F_{t,t} / \overline{F}_t)^2]\ , \\
&\textit{Pot female bycatch fishing mortalities}: \lambda_p [\ln(F_{t,f} / \overline{F}_f)^2], \\
&\textit{Trawl survey catchability}: (Q - \hat{Q})^2 / (2\sigma^2).
\end{aligned} \tag{12}
$$

Where

R_t is the recruitment in year *t*,

$\overline{R}$ is the mean recruitment,

$\overline{R}_M$ is the mean male recruitment,

$\overline{R}_F$ is the mean female recruitment,

$\overline{F}_t$ is the mean trawl bycatch fishing mortality,

$\overline{F}_f$ is the mean pot female bycatch fishing mortality,

Q is summer trawl survey catchability,

σ is the estimated standard deviation of *Q*.

For BSFRF mature male abundance or total survey biomass, *CV* is the survey *CV* plus *AV*, where *AV* is additional *CV* and estimated in the model. The mature male abundance is used for all scenarios except scenario 2. Total survey biomass is used for scenario 2.

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 and about the variances of these random variables.

d. Population State in Year 1.

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

e. Parameter estimation framework:

i. Parameters estimated independently

Basic natural mortality, length-weight relationships, and mean growth increments per molt were estimated independently outside of the model. Mean length of recruits to the model depends on growth and was assumed to be 72.5 for both males and females. High grading parameters hg_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, and 0.0240 in 2012, 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.

(2). Length-weight Relationship

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

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

Ovigerous Females: $W = 0.003593\,L^{2.666076}$, (13)

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

where

W is weight in grams, and
L is 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 1994-2013, respectively, and the data presented in Gray (1963) were used to estimate those for mature females (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 1994-2013, females matured at a slightly higher size, so the growth increment per molt was shifted to high increments for immature crabs (Figure A2). Once mature, the growth increment per molt for male crabs decreases slightly and annual molting probability decreases, whereas the growth increment for female crabs decreases dramatically but annual molting probability remains constant at 1.0 (Powell 1967).

(4). Sizes at Maturity for Females

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 1994-08).

(5). Sizes at Maturity for Males

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

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

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

Bristol Bay red king crab abundance had declined sharply during the early 1980s. Many factors have been speculated for this decline: (i) completely wiped out by fishing: the directed pot fishery, the other directed pot fishery (Tanner crab fishery), and bottom trawling; and (ii) high fishing and natural mortality. With the survey abundance, harvest rates in 1980 and 1981 were among the highest, thus the directed fishing definitely had a big impact on the stock decline, especially legal and mature males. However, for the sharp decline during 1980-1884 for males, 3 out of 5 years had low mature harvest rates.

During 1981-1984 for females, 3 out of 4 years had low mature harvest rates. Also pot catchability for females and immature males are generally much lower than for legal males, so the directed pot fishing alone cannot explain the sharp decline for all segments of the stock during the early 1980s.

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

Several factors may have caused increases in natural mortality. Crab diseases in the early 1980s were documented by Sparks and Morado (1985), but inadequate data were collected to examine their effects on the stock. Stevens (1990) speculated that senescence may be a factor because many crabs 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 crabs. But we lack stomach samples in shallow waters (juvenile habitat) and during the period when red king crabs molt. Also cannibalism occurs during molting periods for red king crabs. 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 crabs, and disease for all crabs. In our model, we estimated one mortality parameter for males and another for females during 1980-1984. We also estimated a mortality parameter for females during 1976-1979 and 1985-1993. These three mortality parameters are additional to the basic natural mortality of 0.18, all directed fishing mortality and non-directed fishing mortality. These three mortality parameters could be attributed to natural mortality as well as undocumented non-directed fishing mortality. The model fit the data much better with these three parameters than without them.

ii. Parameters estimated conditionally

The following model parameters were estimated for male and female crabs: total recruits for each year (year class strength R_t for t = 1976 to 2013), 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 crabs. 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. NMFS survey catchabilities Q for some scenarios were also estimated. Three selectivity parameters are estimated for the survey data from the Bering Fisheries Research Foundation. Annual fishing mortalities were also estimated for the directed pot fishery for males (1975-2012), pot-discarded females from the directed fishery (1990-2012), pot-discarded males and females from the eastern Bering Sea Tanner crab fishery (1991-93), and groundfish trawl discarded males and females (1976-2013). 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 (crabs >64 mm CL) and mature male biomass (males >119 mm CL). Mating time is assumed to Feb. 15.

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

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

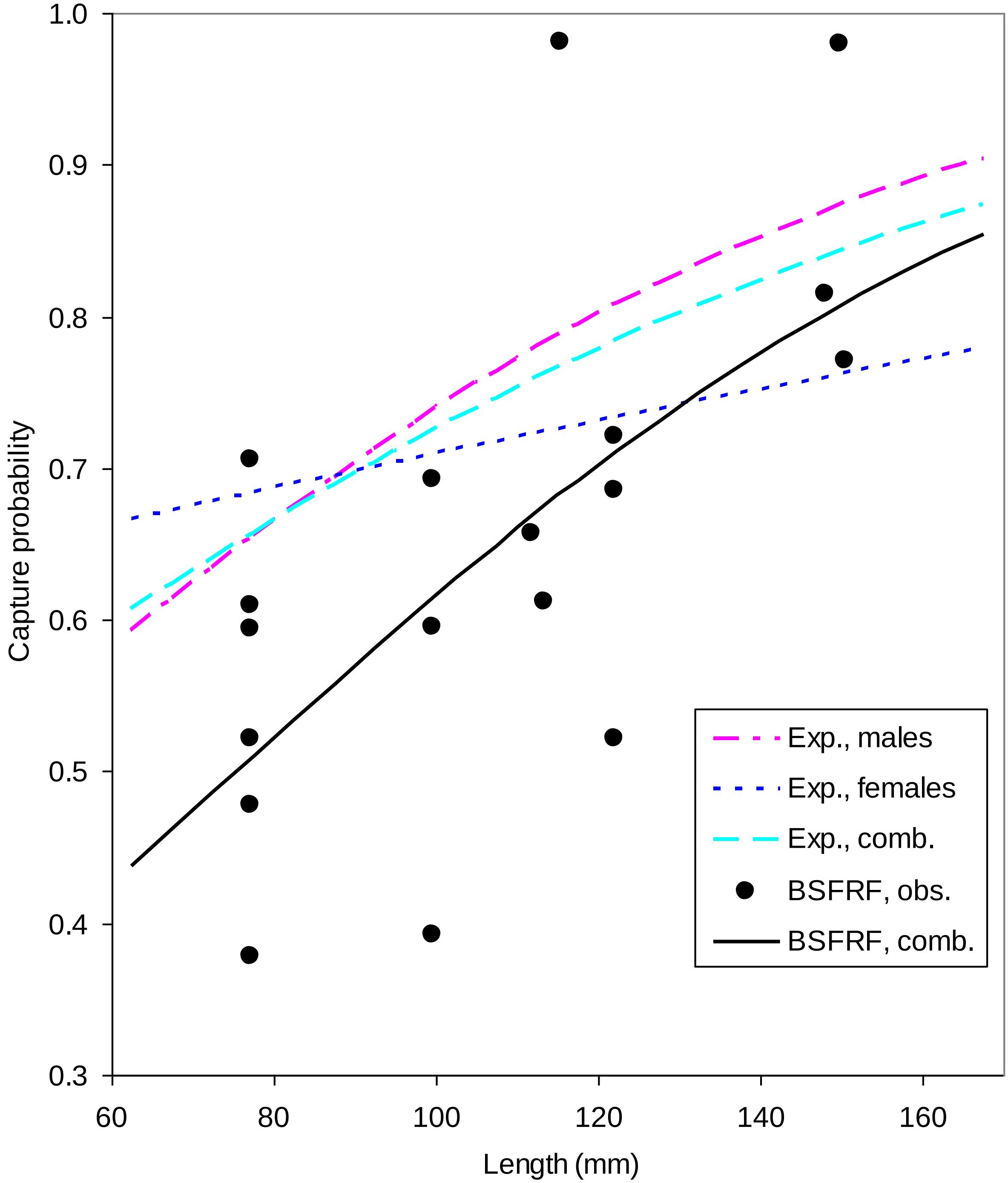


Figure A1. Estimated capture probabilities for NMFS Bristol Bay red king crab trawl surveys by Weinberg et al. (2004) and the Bering Sea Fisheries Research Foundation surveys.

