

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

a. Model Description

i. Population model

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

$$N_{l,t+1}^s = \sum_{l'=1}^l \{P_{l',l,t}^s [(N_{l',t}^s + O_{l',t}^s)e^{-M_t^s} - (C_{l',t}^s + D_{l',t}^s)e^{(y_t-1)M_t^s} - T_{l',t}^s e^{(j_t-1)M_t^s}]m_{l',t}^s\} + R_{t+1}^s U_l^s \quad (\text{A1})$$

$$O_{l,t+1}^s = [(N_{l,t}^s + O_{l,t}^s)e^{-M_t^s} - (C_{l,t}^s + D_{l,t}^s)e^{(y_t-1)M_t^s} - T_{l,t}^s e^{(j_t-1)M_t^s}](1 - m_{l,t}^s)$$

where $N_{l,t}^s$ is the number of new shell crab of sex s in length-class l at the start of year t , $O_{l,t}^s$ the number of old shell crab of sex s in length-class l at the start of year t , $P_{l',l,t}^s$ the proportion during year t of an animals of sex s in length-class l' which grow into length-class l given that they moulted, M_t^s the rate of natural mortality on animals of sex s during year t , $m_{l,t}^s$ the probability that an animal of sex s in length-class l will moult during year t , R_{t+1}^s the recruitment [to the model] of animals of sex s during year t , U_l^s the proportion of recruits of sex s which recruit to length-class l , $C_{l,t}^s$ the retained catch (in numbers) of animals of sex s in length-class l during year t , $D_{l,t}^s$ the discarded catch of animals of sex s in length-class l during year t in the directed fishery, $T_{l,t}^s$ the discarded catch of animals of sex s in length-class l during year t in the Tanner crab fishery and the groundfish fisheries, y_t the time in years between survey and the directed pot fishery during year t , and j_t the time in years between survey and the Tanner and groundfish fisheries during year t .

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

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

$$P_{l',l,t}^s = \int_{L_t - \Delta L/2}^{L_t + \Delta L/2} \frac{x^{\alpha_{l',t}^s} e^{-x/\beta^s}}{(\beta^s)^{\alpha_{l',t}^s} \Gamma(\alpha_{l',t}^s)} dx \quad \alpha_{l',t}^s \beta^s = a_t^s + b_t^s L_t \quad (\text{A2})$$

where L_l is the mid-point of length-class l , ΔL the width of each size-class (5 mm carapace length), a_t^s, b_t^s the parameters of the length–growth increment relationship for sex s and year t , and β^s the parameter determining the variance of the growth increment. Growth is time-invariant for males, and specified for three time-blocks for females (1968-82; 1983-93; 1994-2017) based on changes to the size at maturity for females. The probability of moulting as a function of length for males is given by an inverse logistic function, i.e.:

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

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

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

ii. Catches and Fisheries Selectivities

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

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

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

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

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

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

where $S_l^{dir,land}$ is the selectivity pattern for the landings by the directed fishery, $S_l^{dir,disc,s}$ the selectivity pattern for the discards in the directed fishery by sex, $S_l^{tot,mal}$ the total male selectivity in the directed fishery, $S_{l,t}^{ret}$ the retained proportions of males in the directed fishery, F_t^{dir} the fully-selected fishing mortality during year t (on males), $F_t^{disc,fem}$ the fully-selected fishing mortality on female animals during year t related to discards in the directed fishery, ϕ the handling mortality (the proportion of animals which die due to being returned to the water following capture), and h_t the rate of high-grading during year t , i.e. discards of animals which can be legally-retained by the directed pot fishery (non-zero only for 2005-2016).

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

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

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

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

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

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

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

The bycatches by sex are estimated from the Tanner crab fishery, $TC_{l,t}^s$, groundfish trawl fishery, $GT_{l,t}^s$, and groundfish fixed gear fishery, $GF_{l,t}^s$, as follow:

$$\begin{aligned}
TC_{l,t}^s &= (N_{l,t}^s + O_{l,t}^s) e^{-j_l M_l^s} e^{-F_{l,t}^s} (1 - e^{-\tilde{F}_{l,t}^s}) S_l^{Tanner,s} F_t^{Tanner,s} / \tilde{F}_{l,t}^s \\
GT_{l,t}^s &= (N_{l,t}^s + O_{l,t}^s) e^{-j_l M_l^s} e^{-F_{l,t}^s} (1 - e^{-\tilde{F}_{l,t}^s}) S_l^{trawl} F_t^{trawl} / \tilde{F}_{l,t}^s \\
GF_{l,t}^s &= (N_{l,t}^s + O_{l,t}^s) e^{-j_l M_l^s} e^{-F_{l,t}^s} (1 - e^{-\tilde{F}_{l,t}^s}) S_l^{fixed} F_t^{fixed} / \tilde{F}_{l,t}^s
\end{aligned} \tag{A9}$$

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

$$\begin{aligned}
D_{l,t}^i &= N_{l,t}^i e^{-y_l M_l^{fem}} (1 - e^{-F_{l,t}^{fem}}) \\
D_{l,t}^m &= N_{l,t}^m e^{-y_l M_l^{fem}} (1 - e^{-F_{l,t}^{fem}})
\end{aligned} \tag{A10}$$

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

$$\begin{aligned}
T_{l,t}^i &= N_{l,t}^i e^{-j_l M_l^{fem}} e^{-F_{l,t}^{fem}} (1 - e^{-\tilde{F}_{l,t}^{fem}}) \\
T_{l,t}^m &= N_{l,t}^m e^{-j_l M_l^{fem}} e^{-F_{l,t}^{fem}} (1 - e^{-\tilde{F}_{l,t}^{fem}})
\end{aligned} \tag{A11}$$

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

$$S_l^{type} = \frac{I}{I + e^{-\beta^{type} (l - L_{50}^{type})}} \tag{A12}$$

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

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

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

where φ , κ , γ are parameters.

iii. Trawl Survey Selectivities

Trawl survey selectivities are estimated as

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

with different sets of parameters (β , L_{50}) estimated for males and females as well as two different periods (1975-81 and 1982-17). Survey selectivity for the first length group (67.5 mm) was assumed to be the same for both males and females, so only three parameters (β , L_{50} for females and L_{50} for males) were estimated in the model for each of the four periods. Parameter Q was called the survey catchability that was estimated based on a trawl experiment by Weinberg et al. (2004; Figure A1). Q was assumed to be constant over time.

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

iv. Estimating Bycatch Fishing Mortalities for Years without Observer Data

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

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

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

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

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

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

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

c. Likelihood Components

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

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

$$\sigma^2 = \frac{[p_{l,t,s,sh} (1-p_{l,t,s,sh}) + \frac{0.1}{L}]}{n}$$

where L is the number of length groups, T the number of years, and n the effective sample size, which was estimated for trawl survey and pot retained catch and bycatch length composition data from the directed pot fishery, and was assumed to be 50 for groundfish trawl and Tanner crab fisheries bycatch length composition data. $p_{l,t,s,sh}$ is the observed proportion of crab in length-class l , year t , sex s and shell condition sh and $\hat{p}_{l,t,s,sh}$ is the model-estimate corresponding to $p_{l,t,s,sh}$.

The weighted negative log likelihood functions are:

$$\begin{aligned} \text{Length compositions: } & - \sum \ln (Rf_i) \\ \text{Catch and bycatch biomasses: } & \lambda_j \sum \left[\ln \left(\frac{C_t}{\hat{C}_t} \right)^2 \right] \\ \text{NMFS survey biomass: } & \sum \left[\ln \left(\ln(CV_t^2 + 1) \right)^{0.5} + \frac{\ln \left(\frac{B_t}{\hat{B}_t} \right)^2}{2 \ln(CV_t^2 + 1)} \right] \\ \text{BSFRF survey biomass: } & \sum \left[\ln \left(\ln(CV_t^2 + 1) \right)^{0.5} + \frac{\ln \left(\frac{B_t}{\hat{B}_t} \right)^2}{(2 \ln(CV_t^2 + 1))} \right] \\ \text{R variation: } & \lambda_R \sum \left[\ln \left(\frac{R_t}{\bar{R}} \right)^2 \right] \\ \text{R sex ratio: } & \lambda_s \sum \left[\ln \left(\frac{\bar{R}_M}{\bar{R}_F} \right)^2 \right] \\ \text{Groundfish bycatch fishing mortalities: } & \lambda_t \sum \left[\ln \left(\frac{F_{t,gf}}{\bar{F}_{gf}} \right)^2 \right] \\ \text{Pot female bycatch fishing mortalities: } & \lambda_p \sum \left[\ln \left(\frac{F_{t,f}}{\bar{F}_f} \right)^2 \right] \\ \text{Trawl survey catchability: } & \frac{(Q - \hat{Q})^2}{2\sigma^2} \end{aligned} \quad (A18)$$

where R_t is the recruitment in year t , \bar{R} the mean recruitment, \bar{R}_M the mean male recruitment, \bar{R}_F the mean female recruitment, \bar{F}_{gf} the mean groundfish bycatch fishing mortality (this is separated into trawl and fixed gear fishery bycatch), \bar{F}_f the mean pot female bycatch fishing mortality, Q summer trawl survey catchability, and σ the estimated standard deviation of Q (all models).

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

Weights λ_j are assumed to be 500 for retained catch biomass, 300 for total directed pot fishery male biomass, 100 for all pot bycatch biomasses, and 50 for groundfish bycatch biomasses (trawl and fixed gear fisheries), 2 for recruitment variation, 10 for recruitment sex ratio, 0.2 for pot female bycatch fishing mortality, and 0.1 for trawl bycatch fishing mortality. These λ_j values correspond to CV values of 0.03, 0.04, 0.07, 0.1, 0.53, 0.23, 3.34, and 12.14, respectively, representing prior assumptions about the accuracy of the observed catch biomass data.

d. Population State in Year 1.

