# Draft

## BRISTOL BAY RED KING CRAB STOCK ASSESSMENT IN SPRING 2008

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## EXECUTIVE SUMMARY

A length-based model was applied to eastern Bering Sea trawl survey, catch sampling, and commercial catch data to estimate stock abundance of Bristol Bay red king crab (*Paralithodes camtschaticus*) during 1985-2008. The model assumes constant natural mortality (0.18) and estimates trawl survey selectivities. The model fit the data well, and its results were used to estimate biological reference points and federal overfishing levels for 2008. The biological reference points were estimated as follows:

$B_{35\%}$ = 76.13 million lbs, or 34,531 t,

$F_{35\%}$ = 0.332,

$F_{40\%}$ = 0.270.

Based on $B_{35\%}$ and $F_{35\%}$, the retained catch and total catch limits for 2008 were estimated to be:

Retained catch: 21.523 million lbs, or 9,756.7 t,

Total catch: 25.299 million lbs, or 11,474.0 t,

MMB on 2/15/2009: 100.41 million lbs, or 45,538.0 t.

# INTRODUCTION

## Stock Structure

Red king crab (RKC), *Paralithodes camtschaticus*, are found in several areas of the Aleutian Islands and eastern Bering Sea. 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) 2005). The Aleutian Islands area covers two stocks, Adak and Dutch Harbor, and the Bering Sea area contains two other stocks, the Pribilof Islands and Norton Sound. The largest stock is found in the Bristol Bay area, which includes all waters north of the latitude of Cape Sarichef (54$^{o}$36' N lat.), east of 168$^{o}$ W long., and south of the latitude of Cape Newenham (58$^{o}$39' N lat.) (ADF&G 2005). Besides these five stocks, RKC stocks elsewhere in the Aleutian Islands and eastern Bering Sea are currently too small to support a commercial fishery. This report summarizes the stock assessment results for the Bristol Bay RKC stock.

## Fishery

The RKC stock in Bristol Bay, Alaska, supports one of the most valuable fisheries in the United States (Bowers et al. 2008). The Japanese fleet started the fishery in the early 1930s, stopped fishing from 1940 to 1952, and resumed the fishery from 1953 until 1974 (Bowers et al. 2008). 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 (Bowers et al. 2008). 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 (Bowers et al. 2008). The catch declined dramatically in the early 1980s and has stayed 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 in the previous summer (Zheng and Kruse 2002a). As a result of new regulations for crab

rationalization, the fishery was open longer beginning with the 2005/2006 season from October 15, 2005 to January 15, 2006. With the implementation of crab rationalization, historical guideline harvest levels (GHL) were changed to a total allowable catch (TAC). The GHL/TAC and actual catch are compared in Table 2. The implementation errors are quite high for some years, and total actual catch from 1980 to 2007 is about 6% less than the GHL/TAC (Table 2).

**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) frameworked in the FMP, and (3) discretion of the State of Alaska. The State of Alaska is responsible for developing harvest strategies to determine 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 2005). In attempting to meet these objectives, the GHL/TAC are 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 2005). 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 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 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 million lbs and 15% when ESB is at or above 55 million lbs (Zheng el 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 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 million lbs. The current harvest strategy is illustrated in Figure 1.

The purpose of this report is to document the stock assessments for Bristol Bay RKC. This report includes (1) all data used to conduct the stock assessments, (2) details of the analytic approach, (3) an evaluation of the assessment results, (4) estimating biological reference points and federal overfishing limits for 2008, and (5) future projections and the near future outlook.

## DATA

### 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 2005 (Bowers et al. 2008). Bycatch data are available starting from 1990 and were obtained from the ADF&G observer database and reports (Bowers et al. 2008; Burt and Barnard 2006). Sample sizes for catch by length and shell condition are summarized in Table 3. 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.

### *Catch Biomass*

Retained catch and estimated bycatch biomasses are summarized in Table 1. Retained catch and estimated bycatch from the directed fishery include both the general

open access (i.e., harvest not allocated to Community Development Quota (CDQ) groups) fishery and the CDQ fishery. 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 seasons 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.

### *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.

### *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 fisheries and the number of retained crabs per potlift for the U.S. fishery (Table 4). 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. The U.S. CPUE data have similar trends as survey legal abundance after 1971 (Figure 3).

**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. The survey in Bristol Bay occurs primarily during late May and June. Tow-by-tow trawl survey data for Bristol Bay RKC during 1975-2007 were provided by NMFS.

Abundance estimates by sex, carapace length, and shell condition were derived from survey data using an area-swept approach without post-stratification (Figures 4 and 5). If multiple tows were made for a single station in a given year, the average of the abundances from all tows was used as the estimate of abundance for that station. Until the late 1980s, NMFS used a post-stratification approach, but subsequently treated Bristol Bay as a single stratum. 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 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 NMFS abundance estimates (Stevens et al. 1991). In this study, the average abundances from all tows in the 9 stations (the station itself and the 8 adjacent stations) were used as the estimates of abundance for station H13 in 1984 and station F06 in 1991.

The approach here results in estimates close to those made by NMFS with some exceptions (Figure 6). Two surveys were conducted for Bristol Bay RKC in 1999, 2000, 2006, and 2007: the standard survey that was performed in late May and early June (about two weeks earlier than historic surveys) in 1999 and 2000 and the standard survey that was performed in early June in 2006 and 2007 and a resurvey of 31 stations (1999), 23 stations (2000), 31 stations (2006, 1 bad tow and 30 valid tows), and 32 stations (2007) with high female density that was performed in late July, about six weeks after the standard

survey. The resurveys were necessary because a high proportion of mature females had not yet molted or mated prior to the standard surveys (Figure 7). 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 $t$-tests of paired two sample for 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. NMFS included all survey tows in NMFS estimates in 1999, 2000, 2006 and 2007. To maximize use of the survey data, we used data from both surveys to assess male abundance but only the resurvey data, plus the standard survey data outside the resurveyed stations, to assess female abundance during these four years.

For 1968-1970 and 1972-1974, abundance estimates were obtained from NMFS directly because the original survey data by tow were not available. There were spring and fall surveys in 1968 and 1969. The average of estimated abundances from spring and fall surveys was used for those two years. Different catchabilities were assumed for survey data before 1973 because of an apparent change in survey catchability. A footrope chain was added to the trawl gear starting in 1973, and the crab abundances in all length classes in 1973 and beyond were much greater than those estimated prior to 1973 (Reeves et al. 1977).

## ANALYTIC APPROACH

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 assumed a constant natural mortality over time. Sources of mortality during the early 1980s need to be quantified to include data before 1985 into the research model. In this report, we present only the research model that was fit to the data only from 1985 to 2008.

**Model Scenarios**

Three scenarios with different handling mortalities were run for the research model. The base handling mortality rate was assumed to be 0.2, and alternative handling mortality rates of 0.1 and 0.4 were used for comparison.

**Main Assumptions for the Model**

Many assumptions were made to develop the length-based model. The major assumptions are:

(1) Natural mortality is constant over time, sex, shell condition, and length and was estimated with a maximum age of 25 and the 1% rule (Zheng 2005).
(2) Survey and fisheries selectivities are a function of length and were constant over time and shell condition. Selectivities are a function of sex except for trawl bycatch selectivities, which are the same for both sexes.
(3) Growth is a function of length and did not change over time.
(4) Molting probabilities are an inverse logistic function of length for males.
(5) Annual fishing seasons for the directed fishery are short.
(6) Survey catchabilities were set to 0.774 for females and 0.896 for males based on a trawl experiment by Weinberg et al. (2004).
(7) Female crabs are mature at sizes ≥90 mm CL and males mature at sizes ≥120 mm CL.

(8) 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.

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

**Population Model**

The original LBA model was described in detail by Zheng et al. (1995a, 1995b) and Zheng and Kruse (2002a). Pulse fishing was assumed for the model. 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:

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

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,

$m_l$ is the molting probability for length class $l$,

$R_{l,t}$ is recruitment into length class $l$ in year $t$,

$y_t$ is the lag in years between assessment survey and the mid 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 pot and trawl bycatch.

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:

$$G_l = a + b\,\iota, \tag{2}$$

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

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

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 $[\iota_1, \iota_2)$ of the receiving length class $l_2$ at the beginning of the next year:

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

where $\iota$ 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:

$$m_l = 1 - \frac{1}{1 + e^{-\beta\,(l - L_{50})}}, \tag{5}$$

where

$\beta$, $L_{50}$ are parameters, and

$\iota$ 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. $R_t$ was 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

$$R_{l,t} = R_t U_l, \tag{6}$$

where $U_l$ is described by a gamma distribution similar to equations (3) and (4) with a set

of parameters $\alpha_r$ and $\beta_r$. Because of different growth rates, recruitment was estimated separately for males and females under a constraint of about equal sex ratios 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. All fishery catch and discarded mortality bycatch are estimated as:

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

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*.

The female crab model is the same as the male crab model except that the retained catch equals zero and molting probability equals 1.0 to reflect annual molting (Powell 1967). The minimum carapace length is set at 65 mm, and the last length class includes all crabs ≥140-mm CL, resulting in length groups 1-16.

**Fisheries Selectivities**

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

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

Different sets of parameters ($\beta$, $L_{50}$) are estimated for retained males, female pot bycatch, and male and female trawl bycatch.

Male pot bycatch selectivity is modeled by two linear functions:

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

Where

$\varphi$, $\kappa$, $\gamma$ are parameters.

During 2005-2007, a portion of legal males were also discarded in the pot fishery. The selectivity for this highgrading was estimated to be the retained selectivity in each year times a highgrading parameter, $hg_t$.

**Trawl Survey Selectivities/Catchability**

Trawl survey selectivities/catchability are estimated as

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

with different sets of parameters ($\beta$, $L_{50}$) estimated for males and females. 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 ($\beta$, $L_{50}$ for females and $L_{50}$ for males) were estimated in the model. Parameter $A$ was set to be 0.774 for females and 0.896 for males based on a trawl experiment by Weinberg et al. (2004, Figure 8).

**Parameters Estimated Independently**

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. Highgrading parameters $hg_t$ were estimated to be 0.2785 in 2005, 0.0440 in 2006 and 0.0197 in 2007 based on the proportions of discarded legal males to total caught legal males. Handling mortality rates was set to 0.2 for the pot fishery and 0.8 for the trawl fisheries.

***Natural Mortality***

Based on an assumed maximum age of 25 years and the 1% rule (Zheng 2005), $M$ was estimated to be 0.18 for both males and females.

***Length-weight Relationship***

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

Immature Females: $W = 0.010271\ L^{2.388}$,

Ovigerous Females: $W = 0.02286\ L^{2.234}$, (11)

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Males: $W = 0.000361\ L^{3.16}$,

where

$W$ is weight in grams, and

$L$ is CL in mm.

### *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 9). The results from modal analyses of 1957-1961 and the 1990s were used to estimate mean growth increment per molt for immature females, and the data presented in Gray (1963) were used to estimate those for mature females (Figure 9). 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. These percentages are roughly close to the composition of maturity. 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).

### *Sizes at Maturity for Males*

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 10). 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 10).

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, 120 mm CL as a minimum size of functional maturity for Bristol Bay male RKC is proper and conservative in terms of managing the fishery.

**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 $t$ = 1986 to 2008), total abundance in the first year (1985), growth parameter $\beta$ and recruitment parameter $\beta_r$ for males and females separately. Molting probability parameters $\beta$ and $L_{50}$ were also estimated for male crabs. Estimated parameters also include $\beta$ and $L_{50}$ for retained selectivity, $\beta$ and $L_{50}$ for pot-discarded female selectivity, $\beta$ and $L_{50}$ for groundfish trawl discarded selectivity, $\varphi$, $\kappa$ and $\gamma$ for pot-discarded male selectivity, and $\beta$ for trawl survey selectivity and $L_{50}$ for trawl survey male and females separately. Annual fishing mortalities were also estimated for the directed pot fishery for males (1985-2007), pot-discarded females (1990-2007), and groundfish trawl discarded males and females (1985-2007). Total number of parameters to be estimated is 130. 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.

Among 130 parameters, the following 108 are annual parameters:

| | Recruits | Trawl bycatch | Pot male catch | Pot female bycatch |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| No. of Parameters | 46 | 23 | 23 | 16 |

To increase the efficiency of the parameter-estimation algorithm, we assumed that the relative frequencies of length and shell classes from survey year 1985 approximate the true relative frequencies within sexes. Thus, only total abundances of males and females for the first year were estimated; 3n unknown parameters for the abundances in the first year, where n is the number of length-classes, were reduced to one under this assumption.

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

$$Rf = \prod_{l=1}^{L}\prod_{t=1}^{T}\prod_{s=1}^{2}\prod_{sh=1}^{2}\frac{\left\{\exp\left[-\frac{(p_{l,t,s,sh}-\hat{p}_{l,t,s,sh})^2}{2\sigma^2}\right]+0.01\right\}}{\sqrt{2\pi\sigma^2}}, \qquad (12)$$

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

where

$L$ is the number of length groups,

$T$ is the number of years, and

$n$ is the effective sample size, which was assumed to be 400 for retained males, 200 for trawl survey and 100 for bycatch length composition data.

The weighted negative log-likelihood functions are:

$$\begin{aligned}
&Length\ compositions: \quad -\sum \ln(Rf_i)\,, \\
&Biomasses\ other\ than\ survey: \quad \lambda_j \sum\left[\ln(B_t/\hat{B}_t)^2\right], \\
&Survey\ bimass: \quad \lambda \sum\left[\ln(B_t/\hat{B}_t)^2/(2\,cv^2)\right], \\
&R\ variation: \quad \lambda_R \sum[\ln(R_t/\overline{R})^2]\,, \\
&R\ sex\ ratio: \quad \lambda_s[\ln(\overline{R}_M/\overline{R}_F)^2]\,,
\end{aligned} \qquad (13)$$

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.

Weighted $\lambda_j$ are assumed to be 500 for retained catch biomass, 50 for survey biomass, and 20 for all other biomasses, 2 for recruitment variation, and 20 for recruitment sex ratio. These $\lambda_j$ values represent prior assumptions about the accuracy of the observed biomass data and about the variances of these random variables.

## RESULTS

### Population Abundance

The model fit the fishery biomass data well and fit the survey biomass reasonably well (Figures 11 and 12). 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 did not fit the mature crab abundance directly and depicted the trends of the mature abundance well (Figure 12). Estimated mature crab abundance has increased during the last 20 years with mature females being 6 times more abundant in 2007 than in 1985 and mature males being 2.5 times more abundant in 2007 than in 1985 (Figure 12).

The model also fit the length and shell composition data well (Figures 13-20). Model fit of length compositions in the trawl survey was better for newshell males and females than for oldshell males. The model predicted lower proportions of oldshell males in 1993, 1994 and 2002 and higher proportions of oldshell males in 1988, 1997, 2001, 2003, 2004 and 2006 than the area-swept estimates (Figure 14). In addition to size, molting probability may also be affected by age and environmental conditions. Tagging data show that molting probability changed over time (Basilger 1974). Therefore, the relatively poor fit to oldshell males may be due to use of a constant molting probability function as well as shell aging errors. It is surprising that the model fit the length proportions of the pot male bycatch well with two simple linear selectivity functions (Figure 17). We explored a logistic selectivity function, but due to 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 13 and 15). Cohorts first seen in the trawl survey data in 1986,

1990, 1995, 1999, 2002, 2004 and 2005 can be tracked over time. Some cohorts can be tracked over time in the pot bycatch as well (Figure 17), 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 19 and 20).

The model can be extended to the data before 1985. However, due to a sharp decrease in population abundance in the early 1980s, it is difficult to fit the data with a constant natural mortality. The model can be used to investigate changes in natural mortality and impacts of observed and unobserved bycatch on the population in the late 1970s and early 1980s. These were the original objectives to develop the research model.

**Parameter Estimates**

Parameter estimates are summarized in Tables 5 and 6. Length-specific fishing mortality is equal to its selectivity 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 bycatches 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 21). Both selectivities were applied to the same level of full fishing mortality. Estimated selectivities for female pot bycatch were close to 1 for all mature females (Figure 21), and the estimated full fishing mortalities for female pot bycatch were much lower than for male retained catch and bycatch (Table 5).

One of the most important results is estimated trawl survey selectivity/catchability (Figure 21). Survey selectivity affects not only the fitting of the data but also the absolute abundance estimates. Estimated survey selectivities in Figure 21 are generally smaller than the capture probabilities in Figure 8 because survey selectivities include capture probabilities and crab availability. 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 systematical upward or downward bias of abundance estimates. Information about crab availability to the survey area at survey times will help estimate the survey selectivities.

Estimated molting probabilities during 1985-2007 (Figure 22) were generally lower than those estimated from the 1954-1961 and 1966-1969 tagging data (Balsiger 1974). Lower molting probabilities mean more oldshell crabs, possibly due to changes in molting probabilities over time or shell aging errors.

**Residual Patterns**

Residuals of total survey biomass and proportions of length and shell condition, calculated as observed minus predicted, were plotted to examine their patterns. Residuals of total survey biomass were standardized by the estimated standard deviation. The residuals of total survey biomass did not show any consistent patterns (Figure 23). Residuals of proportions of survey newshell males appear to be random over length and year (Figure 24). Residuals of proportions of survey oldshell males were mostly positive or negative for some years (Figure 25). This is expected since a constant molting probability function over time was used. Changes in molting probability over time or shell aging errors would create such residual patterns. There is an interesting pattern for residuals of proportions of survey females. Residuals were generally negative for large-sized mature females before 1995 and positive after 1994 (Figure 26). The pattern was opposite for small-sized mature females. Several factors could cause such a pattern: (1) a lower natural mortality after 1994, (2) changes in survey selectivities, or (3) an unknown source of mortality before 1995. ADF&G stock assessment model estimates different levels of natural mortality for different periods of years and suggests a lower natural mortality after 1993. The inadequateness of the model can be corrected by adding parameters to address these factors. Even though the residuals for females were not random, the model appears to fit annual mature female abundance quite well (Figure 12).

**Retrospective Analyses**

Two kinds of retrospective analyses were conducted for this report: (1) historical results and (2) the 2008 model results. 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 2008 estimates as the baseline values, we can also evaluate how well the model had done in the past. The 2008 model results

are based on sequentially excluding one-year of data to evaluate the current model performance with less data.

### *Historical Results*

The model first fit the data from 1985 to 2004 in 2004. Thus, five historical assessment results are available. 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 27).

In 2005, to improve the fit for retained catch data, the weight for retained catch biomass increased to 3000 and the weight for retained catch proportions 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 be 500 for retained catch, 200 for survey data, and 100 for bycatch data. Weights for biomasses were changed as 800 for retained catch, 300 for survey and 50 for bycatches. 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 27).

In 2008, estimated coefficients of variation for survey biomass were used to compute likelihood values as suggested by a Crab Plan Team member in 2007. Weights were re-configured because of this change: 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 27).

### *2008 Model Results*

The performance of the 2008 model includes leaving out data as well as a one-year ahead projection. Because the trawl survey occurred in the summer, the abundance estimates made in the spring for the terminal years were a projection without the current-year survey data. The model performed well except estimates for the early 2000s made with terminal years 2002 and 2003 (Figure 28). Lower estimates in the early 2000s were primarily due to extremely low survey estimates in 2001.

Overall, both historical results and the 2008 model results performed reasonably well. No great overestimates or underestimates occurred as observed in Pacific halibut (*Hippoglossus stenolepis*) (Parma 1993) or some eastern Bering Sea groundfish stocks (Zheng and Kruse 2002a; Ianelli et al. 2003). Since the model has not been used to set TAC or overfishing limits, historical implications for management from these assessment errors can not be evaluated at the current time. However, management implications of the ADF&G stock assessment model were evaluated by Zheng and Kruse (2002a).

### Effects of Handling Mortality Rate on Abundance Estimates

The baseline handling mortality rate for the 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 (Figure 29). Differences of estimated legal abundance and mature male biomass were small among these handling mortality rates (Figure 30).

### Effects of Natural Mortality

Changes in natural mortality resulted in changes in model fitting, abundance estimates and $F_{35\%}$ values (Figure 31). Estimated $F_{35\%}$ is highly sensitive to values of natural mortality, and a higher $M$ resulted in a higher $F_{35\%}$. $M$ = 0.18 is close to the best fit

of the data and results in intermediate values of estimated mature male and legal male abundances (Figure 31). Higher *M* values generally result in higher estimates of mature male abundance in 2008.

**Exploitation**

Estimated full pot fishing mortalities ranged from 0.0 to 0.584 during 1985-2007 with estimated values over 0.4 during 1985-1987, 1990-1991, 1993, and 1998 (Table 5). Estimated fishing mortalities for pot female bycatch and trawl bycatch were less than 0.06.

The average of estimated male recruits from 1995 to 2008 (Figure 32) and mature male biomass per recruit was used to estimate $B_{35\%}$. The choice of this recruitment will be discussed in the "Biological Reference Points" section. The full fishing mortalities for the directed pot fishery at the time of fishing were plotted against mature male biomass on Feb. 15 (Figure 33). Before the current harvest strategy was adopted in 1996, many fishing mortalities were above $F_{35\%}$ (Figure 33). Under the current harvest strategy, estimated fishing mortalities were at or above the $F_{35\%}$ limits in 1998, 2005 and 2007 but below the $F_{35\%}$ limits in other years.

**Stock-Recruitment Relationships**

Estimated mature male biomass and recruitment were plotted to illustrate their relationships (Figure 34). Neither the estimated Ricker nor the Beverton-Holt curve was not statistically significant.

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 35). The highest proportion of empty clutches (0.2) was in 1986, and they primarily involved soft shell females (shell condition 1). Clutch fullness fluctuated annually around average levels during two periods: before 1991 and after 1990 (Figure 35). The average clutch fullness was almost identical for these two periods (Figure 35).

## BIOLOGICAL REFERENCE POINTS AND OVERFISHING LIMITS FOR 2008

Bristol Bay RKC is currently placed in Tier 3 (NPFMC 2007). For Tier 3 stocks, estimated biological reference points include $B_{35\%}$, $F_{35\%}$ and $F_{40\%}$. Estimated model parameters were used to conduct mature male biomass per recruit analysis. Because trawl bycatch fishing mortality was not related to pot fishing mortality, average of trawl bycatch fishing mortalities during 1998 to 2007 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 1990-2007. Some discards of legal males occurred since the IFQ fishery started in 2005, but the discard rates were much lower in 2006 and 2007 than in 2005 after the fishing industry minimized discards of legal males. Thus, the average of retained selectivities and discard male selectivities in 2006 and 2007 were used to represent current trends for per recruit analysis and projections. Because of higher estimated recruitment after 1994 than during 1985-1994 and the potential regime shift after 1989 (Overland et al. 1999), which corresponded to recruitment in 1995 and later, we used average of estimated male recruitment during 1995-2008 (Figure 32) to develop $B_{35\%}$. The biological reference points were estimated as follow:

$B_{35\%}$ = 76.130 million lbs, or 34,531 t,

$F_{35\%}$ = 0.332,

$F_{40\%}$ = 0.270.

Based on $B_{35\%}$ and $F_{35\%}$, the retained catch and total catch limits for 2008 are estimated to be:

Retained catch: 21.523 million lbs, or 9,756.7 t,

Total catch: 25.299 million lbs, or 11,474.0 t,

MMB on 2/15/2009: 100.410 million lbs, or 45,538.0 t.

Likelihood profiles of mature male biomass on February 15, retained catch and total catch for 2008 are illustrated in Figure 36. The confidence intervals are quite narrow for all three values.

## PROJECTIONS AND FUTURE OUTLOOK

## 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 1995-2008. Besides recruitment, the other major uncertainty for the projections is estimated abundance in 2008. The 2008 abundance was randomly selected from the estimated normal distribution of the assessment model for each replicate. Four 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.

(4) Current ADF&G harvest strategy with the $F_{35\%}$ constraint.

Each scenario was replicated 1000 times and projections made over 10 years beginning in 2008 (Table 7).

As expected, projected mature male biomasses were much higher without the directed fishing mortality than under the other scenarios. Among three scenarios with directed fishing, the ADF&G harvest strategy produced the most stable mature male biomass and catch over time (Table 7, Figures 37 and 38). With its forward looking feature, the ADF&G harvest strategy reduced fishing mortality one year or two years earlier than the $F_{40\%}$ and $F_{35\%}$ scenarios when recruitment was poor. At the end of 10 years, projected mature male biomass was above $B_{35\%}$ for the $F_{40\%}$ scenario and the ADF&G harvest strategy and similar to $B_{35\%}$ for the $F_{35\%}$ scenario (Figure 37).

## Near Future Outlook

The near future outlook for the Bristol Bay RKC stock is stable. The three recent above-average year classes (hatching years 1990, 1994, and 1997) had largely entered the legal population by 2006 (Figure 39), so recruitment to the legal population during the next two years may be low. However, most individuals from the 1997 year class entered the legal population in 2006 and will continue to gain weight to offset loss of the legal biomass to fishing and natural mortalities. The cohort with lengths centered around 87.5

mm CL for both males and females in 2006 also appears to be above average in abundance (Figure 39). These crabs will enter the mature female population next year and the mature male population in 2 or 3 years. However, no strong cohorts have been observed in the survey data after this cohort (Figure 39). Due to these above average year classes, mature and legal crabs should remain at relatively high abundance levels compared to the previous 20 years if natural mortality does not increase greatly, as happened in the early 1980s for this stock and in 1999 for St. Matthew Island blue king crab (Zheng and Kruse 2002b). 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.

## ECOSYSTEM CONSIDERATIONS

Three aspects of ecosystem considerations are reported in this report: impacts of changes in oceanographic conditions on RKC recruitment strength, predation by groundfish, and impacts of shifts of spatial distribution on crab recruitment success.

### Impacts of Changes in Oceanographic Conditions on RKC Recruitment

Environmental factors may play important roles in determining recruitment strength. Climate variability, ocean temperature, surface winds, ocean currents and their ecological interactions may affect food availability and larval transport, growth and survival, thus affecting recruitment strength (Shepherd et al. 1984; Koslow et al. 1987). Changes in many of these oceanographic processes are associated with atmospheric pressure patterns in winter, such as the strength and position of the Aleutian Low Pressure System, which affects the direction and intensity of storms, and the Arctic Oscillation, which represents the spin up (or spin down) of the polar vortex and indexes the transfer of mass between high and mid latitudes (Overland et al., 1999). For instance, a climate regime shift in the late 1970s was manifested by increased winter storms and precipitation, faster alongshore currents, warmer sea surface temperatures, and higher coastal sea levels in the northeastern Pacific Ocean (Hollowed and Wooster 1992; Hare and Mantua 2000). Overland et al. (1999) found three shifts of wintertime climate forcing patterns that have been identified in the past three decades: 1967-1976 (positive Aleutian Low, mixed Arctic

Oscillation), 1977-1988 (negative Aleutian Low, negative Arctic Oscillation), and 1989-1998 (mixed Aleutian Low, positive Arctic Oscillation).

The recruitment strength of Bristol Bay RKC and the Aleutian Low Pressure index were examined by Zheng and Kruse (2000, 2006). They found that the recruitment trends of Bristol Bay RKC may partly relate to decadal shifts in physical oceanography: all strong year classes occurred before 1977 when the Aleutian Low was weak. One of the largest year classes during the last 20 years, the 1990 year class, was also coincidental with the weak Aleutian Low index during 1989-1991 (Zheng and Kruse 2000, 2006). The mechanisms are uncertain, but food availability is hypothesized to be important to RKC (Zheng and Kruse 2000) because their larvae suffer reduced survival and feeding capability if they do not feed within the first 2-6 days after hatching (Paul and Paul 1980). Diatoms such as *Thalassiosira* are important food for first-feeding RKC larvae (Paul et al. 1989) and they are predominate in the spring bloom in years of light winds when the water column is stable (Ziemann et al. 1991; Bienfang and Ziemann 1995). One hypothesis is that years of strong wind mixing associated with intensified Aleutian Lows may depress RKC larval survival and subsequent recruitment (Zheng and Kruse 2000).

**Predation by Groundfish**

During the period from mating to recruitment, many events can modify crab year-class strength. This may explain the weak relationships between recruitment and spawning biomass as well as individual environmental factors. One such event is groundfish predation. Groundfish consume crabs from the pelagic larval to adult stages. Based on routine examination of stomach contents of some groundfish species (Alaska plaice, arrowtooth flounder, flathead sole, northern rock sole, Pacific cod, Pacific halibut, skates, walleye pollock, and yellowfin sole) in the eastern Bering Sea, a huge amount of early juvenile Tanner and snow crabs are consumed by groundfish each year during summer months, May to September (Lang et al. 2003). Predation on large crabs usually occurs during molting periods (Blau 1986), which are generally during spring. Therefore, few large crabs are in groundfish stomachs during summer months when sampling occurs. Because female RKC molt later than males, sampling may bias against monitoring of predation on adult male RKC relative to females (Table

8). Likewise, juvenile RKC are usually found in nearshore, shallow waters, where hardly any samples of groundfish are taken. Thus, data are not available to estimate groundfish predation on juvenile RKC. Overall, RKC biomass estimated to be consumed by groundfish during summer months were low relative to the crab population abundance (Table 9).

Zheng and Kruse (2006) reported that statistically significant correlations between Pacific cod biomass and Bristol Bay RKC recruitment. Correlations are significant with recruitment time lags from ages 0 to 3 (Zheng and Kruse 2006). Correlations between yellowfin sole biomass and log-transformed Bristol Bay RKC recruitment are also statistically significant with recruitment time lags from ages 0 to 2 ($r$ = -0.85, -0.83, -0.79, and $P$ = 0.03, 0.04, 0.04, respectively, Zheng and Kruse 2006). The spatial distribution of yellowfin sole mainly overlaps with Bristol Bay RKC and has not changed much over time. Higher Pacific cod and yellowfin sole biomass was associated with lower RKC recruitment (Zheng and Kruse 2006). Pacific cod is the main predator of red king crabs (Table 9).