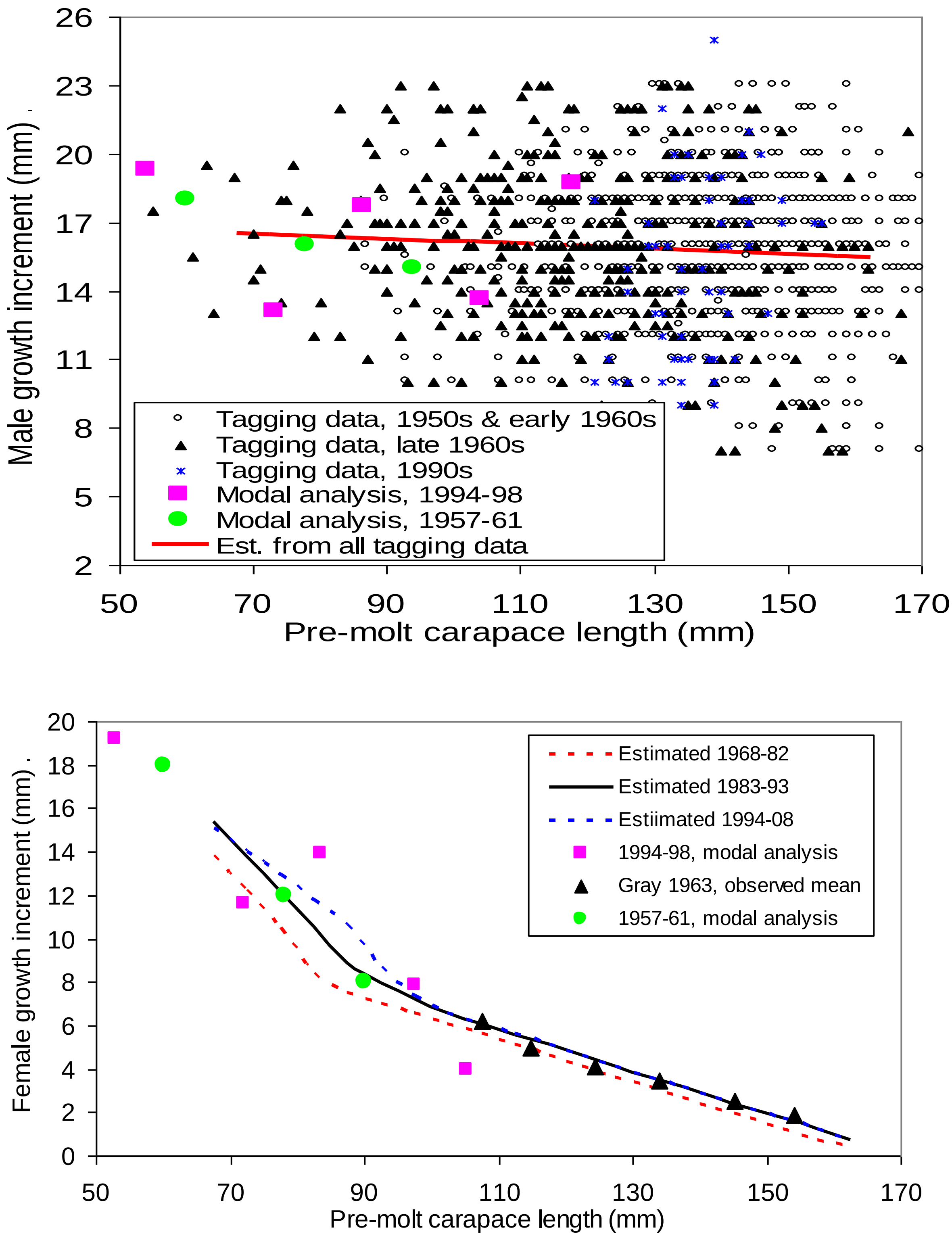


Figure A2. Mean growth increments per molt for Bristol Bay red king crab. Note: "tagging"---based on tagging data; "mode"---based on modal analysis.