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

e. Parameter estimation framework:

i. Parameters estimated independently

Basic natural mortality, length-weight relationships, and mean growth increments per molt were estimated independently outside of the model. Mean length of recruits to the model depends on growth and was assumed to be 72.5 for both males and females. Handling mortality rates were set to 0.2 for the directed pot fishery, 0.25 for the Tanner crab fishery, 0.5 for the groundfish fixed gear fishery, and 0.8 for the groundfish trawl fishery.

(1). Natural Mortality

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

(2). Length-weight Relationship

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

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

$$\text{Ovigerous Females: } W = 0.003593 L^{2.666076} \tag{A19}$$

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

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

(3). Growth Increment per Molt

A variety of data are available to estimate male mean growth increment per molt for Bristol Bay RKC. Tagging studies were conducted during the 1950s, 1960s and 1990s, and mean growth increment per molt data from these tagging studies in the 1950s and 1960s were analyzed by Weber and Miyahara (1962) and Balsiger (1974). Modal analyses were conducted for the data during 1957-1961 and the 1990s (Weber 1967; Loher et al. 2001). Mean growth increment per molt may be a function of body size and shell condition and

vary over time (Balsiger 1974; McCaughran and Powell 1977); however, for simplicity, mean growth increment per molt was assumed to be only a function of body size in the models. Tagging data were used to estimate mean growth increment per molt as a function of pre-molt length for males (Figure A2). The results from modal analyses of 1957-1961 and the 1990s were used to estimate mean growth increment per molt for immature females during 1975-1993 and 1994-2017, respectively, and the data presented in Gray (1963) were used to estimate those for mature females for scenarios 1, 1n and 2 (Figure A2). To make a smooth transition of growth increment per molt from immature to mature females, weighted growth increment averages of 70% and 30% at 92.5 mm CL pre-molt length and 90% and 10% at 97.5 mm CL were used, respectively, for mature and immature females during 1983-1993. These percentages are roughly close to the composition of maturity. During 1975-1982, females matured at a smaller size, so the growth increment per molt as a function of length was shifted to smaller increments. Likewise, during 1994-2017, females matured at a slightly higher size, so the growth increment per molt was shifted to high increments for immature crab (Figure A2). Once mature, the growth increment per molt for male crab decreases slightly and annual molting probability decreases, whereas the growth increment for female crab decreases dramatically but annual molting probability remains constant at 1.0 (Powell 1967).

(4). Sizes at Maturity for Females

The NMFS collected female reproductive condition data during the summer trawl surveys. Mature females are separated from immature females by a presence of egg clutches or egg cases. Proportions of mature females at 5-mm length intervals were summarized and a logistic curve was fitted to the data each year to estimate sizes at 50% maturity. Sizes at 50% maturity are illustrated in Figure A3 with mean values for three different periods (1975-82, 1983-93, and 1994-2017).

(5). Sizes at Maturity for Males

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

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

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

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

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

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

Overall, the likely causes for the sharp decline in the early 1980s are combinations of the above factors, such as pot fisheries on legal males, bycatch, and predation on females and juvenile and sublegal males, senescence for older crab, and disease for all crab. In our model, we estimated one mortality parameter for males and another for females during 1980-1984. We also estimated a mortality parameter for females during 1976-1979 and 1985-1993. These three mortality parameters are additional to the basic natural mortality of 0.18yr^{-1} , all directed fishing mortality, and non-directed fishing mortality. These three mortality parameters could be attributed to natural mortality as well as undocumented non-directed fishing mortality. The model fit the data much better with these three parameters

than without them.

ii. Parameters estimated conditionally

The following model parameters were estimated for male and female crab: total recruits for each year (year class strength R_t for $t = 1976$ to 2019), total abundance in the first year (1975), growth parameter β , and recruitment parameter β_r for males and females separately. Molting probability parameters β and L_{50} were also estimated for male crab. Estimated parameters also include β and L_{50} for retained selectivity, β and L_{50} for pot-discarded female selectivity, β and L_{50} for pot-discarded male and female selectivities from the eastern Bering Sea Tanner crab fishery, β and L_{50} for groundfish trawl discarded selectivity, φ , κ and γ for pot-discarded male selectivity, and β for trawl survey selectivity and L_{50} for trawl survey male and females separately. The NMFS survey catchabilities Q for some models were also estimated. Three selectivity parameters were estimated for the survey data from the Bering Fisheries Research Foundation. Annual fishing mortalities were also estimated for the directed pot fishery for males (1975-2018), pot-discarded females from the directed fishery (1990-2018), pot-discarded males and females from the eastern Bering Sea Tanner crab fishery (1991-93, 2013-15), groundfish trawl discarded males and females (1976-2019), and groundfish fixed gear discarded males and females (1996-2018). Three additional mortality parameters for Mm_t and Mf_t were also estimated. Some estimated parameters were constrained in the model. For example, male and female recruitment estimates were forced to be close to each other for a given year.

f. Definition of model outputs.

- i. Biomass: two population biomass measurements are used in this report: total survey biomass (crab >64 mm CL) and mature male biomass (males >119 mm CL). Mating time is assumed to Feb. 15.
- ii. Recruitment: new entry of number of males in the 1st seven length classes (65- 99 mm CL) and new entry of number of females in the 1st five length classes (65-89 mm CL).
- iii. Fishing mortality: full-selected instantaneous annual fishing mortality rate at the time of fishery.

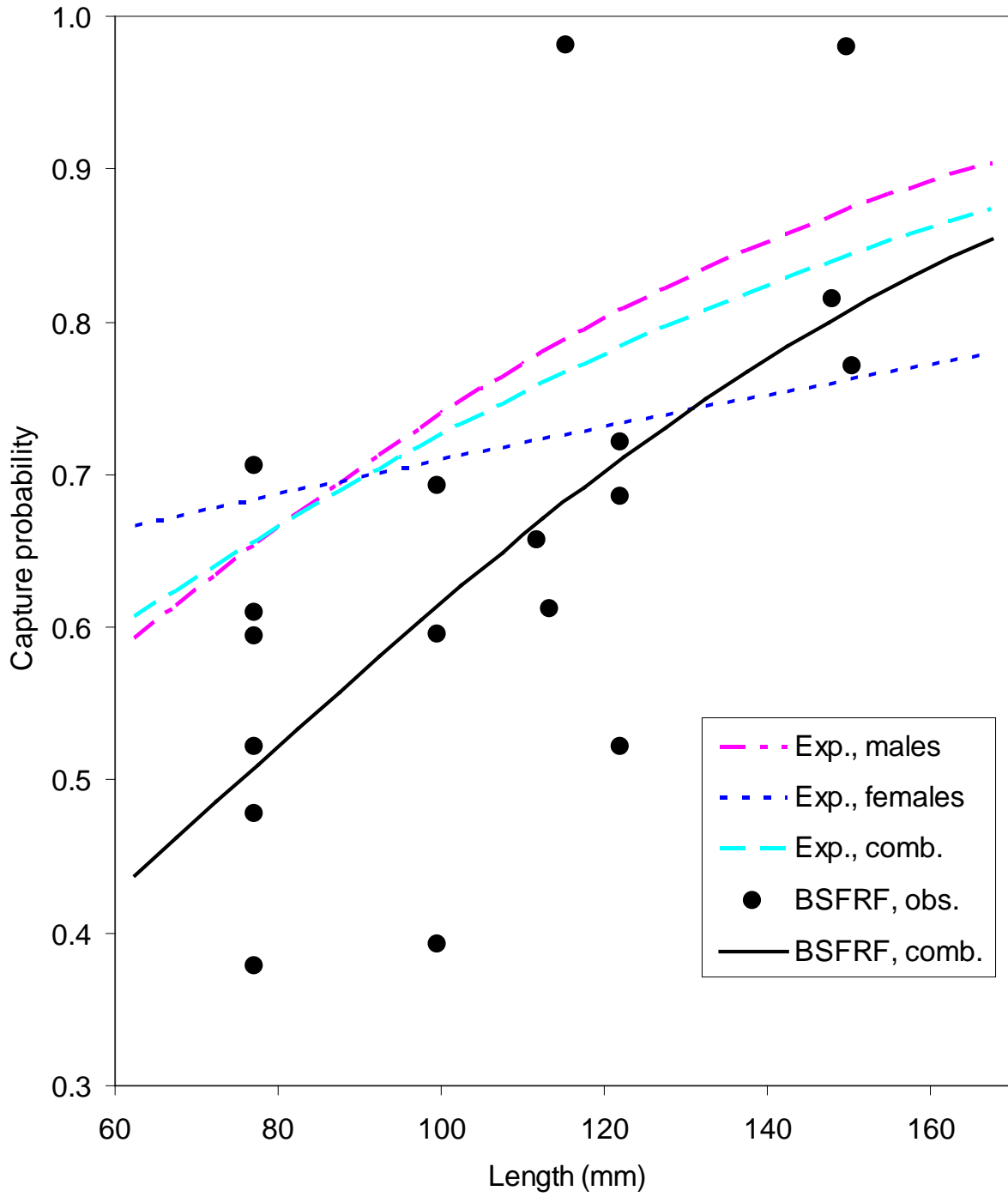


Figure A1. Estimated capture probabilities for NMFS Bristol Bay red king crab trawl surveys by Weinberg et al. (2004) and the Bering Sea Fisheries Research Foundation surveys.