Statistical significance does not necessarily imply biologically meaningful relationships. Multiple statistical tests increase the probability of Type I error. In a detailed study of predation and population trends, Livingston (1989) concluded that cod predation was not responsible for declines of RKC in Bristol Bay in the early 1980s. Estimates of RKC consumed by cod during 1981 and 1983-1996 (Livingston 1991; Livingston et al. 1993, Livingston & deReynier 1996; Lang et al. 2003) constitute only a very small proportion of the crab population. Most RKC in cod stomachs are softshell females >80 mm carapace length (Livingston 1989; Table 8) – well beyond the size at which year class strength is determined. However, as noted earlier, the lack of RKC in groundfish stomachs may also be due to sampling problems. Therefore, the lack of large numbers of early juvenile RKC in groundfish stomach data obtained during summer months in offshore waters does not necessarily invalidate the apparent negative relationships between RKC year-class strength and biomass of Pacific cod and yellowfin sole. Groundfish stomachs must be sampled at the appropriate spatial and temporal scales to resolve questions about groundfish predation on juvenile king crabs.

Spatial distributions of crabs and groundfish may also play an important role on groundfish predation on crabs. Like crab stocks, spatial distributions of groundfish stocks in the eastern Bering Sea changed over time (Figure 40). During recent years, biomass distribution centers of Pacific cod, flathead sole and arrowtooth flounder shifted to the northwest, those of rock sole, skates and Alaska plaice shifted to the northeast, whereas spatial distributions of yellowfin sole remained relatively stable (Figure 40). The northward expansion for some groundfish seems to relate to warmer bottom temperatures, perhaps due to a northward extension of suitable habitat. With warmer temperatures, the center of groundfish spatial distributions moved farther to the north (Zheng and Kruse 2006).

Changes in spatial distributions of groundfish in the eastern Bering Sea are best illustrated by distributions of Pacific cod biomass from 1982 to 2004 (Figure 41). In the early 1980s, Pacific cod mainly occurred in shallow waters <50 m in the Bristol Bay area and in deep waters >100 m in the northwest of the eastern Bering Sea. However, during 1985-1988 and 1991-1996 the distribution of Pacific cod biomass was widespread across the shelf. In recent years, cod abundance concentrated in the north, around St. Matthew Island, and stayed at a relatively low density in Bristol Bay.

Other striking examples of changes in spatial distributions are provided by rock sole and skates (Figure 42). Rock sole mainly occurred in Bristol Bay and the Pribilof Islands in the 1980s. During the last 15 years, rock sole have expanded to the north up to St. Matthew Island. The biomass of skates has also increased greatly during the last 20 years and expanded northward. Among other commercially important species, biomass of arrowtooth flounder and flathead sole has also increased during the 1980s.

**Impacts of Shifts of Spatial Distribution on Crab Recruitment Success**

Spatial distributions of Bristol Bay RKC changed profoundly during the last three decades (Hsu 1987; Loher 2001; Zheng and Kruse 2006; Figure 43). Generally speaking, RKC abundance in southern Bristol Bay was high during the 1970s, declined, and was extremely low after 1979 (Zheng and Kruse 2006). Female RKC were found primarily in central Bristol Bay during 1980-1987 and 1992-2006 (Zheng and Kruse 2006). The distribution centers of mature females moved south slightly during 1988-1991 but did not

reach the southern locations previously occupied in the 1970s. Loher (2001) hypothesized that changes in near bottom temperatures associated with the 1976/77 regime shift are causes for spatial shifts of RKC female distributions. Because small juvenile RKC are generally located downstream of the mature females (Zheng and Kruse 2006), larval advection appears to be an important process for RKC.

Zheng and Kruse (2008) used the ocean surface current simulator (OSCURS) to perform retrospective analyses of movements of Bristol Bay red king crab larvae from 1967 to 2002. Simulations started at the annual distribution centers of mature females >99 mm CL. The distribution centers were assumed to be the centers of larval hatching. Mature RKC females >99 mm CL are mostly multiparous females. The locations of larval settlements were taken to be the places where 325 degree-days were estimated to have been reached. To estimate larval durations, monthly sea surface temperatures for each year from 1967 to 2002 were estimated for grids of 1 degree longitude and 0.5 degree latitude in the eastern Bering Sea based on the Comprehensive Ocean-Atmosphere Dataset (COADS) from the National Climate Data Center (NCDC). To demonstrate the larval drift tracking for different locations and years, Zheng and Kruse (2008) also simulated the RKC larval drifts in 1975, 1987, and 2004 for two months starting at three locations −− south, middle and north − representing hatching locations of larvae from the southern, middle and northern range of the mature female distribution.

RKC larval drifts were similar among three years (1975, 1987 and 2004) but very different among different hatching locations (Figure 44). At southern and middle locations, larvae generally drifted to the northeast, and at the northern location, larvae drifted to the north or northwest. Larvae hatched in the southern location were estimated to reach central Bristol Bay, whereas larvae hatched in central Bristol Bay were estimated to settle in the northernmost reaches of Bristol Bay. Owing to prevailing currents, larvae hatched in central and northern Bristol Bay are very unlikely to settle in the southern portions of Bristol Bay (Figure 44).

Settling locations appear to have an important impact on resultant year-class strength for Bristol Bay RKC (Figure 45). For years with strong year classes, crab larvae were generally estimated to have settled in the central portion of Bristol Bay (Zheng and Kruse 2008). Because the simulations started at the centers of the annual distribution of

the brood stock, larval settling locations from these years likely also represent the centers of a broader distribution of settling larvae that are well dispersed from south to north along the shallow shelf of Bristol Bay. Larvae associated with weak year-classes generally settled farther downstream in northern Bristol Bay or to the northwest outside of Bristol Bay. Occasionally, larvae hatched in the southern Bristol Bay settled there. Larvae hatching in the middle or later portion of the hatching period may contribute disproportionately to subsequent recruitment; early hatching larvae had longer larval stages and were dispersed farther downstream from the hatching locations than those hatched late in a spawning season (Figure 45).

The simulation results by Zheng and Kruse (2008) show that the northward shifts in mature female distributions made it very difficult to supply larvae to the southern portions of their traditional nursery areas. This reduces the number of suitable habitats to which larvae are delivered (Armstrong et al. 1983; Loher 2001) and may affect recruitment strength. Perhaps this has contributed to long-term decline in recruitment and subsequent mature biomass of Bristol Bay RKC.

## ACKNOWLEDGMENTS

We thank Doug Woodby and the Crab Plan Team for reviewing the earlier draft of this manuscript. This report is funded in part by a cooperative agreement from the National Oceanic and Atmospheric Administration. The views expressed herein are those of the author and do not necessarily reflect the views of NOAA or any of its sub-agencies.

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Table 1. Bristol Bay red king crab annual catch and bycatch mortality biomass (million lbs) 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.

| | Retained Catch | | | | Pot Bycatch | | Trawl |
|---|---|---|---|---|---|---|---|
| Year | U.S. | Cost-recovery | Foreign | Total | Males | Females | Bycatch |
| 1960 | 0.600 | | 26.898 | 27.498 | | | |
| 1961 | 0.427 | | 44.592 | 45.019 | | | |
| 1962 | 0.068 | | 54.275 | 54.343 | | | |
| 1963 | 0.653 | | 54.963 | 55.616 | | | |
| 1964 | 0.823 | | 58.170 | 58.993 | | | |
| 1965 | 1.429 | | 41.294 | 42.723 | | | |
| 1966 | 0.997 | | 42.356 | 43.353 | | | |
| 1967 | 3.102 | | 33.636 | 36.738 | | | |
| 1968 | 8.686 | | 27.469 | 36.155 | | | |
| 1969 | 10.403 | | 14.383 | 24.786 | | | |
| 1970 | 8.559 | | 12.984 | 21.543 | | | |
| 1971 | 12.946 | | 6.134 | 19.080 | | | |
| 1972 | 21.745 | | 4.720 | 26.465 | | | |
| 1973 | 26.914 | | 0.228 | 27.142 | | | |
| 1974 | 42.266 | | 0.476 | 42.742 | | | |
| 1975 | 51.326 | | 0.000 | 51.326 | | | |
| 1976 | 63.920 | | 0.000 | 63.920 | | | 1.426 |
| 1977 | 69.968 | | 0.000 | 69.968 | | | 2.685 |
| 1978 | 87.618 | | 0.000 | 87.618 | | | 2.757 |
| 1979 | 107.828 | | 0.000 | 107.828 | | | 2.783 |
| 1980 | 129.948 | | 0.000 | 129.948 | | | 2.135 |
| 1981 | 33.591 | | 0.000 | 33.591 | | | 0.448 |
| 1982 | 3.001 | | 0.000 | 3.001 | | | 1.201 |
| 1983 | 0.000 | | 0.000 | 0.000 | | | 0.885 |
| 1984 | 4.182 | | 0.000 | 4.182 | | | 2.316 |
| 1985 | 4.175 | | 0.000 | 4.175 | | | 0.829 |
| 1986 | 11.394 | | 0.000 | 11.394 | | | 0.432 |
| 1987 | 12.289 | | 0.000 | 12.289 | | | 0.311 |
| 1988 | 7.388 | | 0.000 | 7.388 | | | 1.174 |
| 1989 | 10.265 | | 0.000 | 10.265 | | | 0.374 |
| 1990 | 20.362 | 0.081 | 0.000 | 20.443 | 1.139 | 1.154 | 0.501 |
| 1991 | 17.178 | 0.206 | 0.000 | 17.384 | 0.881 | 0.142 | 0.576 |
| 1992 | 8.043 | 0.074 | 0.000 | 8.117 | 1.191 | 0.780 | 0.571 |
| 1993 | 14.629 | 0.053 | 0.000 | 14.682 | 1.649 | 1.133 | 0.836 |
| 1994 | 0.000 | 0.093 | 0.000 | 0.093 | 0.000 | 0.000 | 0.180 |
| 1995 | 0.000 | 0.080 | 0.000 | 0.080 | 0.000 | 0.000 | 0.213 |
| 1996 | 8.406 | 0.108 | 0.000 | 8.514 | 0.356 | 0.002 | 0.238 |
| 1997 | 8.756 | 0.155 | 0.000 | 8.911 | 0.528 | 0.034 | 0.168 |
| 1998 | 14.757 | 0.188 | 0.000 | 14.946 | 2.074 | 1.547 | 0.355 |
| 1999 | 11.670 | 0.186 | 0.000 | 11.856 | 0.679 | 0.015 | 0.408 |
| 2000 | 8.154 | 0.086 | 0.000 | 8.241 | 0.779 | 0.078 | 0.230 |
| 2001 | 8.403 | 0.120 | 0.000 | 8.523 | 0.902 | 0.309 | 0.330 |
| 2002 | 9.570 | 0.096 | 0.000 | 9.666 | 0.956 | 0.013 | 0.245 |
| 2003 | 15.697 | 0.034 | 0.000 | 15.731 | 1.945 | 0.709 | 0.298 |
| 2004 | 15.245 | 0.202 | 0.000 | 15.447 | 0.746 | 0.338 | 0.277 |
| 2005 | 18.309 | 0.209 | 0.000 | 18.518 | 2.923 | 0.879 | 0.403 |
| 2006 | 15.444 | 0.304 | 0.000 | 15.748 | 1.199 | 0.067 | 0.205 |
| 2007 | 20.366 | 0.146 | 0.000 | 20.512 | 2.150 | 0.330 | 0.233 |

Table 2. Comparison of GHL/TAC and actual catch (million lbs) of Bristol Bay red king crab.

| Year | GHL Range | GHL Mid-point | Actual Catch | Rel.Error | %Rel.Error |
|---|---|---|---|---|---|
| 1980 | 70-120 | 95.00 | 129.95 | 34.95 | 36.79 |
| 1981 | 70-100 | 85.00 | 33.59 | -51.41 | -60.48 |
| 1982 | 10-20 | 15.00 | 3.00 | -12.00 | -79.99 |
| 1983 | 0 | 0.00 | 0.00 | NA | NA |
| 1984 | 2.5-6 | 4.25 | 4.18 | -0.07 | -1.59 |
| 1985 | 3-5 | 4.00 | 4.18 | 0.18 | 4.38 |
| 1986 | 6-13 | 9.50 | 11.39 | 1.89 | 19.94 |
| 1987 | 8.5-17.7 | 13.10 | 12.29 | -0.81 | -6.19 |
| 1988 | | 7.50 | 7.39 | -0.11 | -1.50 |
| 1989 | | 16.50 | 10.26 | -6.24 | -37.79 |
| 1990 | | 17.10 | 20.36 | 3.26 | 19.08 |
| 1991 | | 18.00 | 17.18 | -0.82 | -4.57 |
| 1992 | | 10.30 | 8.04 | -2.26 | -21.91 |
| 1993 | | 16.80 | 14.63 | -2.17 | -12.93 |
| 1994 | | 0.00 | 0.00 | 0.00 | |
| 1995 | | 0.00 | 0.00 | 0.00 | |
| 1996 | | 5.00 | 8.41 | 3.41 | 68.11 |
| 1997 | | 7.00 | 8.76 | 1.76 | 25.09 |
| 1998 | | 16.40 | 14.76 | -1.64 | -10.02 |
| 1999 | | 10.66 | 11.67 | 1.01 | 9.48 |
| 2000 | | 8.35 | 8.15 | -0.20 | -2.34 |
| 2001 | | 7.15 | 8.40 | 1.25 | 17.52 |
| 2002 | | 9.27 | 9.57 | 0.30 | 3.24 |
| 2003 | | 15.71 | 15.70 | -0.01 | -0.08 |
| 2004 | | 15.40 | 15.25 | -0.15 | -1.00 |
| 2005 | | 18.33 | 18.31 | -0.02 | -0.11 |
| 2006 | | 15.53 | 15.44 | -0.08 | -0.53 |
| 2007 | | 20.38 | 20.37 | -0.02 | -0.08 |
| Total | | 461.23 | 431.38 | -29.85 | -6.47 |

Table 3. Annual sample sizes for catch by length and shell condition for retained catch and bycatch of Bristol Bay red king crab.

| | Trawl Survey | | Retained | Pot Bycatch | | Trawl Bycatch | |
|---|---|---|---|---|---|---|---|
| Year | 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 | 820 | 540 | 17,666 | 1,048 | 36 | 16,653 | 5,187 |
| 2000 | 1,278 | 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 | 2,321 | 2,672 | 18,027 | 29,383 | 3,594 | 217 | 168 |
| 2007 | 2,252 | 2,499 | 22,387 | 58,097 | 12,411 | 1,981 | 2,880 |

Table 4. Annual catch (million crabs) and catch per unit effort of the Bristol Bay red king crab fishery.

| | Japanese Tanglenet | | Russian Tanglenet | | U.S. Pot/trawl | | Standardized |
|---|---|---|---|---|---|---|---|
| Year | Catch | Crabs/tan | Catch | Crabs/tan | Catch | Crabs/potlift | Crabs/tan |
| 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 | | | | | 3.131 | 28 | |

Table 5. Summary of parameter estimates (except recruits, that are in Table 6) for Bristol Bay red king crab.

| | F for Pot Fishery | | F for Trawl |
|---|---|---|---|
| Year | Males | Female | Fishery Discard |
| 1985 | 0.4307 | | 0.0215 |

| | | | |
|---|---|---|---|
| 1986 | 0.5840 | | 0.0123 |
| 1987 | 0.4441 | | 0.0071 |
| 1988 | 0.1840 | | 0.0198 |
| 1989 | 0.2119 | | 0.0046 |
| 1990 | 0.4249 | 0.0513 | 0.0088 |
| 1991 | 0.4012 | 0.0042 | 0.0093 |
| 1992 | 0.2064 | 0.0249 | 0.0144 |
| 1993 | 0.4613 | 0.0557 | 0.0171 |
| 1994 | 0.0000 | 0.0000 | 0.0022 |
| 1995 | 0.0000 | 0.0000 | 0.0068 |
| 1996 | 0.1719 | 0.0001 | 0.0023 |
| 1997 | 0.2022 | 0.0006 | 0.0023 |
| 1998 | 0.4012 | 0.0261 | 0.0046 |
| 1999 | 0.2705 | 0.0003 | 0.0058 |
| 2000 | 0.1530 | 0.0012 | 0.0028 |
| 2001 | 0.1391 | 0.0046 | 0.0041 |
| 2002 | 0.1567 | 0.0002 | 0.0031 |
| 2003 | 0.2580 | 0.0088 | 0.0036 |
| 2004 | 0.2629 | 0.0050 | 0.0022 |
| 2005 | 0.3849 | 0.0091 | 0.0029 |
| 2006 | 0.2786 | 0.0006 | 0.0025 |
| 2007 | 0.3337 | 0.0029 | 0.0021 |

Growth $\beta$: males: 0.4028, females: 0.4604;
Recruits $\beta$: males: -0.3082, females: -0.4581;
Molting: *L50*: 137.9050, $\beta$: 0.08603;
Total abundance in 1985: 67.2011 million crabs;
Retained selectivity: *L50*: 138.0440, $\beta$: 0.4796;
Pot disc. female selectivity: *L50*: 81.7570, $\beta$: 0.4587;
Pot disc. male selectivity parameters: $\varphi$: -0.2377, $\kappa$: 0.0027, $\gamma$: -0.0117;
Groundfish trawl disc. selectivity: *L50*: 144.3500, $\beta$: 0.0592;
Trawl survey male selectivity: *L50*: 89.5867;
Trawl survey female selectivity: *L50*: 78.5749;
Trawl survey selectivity: $\beta$: 0.0580.

Table 6. Annual abundance estimates (million crabs) and mature male biomass (MMB, million lbs) for red king crab in Bristol Bay estimated by length-based analysis from 1985-2008. Mature male biomass for year *t* is on Feb. 15, year *t*+1. Size measurements are mm CL.

| | Males | | | | Females | |
|---|---|---|---|---|---|---|
| Year (t) | Recruits (to model) | Mature (>119mm) | Legal (>134mm) | MMB (>119mm) | Recruits (to model) | Mature (>89mm) |

| | | | | | | |
|---|---|---|---|---|---|---|
| 1985 | NA | 9.6557 | 2.9831 | 29.280 | NA | 10.9701 |
| 1986 | 14.831 | 13.9307 | 5.7973 | 40.607 | 14.602 | 16.7515 |
| 1987 | 7.025 | 16.1572 | 7.6824 | 50.704 | 6.669 | 20.8324 |
| 1988 | 2.039 | 16.6999 | 9.3079 | 61.594 | 1.639 | 24.7973 |
| 1989 | 4.652 | 17.9769 | 10.8720 | 67.921 | 2.036 | 24.8289 |
| 1990 | 11.452 | 18.0612 | 11.7234 | 60.802 | 9.033 | 22.4135 |
| 1991 | 6.992 | 14.3249 | 10.2053 | 49.978 | 3.610 | 20.8139 |
| 1992 | 0.624 | 11.5435 | 8.2128 | 46.676 | 0.646 | 21.7662 |
| 1993 | 6.516 | 12.3596 | 7.6847 | 40.992 | 3.654 | 19.9805 |
| 1994 | 0.486 | 11.8023 | 6.9457 | 52.351 | 0.641 | 17.1617 |
| 1995 | 31.961 | 12.0802 | 8.6303 | 57.369 | 33.235 | 15.9469 |
| 1996 | 8.275 | 12.1707 | 9.1870 | 52.774 | 8.134 | 21.8712 |
| 1997 | 0.486 | 11.7468 | 8.2972 | 49.255 | 0.540 | 33.0230 |
| 1998 | 6.736 | 17.0060 | 8.1548 | 57.307 | 7.215 | 33.7575 |
| 1999 | 18.566 | 19.6077 | 10.1354 | 70.137 | 18.845 | 30.2284 |
| 2000 | 5.906 | 17.6104 | 11.9925 | 71.867 | 5.469 | 32.5938 |
| 2001 | 2.276 | 16.4250 | 11.9093 | 70.368 | 6.095 | 36.3477 |
| 2002 | 32.347 | 18.5435 | 11.6101 | 76.424 | 38.730 | 35.4512 |
| 2003 | 5.375 | 19.3235 | 12.6044 | 74.749 | 5.295 | 41.8194 |
| 2004 | 18.557 | 17.6150 | 12.1364 | 68.684 | 17.515 | 51.1770 |
| 2005 | 31.690 | 21.2223 | 11.4944 | 72.938 | 35.585 | 52.1951 |
| 2006 | 11.701 | 22.6099 | 12.6396 | 82.050 | 8.073 | 59.0269 |
| 2007 | 1.355 | 24.4859 | 14.1019 | 85.967 | 2.003 | 66.3905 |
| 2008 | 4.186 | 28.9920 | 15.1684 | 100.405 | 9.545 | 62.0734 |

Table 7. Comparison of projected mature male biomass (million lbs) on Feb. 15, retained catch (million lbs), their 95% limits, and mean fishing mortality with no directed fishery, $F_{40\%}$, $F_{35\%}$, and ADF&G harvest strategy with $F_{35\%}$ constraint during 2008-2017.

No directed fishery

| Year | MMB | 95% limits of MMB | | Catch | 95% limits of catch | | Mean F |
|---|---|---|---|---|---|---|---|
| 2008 | 122.025 | 108.921 | 135.803 | 0 | 0 | 0 | 0 |
| 2009 | 150.607 | 134.433 | 167.611 | 0 | 0 | 0 | 0 |
| 2010 | 158.254 | 141.264 | 176.115 | 0 | 0 | 0 | 0 |
| 2011 | 155.194 | 138.344 | 172.152 | 0 | 0 | 0 | 0 |
| 2012 | 155.056 | 133.760 | 183.621 | 0 | 0 | 0 | 0 |
| 2013 | 159.940 | 126.290 | 209.080 | 0 | 0 | 0 | 0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 2014 | 166.948 | 121.330 | 230.112 | 0 | 0 | 0 | 0 |
| 2015 | 173.704 | 114.619 | 246.219 | 0 | 0 | 0 | 0 |
| 2016 | 179.263 | 110.777 | 261.916 | 0 | 0 | 0 | 0 |
| 2017 | 184.560 | 111.296 | 273.774 | 0 | 0 | 0 | 0 |
| $F_{40\%}$ | | | | | | | |
| 2008 | 103.860 | 92.707 | 115.587 | 17.741 | 15.836 | 19.745 | 0.270 |
| 2009 | 112.134 | 100.093 | 124.795 | 21.027 | 18.769 | 23.401 | 0.270 |
| 2010 | 100.581 | 89.784 | 111.931 | 22.735 | 20.294 | 25.302 | 0.270 |
| 2011 | 83.154 | 74.354 | 92.587 | 20.900 | 18.289 | 23.287 | 0.269 |
| 2012 | 75.009 | 62.814 | 95.149 | 16.627 | 13.151 | 19.649 | 0.252 |
| 2013 | 75.309 | 53.423 | 115.062 | 14.436 | 9.406 | 19.677 | 0.242 |
| 2014 | 78.533 | 48.642 | 123.840 | 14.426 | 7.405 | 23.051 | 0.243 |
| 2015 | 81.448 | 45.777 | 132.680 | 15.106 | 6.104 | 25.123 | 0.245 |
| 2016 | 83.118 | 44.809 | 135.131 | 15.749 | 5.535 | 26.784 | 0.246 |
| 2017 | 84.650 | 45.740 | 138.007 | 16.174 | 5.758 | 27.669 | 0.246 |
| $F_{35\%}$ | | | | | | | |
| 2008 | 100.248 | 89.482 | 111.566 | 21.242 | 18.961 | 23.640 | 0.332 |
| 2009 | 105.349 | 94.036 | 117.244 | 24.250 | 21.646 | 26.988 | 0.332 |
| 2010 | 91.538 | 81.712 | 101.867 | 25.464 | 22.730 | 28.340 | 0.332 |
| 2011 | 73.922 | 67.238 | 81.397 | 21.908 | 17.966 | 25.256 | 0.318 |
| 2012 | 66.981 | 56.505 | 84.271 | 16.305 | 12.839 | 20.592 | 0.282 |
| 2013 | 67.977 | 47.983 | 104.263 | 14.535 | 9.107 | 20.782 | 0.277 |
| 2014 | 71.419 | 43.864 | 112.498 | 14.918 | 7.083 | 24.898 | 0.283 |
| 2015 | 74.264 | 41.595 | 120.775 | 15.831 | 6.077 | 27.074 | 0.287 |
| 2016 | 75.721 | 41.364 | 123.586 | 16.601 | 5.542 | 29.209 | 0.289 |
| 2017 | 76.992 | 42.486 | 124.433 | 17.076 | 5.836 | 29.853 | 0.291 |
| ADF&G harvest strategy | | | | | | | |
| 2008 | 100.845 | 90.498 | 111.625 | 20.664 | 16.584 | 23.640 | 0.321 |
| 2009 | 108.020 | 98.260 | 117.838 | 22.195 | 17.900 | 26.722 | 0.297 |
| 2010 | 99.918 | 91.383 | 107.709 | 19.516 | 16.195 | 23.322 | 0.237 |
| 2011 | 86.790 | 80.191 | 93.422 | 16.584 | 14.084 | 19.101 | 0.209 |
| 2012 | 79.164 | 69.182 | 94.734 | 15.796 | 12.160 | 21.702 | 0.227 |
| 2013 | 77.642 | 58.846 | 111.409 | 15.853 | 9.194 | 23.478 | 0.253 |
| 2014 | 79.068 | 52.381 | 118.056 | 15.896 | 7.341 | 26.689 | 0.262 |
| 2015 | 80.857 | 48.306 | 124.078 | 16.029 | 5.780 | 28.163 | 0.260 |
| 2016 | 81.986 | 46.830 | 125.816 | 16.195 | 5.356 | 29.840 | 0.255 |
| 2017 | 83.276 | 48.622 | 127.072 | 16.386 | 5.388 | 30.226 | 0.254 |

Table 8. List of years, survey stations, dates and red king crab sizes founded in groundfish stomachs during NMFS summer trawl surveys. All identified crabs are females, mostly mature females. (Source: G.M. Lang, NMFS, Seattle).

| YEAR | RLAT | RLONG | STATION | DATE | PRED_LEN | RKC CL(mm) |
|---|---|---|---|---|---|---|
| 1984 | 57.99 | -160.87 | J-12 | 6/13/1984 | 92 | 110 |
| 1984 | 57.33 | -162.16 | H-10 | 6/14/1984 | 79 | 130 |
| 1981 | 57.34 | -162.13 | H-10 | 5/29/1981 | 67 | 120.75 |
| 1981 | 57.34 | -162.13 | H-10 | 5/29/1981 | 67 | 106.15 |
| 1981 | 56.69 | -161.00 | F-12 | 6/1/1981 | 66 | 99.95 |
| 1981 | 56.69 | -161.00 | F-12 | 6/1/1981 | 69 | 53.4 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 1981 | 57.01 | -160.95 | G-12 | 6/1/1981 | 69 | 160.3 |
| 1981 | 57.99 | -160.87 | J-12 | 6/21/1981 | 51 | 90.95 |
| 1981 | 57.99 | -160.87 | J-12 | 6/21/1981 | 62 | 95 |
| 1985 | 56.95 | -159.85 | G-14 | 10/29/1985 | 85 | 52 |
| 1986 | 57.67 | -161.49 | I-11 | 6/7/1986 | 89 | 90.5 |
| 1989 | 56.17 | -161.52 | D-11 | 6/4/1989 | 95 | 83.9 |
| 1989 | 56.17 | -161.52 | D-11 | 6/4/1989 | 95 | 99.4 |
| 1991 | 57.00 | -159.12 | G-15 | 6/8/1991 | 56 | 17 |
| 1992 | 57.32 | -162.15 | H-10 | 6/9/1992 | 98 | 101 |
| 1992 | 57.32 | -162.15 | H-10 | 6/9/1992 | 98 | 87 |
| 1992 | 57.32 | -162.15 | H-10 | 6/9/1992 | 98 | 95 |
| 1992 | 57.32 | -162.15 | H-10 | 6/9/1992 | 97 | 117 |
| 1992 | 56.67 | -160.99 | F-12 | 6/7/1992 | 89 | 144 |
| 1985 | 56.42 | -161.58 | E-11 | 4/25/1985 | 82 | 94 |
| 1992 | 56.67 | -160.99 | F-12 | 6/7/1992 | 89 | 144 |
| 1992 | 57.32 | -162.15 | H-10 | 6/9/1992 | 98 | 101 |
| 1992 | 57.32 | -162.15 | H-10 | 6/9/1992 | 98 | 87 |
| 1992 | 57.32 | -162.15 | H-10 | 6/9/1992 | 98 | 95 |
| 1992 | 57.32 | -162.15 | H-10 | 6/9/1992 | 97 | 117 |
| 2000 | 56.00 | -162.25 | D-10 | 5/28/2000 | 75 | 120 |
| 2002 | 57.68 | -160.27 | I-13 | 6/3/2002 | 70 | 125 |

Table 9. Summary of red king crab biomass (million lbs) in Bristol Bay that were consumed by groundfish during late May to September. Pacific cod is the main predator. (Source: G.M. Lang, NMFS, Seattle).