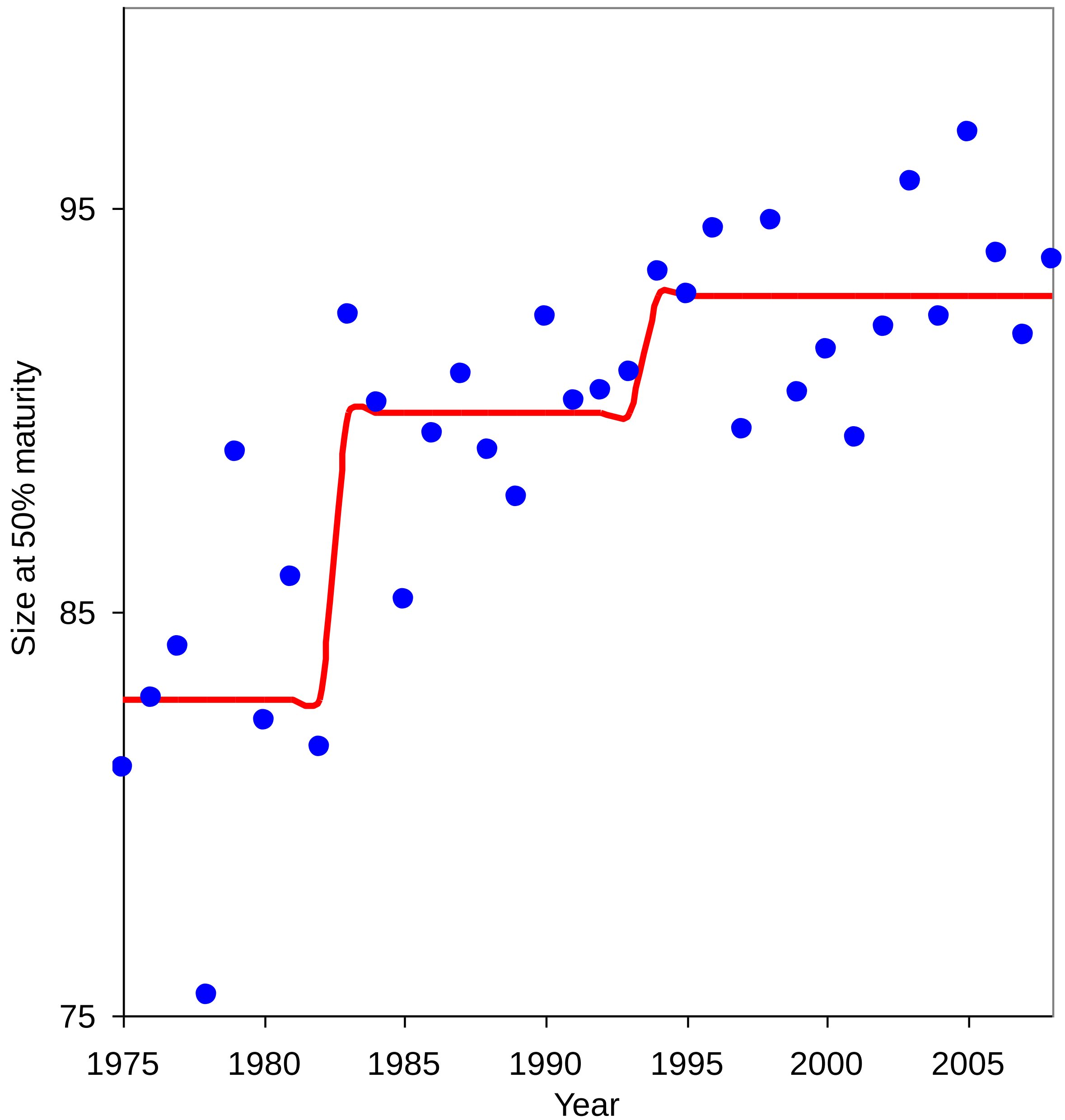


Figure A3. Estimated sizes at 50% maturity for Bristol Bay female red king crab from 1975 to 2008. Averages for three periods (1975-82, 1983-93, and 1994-08) are plotted with a line.

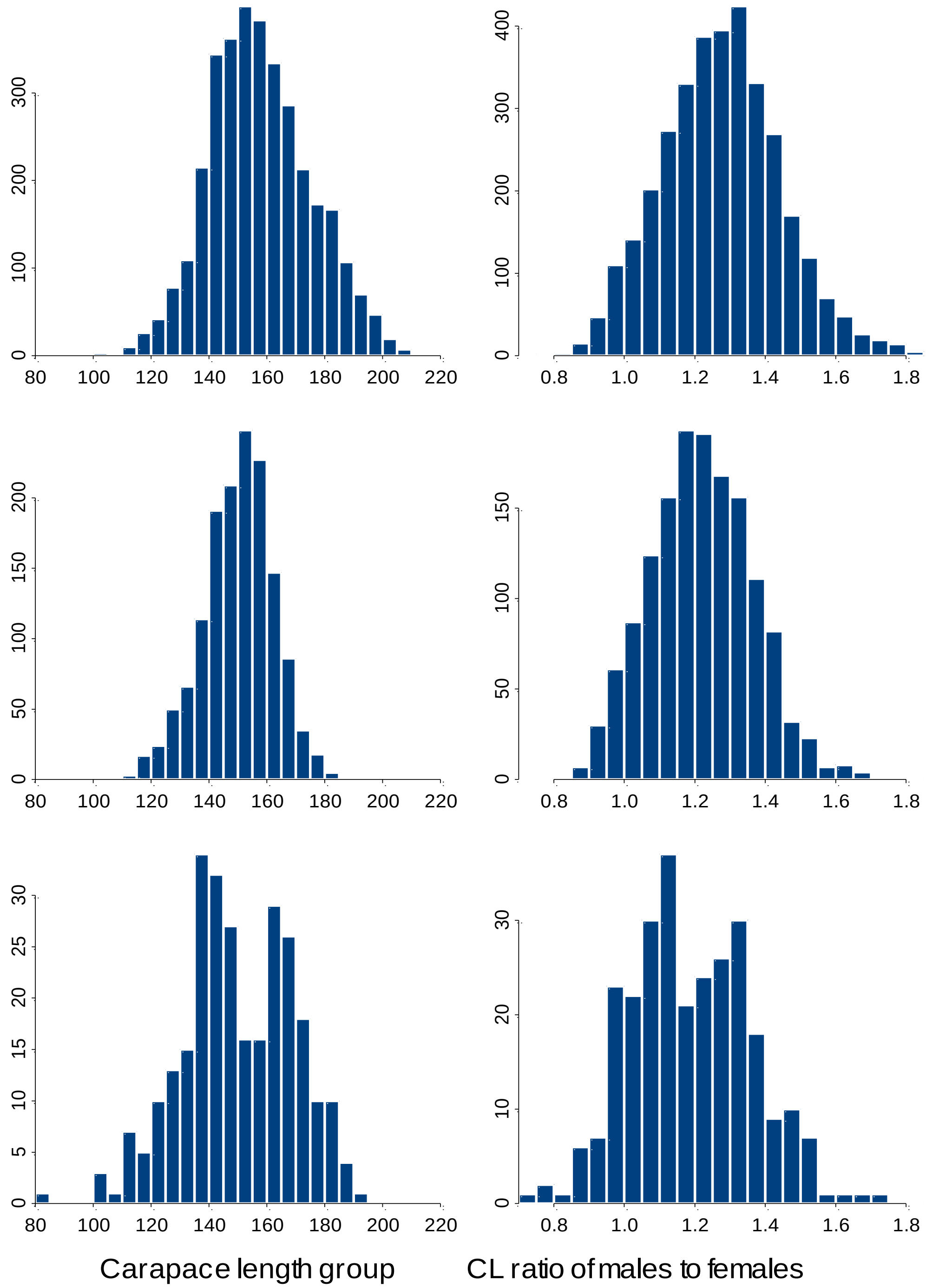


Figure A4. Histograms of carapace lengths (CL) and CL ratios of males to females for male shell ages ≤13 months of red king crab males in grasping pairs; Powell's Kodiak data. Upper plot: all locations and years pooled; middle plot: location 11; lower plot: locations 4 and 13. Sizes at maturity for Kodiak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