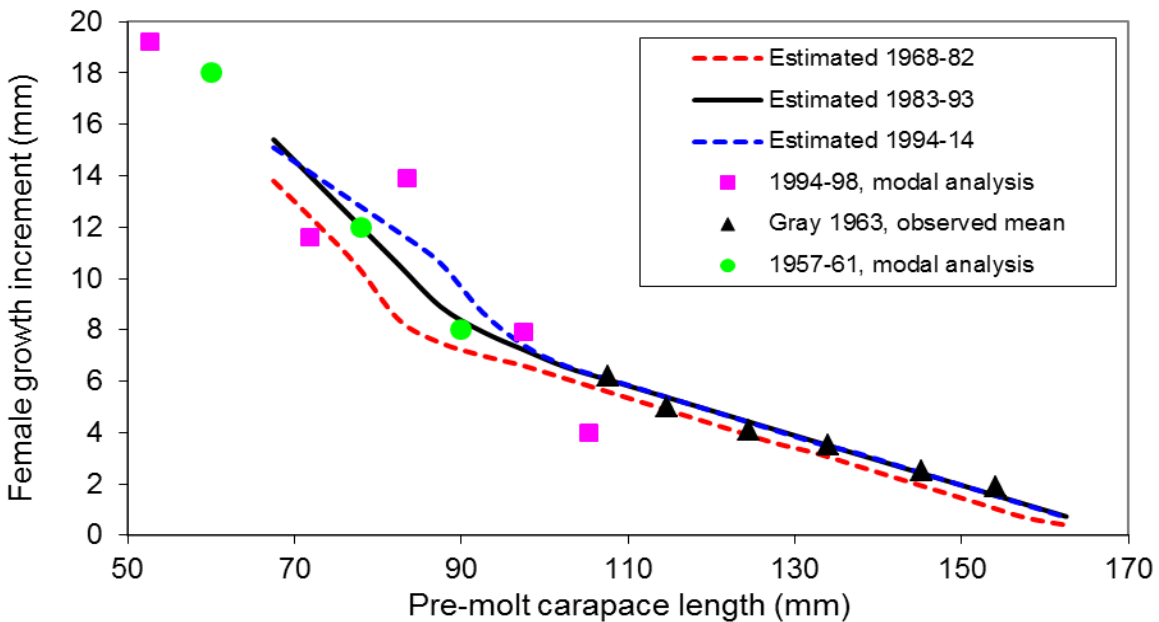
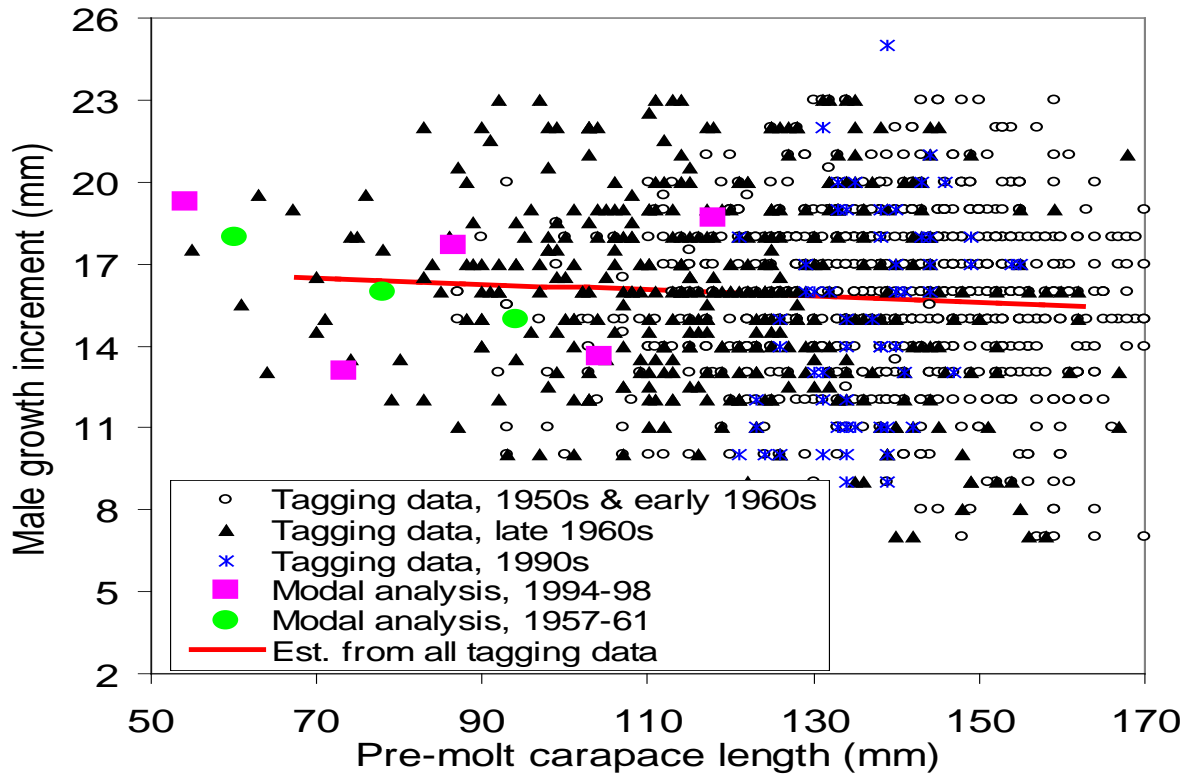


Figure A2. Mean growth increments per molt for Bristol Bay red king crab. Note: “tagging”---based on tagging data; “mode”---based on modal analysis. The female growth increments per molt are for models 18.0d, 18.0e and 19.0.

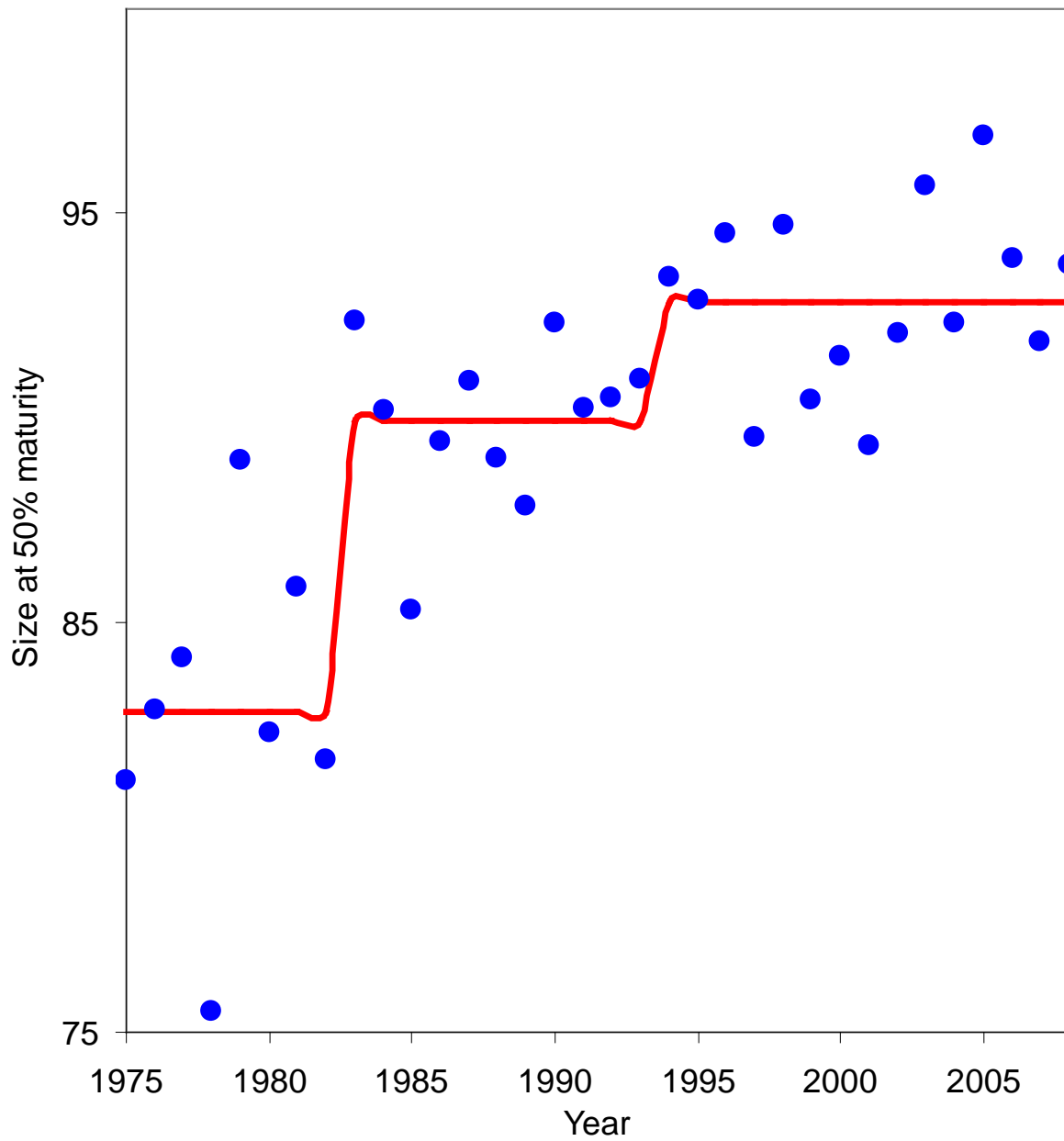


Figure A3. Estimated sizes at 50% maturity for Bristol Bay female red king crab from 1975 to 2008. Averages for three periods (1975-82, 1983-93, and 1994-08) are plotted with a line.