| Year | Red king crab biomass |
|---|---|
| 1984 | 3.719 |
| 1985 | 0.000 |
| 1986 | 14.457 |
| 1987 | 7.403 |
| 1988 | 0.000 |
| 1989 | 0.203 |
| 1990 | 1.853 |

| | |
|---|---|
| 1991 | 0.039 |
| 1992 | 4.488 |
| 1993 | 3.833 |
| 1994 | 1.545 |
| 1995 | 0.993 |
| 1996 | 0.000 |
| 1997 | 0.000 |
| 1998 | 2.192 |
| 1999 | 1.718 |
| 2000 | 1.199 |
| 2001 | 0.000 |
| 2002 | 2.008 |
| 2003 | 0.000 |
| 2004 | 0.000 |
| 2005 | 11.677 |

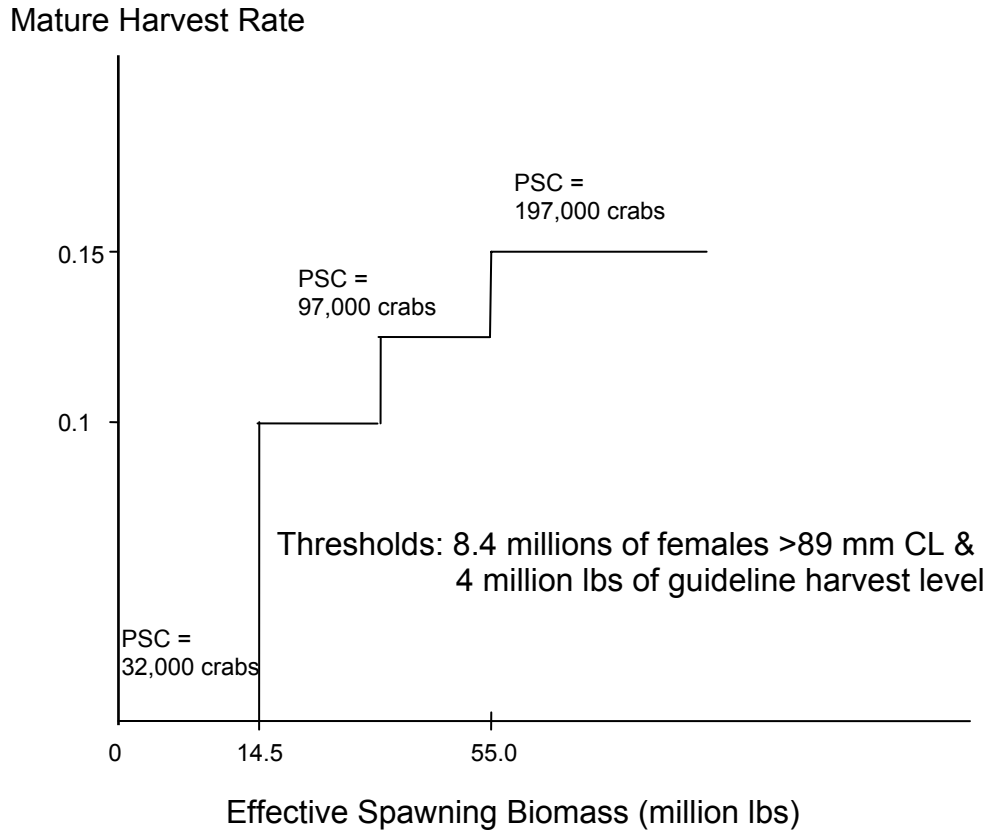



Figure 1. Current harvest rate strategy (line) for the Bristol Bay red king crab fishery and annual prohibited species catch (PSC) limits (numbers of crabs) of Bristol Bay red king crabs in the groundfish fisheries in zone 1 in the eastern Bering Sea. Harvest rates are based on current-year estimates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

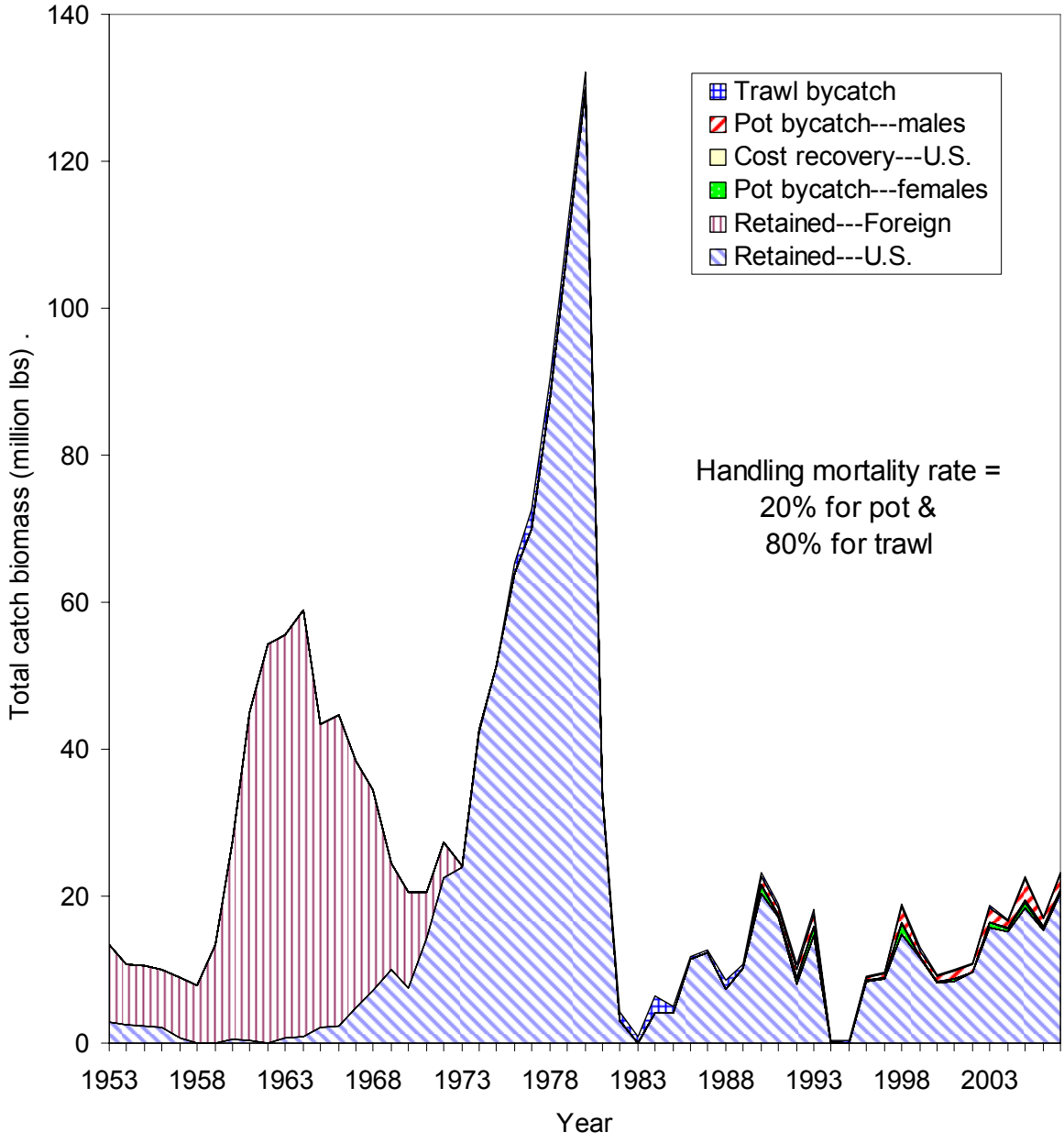



Figure 2. Retained catch biomass and bycatch mortality biomass (million lbs) for Bristol Bay red king crab from 1960 to 2007. Handling mortality rates were assumed to be 0.2 for the directed pot fishery and 0.8 for the trawl fisheries.

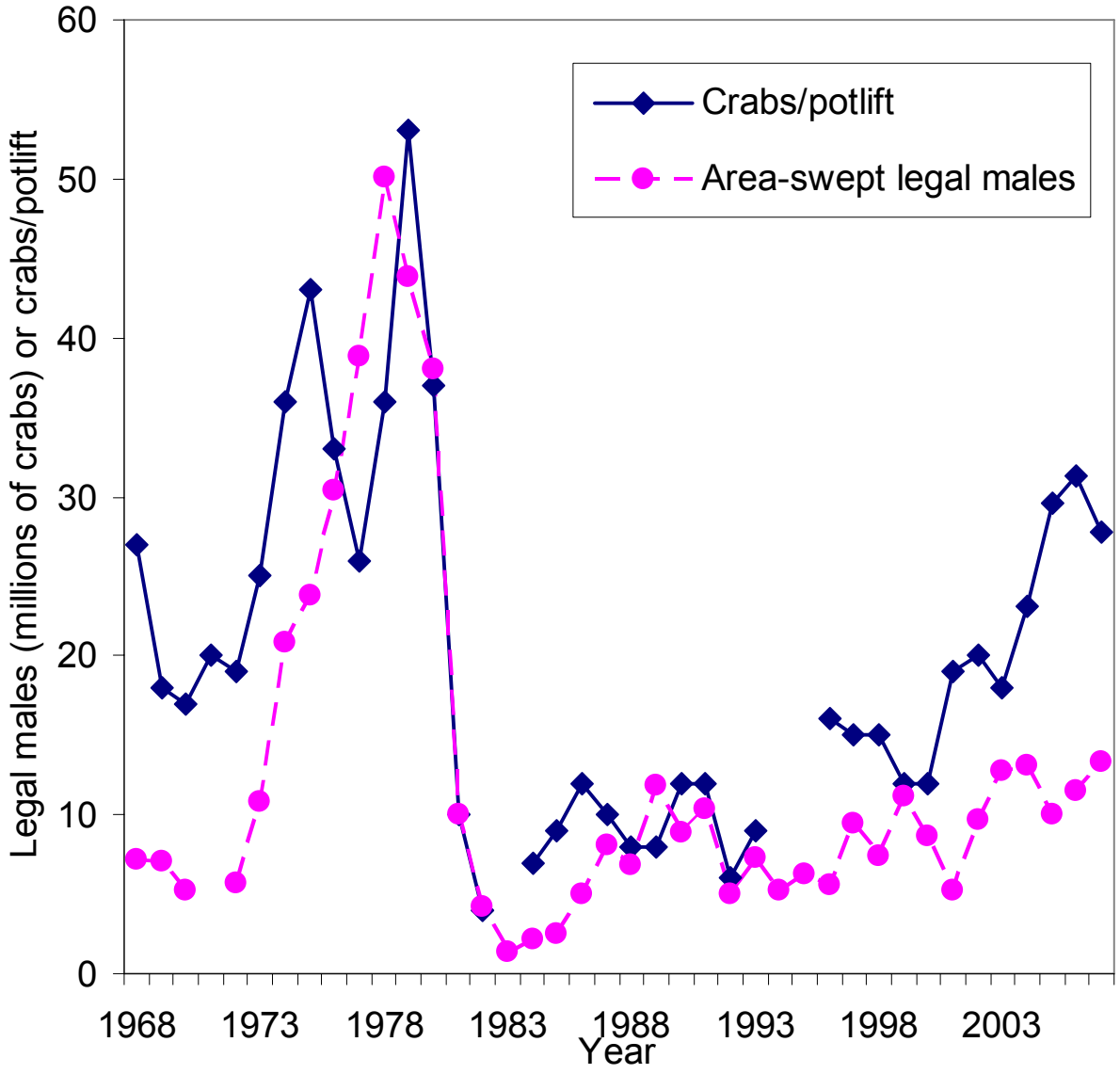



Figure 3. Comparison of survey legal male abundances and catches per unit effort for Bristol Bay red king crab from 1968 to 2007.

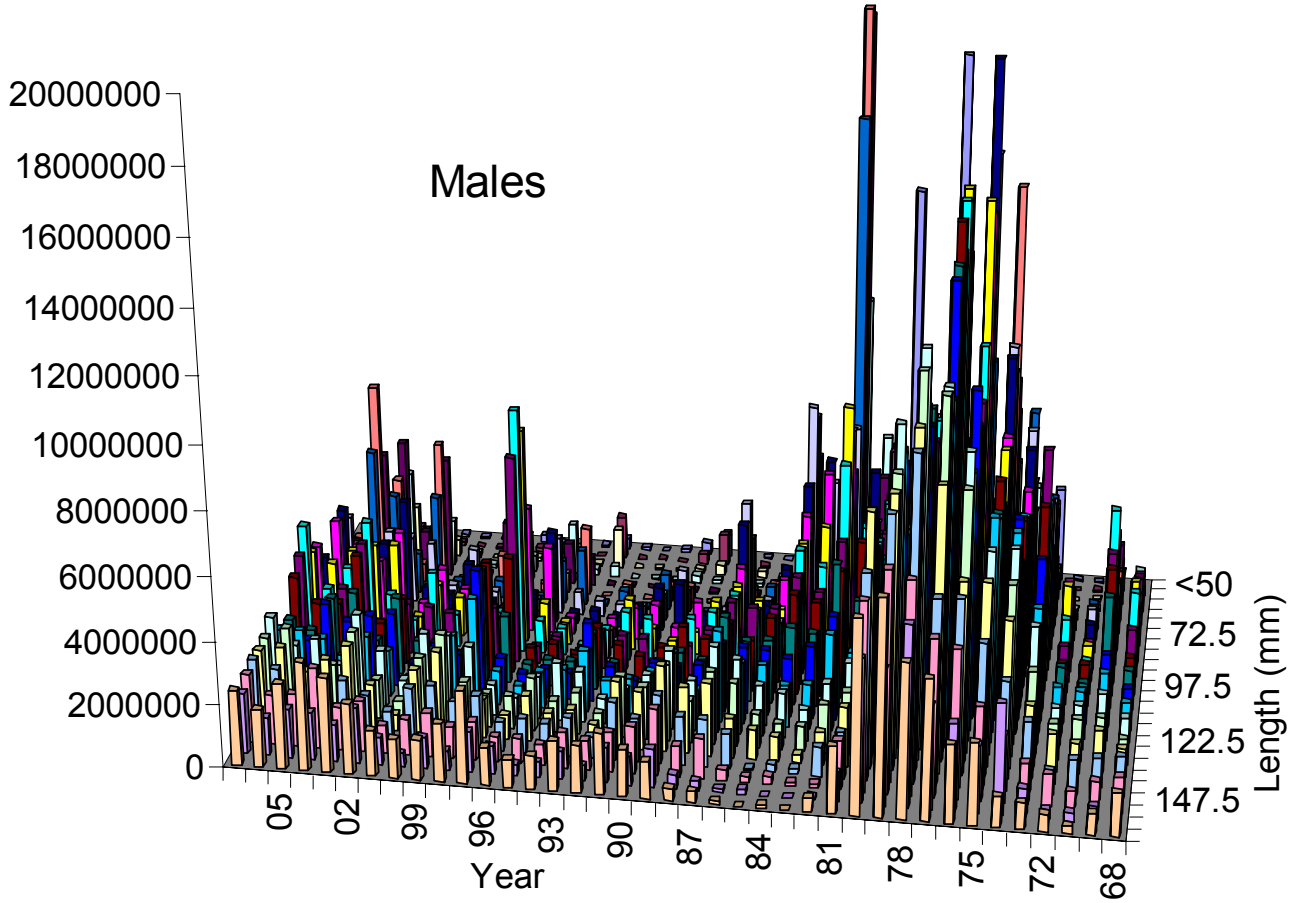



Figure 4. Survey abundances by length for male Bristol Bay red king crabs from 1968 to 2007.

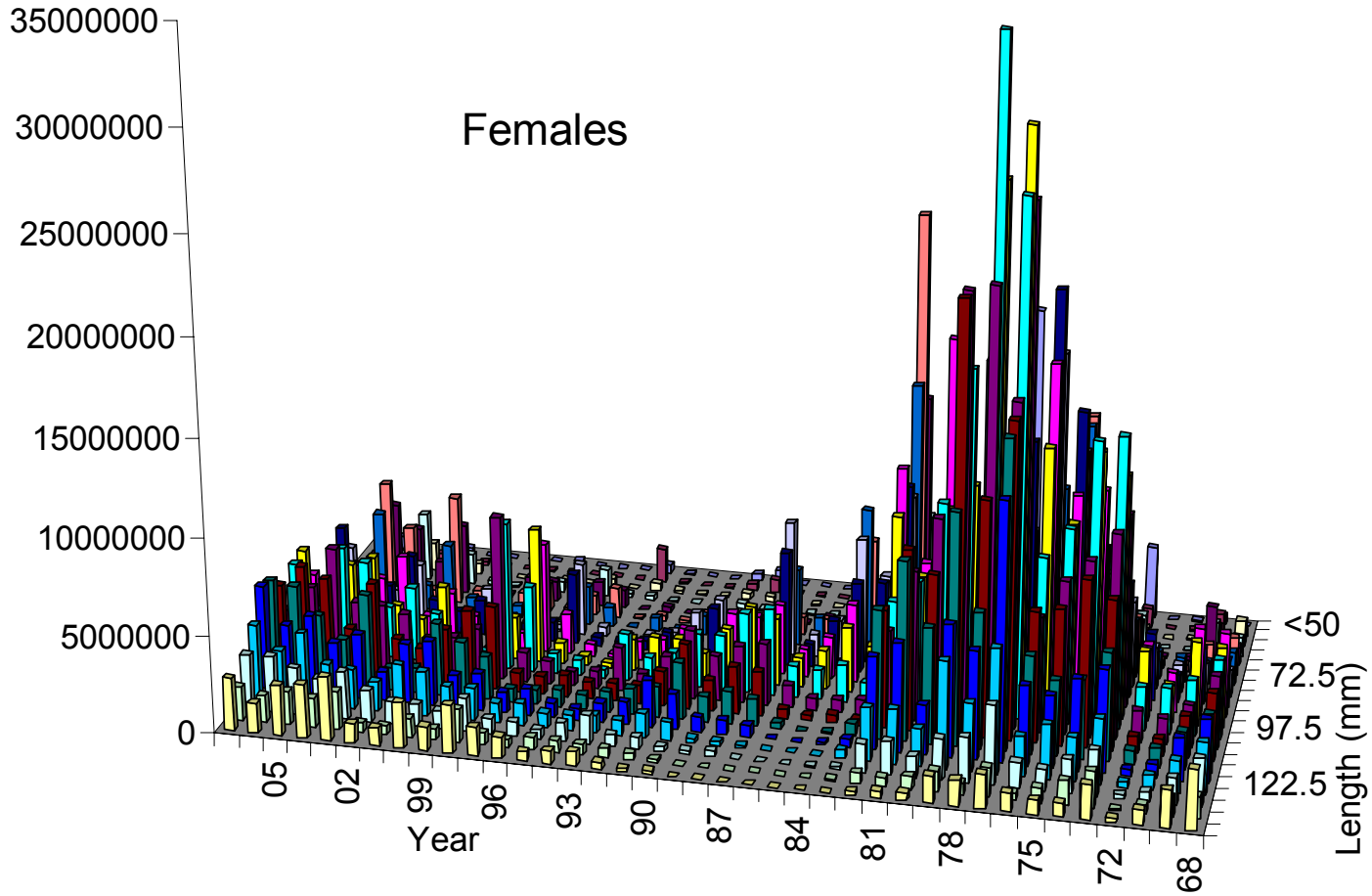



Figure 5. Survey abundances by length for female Bristol Bay red king crabs from 1968 to 2007.

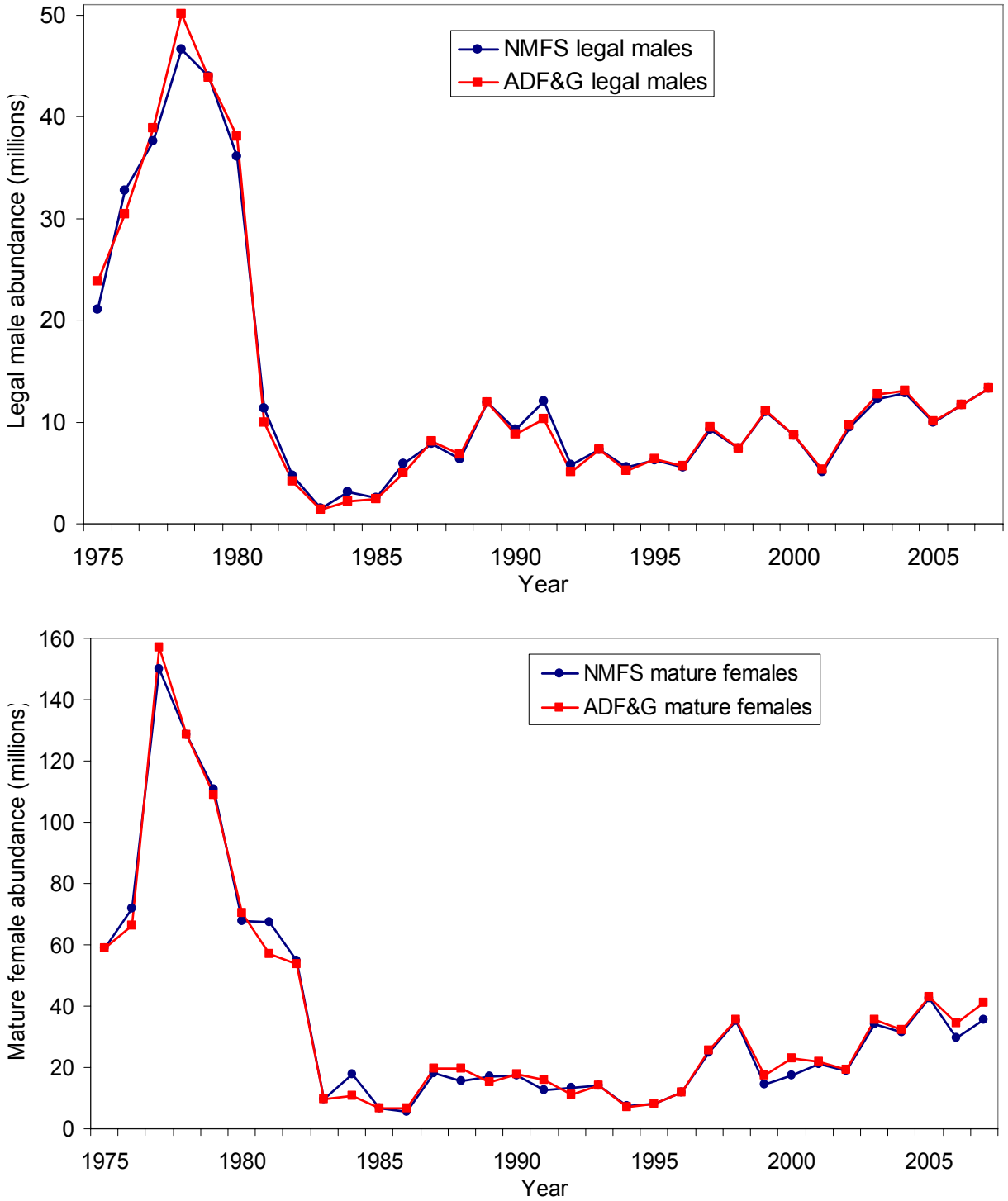



Figure 6. Comparison of survey abundance estimates by NMFS and ADF&G for Bristol Bay red king crab from 1975 to 2007.

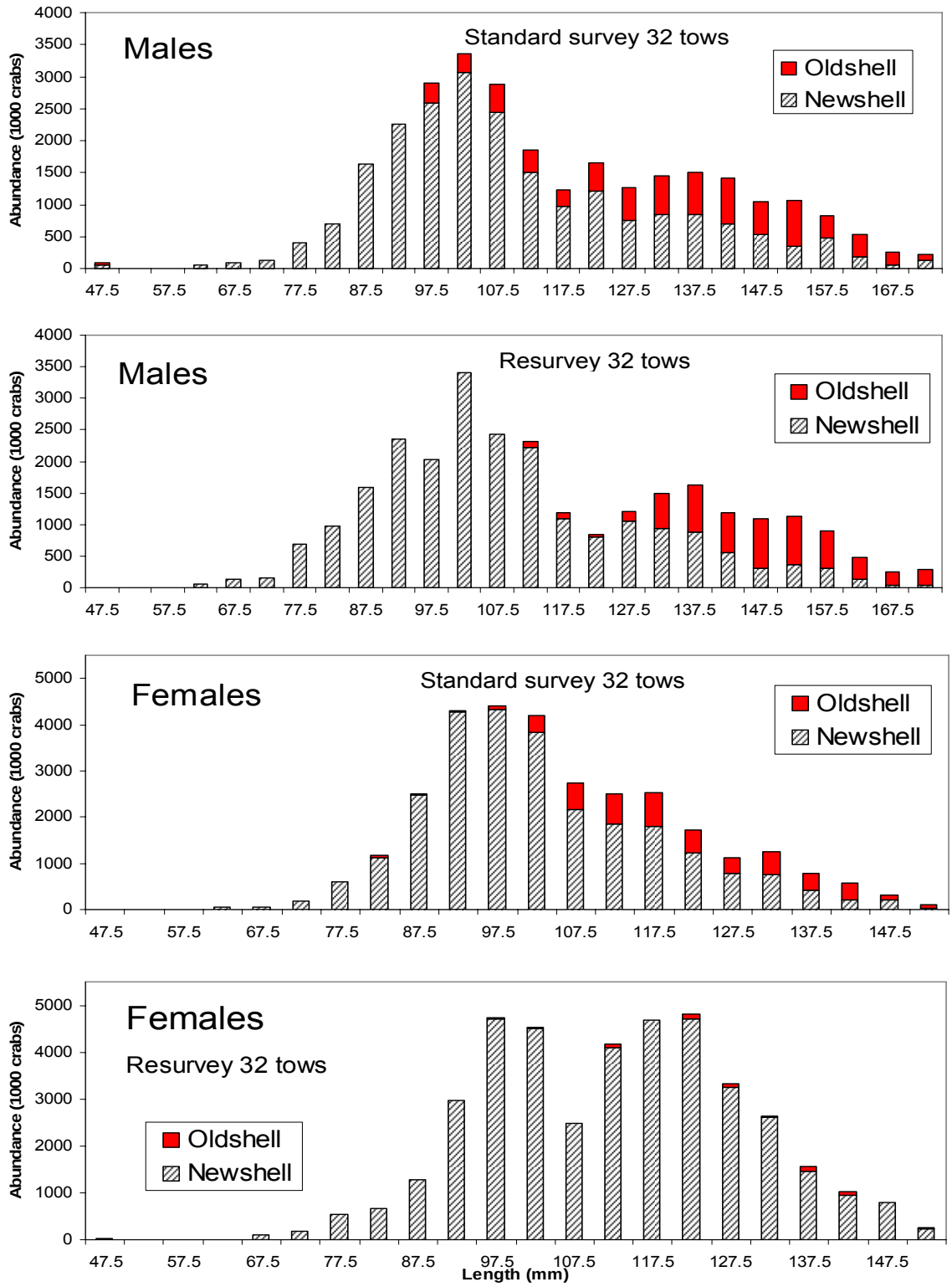



Figure 7. Comparison of area-swept estimates of abundance in 32 stations from the standard trawl survey and resurvey in 2007.