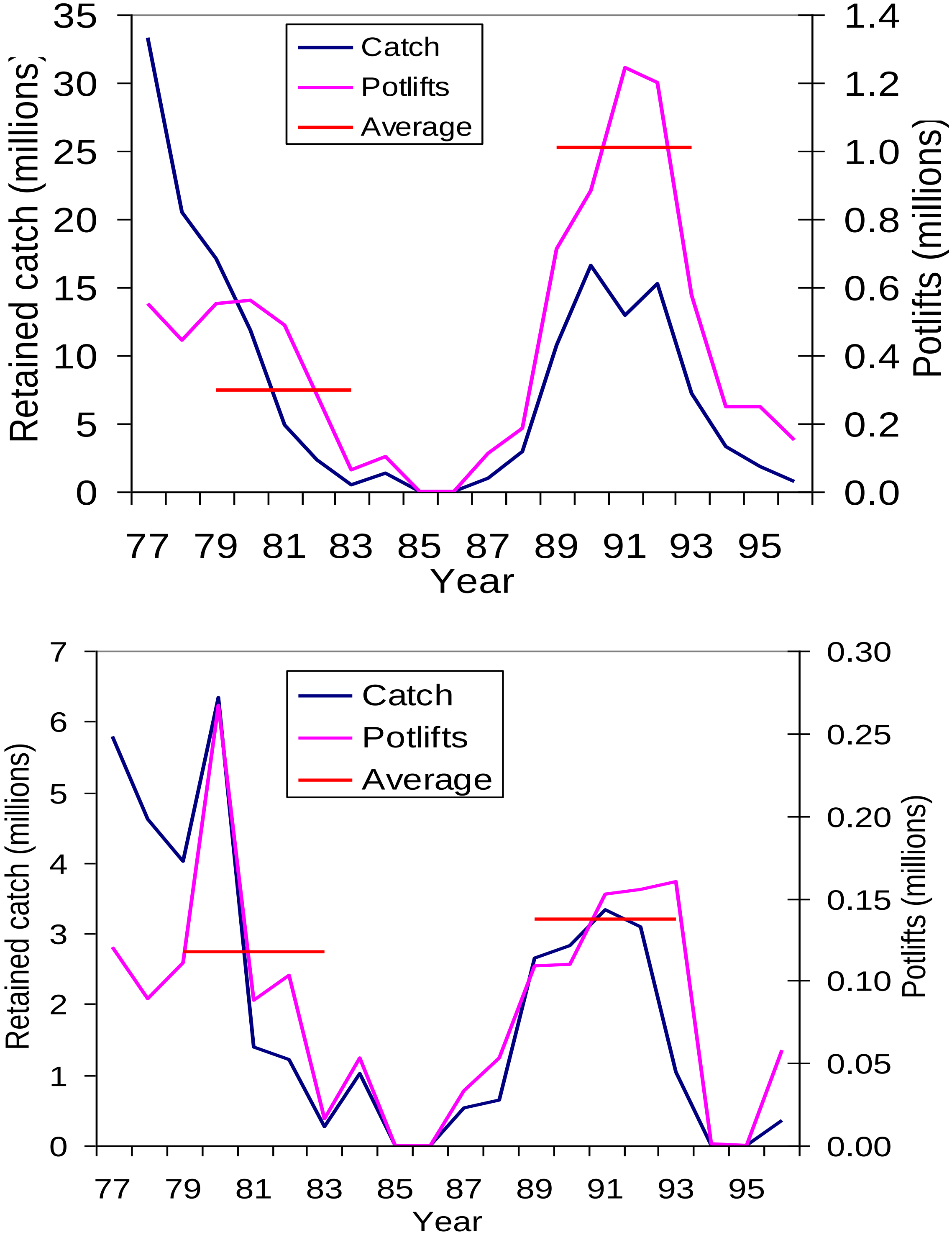
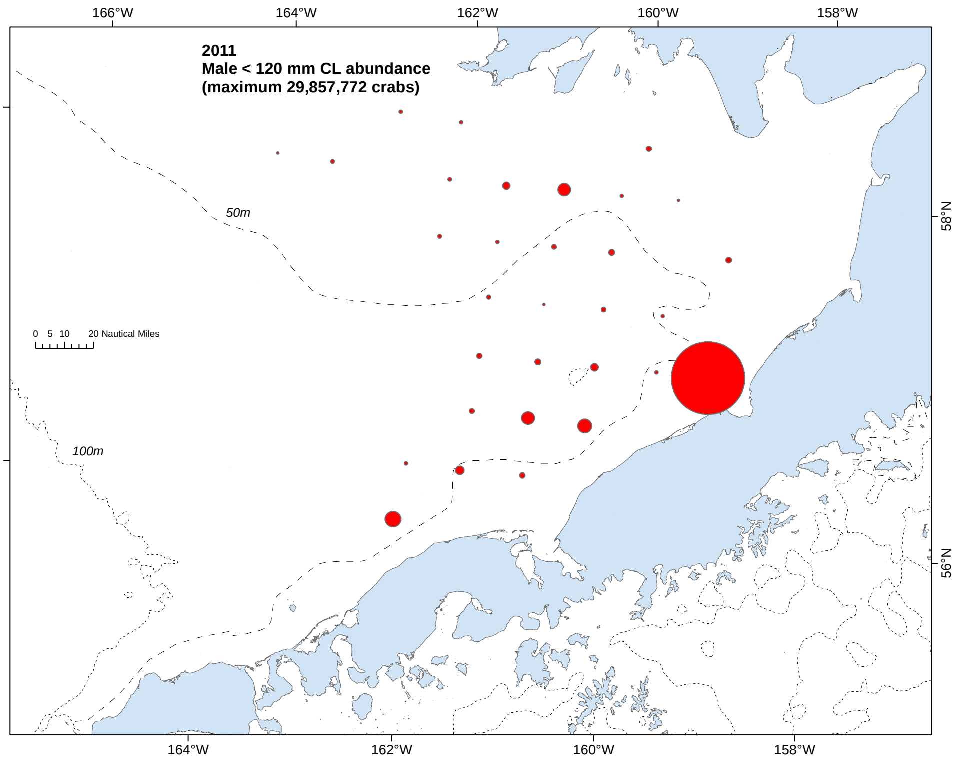
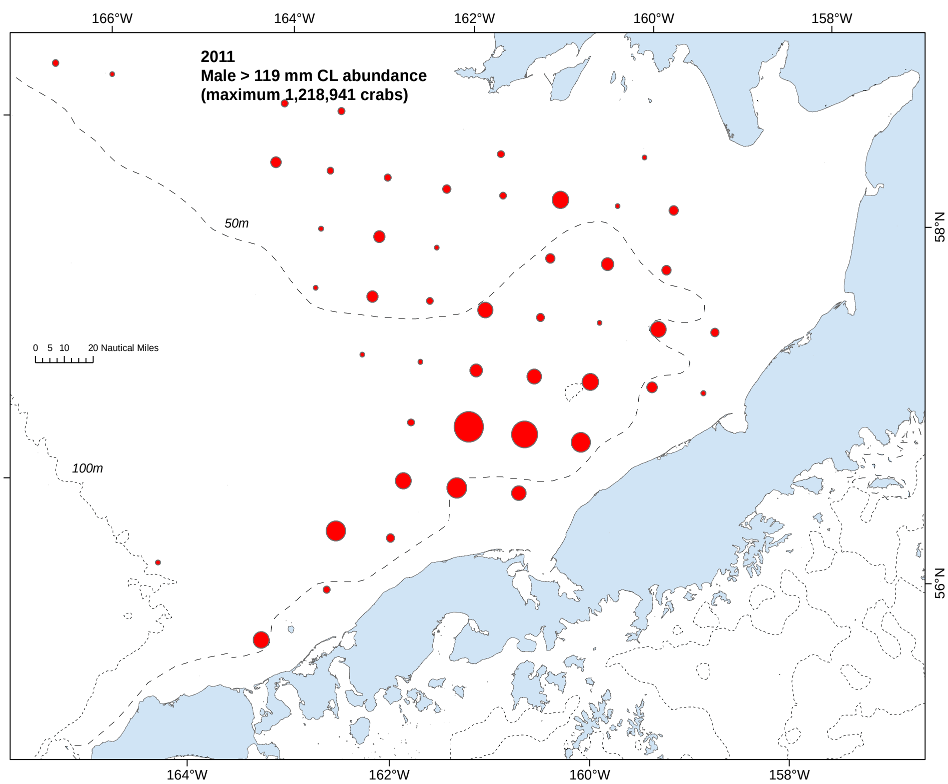
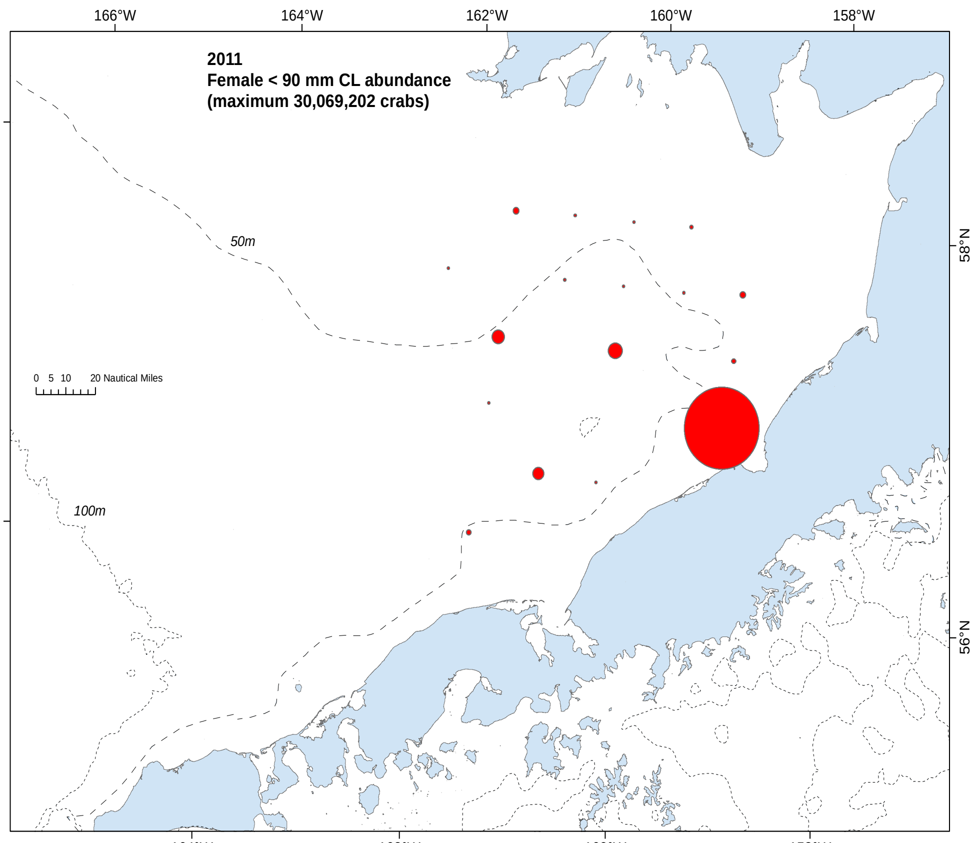