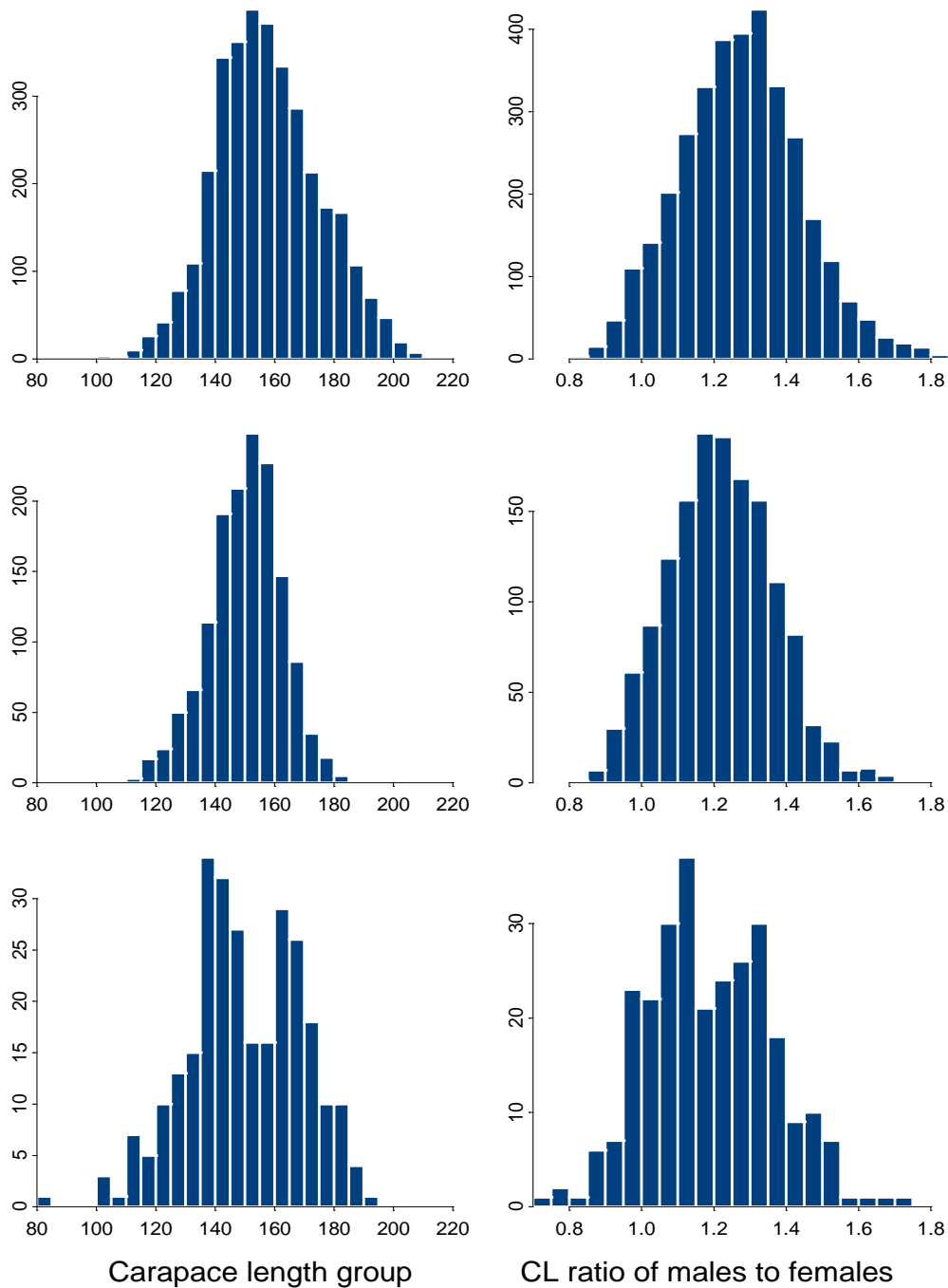


Figure A4. Histograms of carapace lengths (CL) and CL ratios of males to females for male shell ages ≤ 13 months of red king crab males in grasping pairs; Powell's Kodiak data. Upper plot: all locations and years pooled; middle plot: location 11; lower plot: locations 4 and 13. Sizes at maturity for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

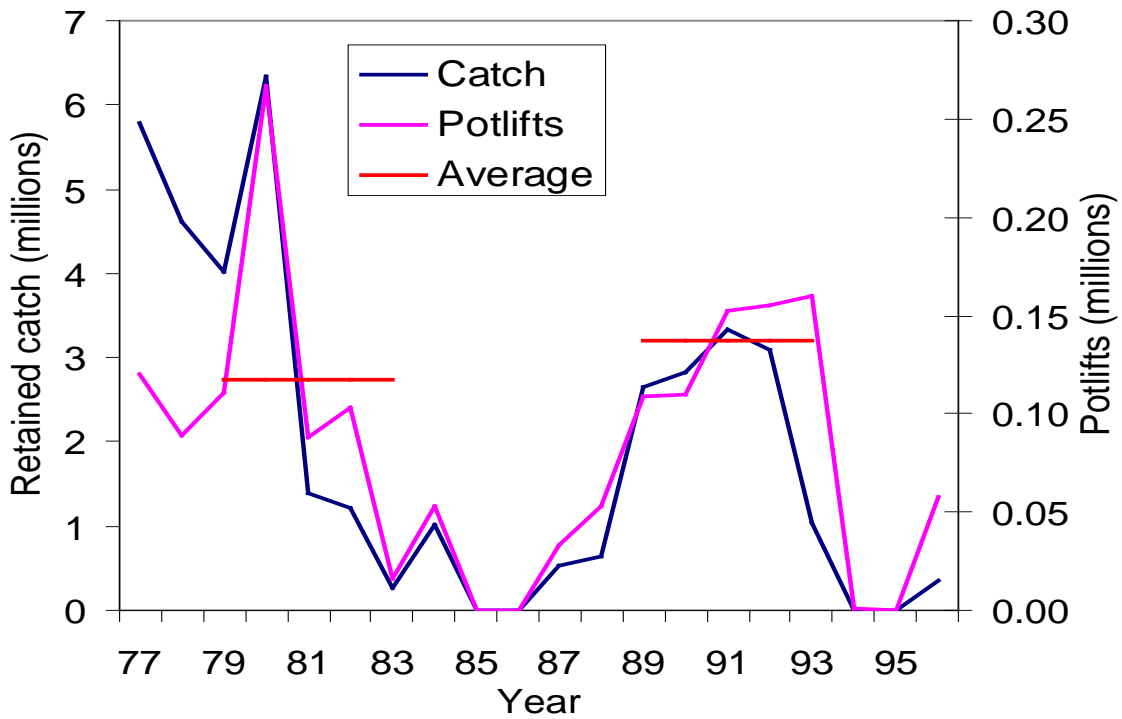
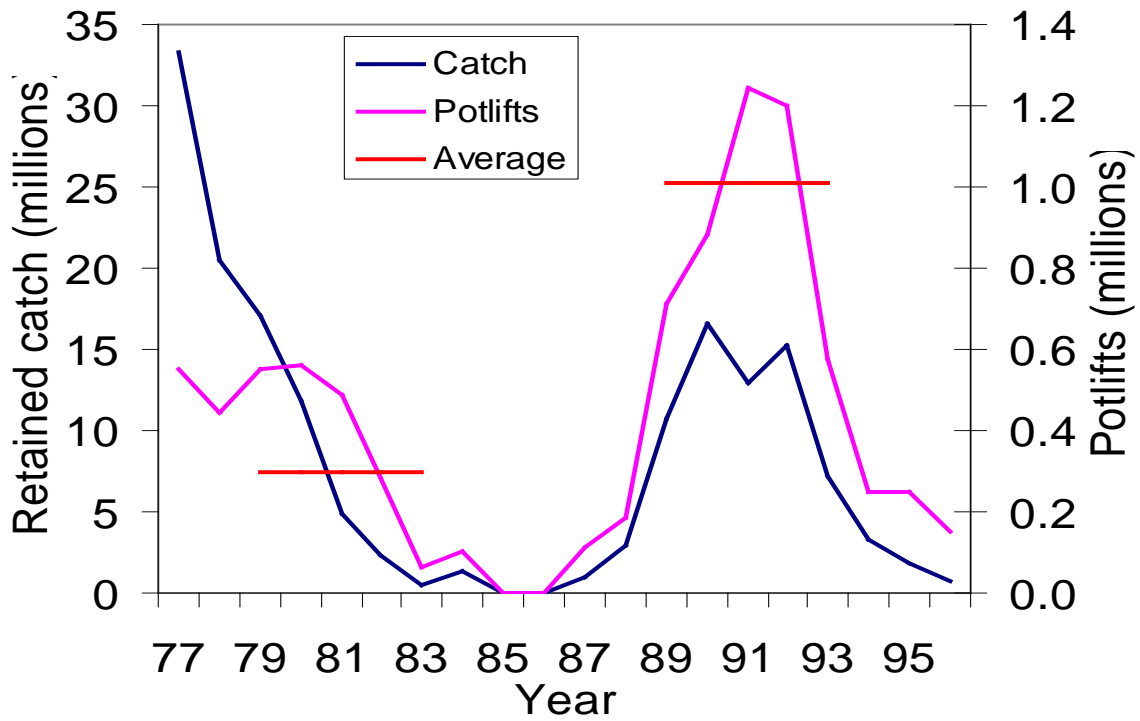


Figure A5. Retained catch and potlifts for total eastern Bering Sea Tanner crab fishery (upper plot) and the Tanner crab fishery east of 163° W (bottom).