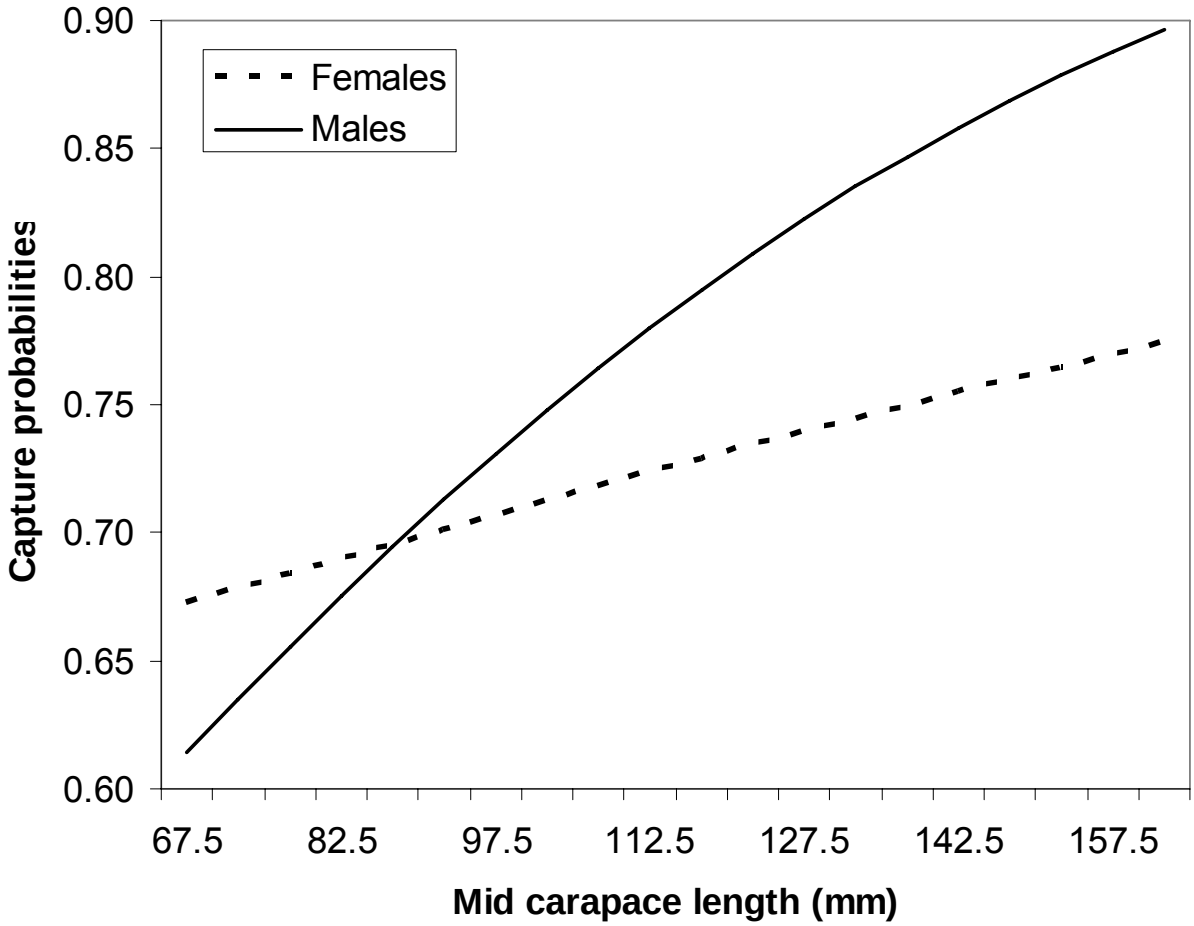
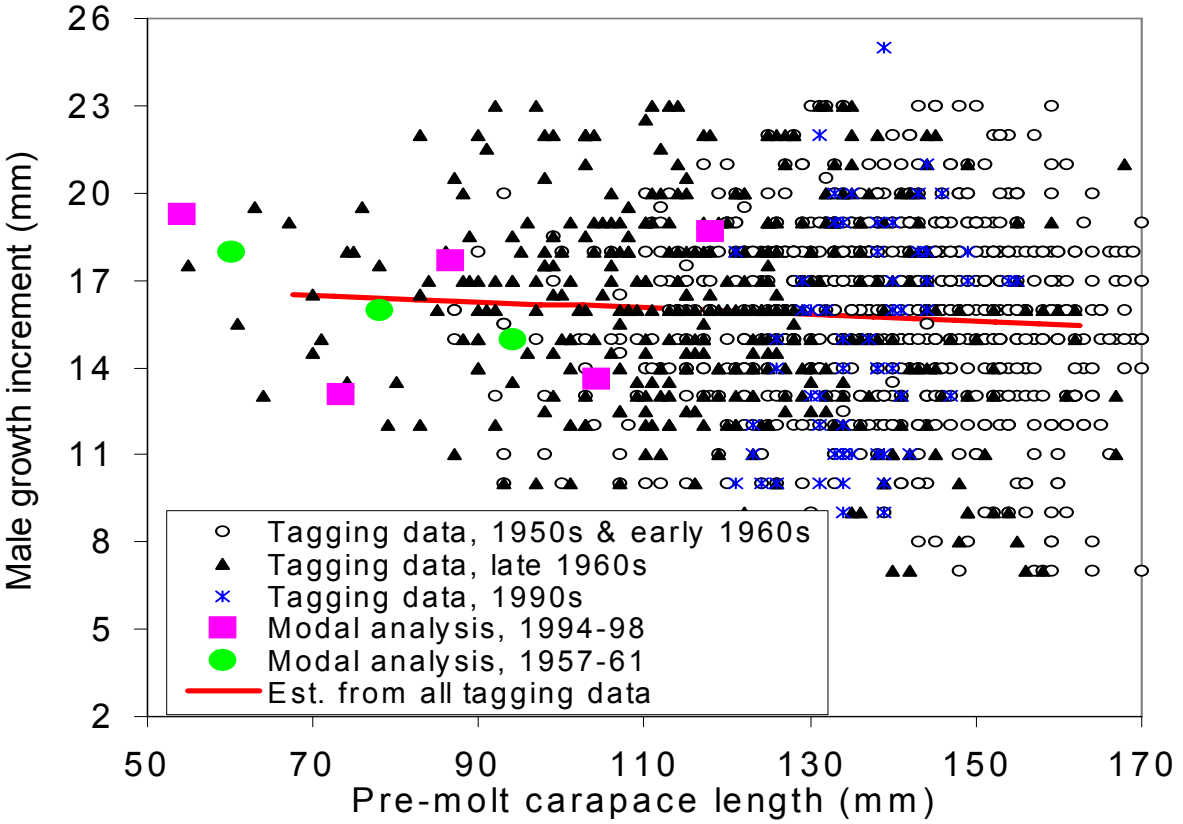



Figure 8. Estimated capture probabilities for Bristol Bay red king crab trawl survey by Weinberg et al. (2004).



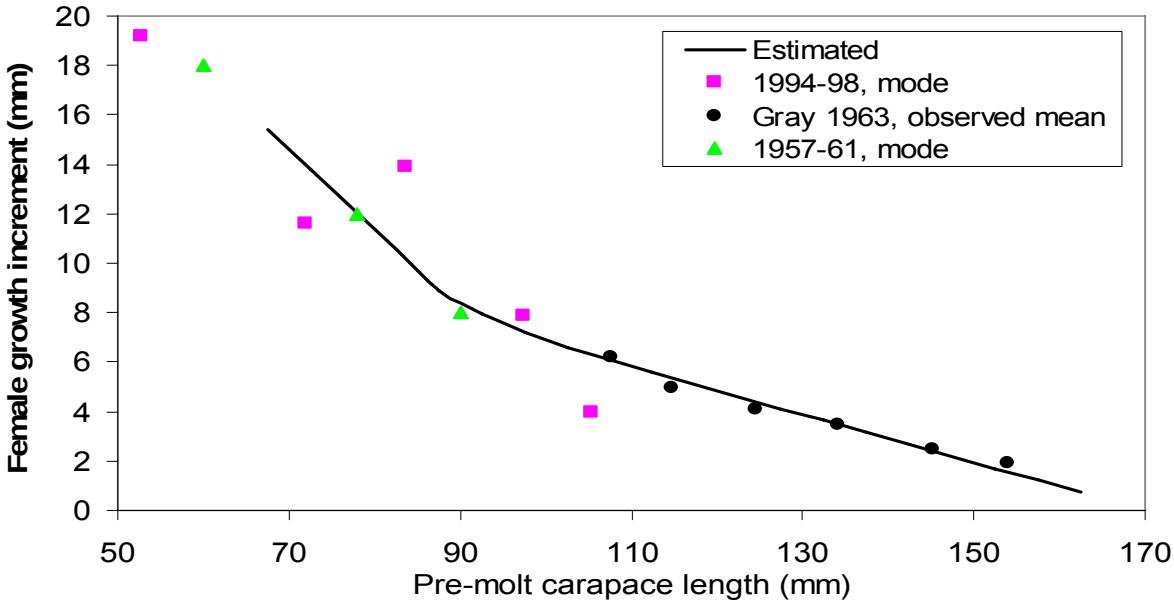




Figure 9. Mean growth increments per molt for Bristol Bay red king crab. Note: "tagging"---based on tagging data; "mode"---based on modal analysis.

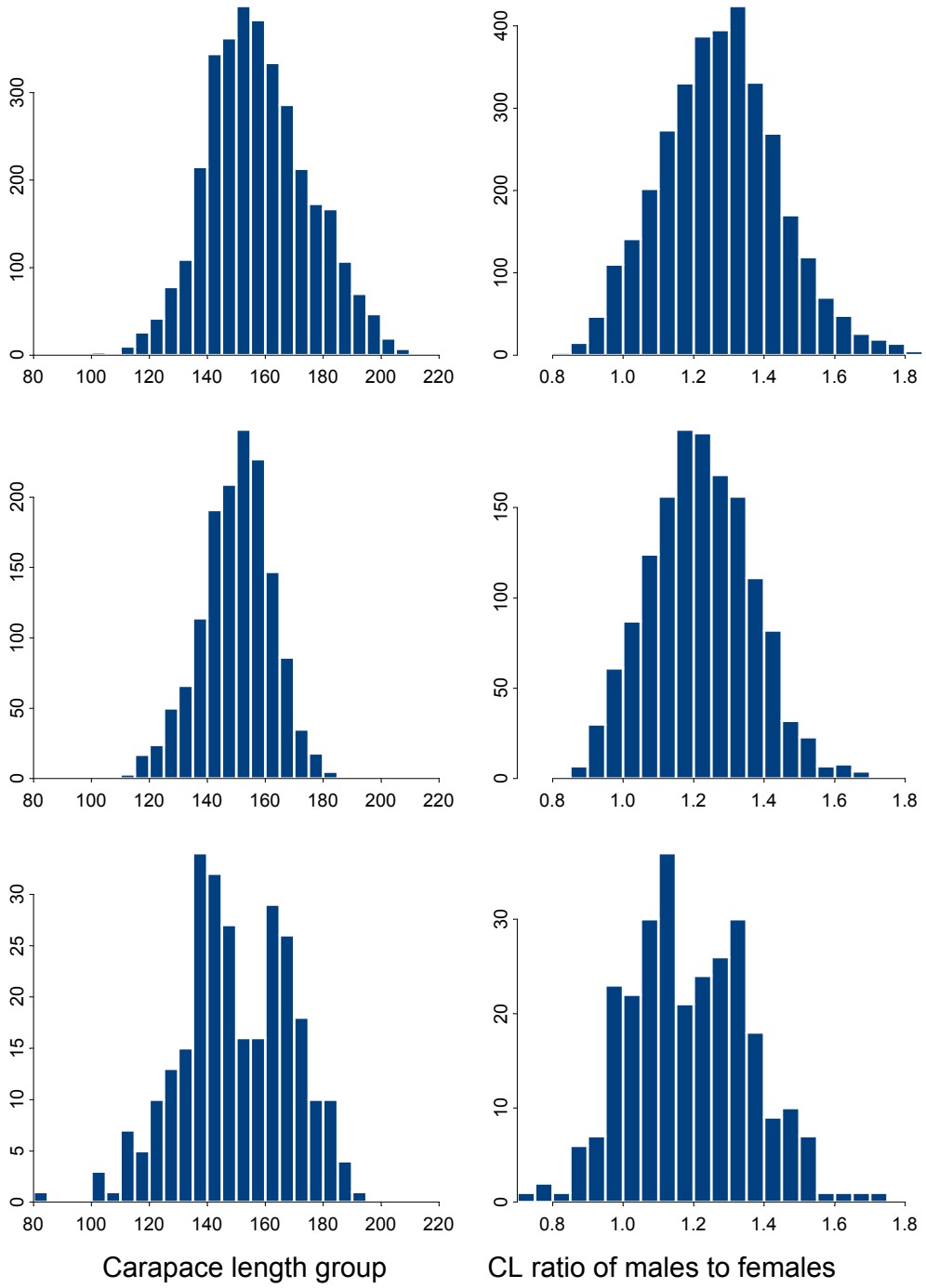



Figure 10. Histograms of carapace lengths (CL) and CL ratios of males to females for male shell ages ≤13 months of red king crab males in grasping pairs; Powell's Kodiak data. Upper plot: all locations and years pooled; middle plot: location 11; lower plot: locations 4 and 13. Sizes at maturity for Kodiak red king crab are about 15 mm larger than those for Bristol Bay red king crab. (Source: Doug Pengilly, ADF&G).

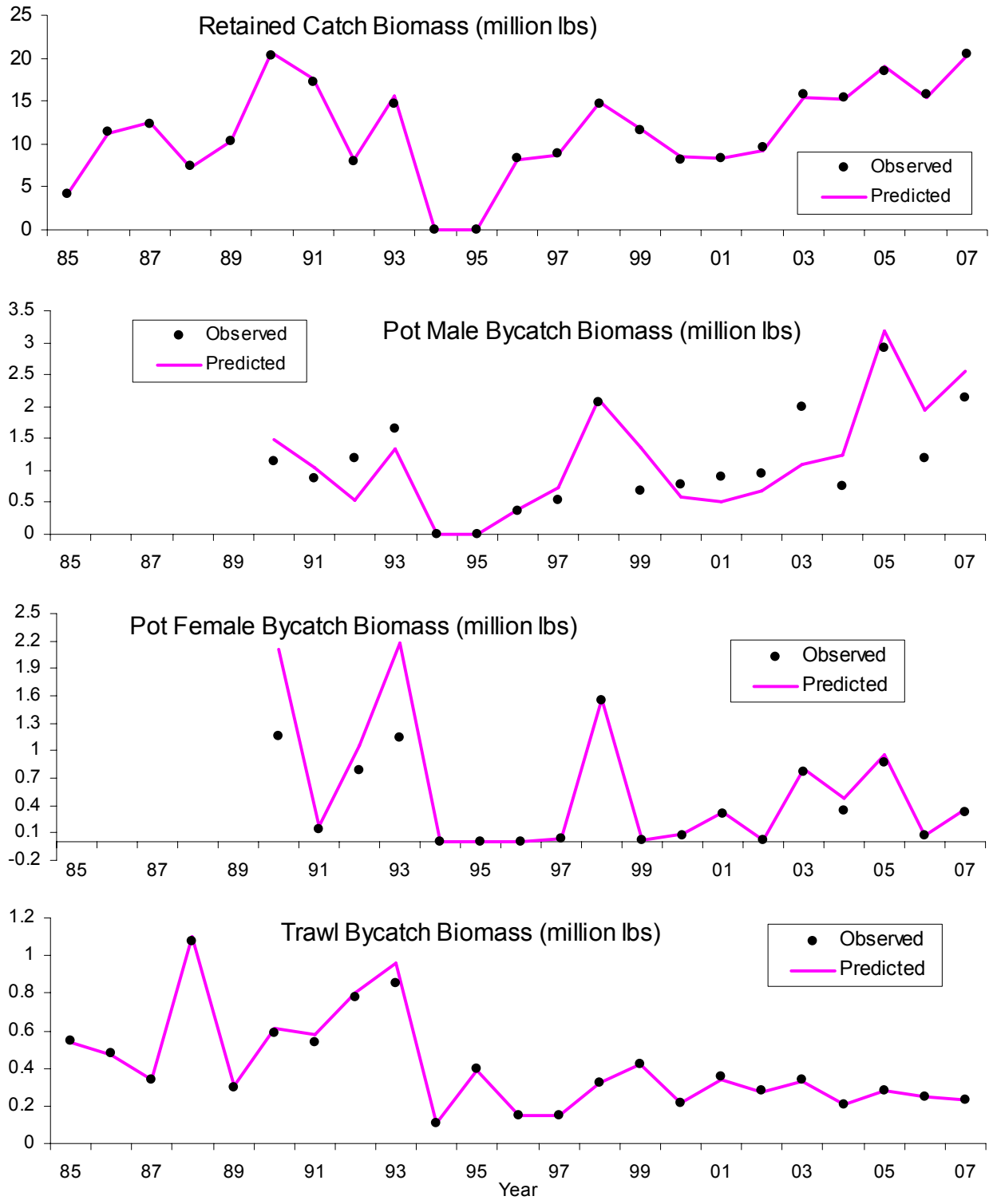



Figure 11. Observed and predicted catch mortality biomass. Mortality biomass is equal to caught biomass times a handling mortality rate. Pot handling mortality rate is 0.2.

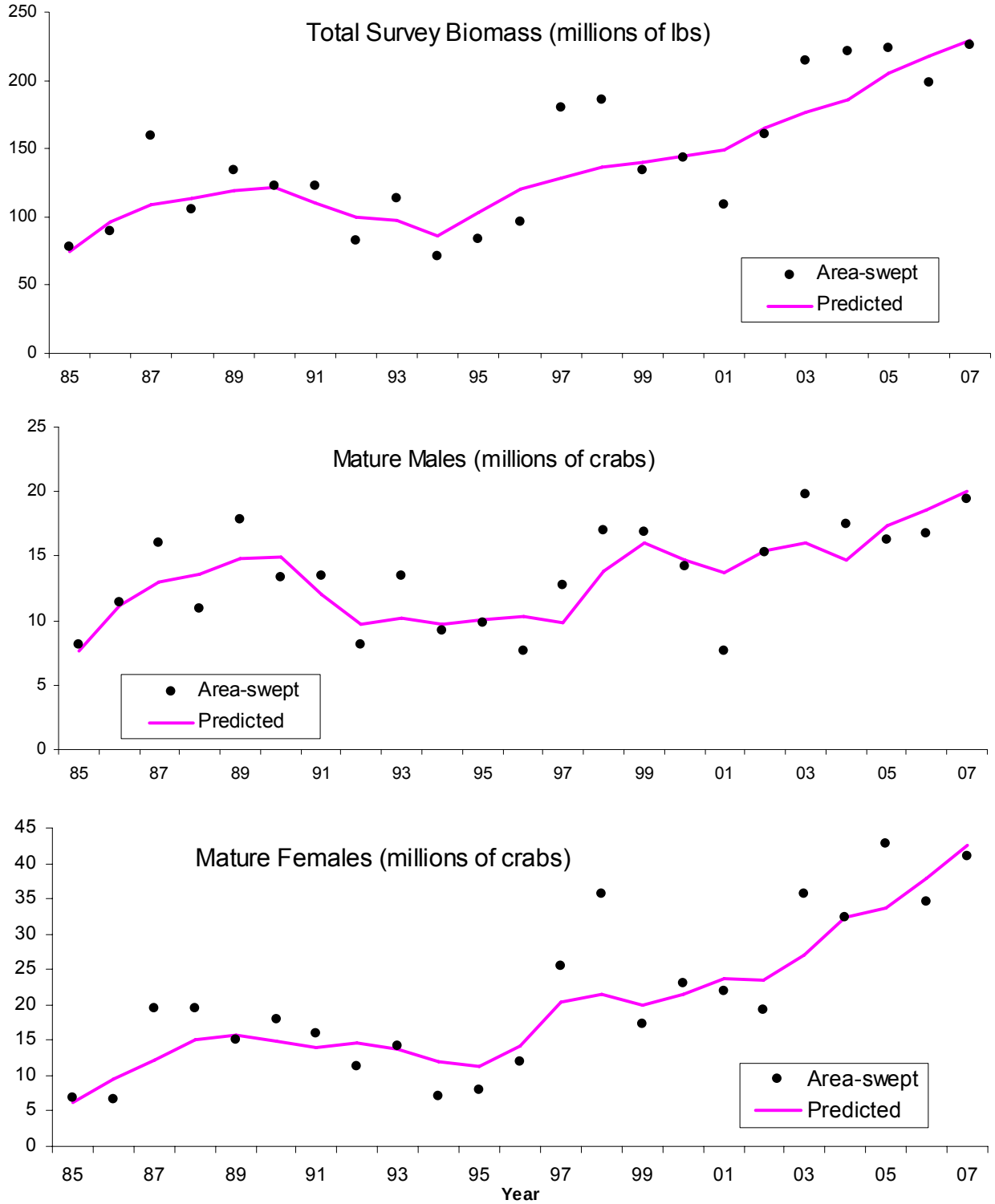



Figure 12. Comparisons of area-swept estimates of total survey biomass, mature male (>119 mm) and mature female (>89 mm) abundance and model prediction. Pot handling mortality rate is 0.2.

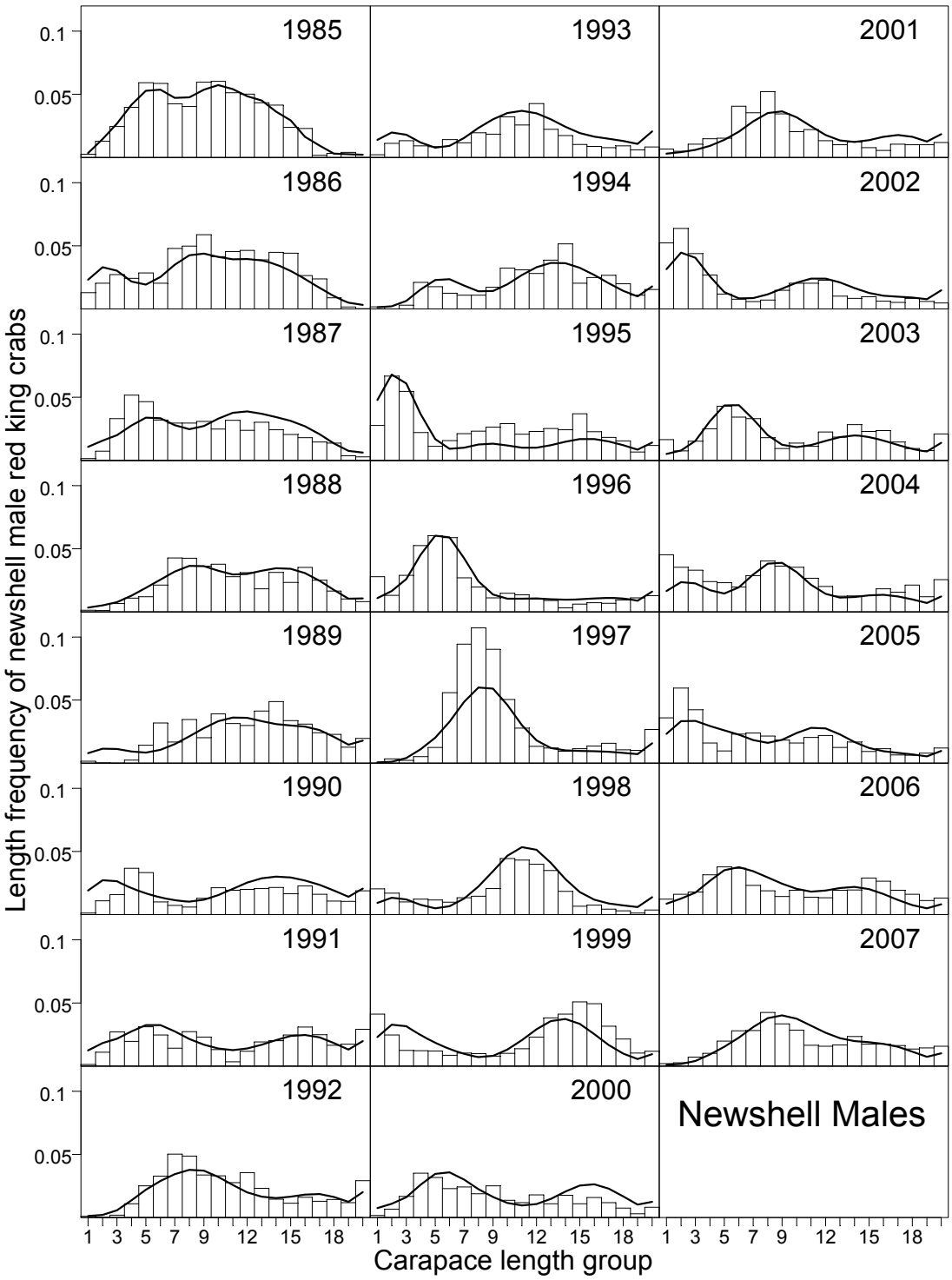



Figure 13. Comparison of area-swept and model estimated survey length frequencies of Bristol Bay newshell male red king crabs by year. Pot handling mortality rate is 0.2, and the first length group is 67.5 mm.

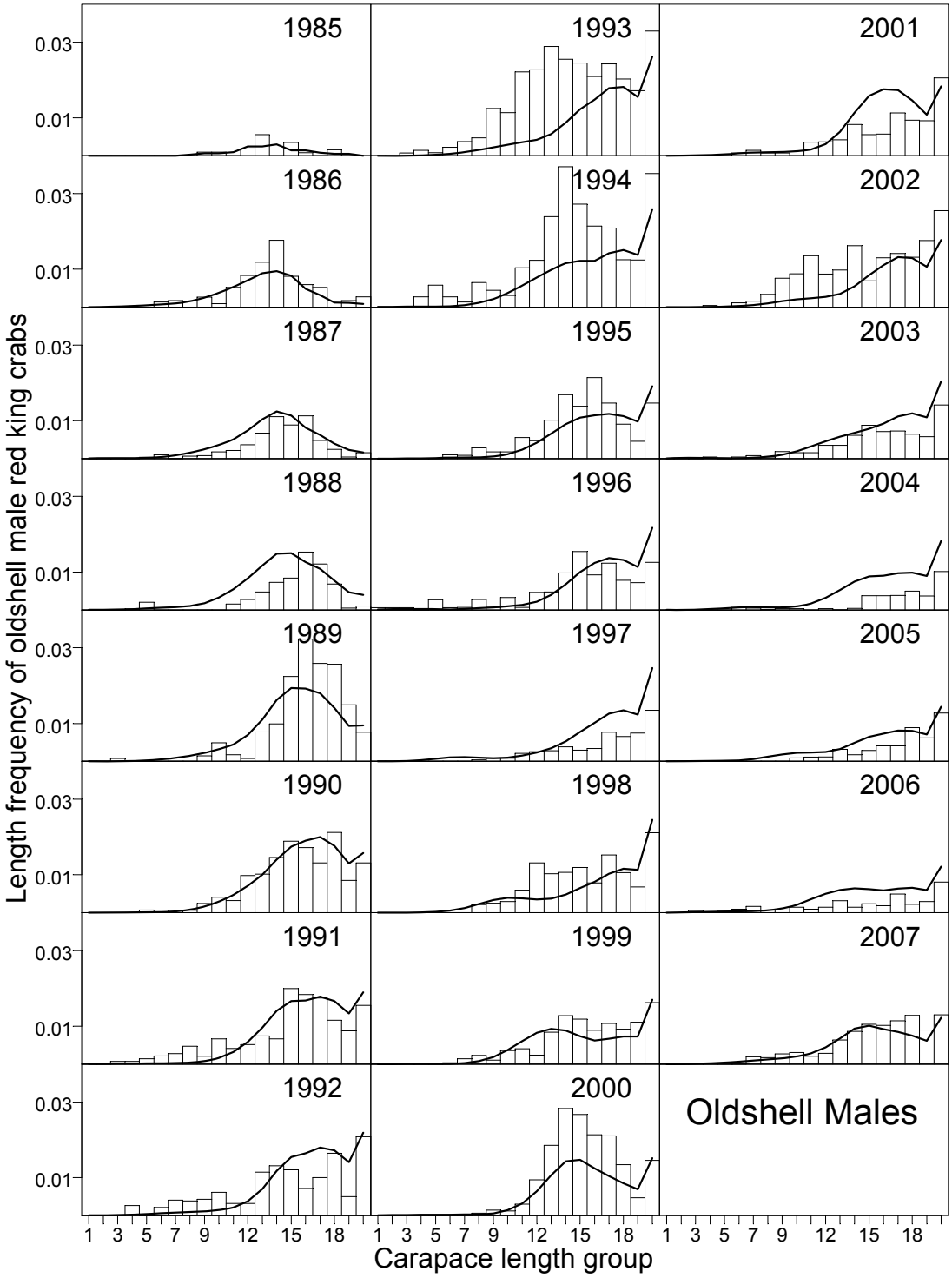



Figure 14. Comparison of area-swept and model estimated survey length frequencies of Bristol Bay oldshell male red king crabs by year. Pot handling mortality rate is 0.2, and the first length group is 67.5 mm.

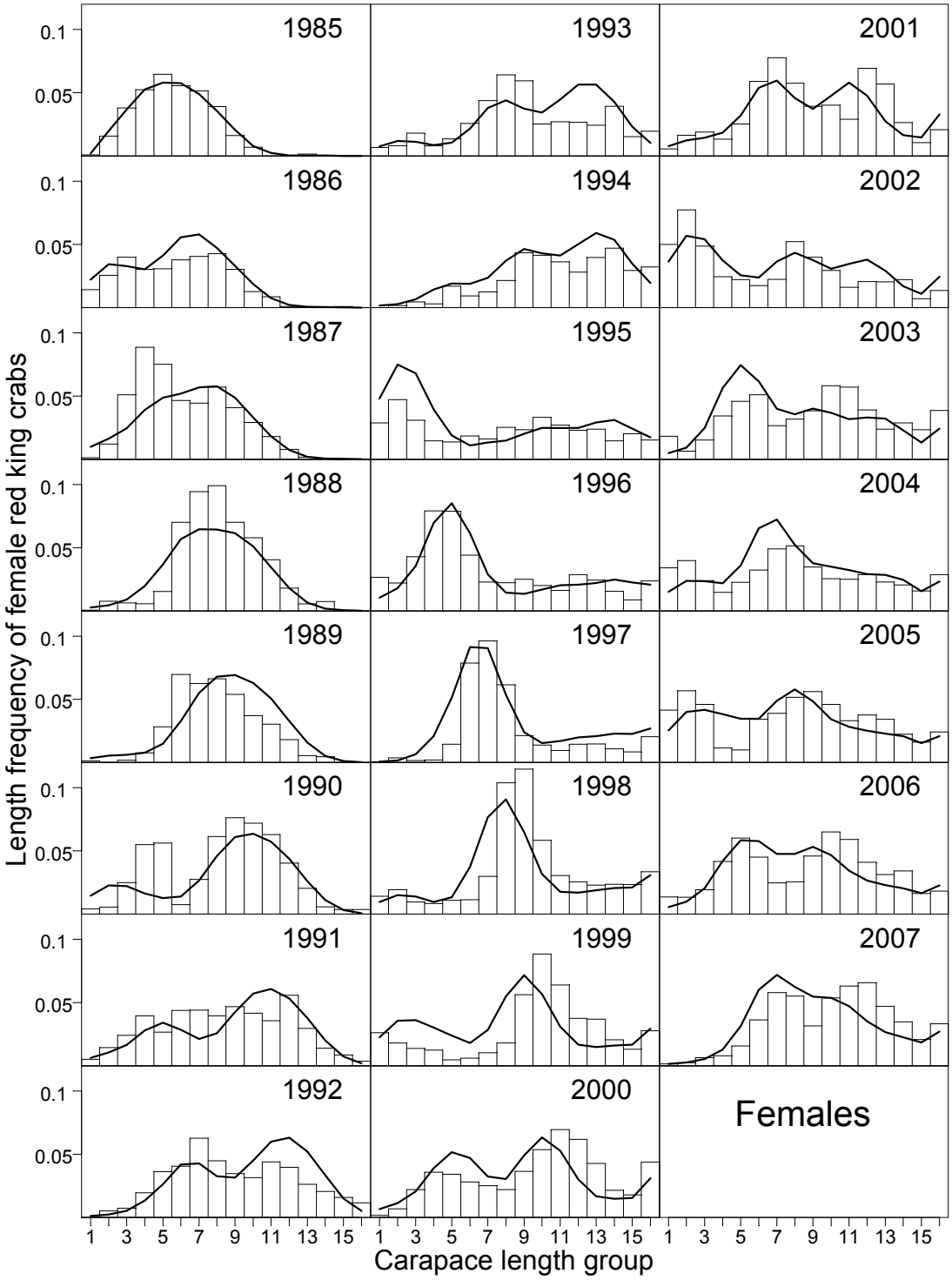



Figure 15. Comparison of area-swept and model estimated survey length frequencies of Bristol Bay female red king crabs by year. Pot handling mortality rate is 0.2, and the first length group is 67.5 mm.