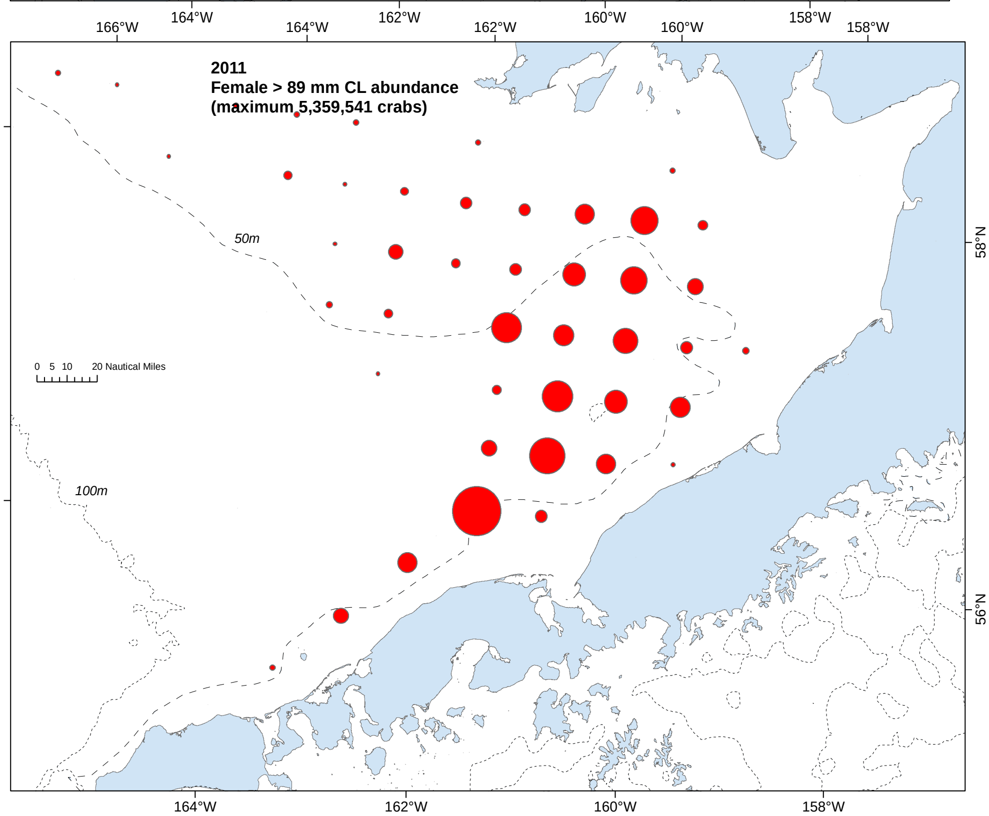
Figure A5. Retained catch and potlifts for total eastern Bering Sea Tanner crab fishery (upper plot) and the Tanner crab fishery east of 163^{o} W (bottom).

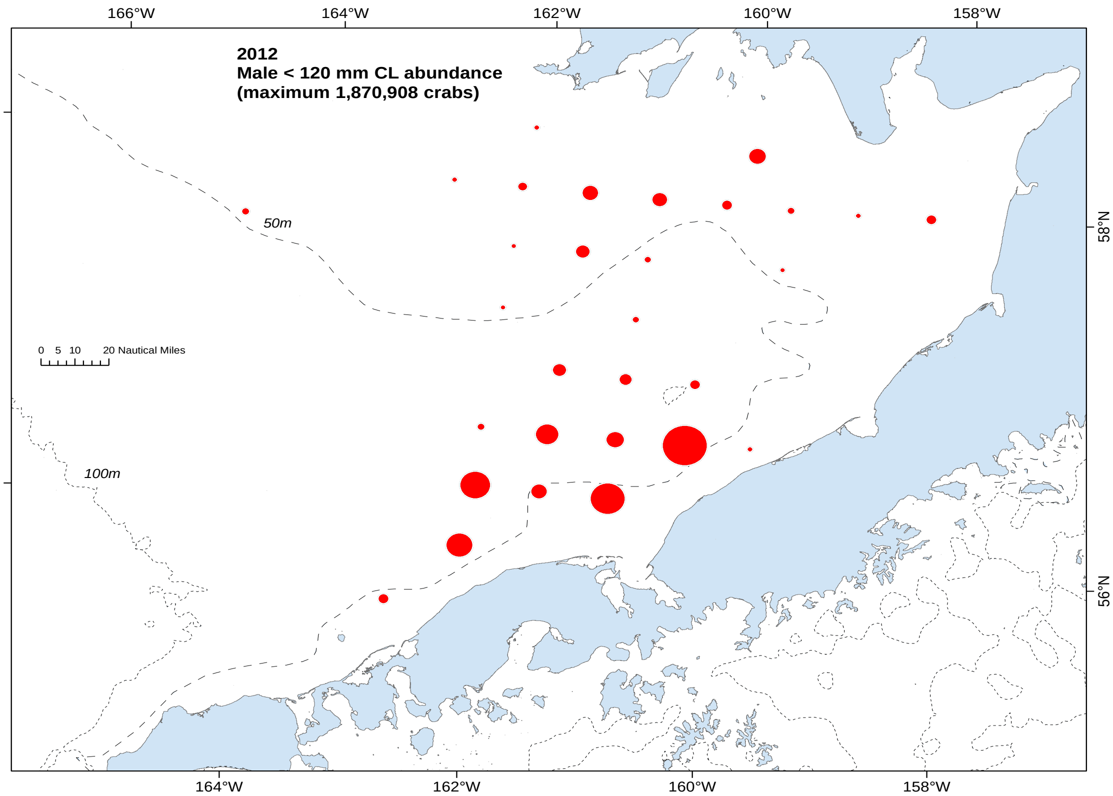
Appendix B. Spatial distributions of mature and juvenile male and female red king crabs in Bristol Bay from 2011-2013 summer standard trawl surveys.