Appendix B. Recruitment Breakpoint Analysis in May 2019

Introduction

SSC asked authors to conduct a recruitment breakpoint analysis similar to that conducted for eastern Bering Sea Tanner crab in 2013 (Stockhausen 2013). We obtained the R codes from Dr. William (Buck) Stockhausen of NMFS and slightly modified them to conduct the analysis for Bristol Bay red king crab for better understanding the temporal change of stock productivity and the recruitment time series used for overfishing/overfished definitions. Results from assessment model model 18.0a are used for this analysis. We are very grateful for the help of Dr. Stockhausen for this analysis.

Methods

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

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

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

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

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

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

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

where $\mathbf{\Omega}$ contains observation and process error as

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

where \mathbf{O} is the observation error covariance matrix estimated from the stock assessment model and \mathbf{P} is the process error matrix and is assumed to reflect a first-order autoregressive process to

have σ^2 on the diagonal and $\sigma^2 \rho^{|t-j|}$ on the off-diagonal elements. σ^2 represents process error variance and ρ represents the degree of autocorrelation.

For each candidate breakpoint year b , the negative log likelihood value of equation (3) is minimized with respect to the six model parameters: $\alpha_1, \beta_1, \alpha_2, \beta_2, \ln(\sigma)$ and $\tan(\rho)$. The minimum time span considered as a potential regime is 5 years. Each brood year from 1980 to 2007 is evaluated as a potential breakpoint b using time series of $\ln(R/MMB)$ and MMB for brood years 1975-2012. A model with no breakpoint is also evaluated. Models with different breakpoints are then ranked using AICc (AIC corrected for small sample size; Burnham and Anderson 2004),

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

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

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

Results

Results are summarized in Tables B1-B4 and Figures B1-B6. Discarding the implausible breakpoint year of 1980 for the Ricker model due to implausible stock-recruitment model parameters, the Ricker model has a breakpoint of brood year of 1986 (recruitment year of 1992), and the Beverton-Holt model results in the same breakpoint brood year of 1984, which corresponds to recruitment year of 1990. The model with no breakpoint (i.e., a single time period) is about 18 times less probable than the 1984 breakpoint model for Beverton-Holt stock-recruitment models and about 17 times less probable for Ricker stock-recruitment relationships, which may suggest a possible change in stock productivity from the early high period to the recent low period. Alternative breakpoint brood years of 1980-1986 for both Ricker and Beverton-Holt models are also reasonably reported. Both Ricker and Beverton-Holt stock-recruitment models fit the data poorly.

Discussion

A recruitment breakpoint analysis was conducted on Bristol Bay red king crab by Punt et al. (2014) with data from 1968 to 2010 to estimate a breakpoint brood year of 1984, corresponding to recruitment year of 1990, which is the same as our estimate with the Beverton-Holt model. Our data start in 1975 and have only two brood-year data points before the regime shift of 1976/77 and thus we cannot detect any stock productivity changes due to the 1976/77 regime shift because of lack of data. Without the early data, the fits of stock-recruitment models to the data are also more poorly.

Time series of estimated recruitment during 1984-present have been used to compute Bmsy proxy. The mean recruitment with model 18.0e during 1984-present is 17.70 million of crab, compared to the mean recruitment of 16.21 million of crab during 1990-present, about 8.4% reduction

(Figure 12(18.0a)). If the estimated breakpoint year is used to set the new recruitment time series, estimated Bmsy proxy will be correspondingly lower than the current estimated value.

References

- Burnham, K.P., and D.R. Anderson. 2004. Multimodal inference: understanding AIC and BIC in model selection. *Sociological Methods & Research* 33:261–304.
- Punt, A.E., C.S. Szuwalski, and W. Stockhausen. 2014. An evaluation of stock-recruitment proxies and environmental change points for implementing the US Sustainable Fisheries Act. *Fisheries Research* 157:28-40.
- Stockhausen, W.T. 2013 Recruitment Analysis for Stock Status Determination and Harvest Recommendations. Appendix to: 2013 Stock Assessment and Fishery Evaluation Report for the Tanner Crab Fisheries in the Bering Sea and Aleutian Islands Regions. In: Stock Assessment and Fishery Evaluation Report for the King and Tanner Crab Fisheries of the Bering Sea and Aleutian Islands Regions. North Pacific Fishery Management Council, Anchorage. pp.450-478.

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

Year	AICc	Odds
NA	30.9238	22.6194
1980	24.6862	1.0000
1981	26.0669	1.9944
1982	26.1803	2.1107
1983	26.1267	2.0549
1984	26.1003	2.0280
1985	25.6051	1.5832
1986	25.3132	1.3682
1987	28.6416	7.2259
1988	29.9626	13.9875
1989	32.4417	48.3160
1990	29.2430	9.7607
1991	31.1066	24.7833
1992	31.1349	25.1368
1993	30.8432	21.7255
1994	31.8353	35.6785
1995	32.0101	38.9364
1996	32.2674	44.2836
1997	30.7012	20.2369
1998	31.6248	32.1144
1999	32.0321	39.3669
2000	29.4065	10.5927
2001	28.6866	7.3904
2002	29.3953	10.5332
2003	30.9657	23.0977
2004	31.5810	31.4179
2005	30.1676	15.4974
2006	29.9998	14.2502
2007	31.0384	23.9530

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

Year	α_1	std.dev.	α_2	std.dev.	β_1	std.dev.	β_2	std.dev.	$\ln(\sigma)$	std.dev.	$\tan(\rho)$	std.dev.
			-0.319	0.260			0.006	0.006	-0.224	0.127	0.367	0.304
1980	-4.927	3.085	0.825	0.358	-0.043	0.030	0.057	0.014	-0.406	0.123	-0.021	0.282
1981	0.215	0.869	0.789	0.353	0.007	0.009	0.056	0.014	-0.388	0.124	-0.082	0.279
1982	0.527	0.563	0.734	0.394	0.010	0.007	0.054	0.016	-0.387	0.124	-0.056	0.275
1983	0.406	0.440	0.818	0.436	0.009	0.006	0.057	0.017	-0.388	0.124	-0.066	0.271
1984	0.397	0.376	0.858	0.498	0.009	0.005	0.059	0.019	-0.389	0.124	-0.060	0.271
1985	0.623	0.333	0.336	0.608	0.011	0.005	0.040	0.023	-0.395	0.124	-0.059	0.273
1986	0.581	0.307	0.087	0.728	0.011	0.005	0.031	0.027	-0.398	0.124	-0.047	0.277
1987	0.337	0.300	0.555	0.820	0.009	0.005	0.047	0.030	-0.354	0.124	-0.043	0.270
1988	0.223	0.308	0.645	0.912	0.008	0.005	0.050	0.033	-0.335	0.123	0.058	0.271
1989	0.057	0.302	0.727	0.929	0.007	0.005	0.052	0.034	-0.302	0.123	0.037	0.274
1990	0.172	0.309	0.809	0.949	0.008	0.005	0.057	0.035	-0.347	0.125	0.169	0.282
1991	0.036	0.298	0.946	0.971	0.007	0.005	0.061	0.035	-0.320	0.125	0.152	0.274
1992	-0.083	0.288	1.514	1.041	0.006	0.005	0.080	0.037	-0.320	0.125	0.159	0.276
1993	-0.097	0.275	1.800	1.140	0.006	0.005	0.089	0.041	-0.325	0.125	0.149	0.274
1994	-0.002	0.275	0.929	1.586	0.007	0.005	0.060	0.055	-0.309	0.124	0.156	0.286
1995	-0.046	0.261	1.410	1.784	0.006	0.005	0.076	0.061	-0.308	0.124	0.129	0.273
1996	-0.080	0.253	1.675	1.881	0.006	0.005	0.084	0.064	-0.305	0.124	0.116	0.272
1997	0.009	0.256	-0.664	2.251	0.007	0.005	0.008	0.076	-0.324	0.125	0.182	0.287
1998	-0.048	0.241	-0.088	3.178	0.006	0.005	0.027	0.106	-0.315	0.124	0.114	0.271
1999	-0.079	0.233	-0.453	4.442	0.006	0.005	0.015	0.146	-0.309	0.124	0.078	0.276
2000	-0.047	0.219	-1.902	4.333	0.006	0.004	-0.029	0.142	-0.350	0.125	0.049	0.275
2001	-0.060	0.206	-2.645	4.313	0.006	0.004	-0.052	0.141	-0.360	0.125	-0.016	0.277
2002	-0.086	0.211	-2.603	4.317	0.006	0.004	-0.050	0.141	-0.348	0.124	0.023	0.271
2003	-0.126	0.215	-4.313	5.199	0.006	0.005	-0.108	0.172	-0.325	0.124	0.038	0.273
2004	-0.150	0.215	-5.235	6.326	0.006	0.005	-0.139	0.211	-0.315	0.123	0.039	0.276
2005	-0.142	0.211	-4.701	6.169	0.006	0.005	-0.118	0.206	-0.336	0.124	0.056	0.274
2006	-0.155	0.209	-3.551	6.362	0.006	0.005	-0.077	0.213	-0.337	0.124	0.051	0.272
2007	-0.181	0.210	-3.992	9.066	0.006	0.005	-0.093	0.308	-0.322	0.123	0.059	0.277