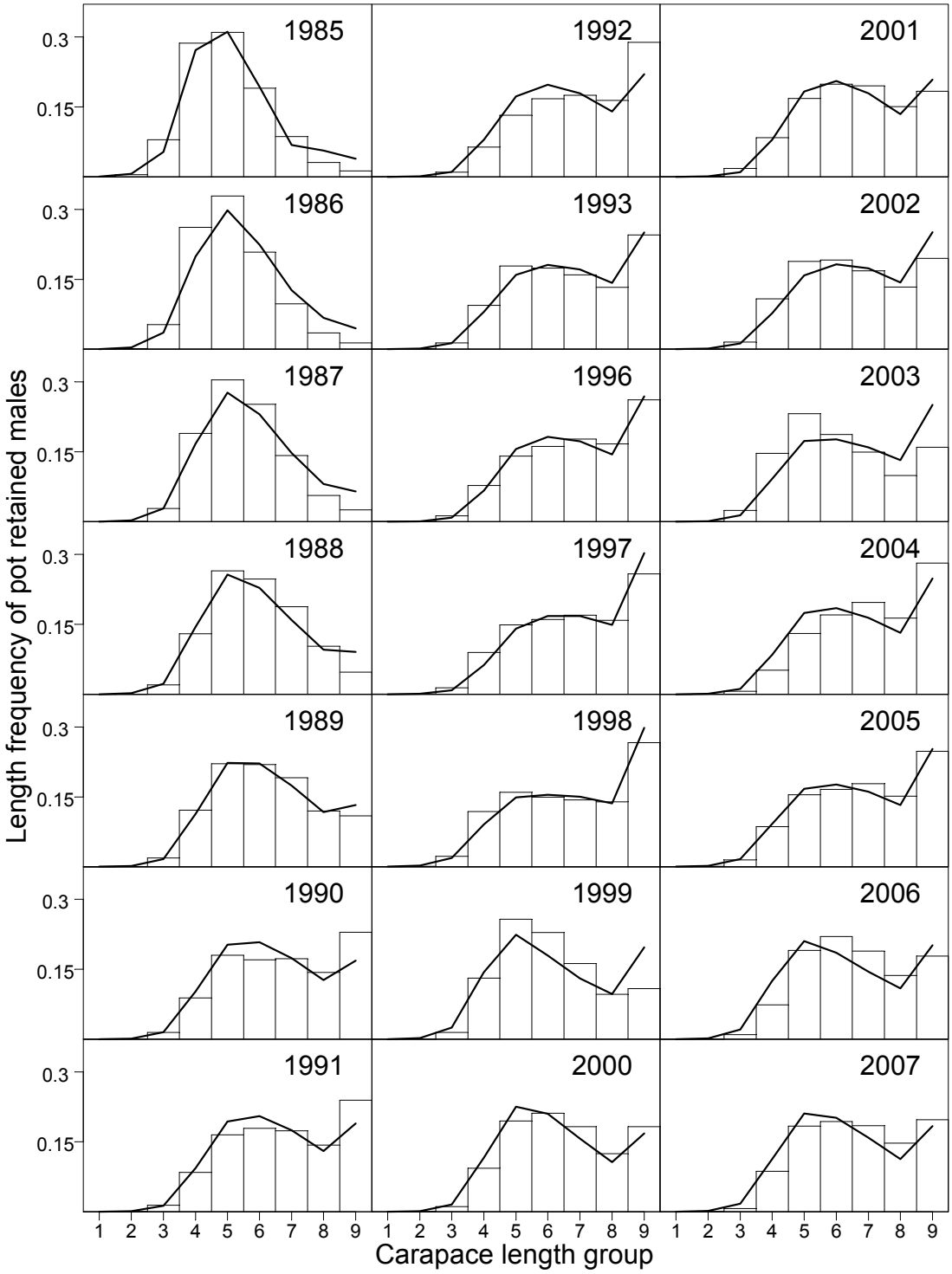



Figure 16. Comparison of observed and model estimated retained length frequencies of Bristol Bay male red king crabs by year in the directed pot fishery. Pot handling mortality rate is 0.2, and the first length group is 122.5 mm.

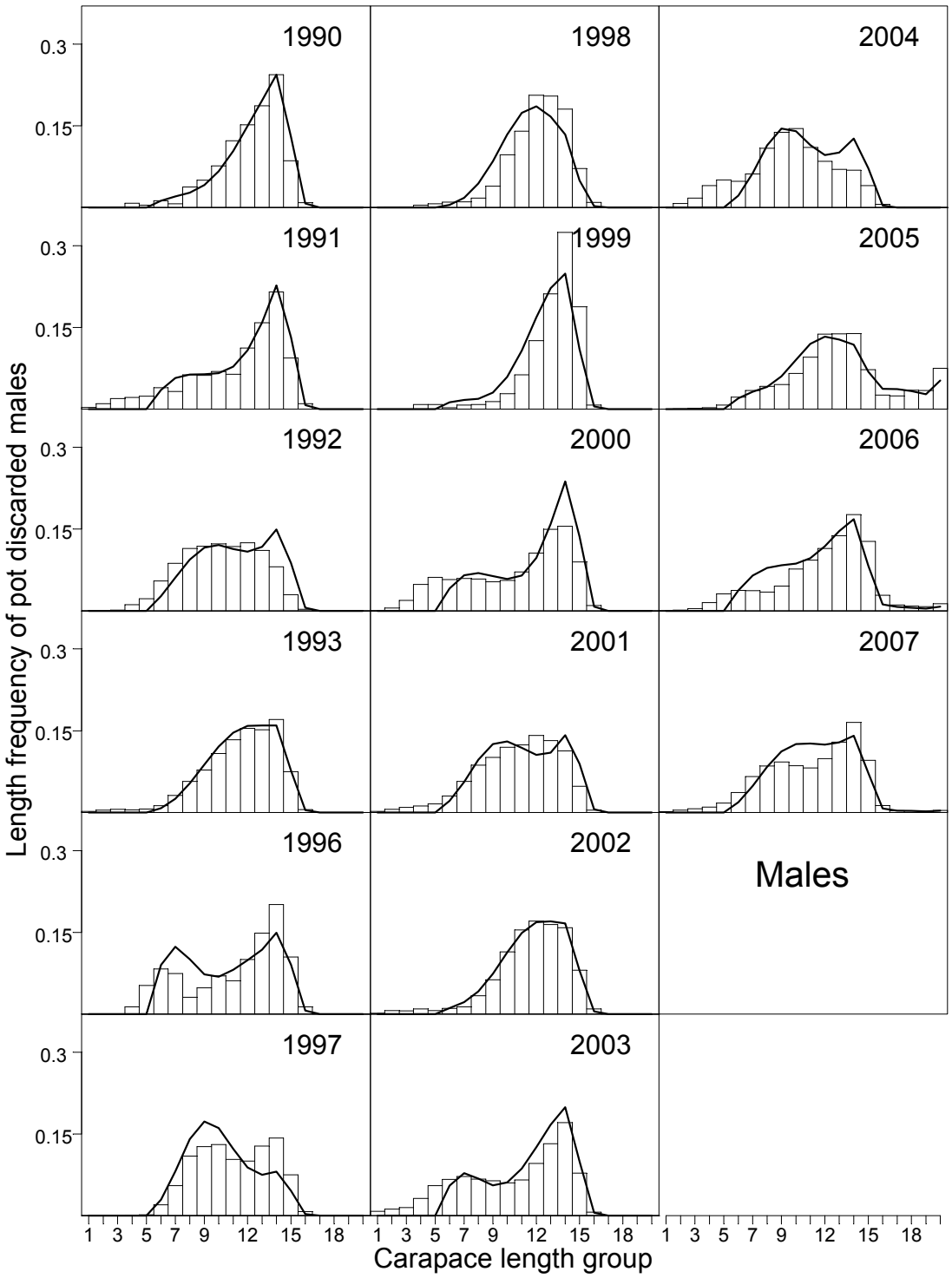



Figure 17. Comparison of observer and model estimated discarded length frequencies of Bristol Bay male red king crabs by year in the directed pot fishery. Pot handling mortality rate is 0.2, and the first length group is 67.5 mm.

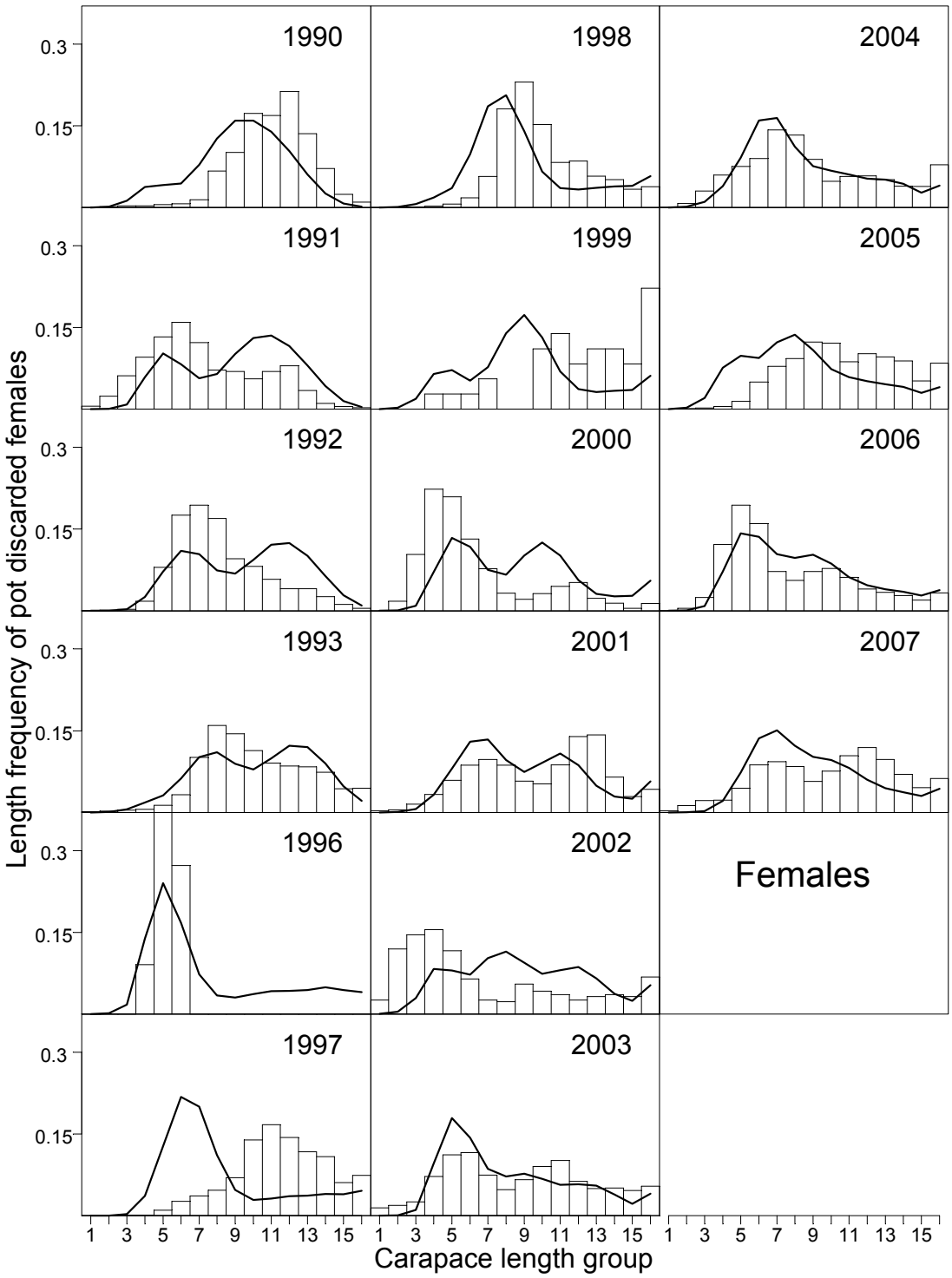



Figure 18. Comparison of observer and model estimated discarded length frequencies of Bristol Bay female red king crabs by year in the directed pot fishery. Pot handling mortality rate is 0.2, and the first length group is 67.5 mm.

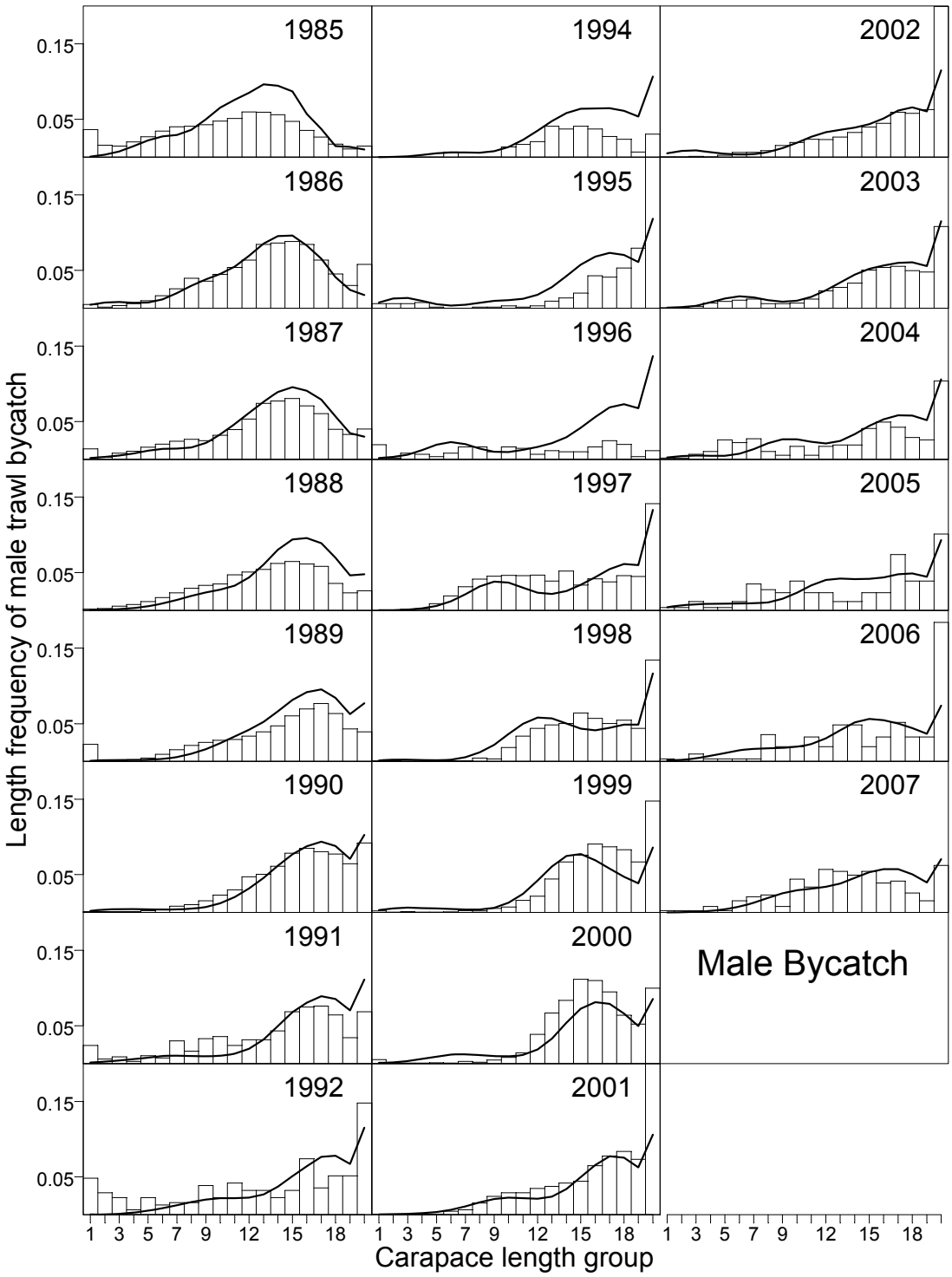



Figure 19. Comparison of observer and model estimated discarded length frequencies of Bristol Bay male red king crabs by year in the groundfish trawl fisheries. Pot handling mortality rate is 0.2, and the first length group is 67.5 mm.

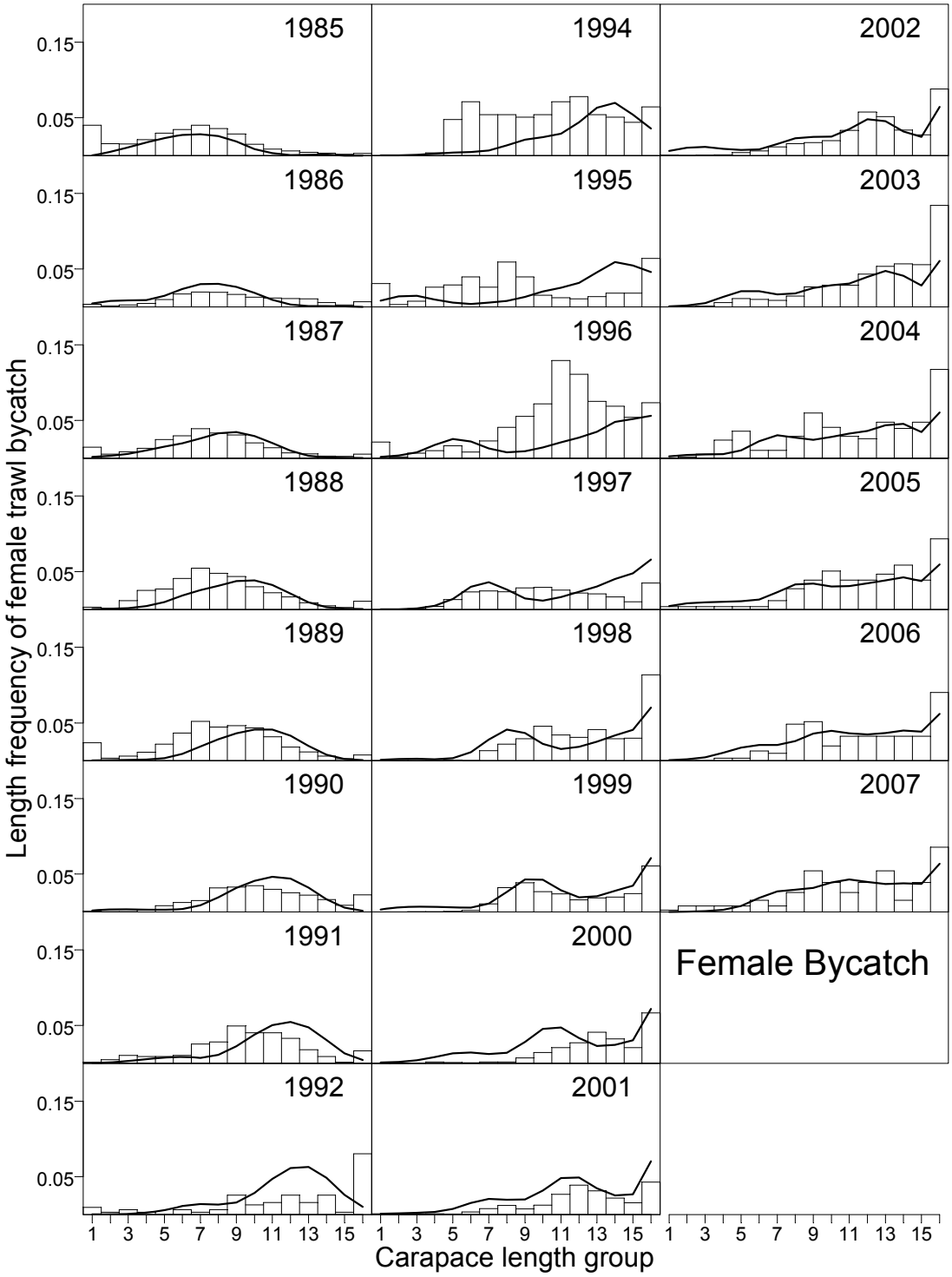



Figure 20. Comparison of observer and model estimated discarded length frequencies of Bristol Bay female red king crabs by year in the groundfish trawl fisheries. Pot handling mortality rate is 0.2, and the first length group is 67.5 mm.

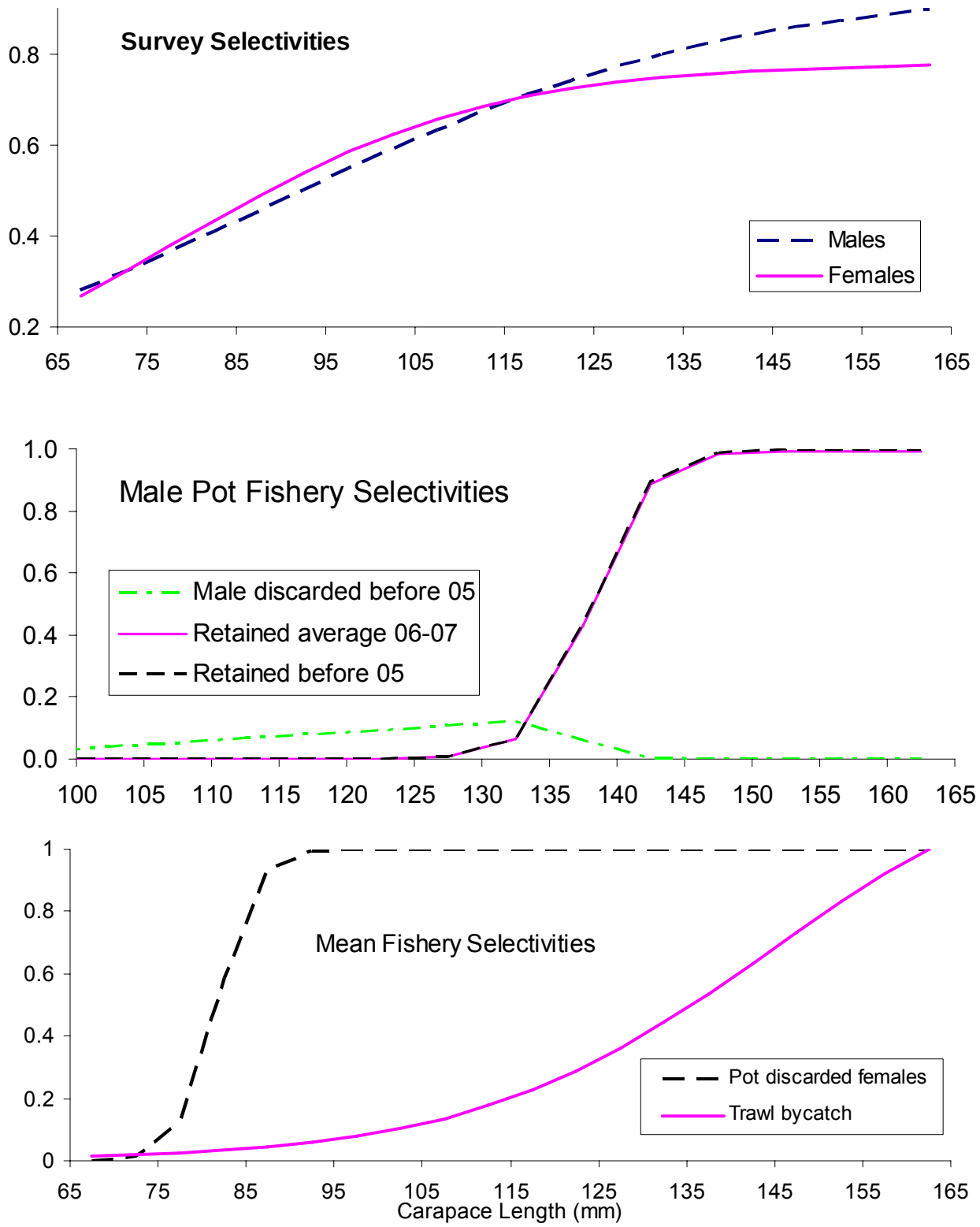



Figure 21. Estimated trawl survey selectivities, pot fishery selectivities, and groundfish trawl bycatch selectivities. Pot handling mortality rate is 0.2.

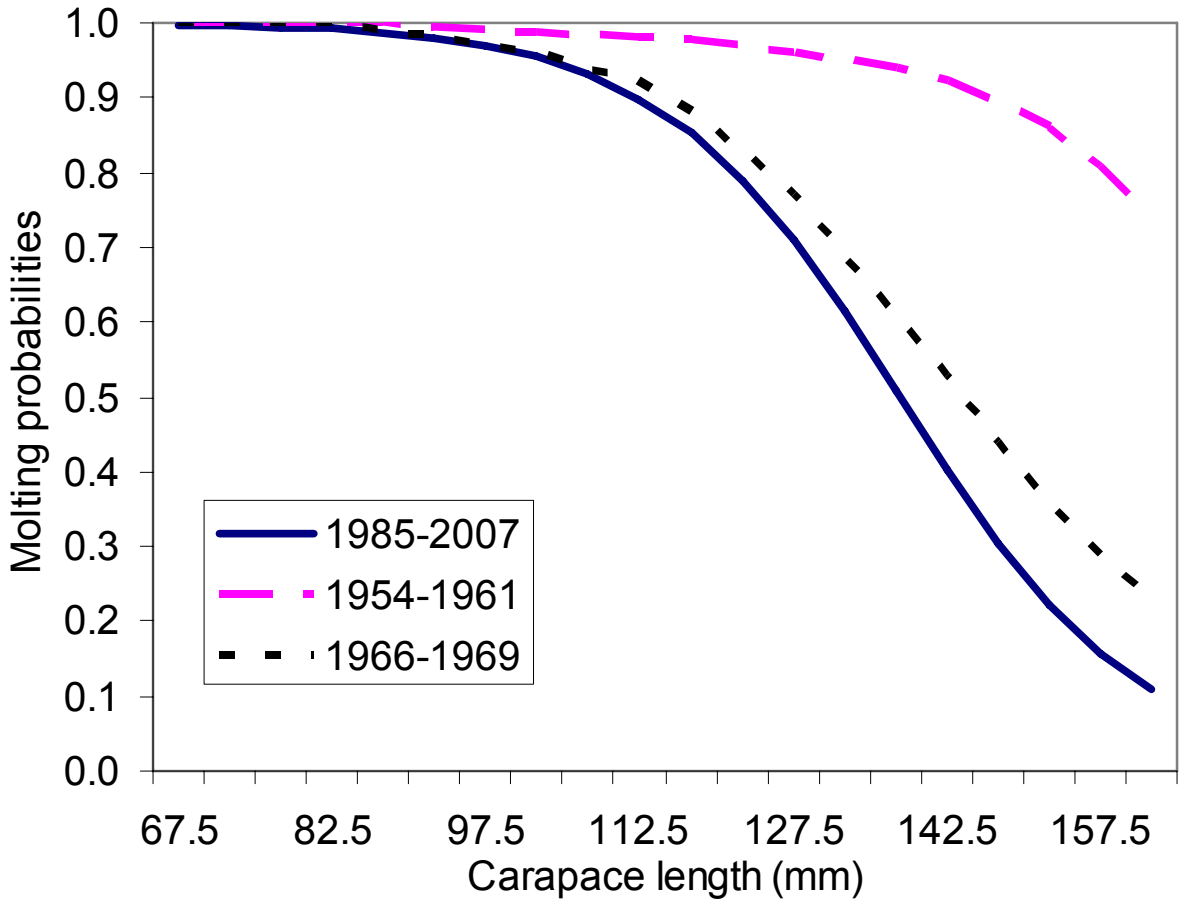



Figure 22. Comparison of estimated probabilities of molting of male red king crabs in Bristol Bay for different periods. Molting probabilities for periods 1954-1961 and 1966-1969 were estimated by Balsiger (1974) from tagging data. Molting probabilities for 1985-2007 were estimated with a length-based model with pot handling mortality rate to be 0.2.