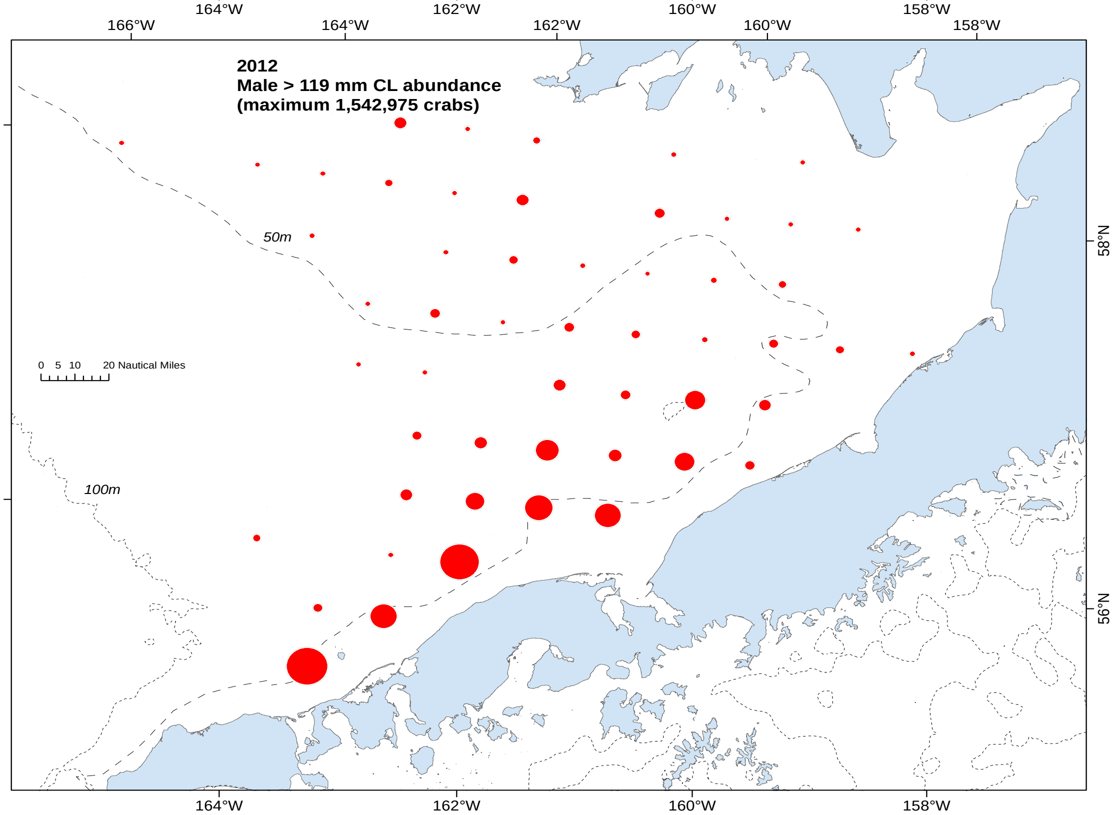


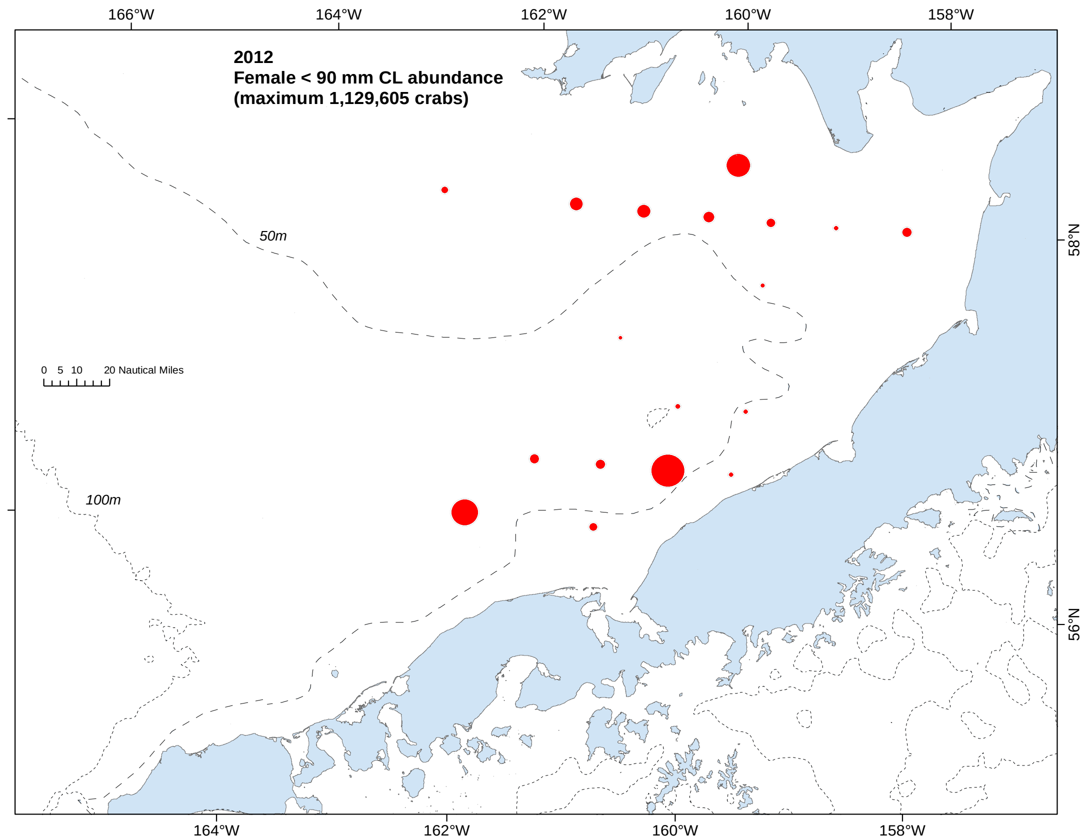


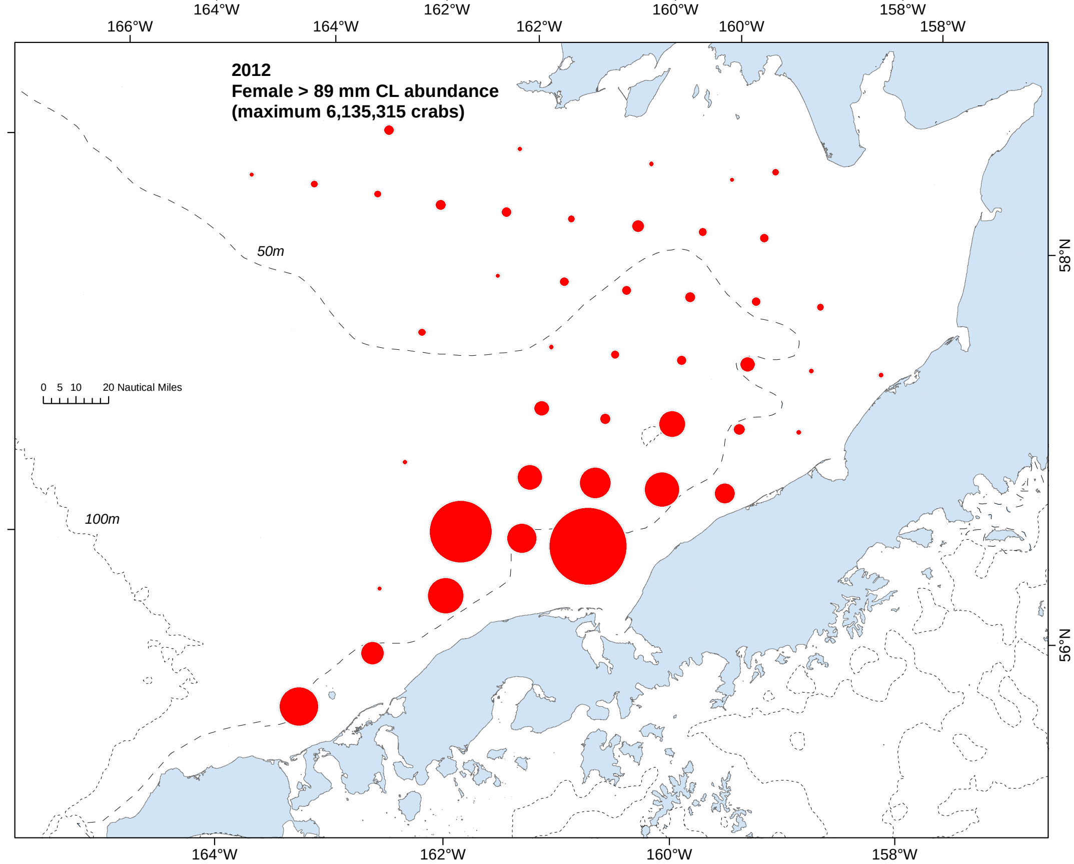

2011
Female < 90 mm CL abundance
(maximum 30,069,202 crabs)
166°W
164°W
162°W
160°W
158°W
58°N
56°N
50m
100m
0 5 10 20 Nautical Miles

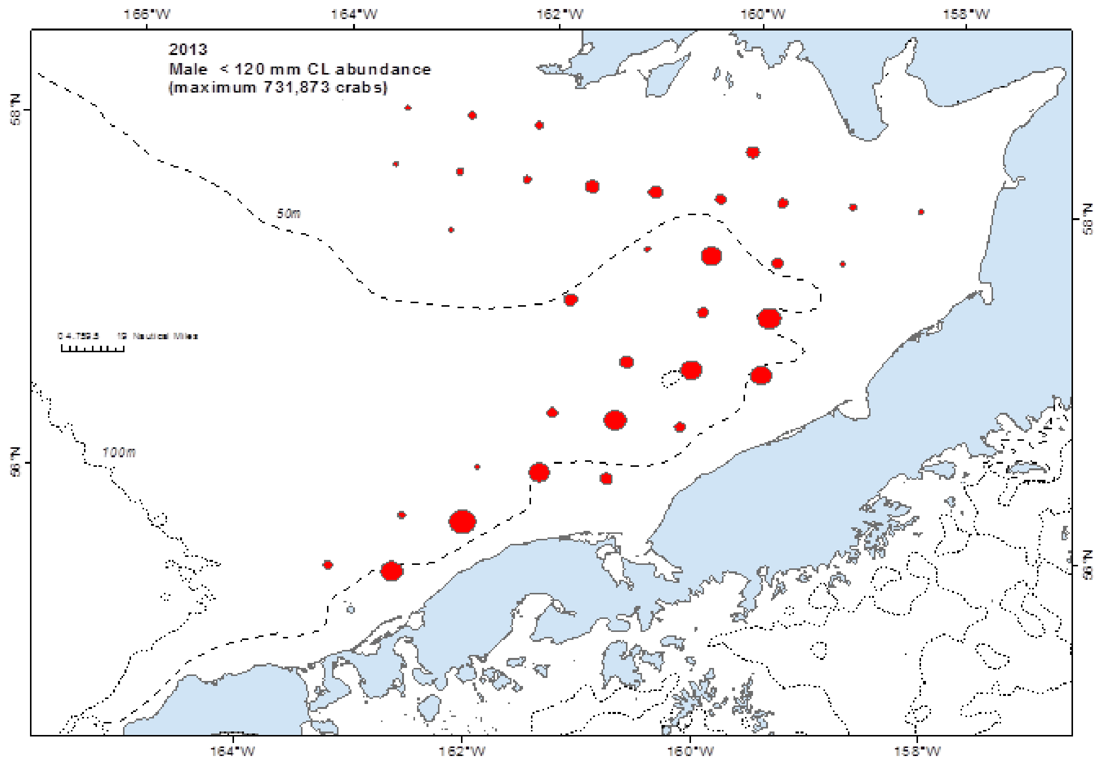