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

Year	AICc	Odds
NA	29.7727	18.4149
1980	25.7843	2.5066
1981	24.5863	1.3770
1982	24.5910	1.3803
1983	24.1006	1.0801
1984	23.9464	1.0000
1985	24.8023	1.5341
1986	24.7628	1.5041
1987	27.9016	7.2254
1988	29.2177	13.9523
1989	31.7329	49.0694
1990	28.6093	10.2928
1991	30.6450	28.4827
1992	31.5624	45.0590
1993	31.6181	46.3324
1994	31.3514	40.5480
1995	31.7759	50.1358
1996	32.1970	61.8866
1997	30.0083	20.7162
1998	31.0013	34.0360
1999	31.4110	41.7743
2000	28.8322	11.5062
2001	28.1772	8.2927
2002	28.8375	11.5366
2003	30.5744	27.4948
2004	31.1698	37.0289
2005	29.6270	17.1211
2006	29.2277	14.0223
2007	30.1635	22.3878

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

Year	α_1	std.dev.	α_2	std.dev.	β_1	std.dev.	β_2	std.dev.	$\ln(\sigma)$	std.dev.	$\tan(\rho)$	std.dev.
			0.224	0.851			-3.290	1.684	-0.236	0.129	0.403	0.324
1980	-0.556	0.310	2.686	3.333	-10.91	35.202	0.094	3.500	-0.388	0.125	-0.146	0.282
1981	0.672	1.635	2.762	3.782	-3.736	2.500	0.203	3.952	-0.409	0.124	-0.052	0.296
1982	0.799	0.787	2.882	4.945	-3.551	1.225	0.326	5.129	-0.409	0.124	-0.045	0.282
1983	0.538	0.526	8.307	57.004	-3.945	0.992	5.768	57.013	-0.416	0.124	-0.068	0.275
1984	0.501	0.436	9.152	68.364	-4.003	0.889	6.604	68.368	-0.418	0.124	-0.064	0.273
1985	0.776	0.421	2.594	11.533	-3.580	0.785	0.026	11.994	-0.406	0.124	-0.051	0.275
1986	0.727	0.393	0.795	2.881	-3.643	0.777	-1.978	3.689	-0.405	0.124	-0.041	0.278
1987	0.482	0.385	8.354	122.464	-3.906	0.876	5.793	122.479	-0.364	0.124	-0.035	0.273
1988	0.394	0.421	8.228	111.591	-3.939	0.996	5.652	111.606	-0.344	0.123	0.079	0.274
1989	0.249	0.434	7.025	61.785	-4.023	1.107	4.410	61.814	-0.312	0.123	0.060	0.278
1990	0.370	0.452	7.051	52.894	-3.911	1.065	4.513	52.916	-0.354	0.125	0.187	0.288
1991	0.237	0.452	7.762	72.745	-4.018	1.157	5.185	72.760	-0.326	0.125	0.164	0.279
1992	0.084	0.433	7.678	54.671	-4.237	1.267	5.051	54.684	-0.311	0.124	0.178	0.279
1993	0.058	0.419	7.628	51.998	-4.281	1.277	4.996	52.011	-0.310	0.124	0.180	0.280
1994	0.206	0.450	5.852	54.545	-4.008	1.204	3.282	54.618	-0.313	0.125	0.199	0.288
1995	0.145	0.426	6.347	56.553	-4.097	1.219	3.763	56.599	-0.309	0.124	0.165	0.280
1996	0.100	0.411	6.545	58.063	-4.156	1.234	3.954	58.102	-0.304	0.124	0.132	0.280
1997	0.212	0.430	-0.690	2.493	-4.005	1.178	-4.849	13.254	-0.333	0.126	0.196	0.296
1998	0.130	0.391	0.233	9.064	-4.143	1.176	-2.668	13.428	-0.324	0.125	0.119	0.276
1999	0.094	0.380	-0.473	6.417	-4.193	1.186	-4.029	18.286	-0.318	0.124	0.081	0.281
2000	0.113	0.352	-1.011	0.284	-4.231	1.113	-9.764	109.299	-0.358	0.125	0.065	0.272
2001	0.098	0.336	-1.063	0.260	-4.258	1.083	-9.645	77.507	-0.368	0.125	0.012	0.272
2002	0.088	0.356	-1.074	0.349	-4.211	1.121	-8.571	46.119	-0.357	0.125	0.041	0.272
2003	0.087	0.401	-1.046	0.280	-4.085	1.186	-9.606	63.896	-0.331	0.124	0.073	0.275
2004	0.086	0.425	-1.051	0.334	-4.022	1.217	-8.858	47.684	-0.321	0.124	0.082	0.278
2005	0.089	0.411	-1.171	0.310	-4.033	1.179	-9.685	77.778	-0.344	0.124	0.081	0.277
2006	0.080	0.407	-1.248	0.398	-4.032	1.168	-8.833	63.349	-0.349	0.124	0.056	0.277
2007	0.082	0.440	-1.261	0.596	-3.954	1.211	-8.167	60.765	-0.336	0.124	0.075	0.281

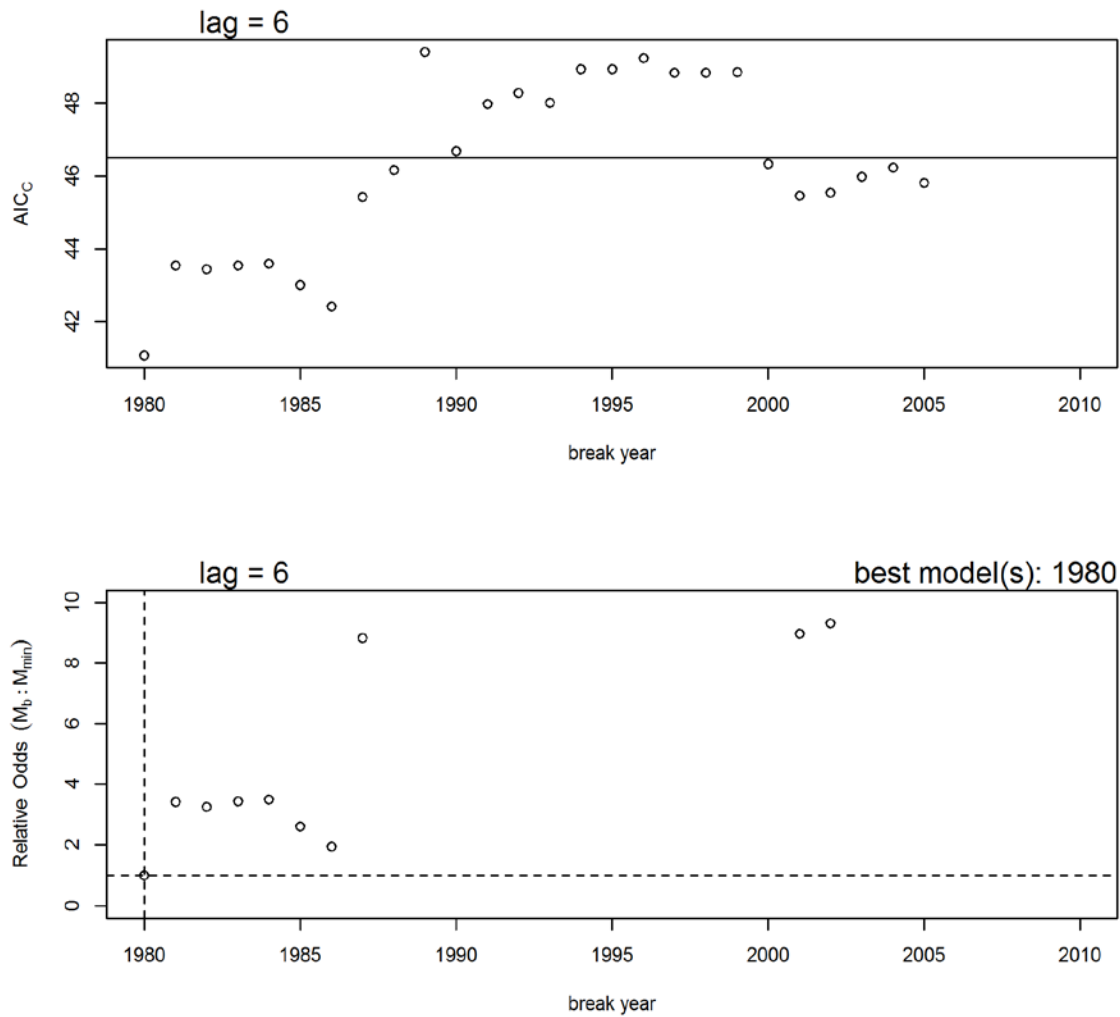


Figure B1. Results from the Ricker stock-recruit breakpoint analysis. Upper graph: AIC_c vs. year of breakpoint for the 1-breakpoint models (circles) and AIC_c for the model with no breakpoint (horizontal line). Lower graph: probabilistic odds for all 1-breakpoint models (circles) and the no breakpoint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