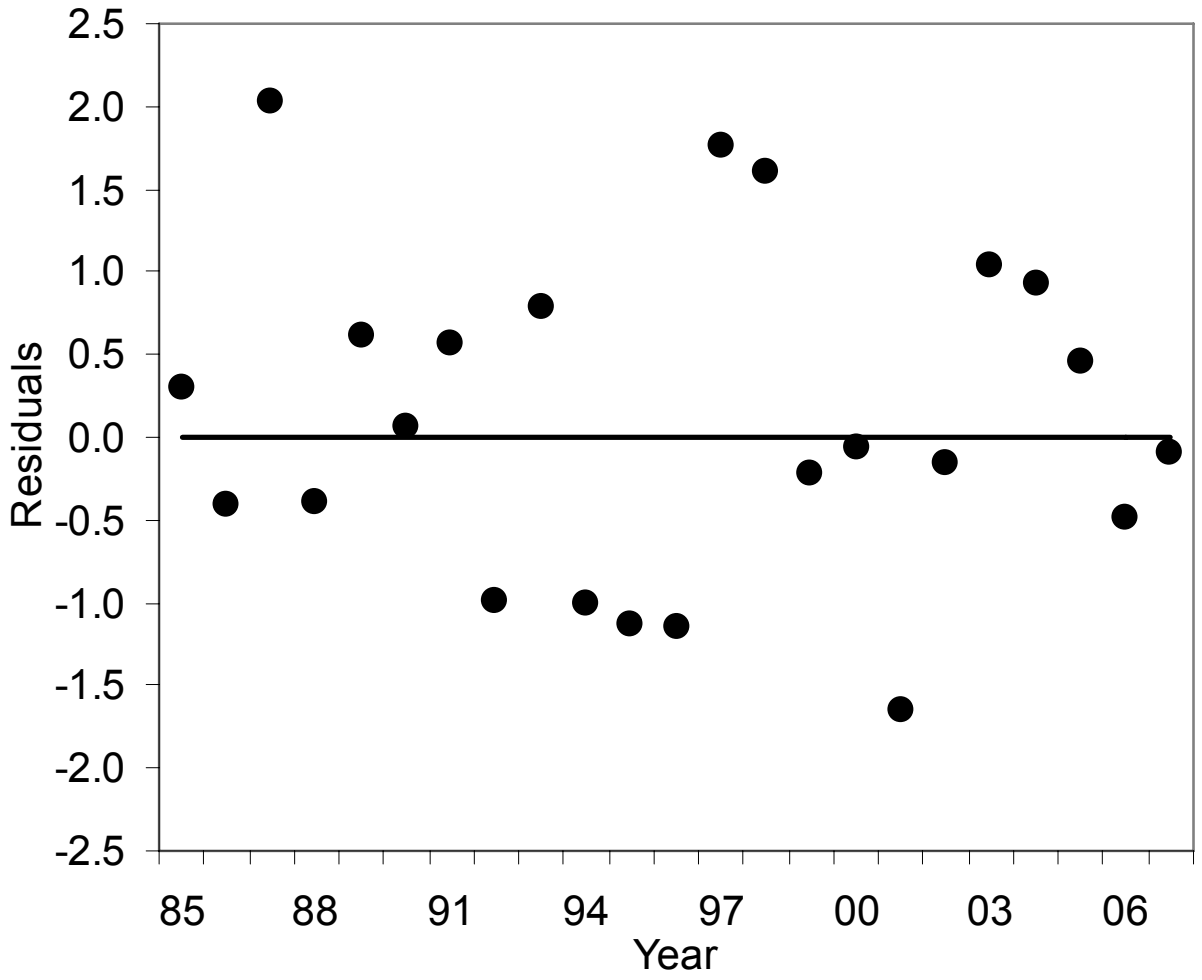



Figure 23. Standardized residuals of total survey biomass. Pot handling mortality rate is 0.2.

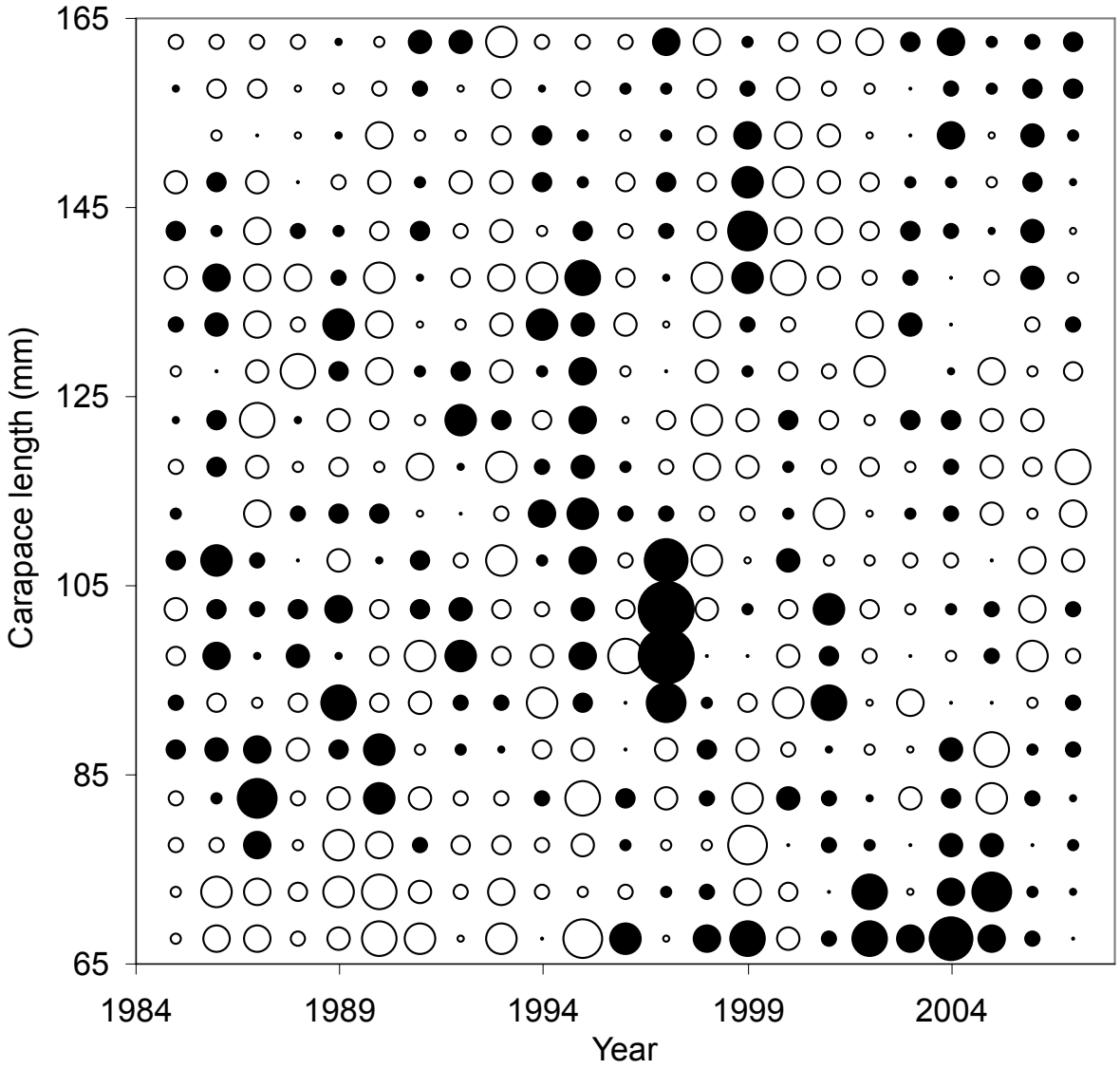



Figure 24. Residuals of proportions of survey newshell male red king crabs. Solid circles are positive residuals, and open circles are negative residuals. Pot handling mortality rate is 0.2.

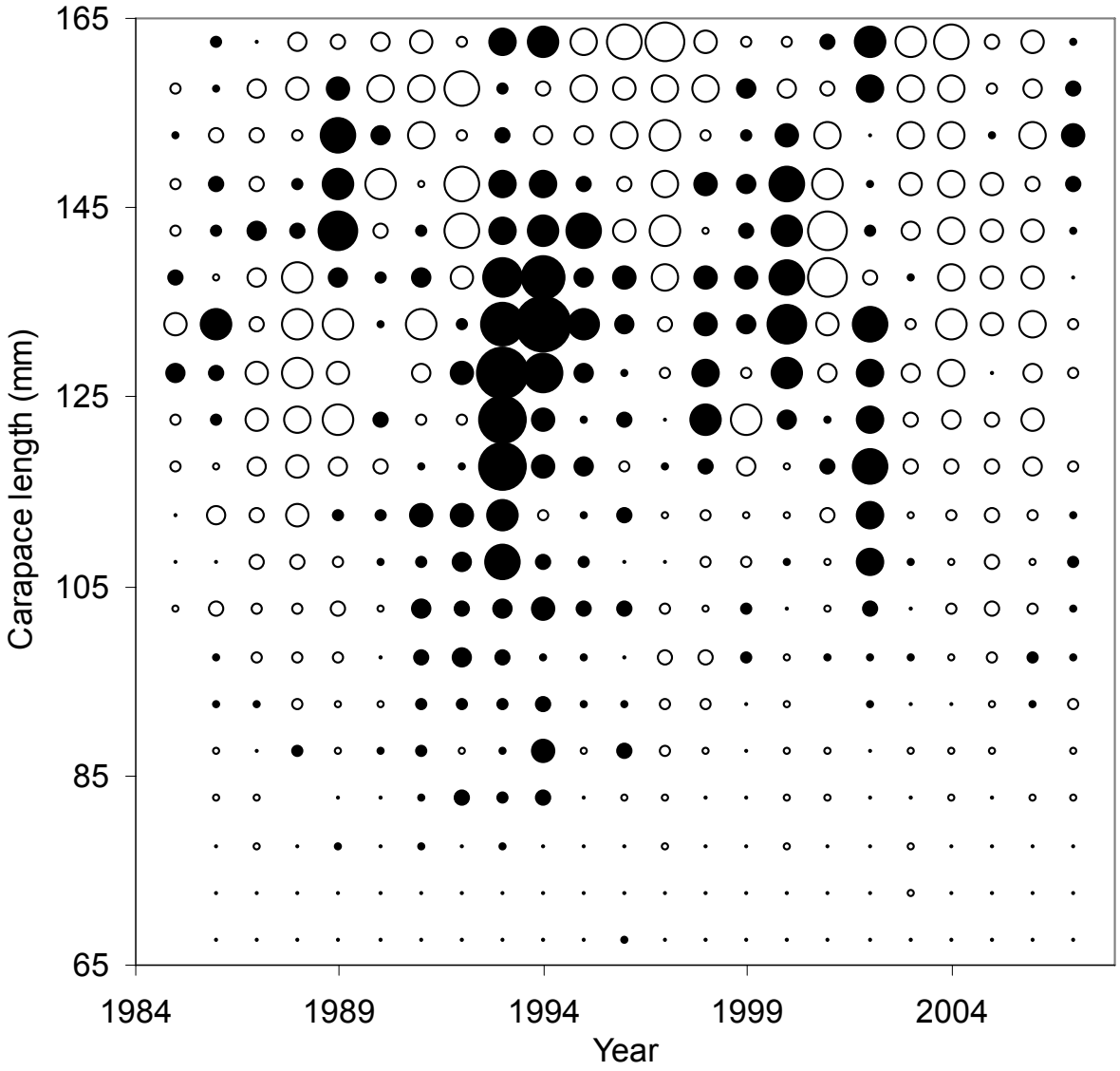



Figure 25. Residuals of proportions of survey oldshell male red king crabs. Solid circles are positive residuals, and open circles are negative residuals. Pot handling mortality rate is 0.2.

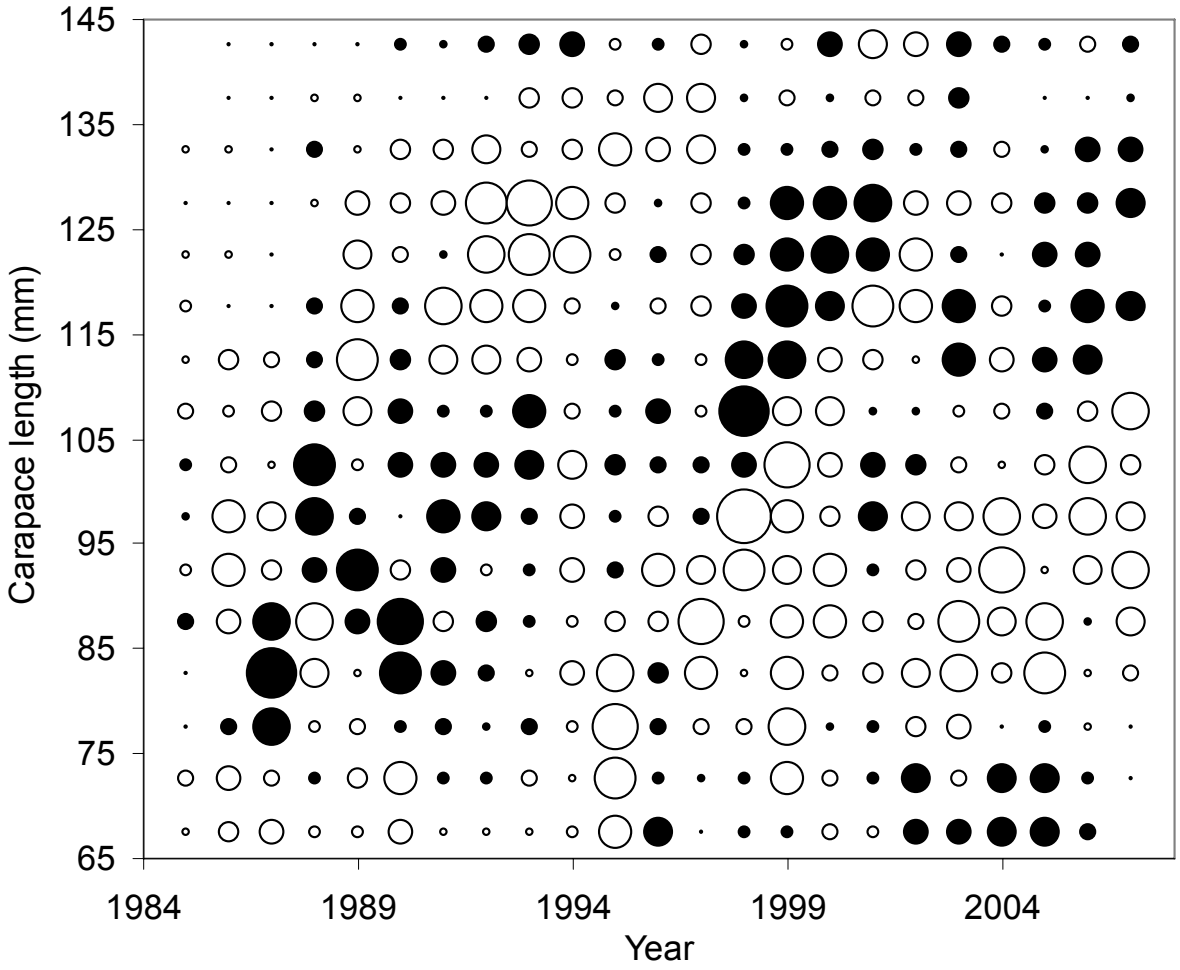



Figure 26. Residuals of proportions of survey female red king crabs. Solid circles are positive residuals, and open circles are negative residuals. Pot handling mortality rate is 0.2.

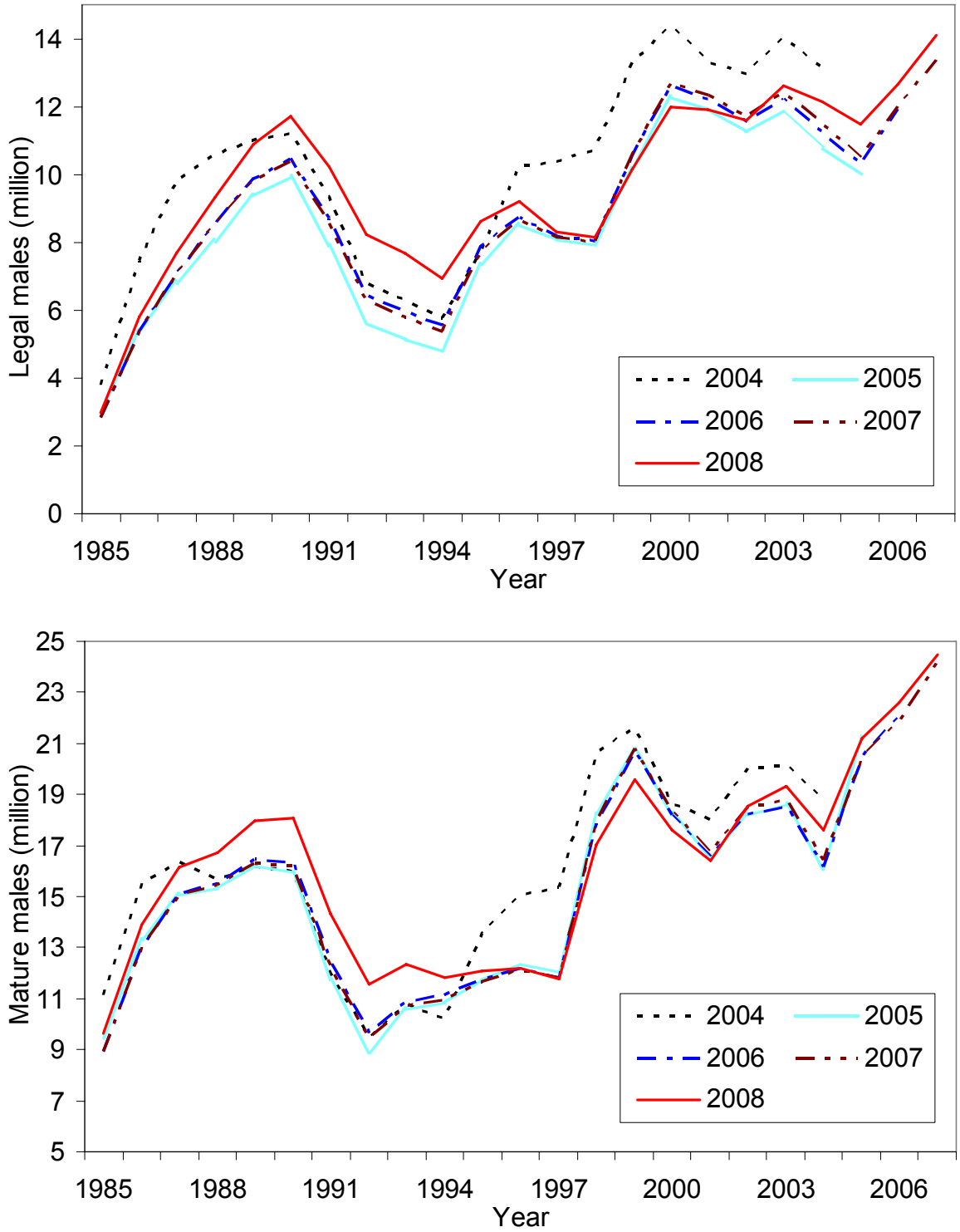



Figure 27. Comparison of estimates of legal male abundance (top) and mature males (bottom) of Bristol Bay red king crab from 1985 to 2007 made with terminal years 2004-2008. These are results of historical assessments. Legend shows the year in which the assessment was conducted. Pot handling mortality rate is 0.2.

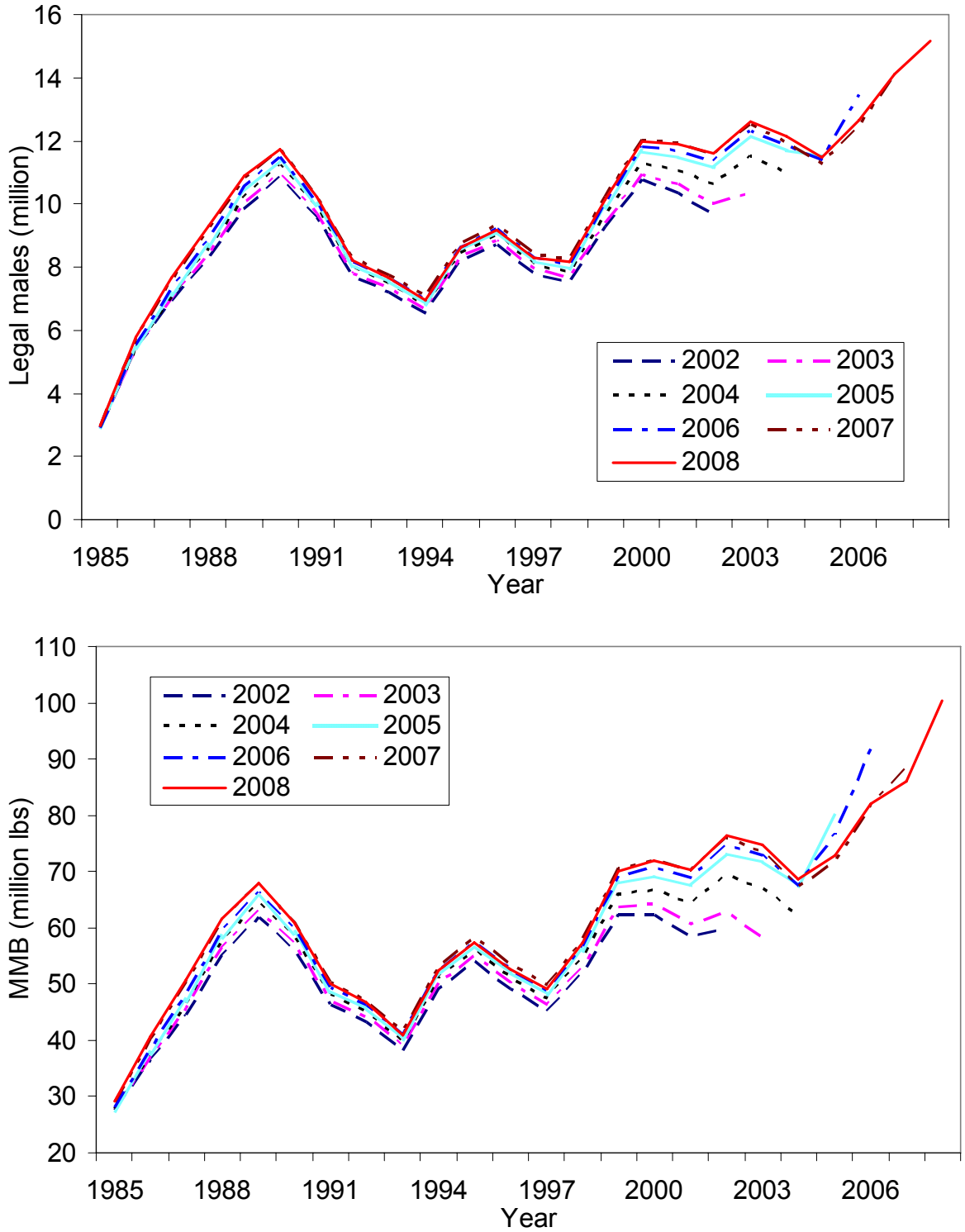
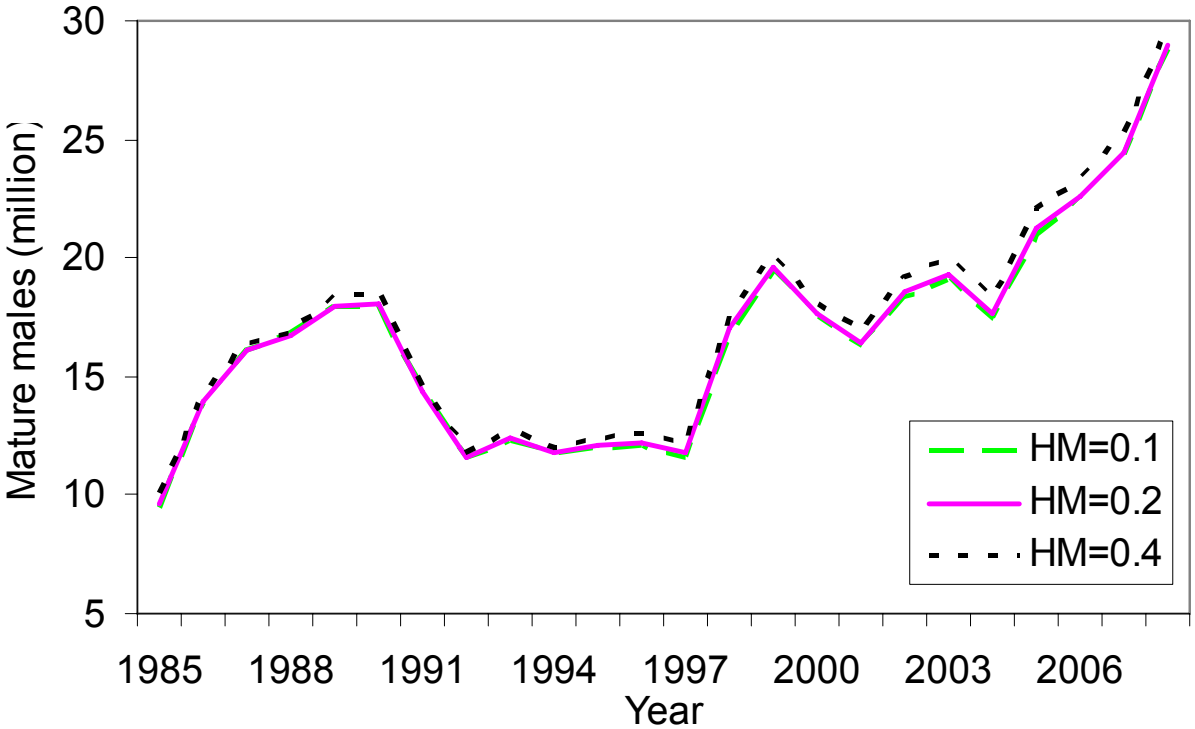



Figure 28. Comparison of estimates of legal male abundance (top) and mature male biomass (bottom) on Feb. 15 of Bristol Bay red king crab from 1985 to 2008 made with terminal years 2002-2008. These are results of the 2008 model. Legend shows the year in which the assessment was conducted. Pot handling mortality rate is 0.2.



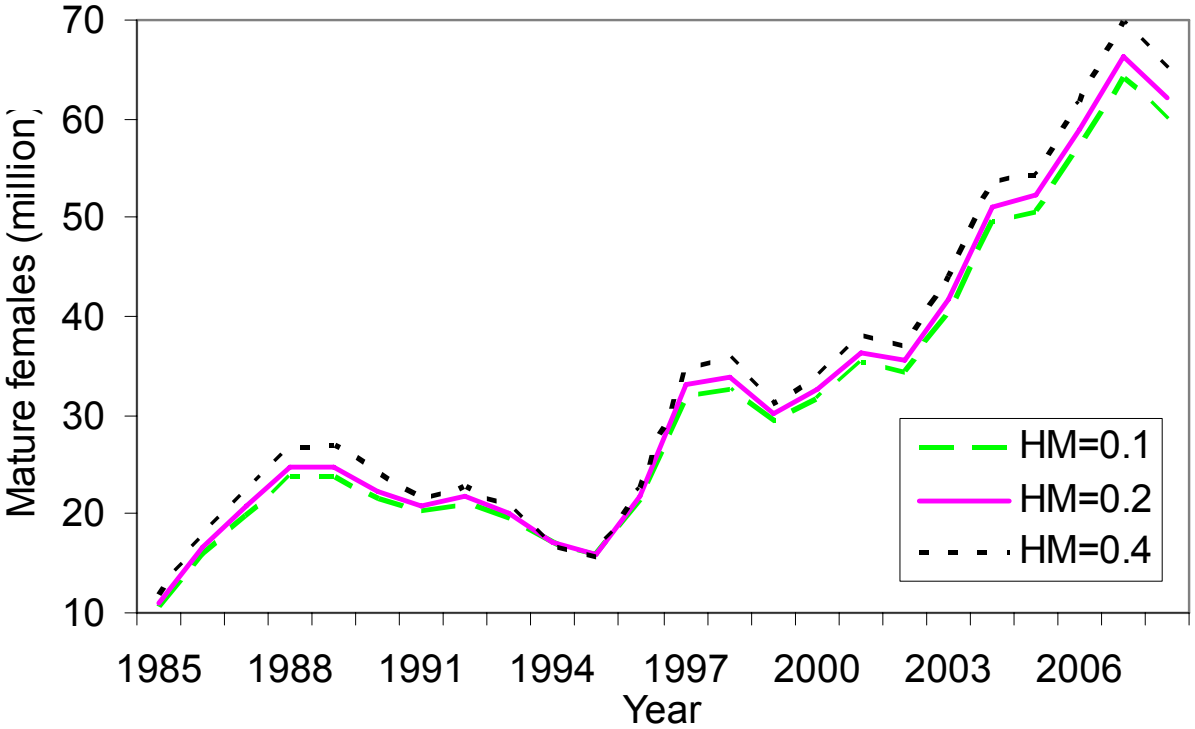
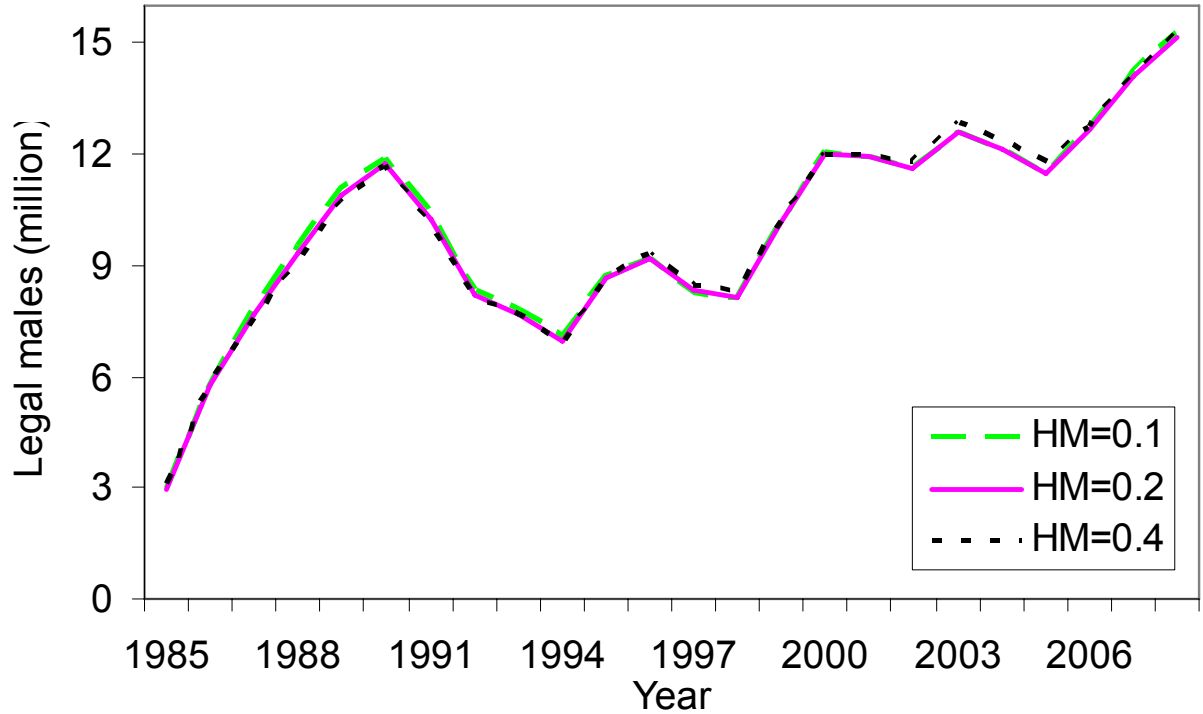




Figure 29. Comparison of mature abundance estimates for pot handling mortality rates of 0.1, 0.2 and 0.4.