2011
Female > 89 mm CL abundance
(maximum 5,359,541 crabs)
166°W
164°W
162°W
160°W
158°W
58°N
56°N
50m
100m
0 5 10 20 Nautical Miles

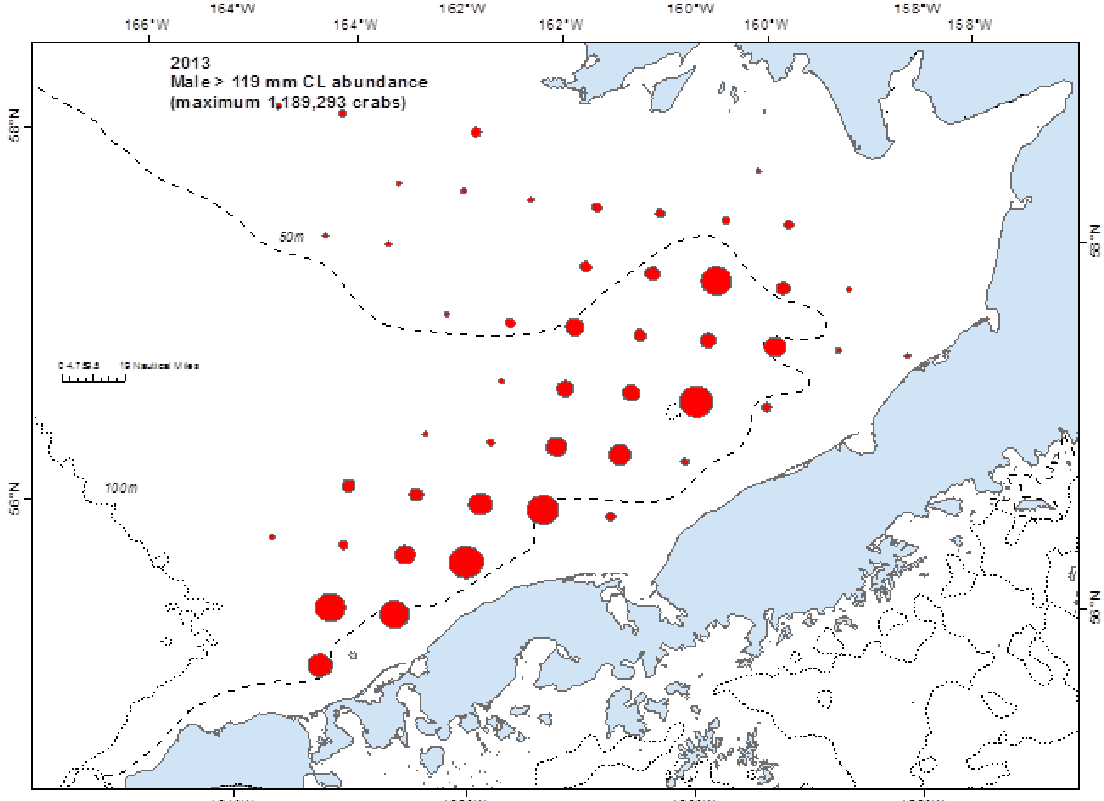

2012
Male < 120 mm CL abundance
(maximum 1,870,908 crabs)
166°W
164°W
162°W
160°W
158°W
58°N
56°N
50m
100m
0 5 10 20 Nautical Miles