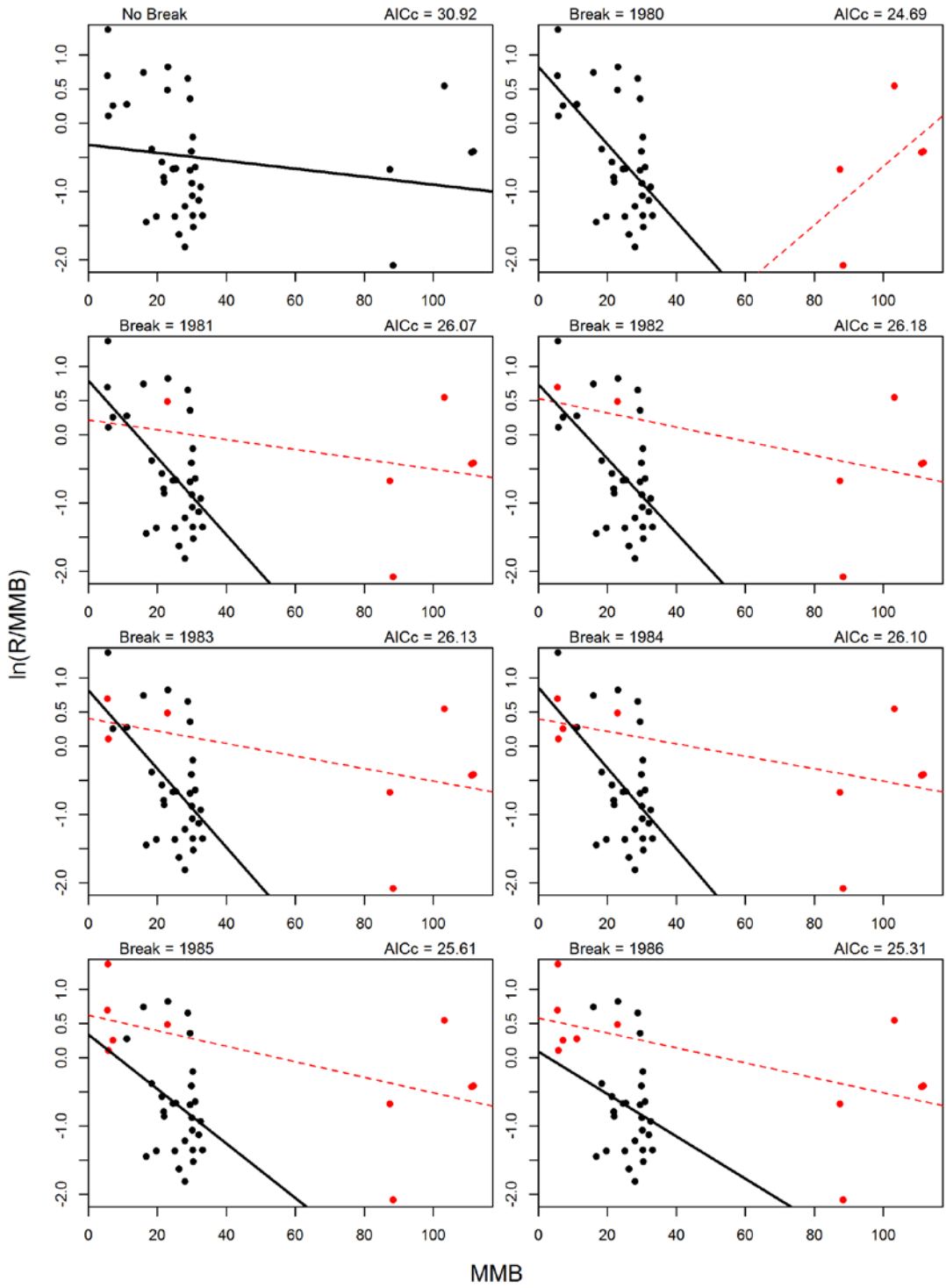


Figure B2. Fits for Ricker models with no breakpoint (upper left graph) and with 1-breakpoint for break years 1975-2007. For 1-breakpoint models, the pre-break data (circles) and model fit (line) are shown in red, whereas the post-break data and fit are shown in black.

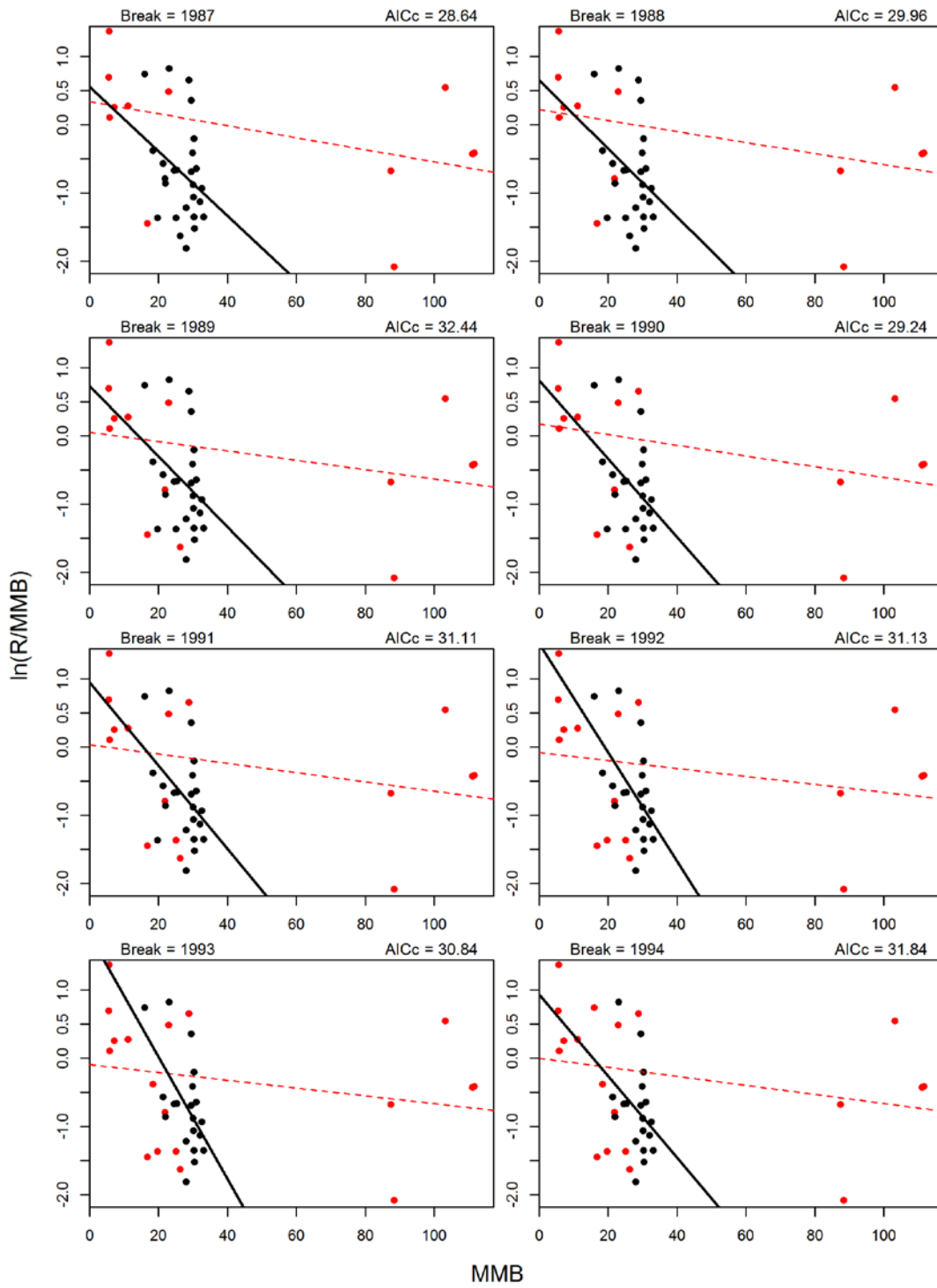


Figure B2. Continue.