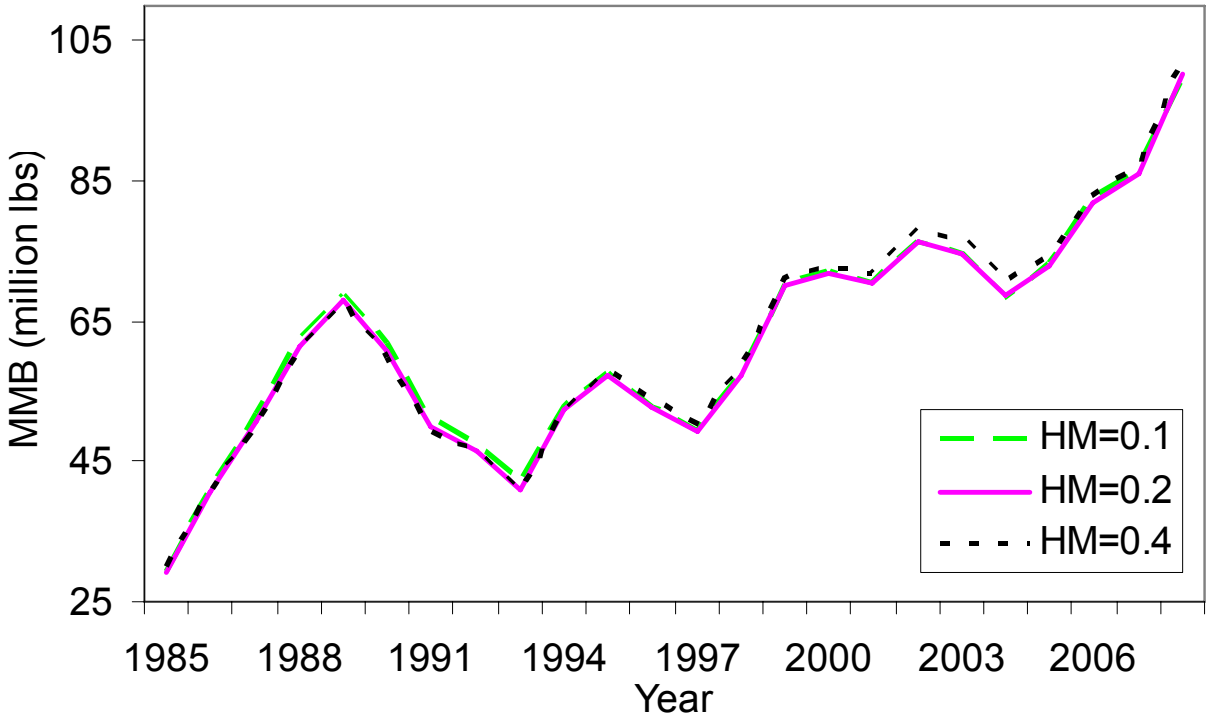




Figure 30. Comparison of legal male abundance estimates and mature male biomass on Feb. 15 for pot handling mortality rates of 0.1, 0.2 and 0.4.

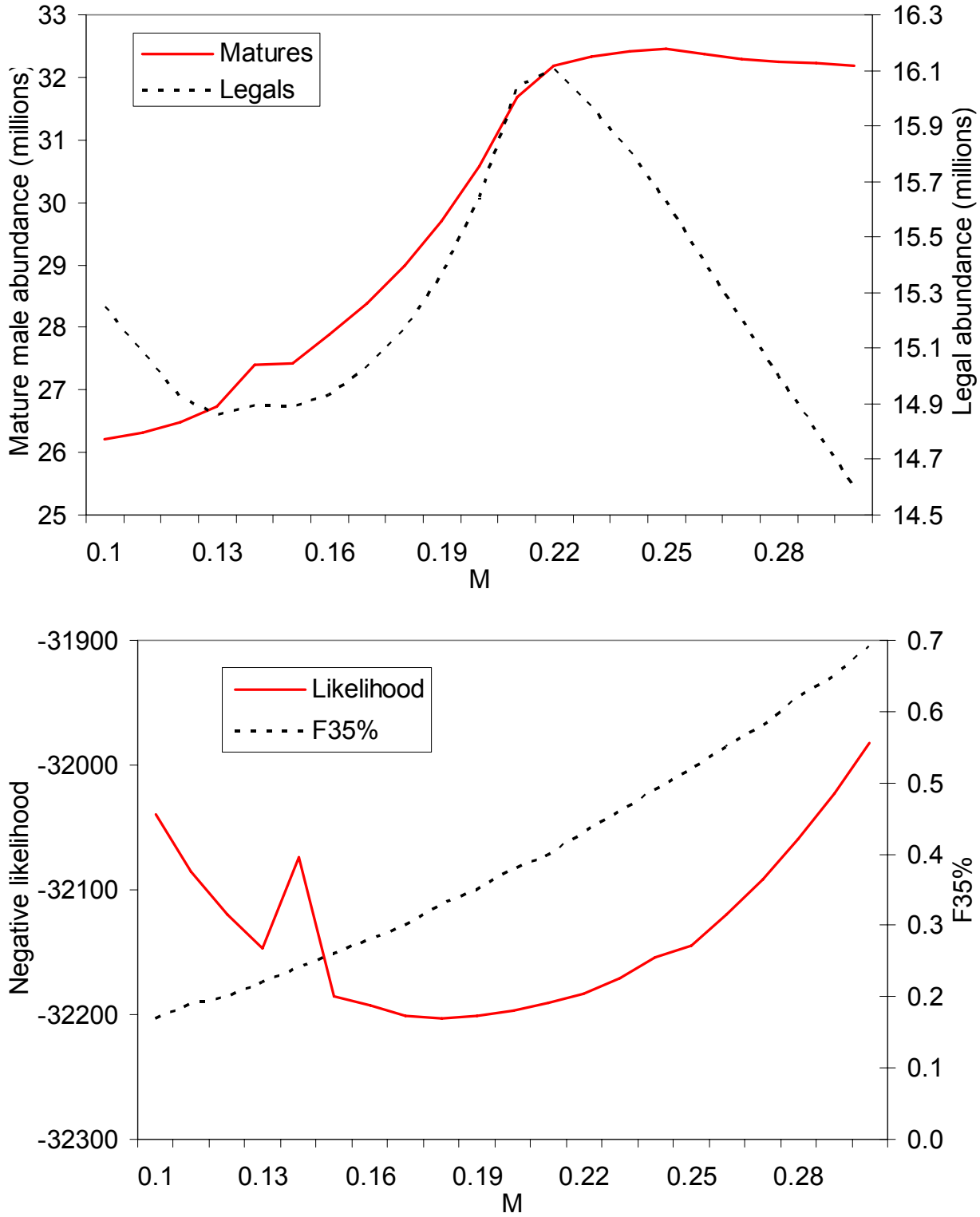



Figure 31. Estimated mature male and legal male abundances in 2008, likelihood profile, and estimated $F_{35\%}$ as a function of natural mortality.

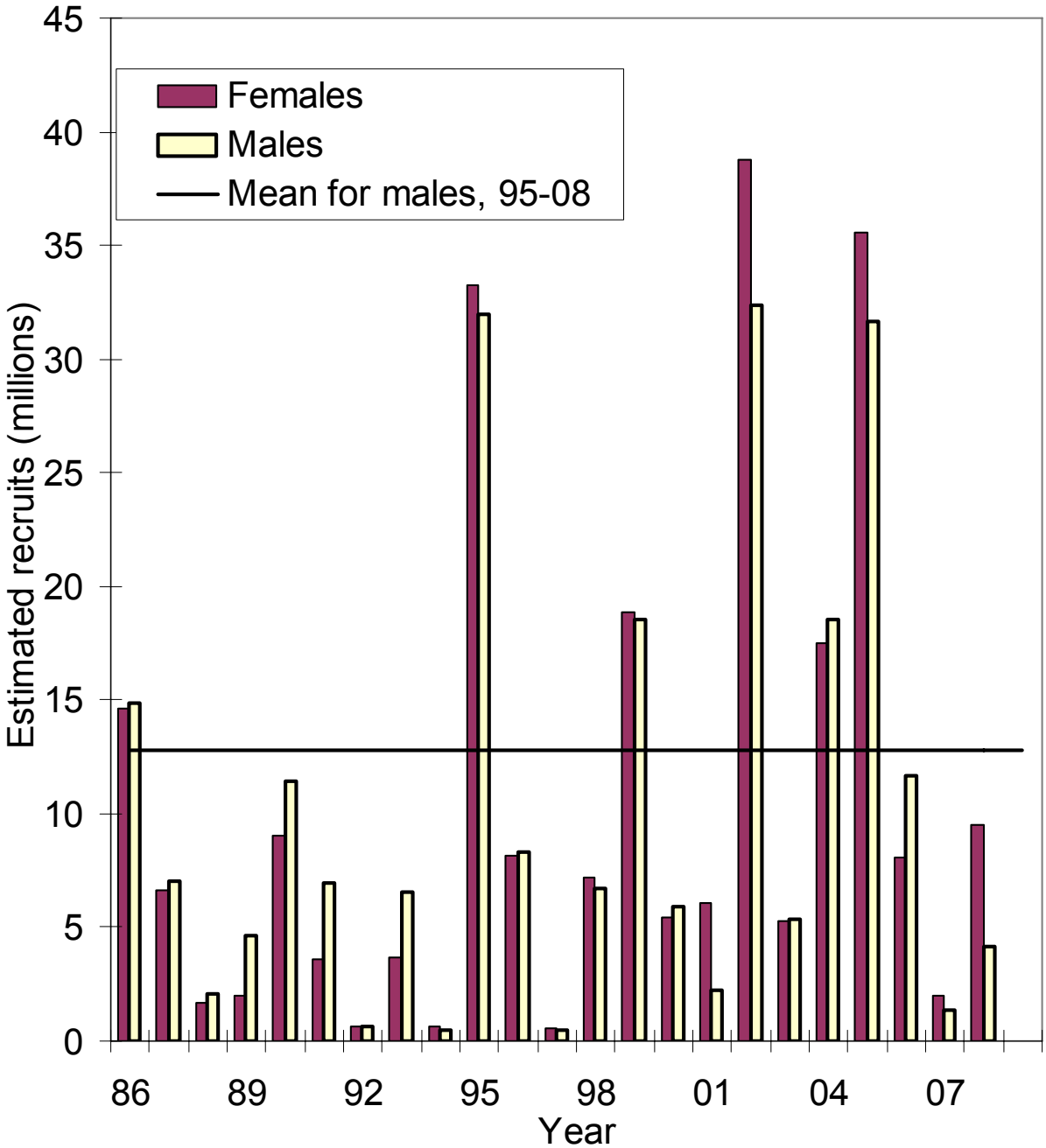



Figure 32. Estimated recruitment time series during 1986-2008. Mean male recruits during 1995-2008 was used to estimate $B_{35\%}$.

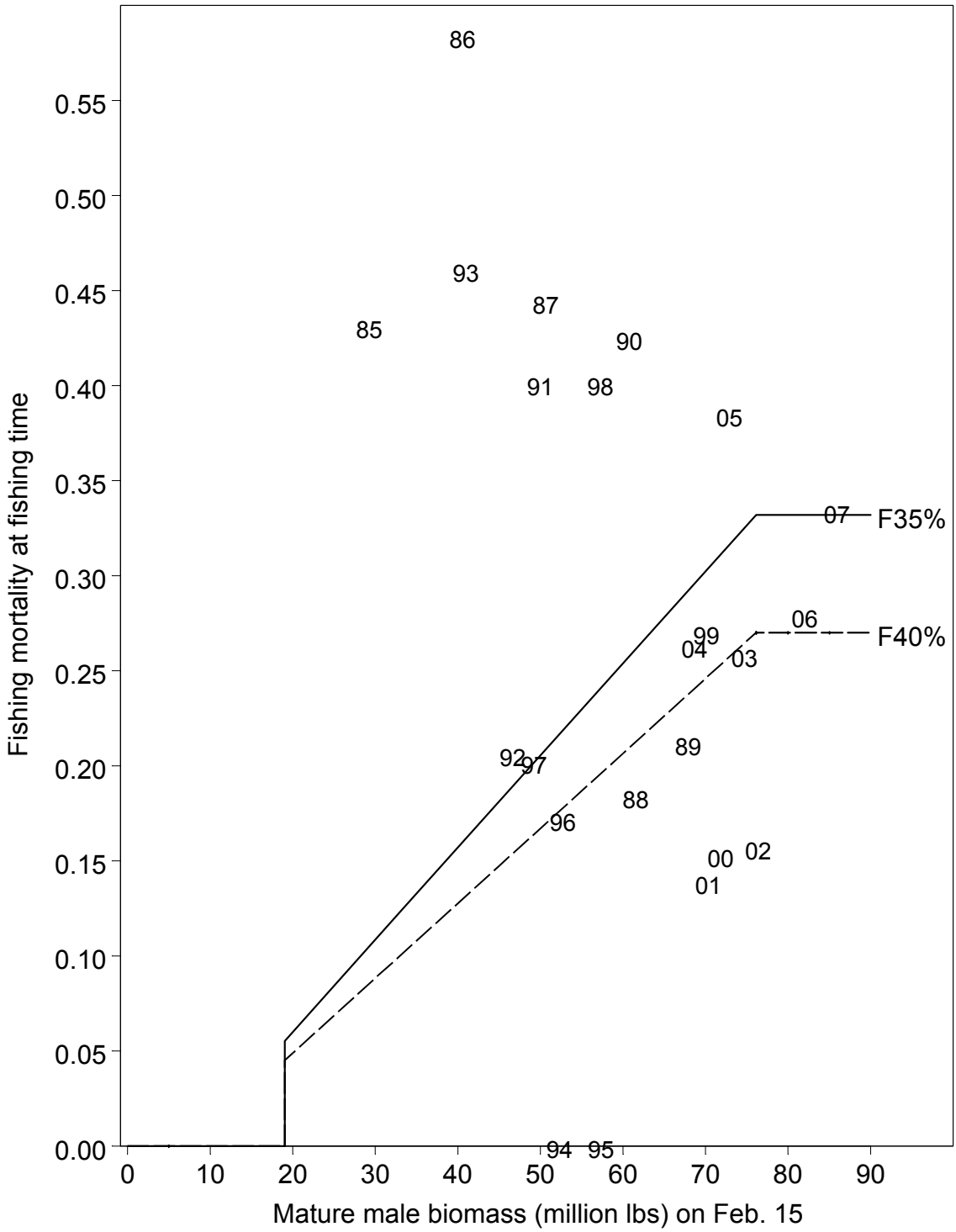



Figure 33. Relationships between full fishing mortalities for the directed pot fishery and mature male biomass on Feb. 15 during 1985-2007. Pot handling mortality rate is 0.2.

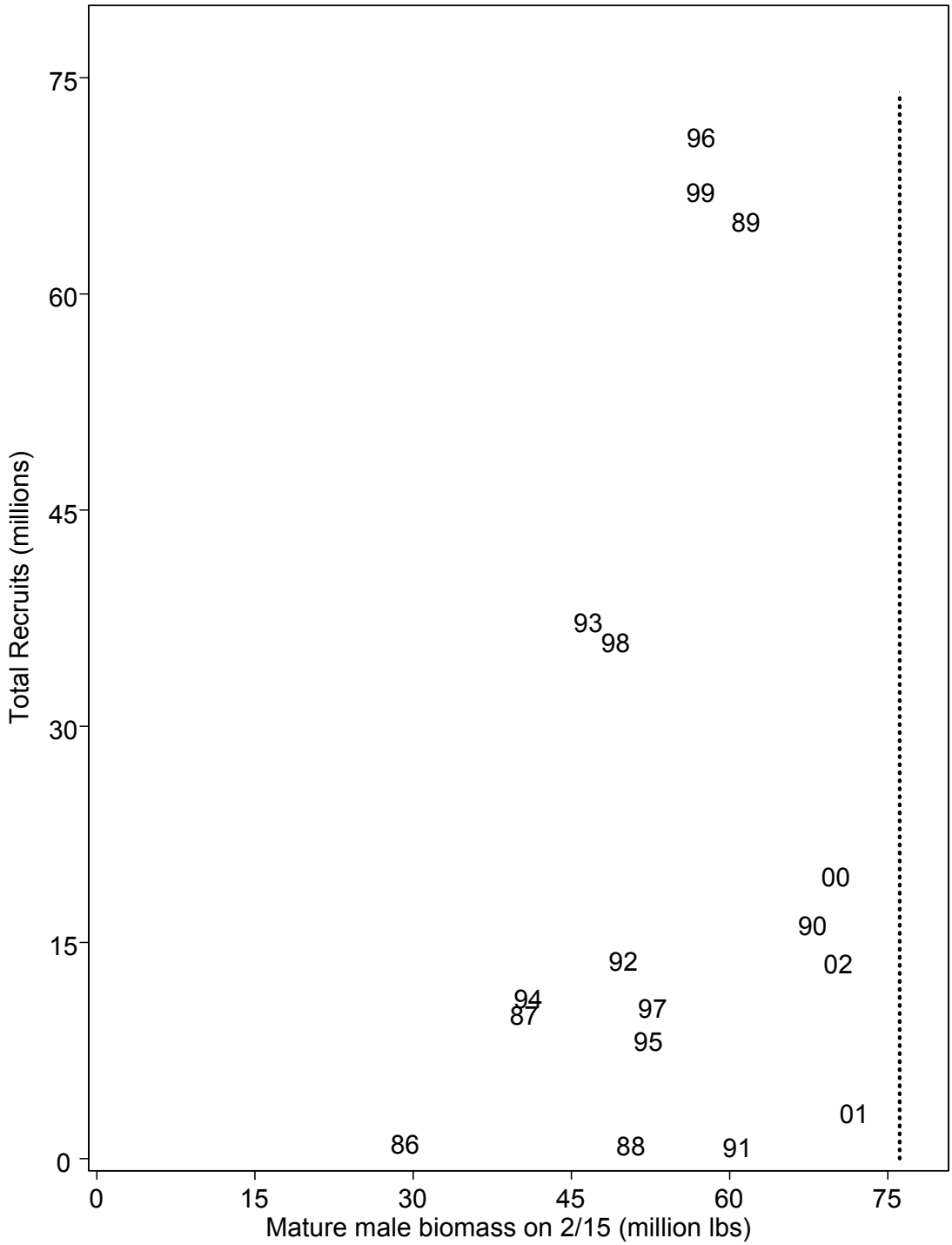



Figure 34. Relationships between mature male biomass on Feb. 15 and total recruits at age 5 (i.e., 6-year time lag) for Bristol Bay red king crab with pot handling mortality rate to be 0.2. Numerical labels are years of mating, and the vertical dotted line is the estimated $B_{35\%}$.

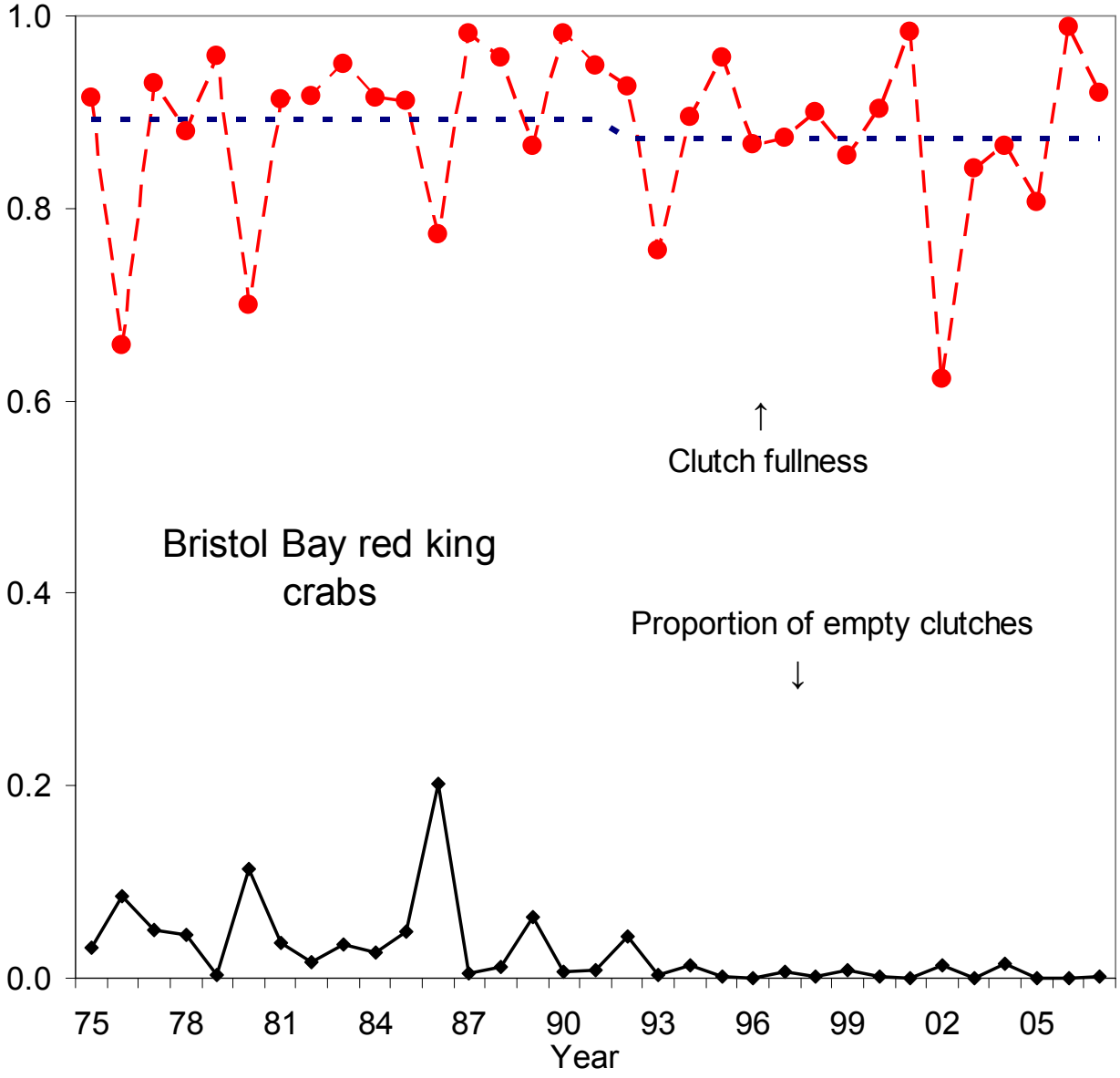



Figure 35. Average clutch fullness and proportion of empty clutches of newshell (shell conditions 1 and 2) mature female crabs >89 mm CL from 1975 to 2007 from survey data. Oldshell females were excluded.

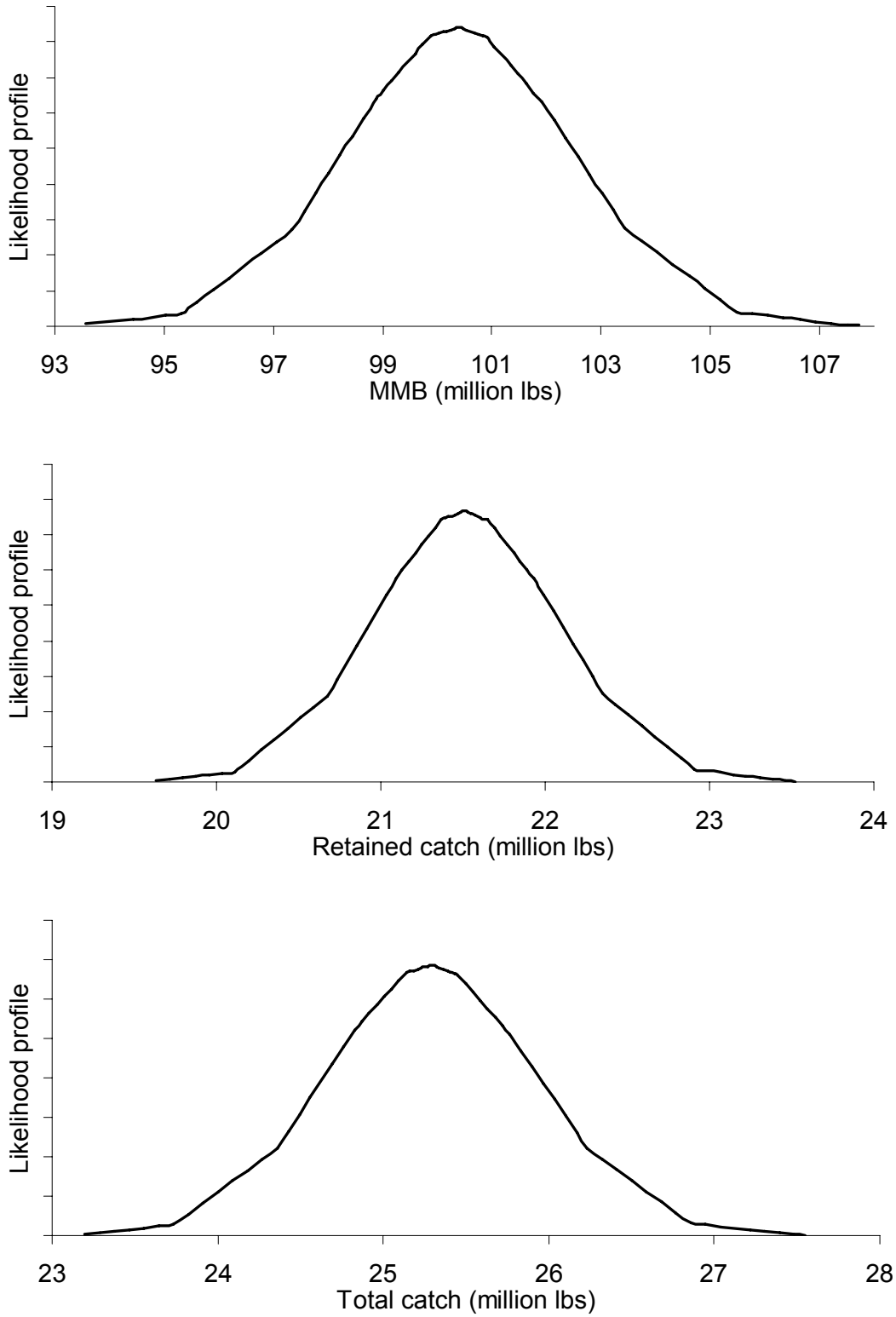



Figure 36. Likelihood profiles for estimated mature male biomass on Feb. 15 and overfishing limits of retained catch and total catch for the 2008 season with $F_{35\%}$. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

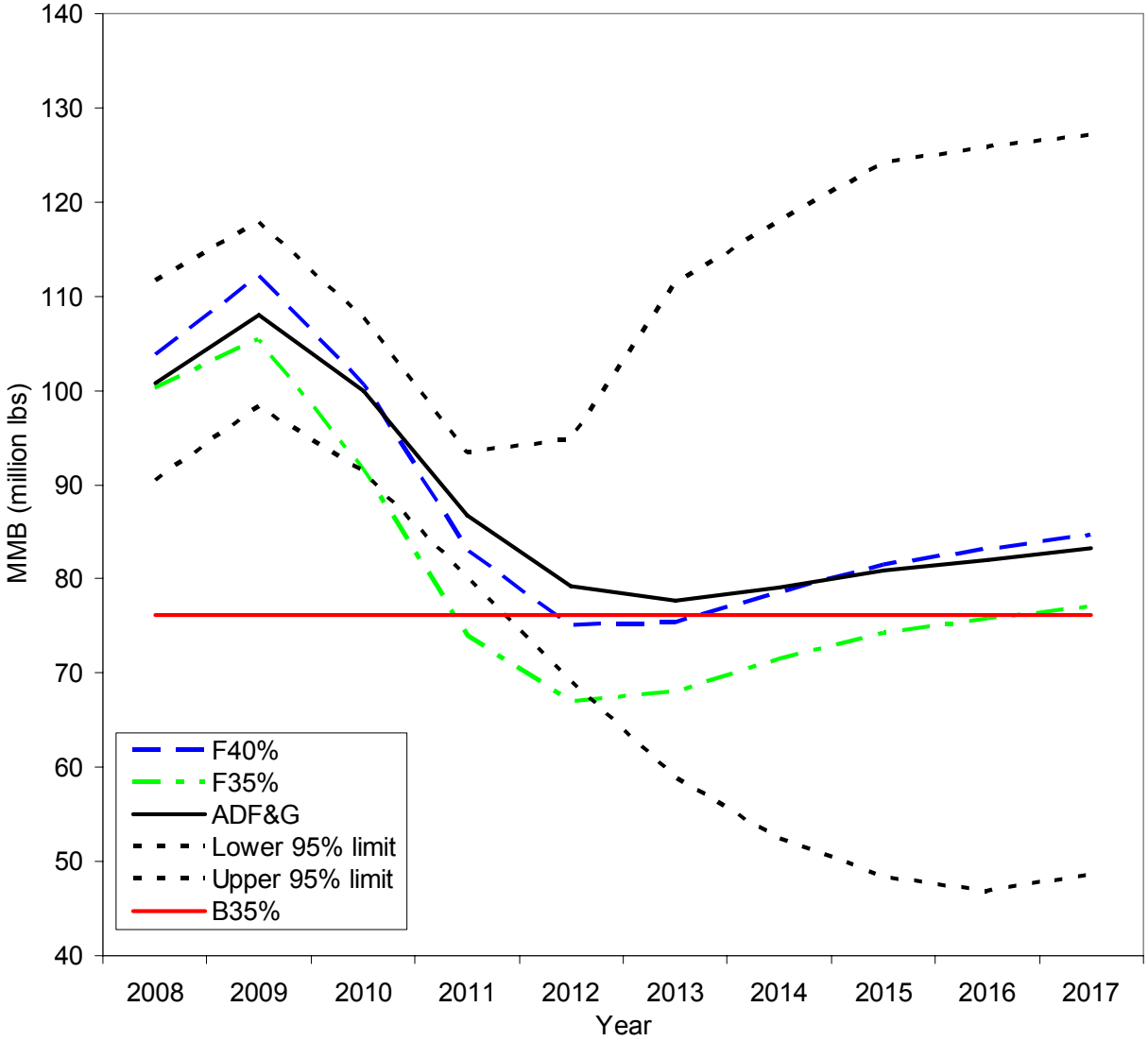



Figure 37. Projected mature male biomass on Feb. 15 with $F_{40\%}$, $F_{35\%}$ and the ADF&G harvest strategy with $F_{35\%}$ constraint during 2008-2117. Pot handling mortality rate is 0.2 and the confidence limits are for the ADF&G harvest strategy.