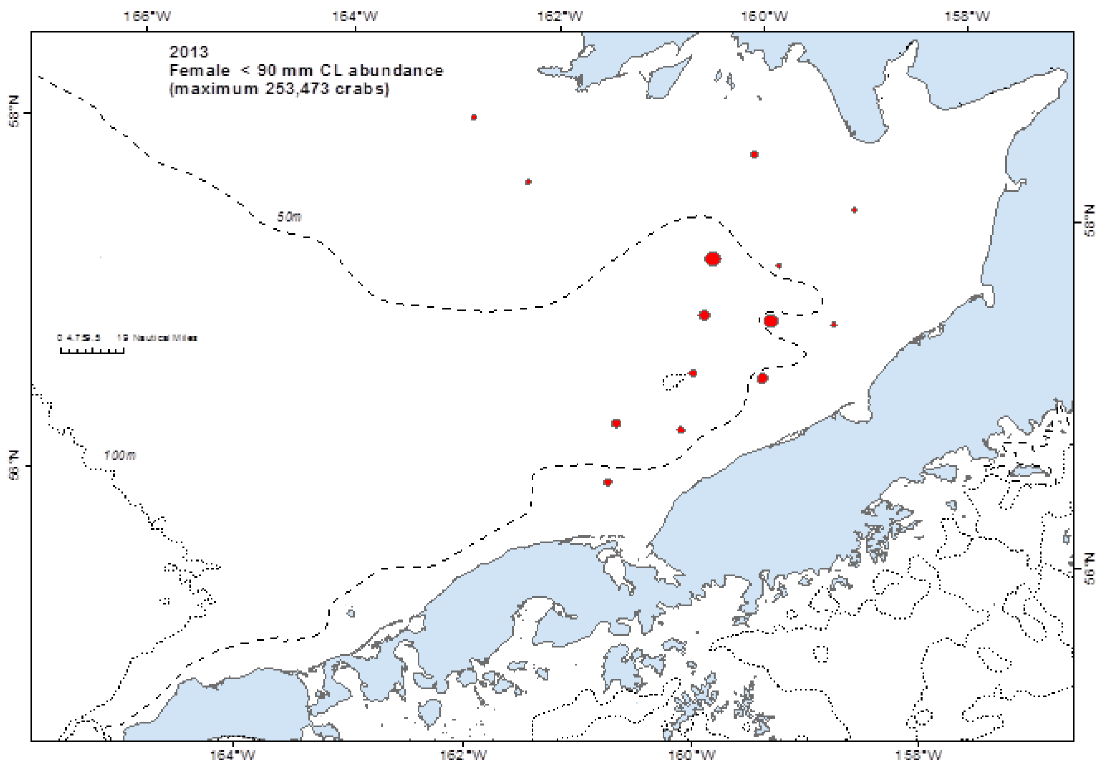

2012
Male > 119 mm CL abundance
(maximum 1,542,975 crabs)
166°W
164°W
162°W
160°W
158°W
58°N
56°N
50m
100m
0 5 10 20 Nautical Miles

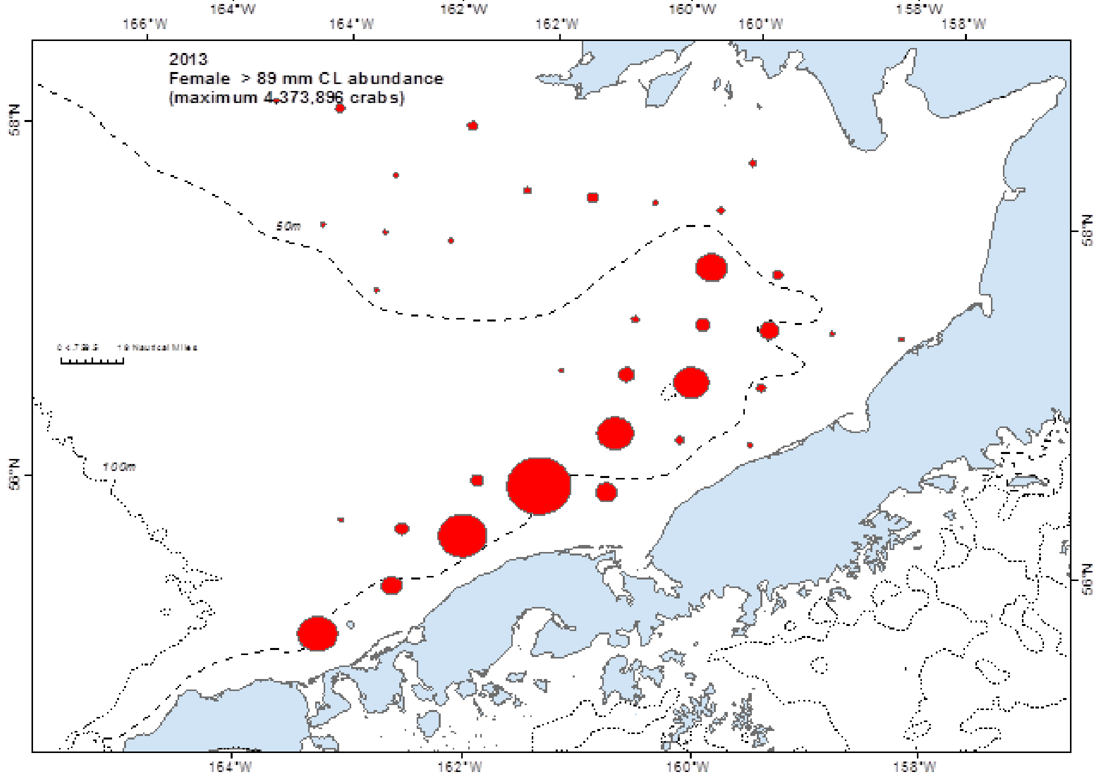

2012
Female < 90 mm CL abundance
(maximum 1,129,605 crabs)
50m
100m
0 5 10 20 Nautical Miles
166°W
164°W
162°W
160°W
158°W
58°N
56°N


2012
Female > 89 mm CL abundance
(maximum 6,135,315 crabs)
50m
100m
0 5 10 20 Nautical Miles
166°W
164°W
162°W
160°W
158°W
58°N
56°N


2013
Male < 120 mm CL abundance
(maximum 731,873 crabs)
50m
100m
166°W
164°W
162°W
160°W
158°W
58°N
56°N


2013
Male > 119 mm CL abundance
(maximum 1,189,293 crabs)
50m
100m
166°W
164°W
162°W
160°W
158°W
58°N
56°N


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


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