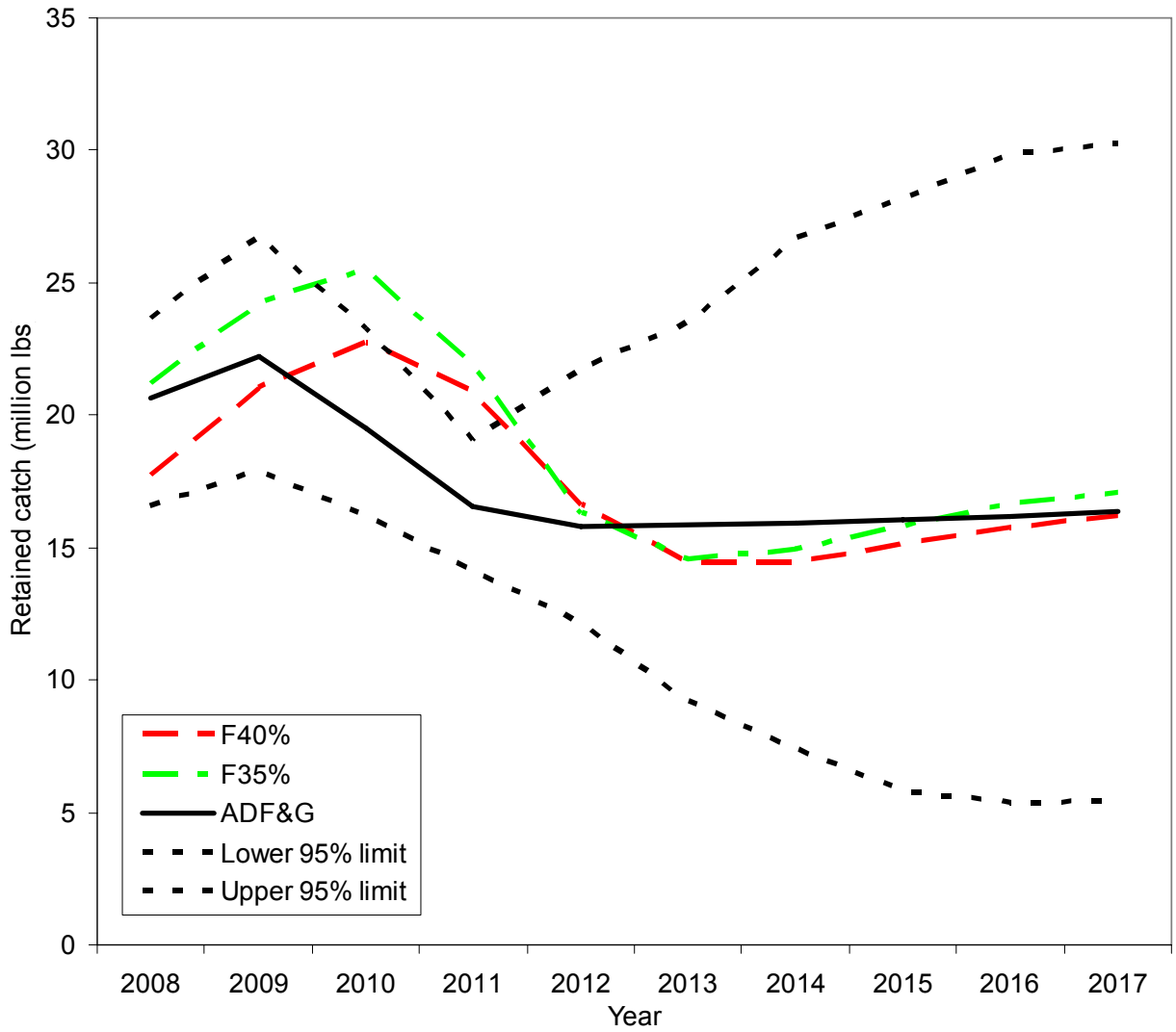



Figure 38. Projected retained catch biomass on Feb. 15 with $F_{40\%}$, $F_{35\%}$ and the ADF&G harvest strategy with $F_{35\%}$ constraint during 2008-2117. Pot handling mortality rate is 0.2 and the confidence limits are for the ADF&G harvest strategy.

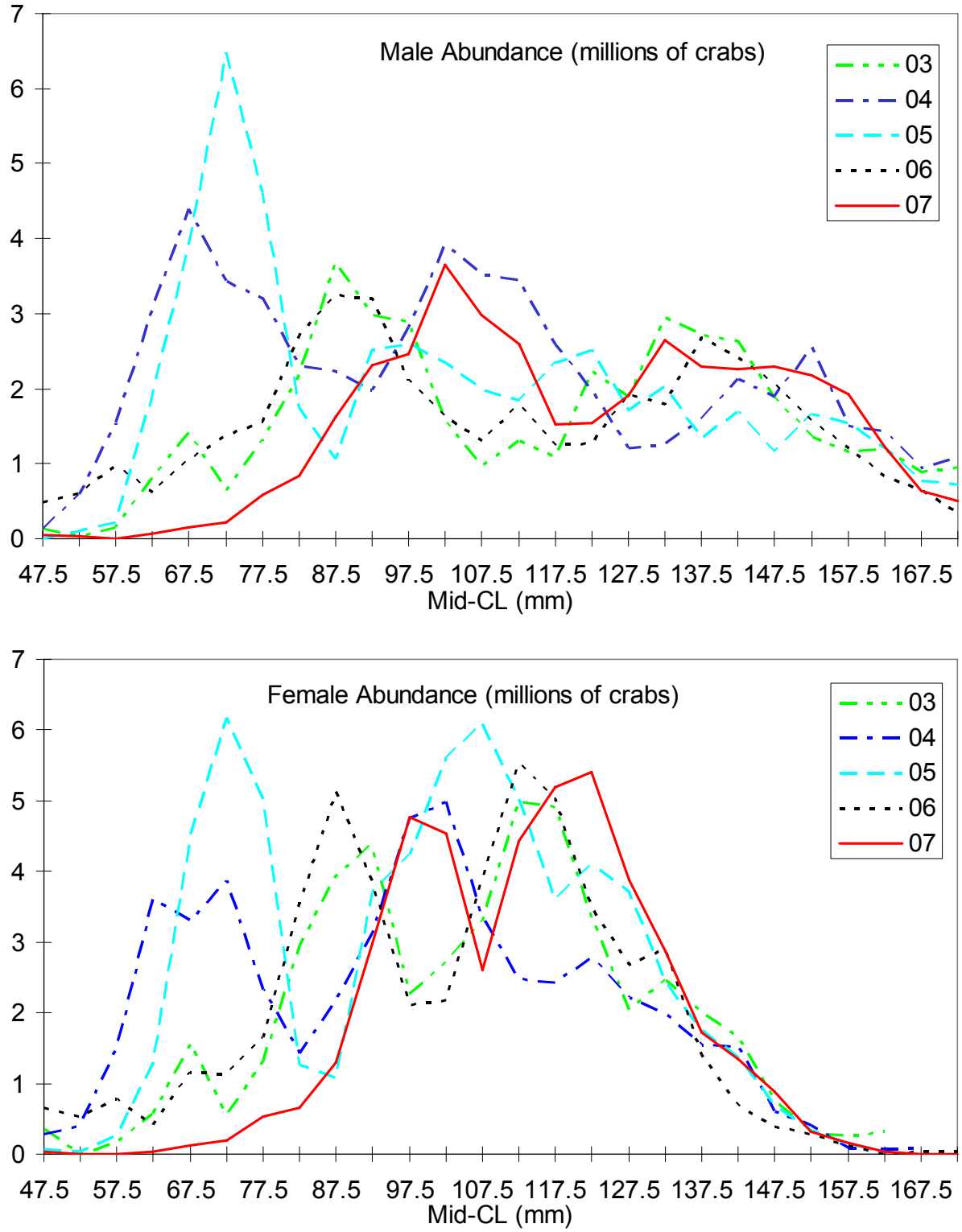



Figure 39. Length frequency distributions of male (top panel) and female (bottom panel) red king crabs in Bristol Bay from NMFS trawl surveys during 2003-2007. For purposes of these graphs, abundance estimates are based on area-swept methods.

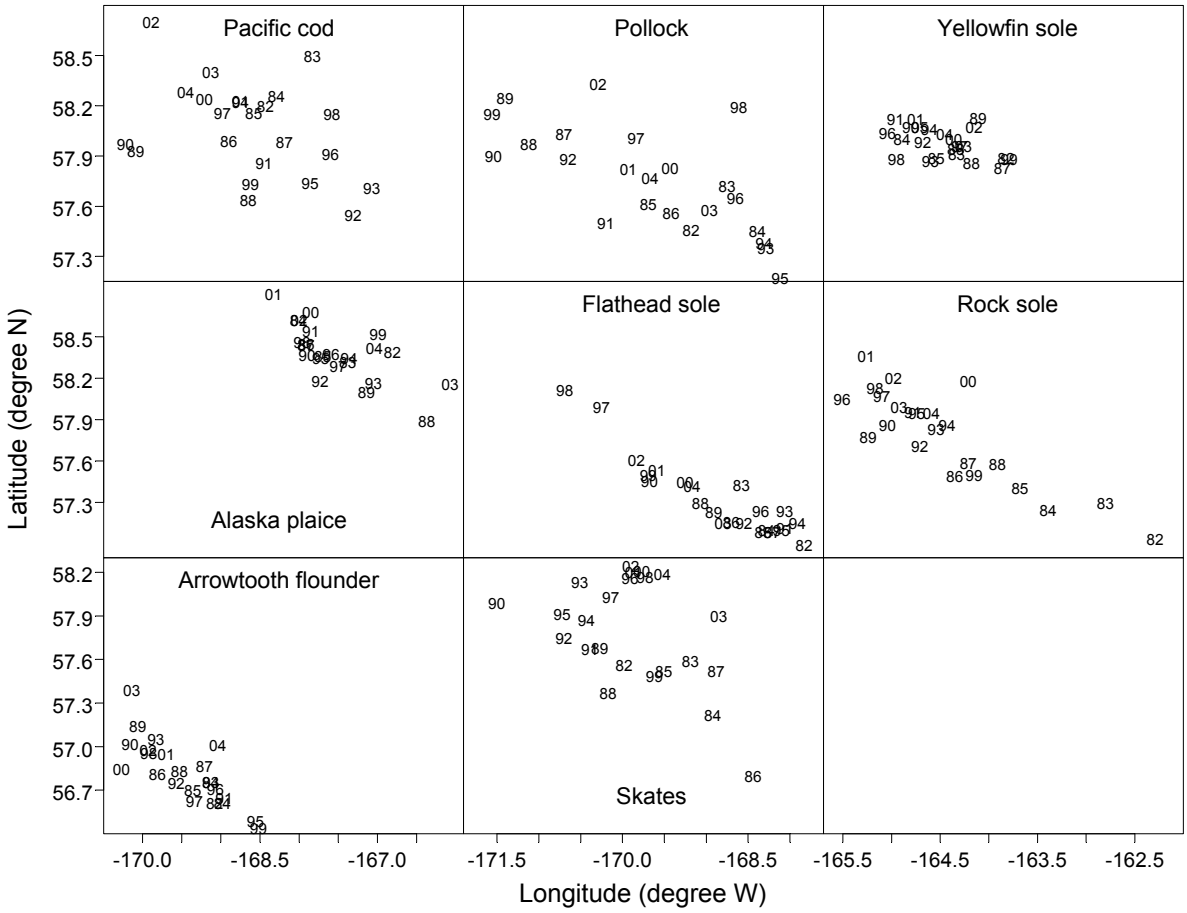



Figure 40. Biomass distribution centers of Pacific cod, walleye pollock, yellowfin sole, Alaska plaice, flathead sole, rock sole, arrowtooth flounder, and skates derived from NMFS summer trawl survey data in the eastern Bering Sea. (Source: Zheng and Kruse 2006).

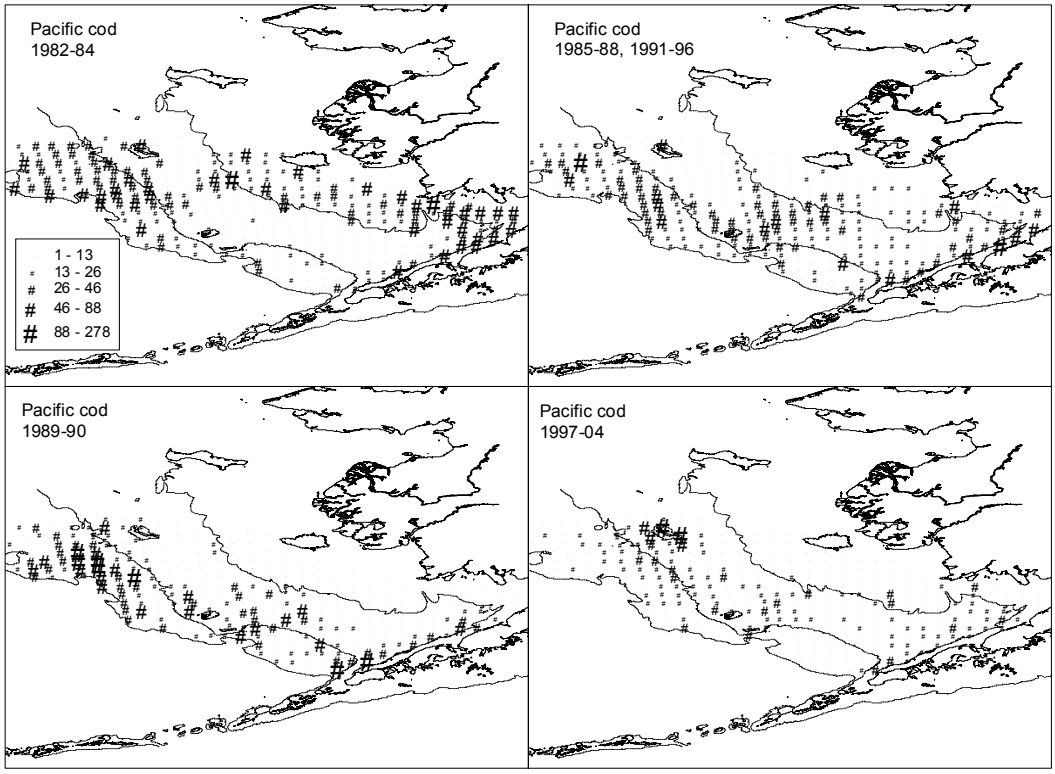



Figure 41. Distributions of relative biomass of Pacific cod in the eastern Bering Sea from 1982 to 2004 derived from NMFS summer trawl survey data. Relative biomass is expressed as kg/ha. Three depth contour lines are 50, 100, and 200 m. (Source: Zheng and Kruse 2006).

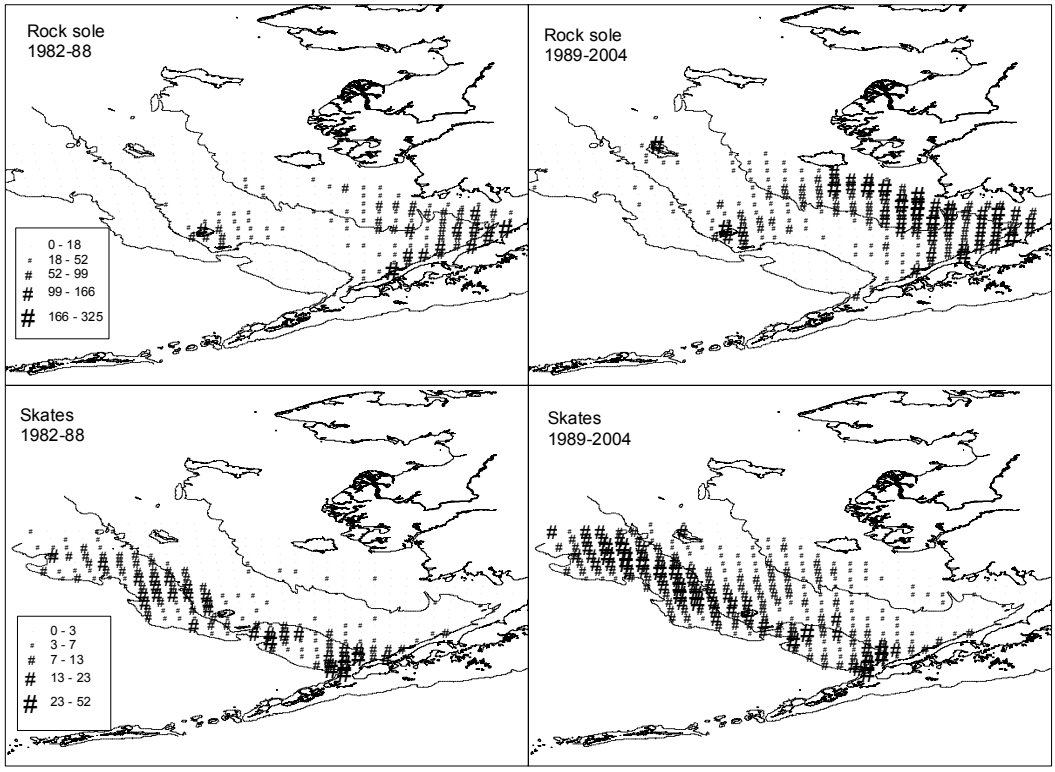



Figure 42. Distributions of relative biomass of rock sole and skates in the eastern Bering Sea from 1982 to 2004 derived from NMFS summer trawl survey data. Relative biomass is expressed as kg/ha. Three depth contour lines are 50, 100, and 200 m. (Source: Zheng and Kruse 2006).

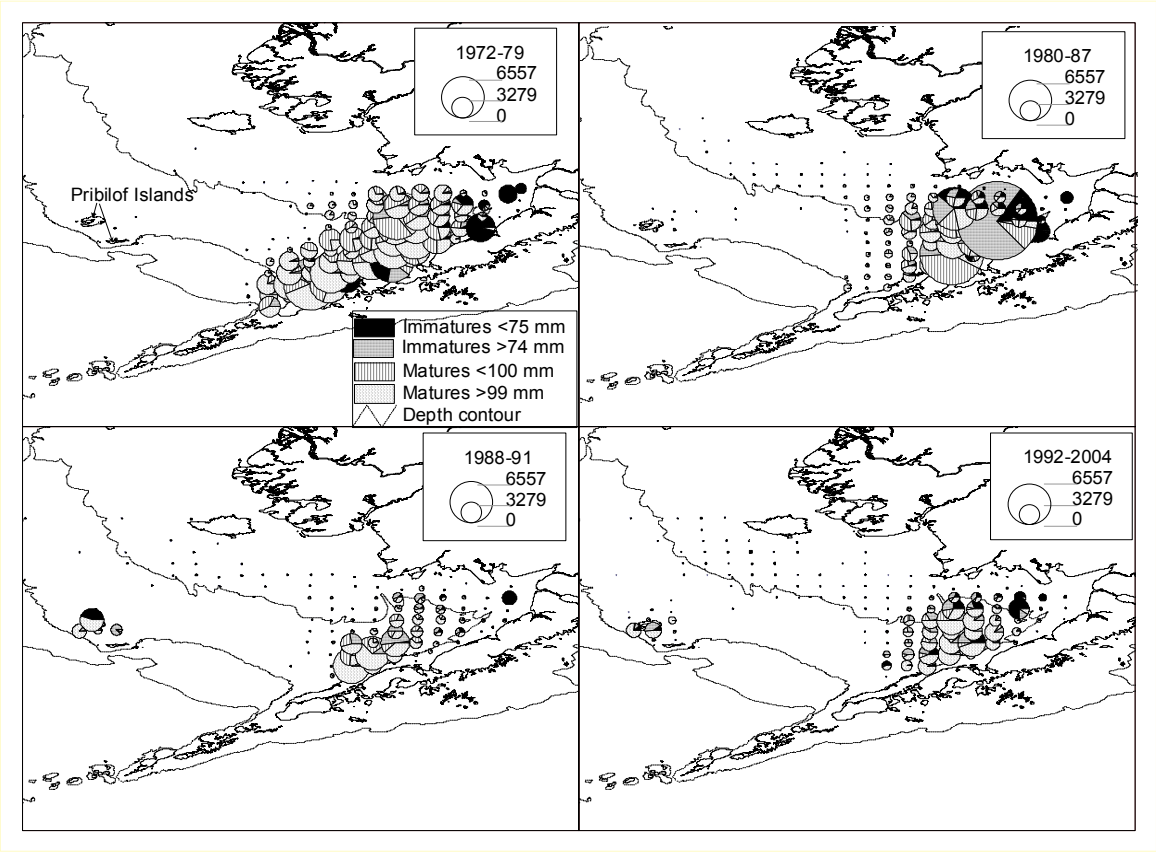



Figure 43. Geographic distributions of immature and mature female red king crabs from 1972 to 2004 in the eastern Bering Sea derived from NMFS summer trawl survey data. The diameter of each pie represents crab density expressed as the number of crabs per square nautical mile. Three depth contour lines are 50, 100, and 200 m. (Source: Zheng and Kruse 2006).

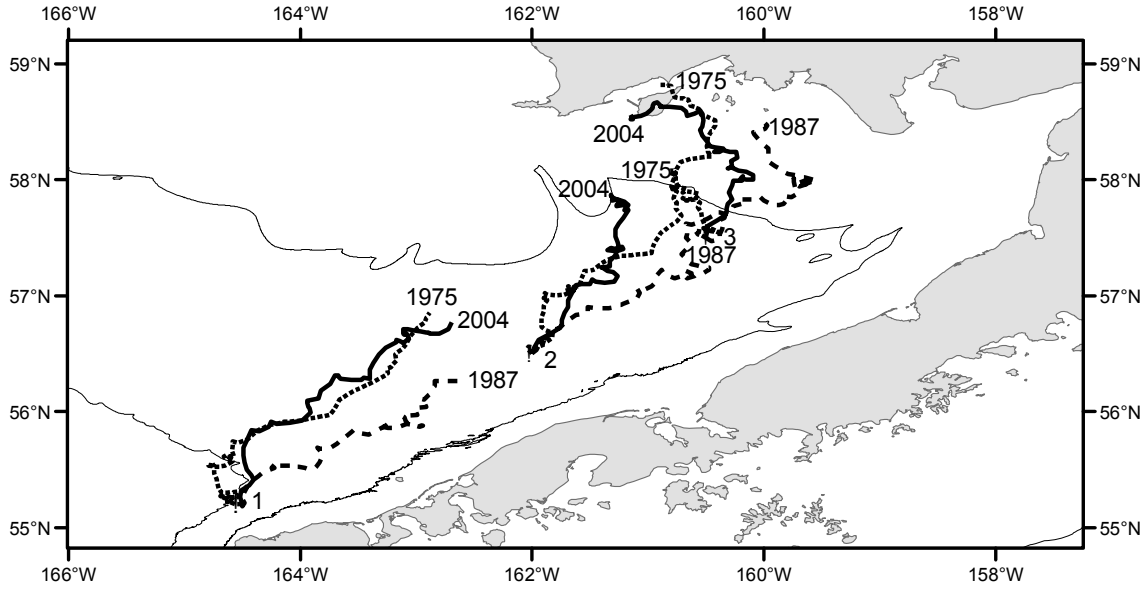



Figure 44. Larval movements after hatching on May 15, 1975, 1987, and 2004 from three different locations for Bristol Bay red king crab during two months. (Source: Zheng and Kruse 2008).

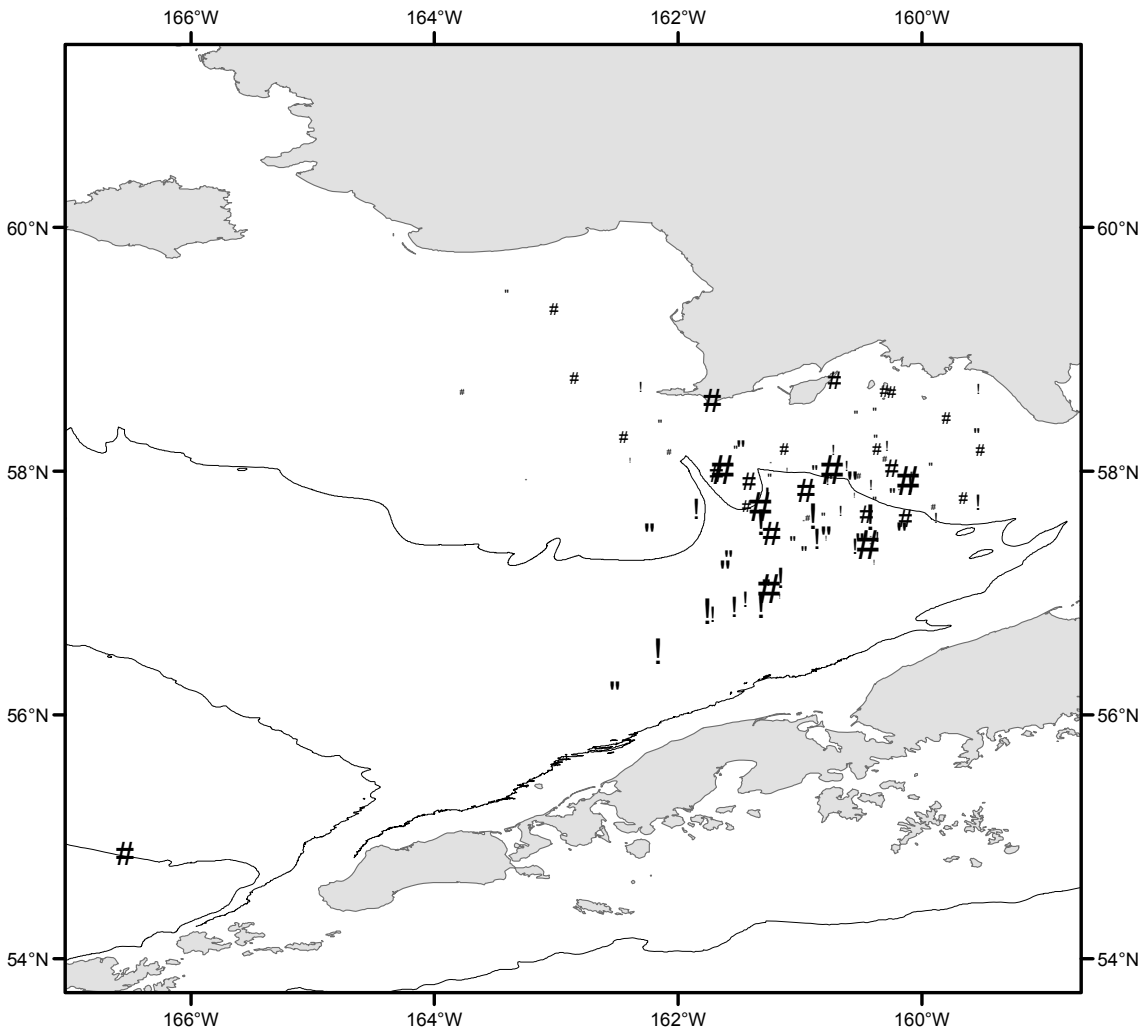



Figure 45. Estimated settling locations from the distribution centers of Bristol Bay mature female red king crabs >99 mm CL during 1967-1999. Hatching dates of April 15, May 15, and June 15 are triangles, squares, and circles, respectively. Symbol sizes are proportional to year-class strength.