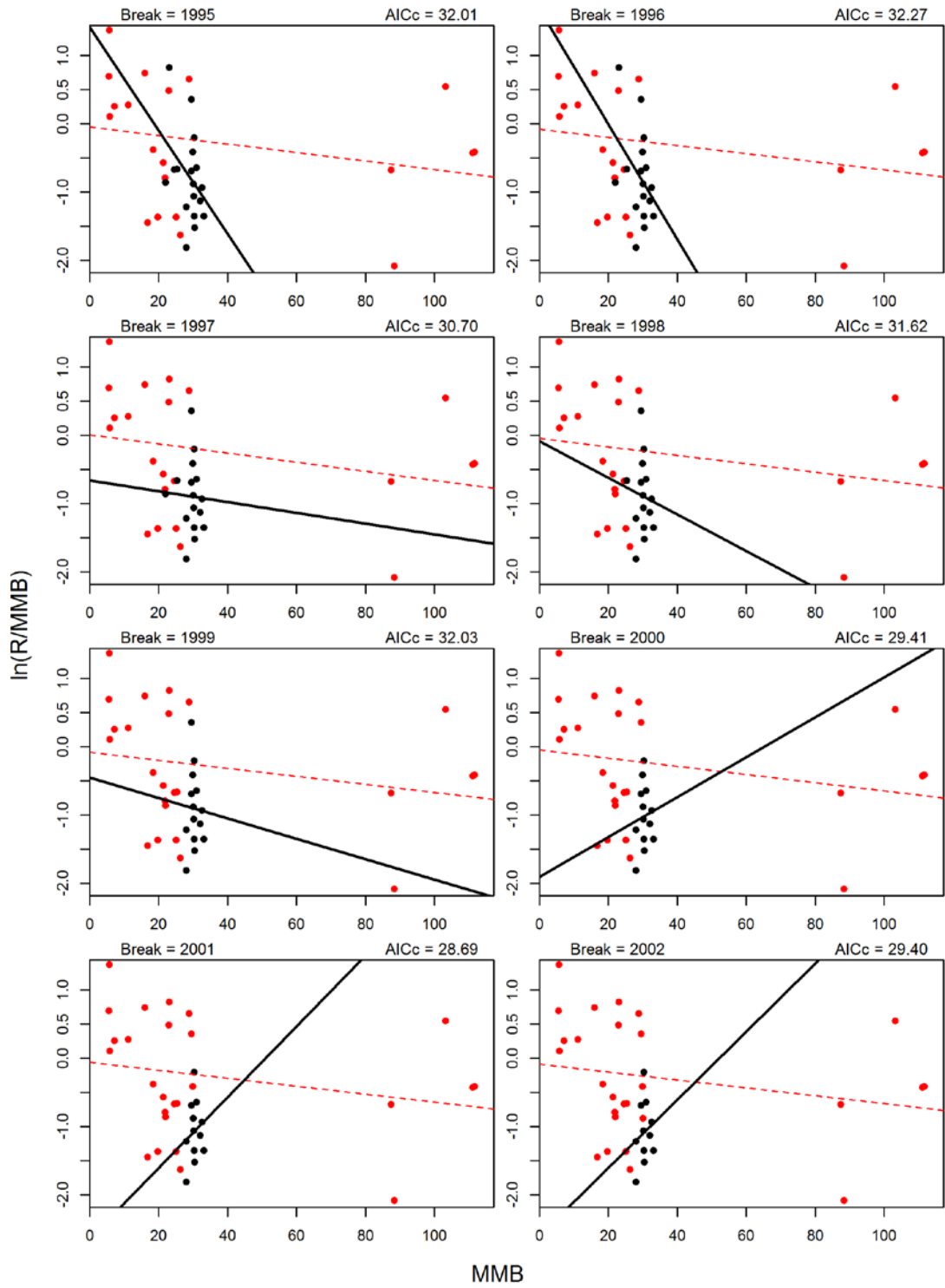
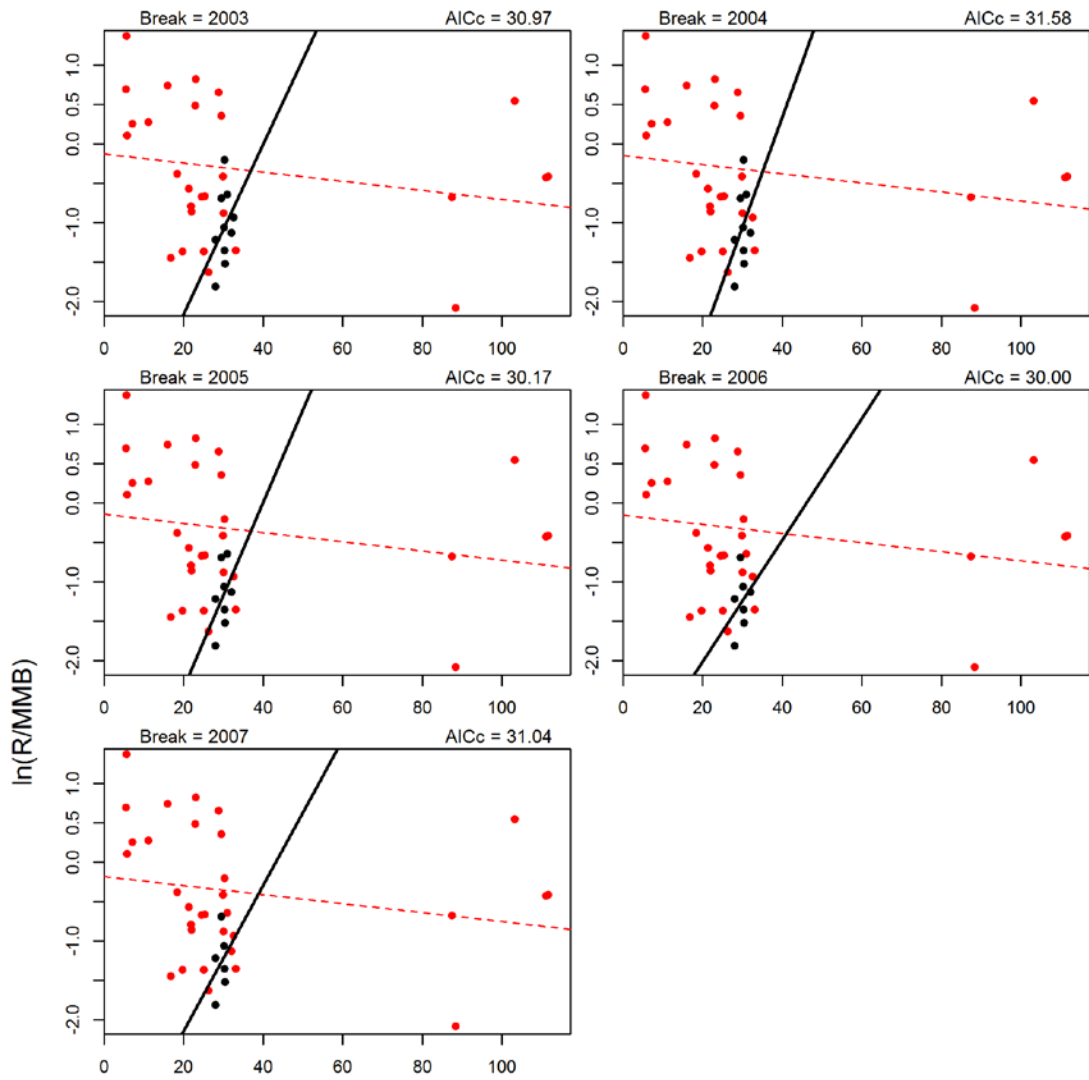


Figure B2. Continue.



MMB

Figure B2. Continue.

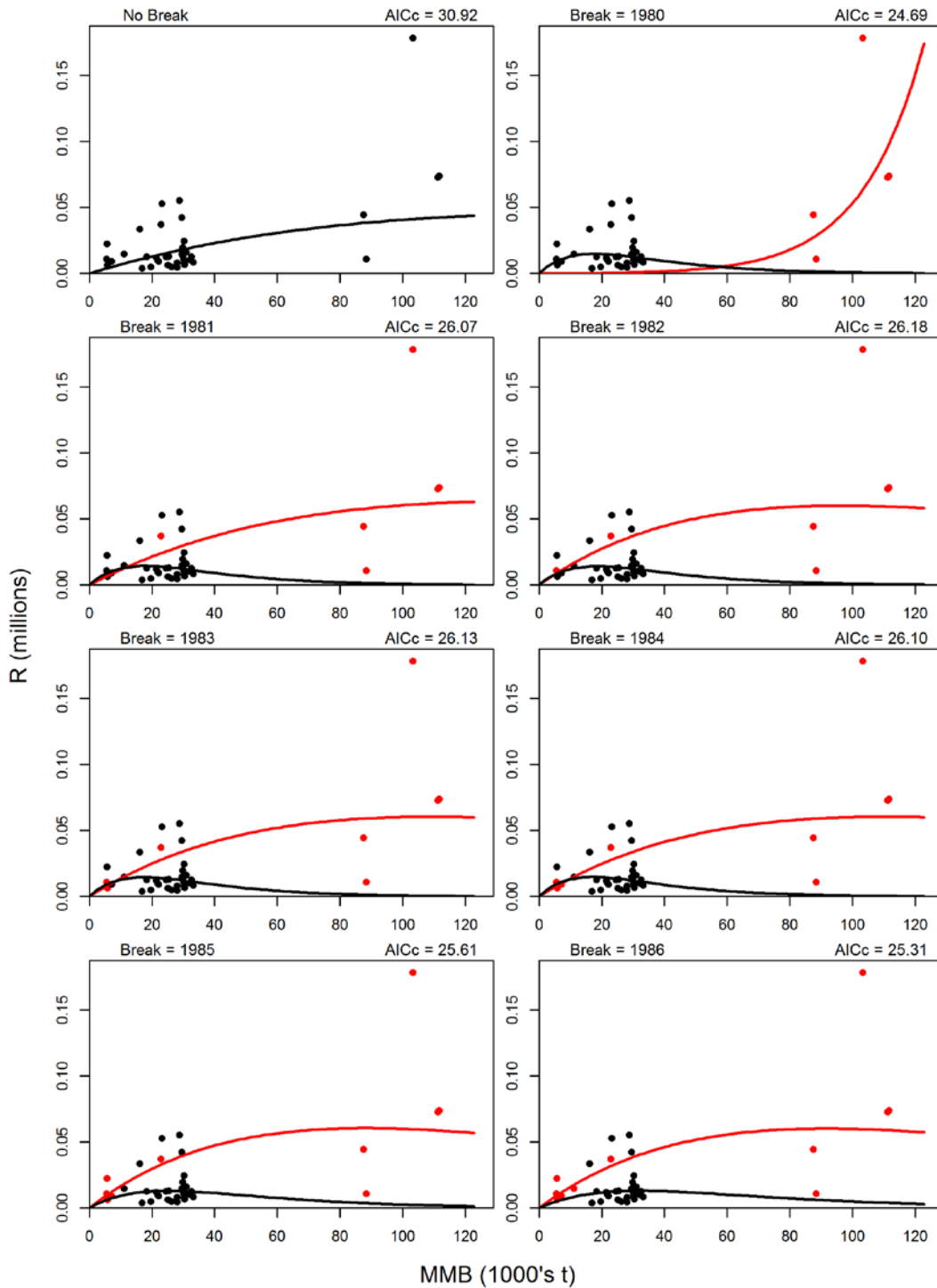


Figure B3. Fits on the arithmetic scale for Ricker models with no breakpoint (upper left graph) and with 1-breakpoint for break years 1975-2007. For 1-breakpoint models, the pre-break data (circles) and model fit (line) are shown in red, whereas the post-break data and fit are shown in black.

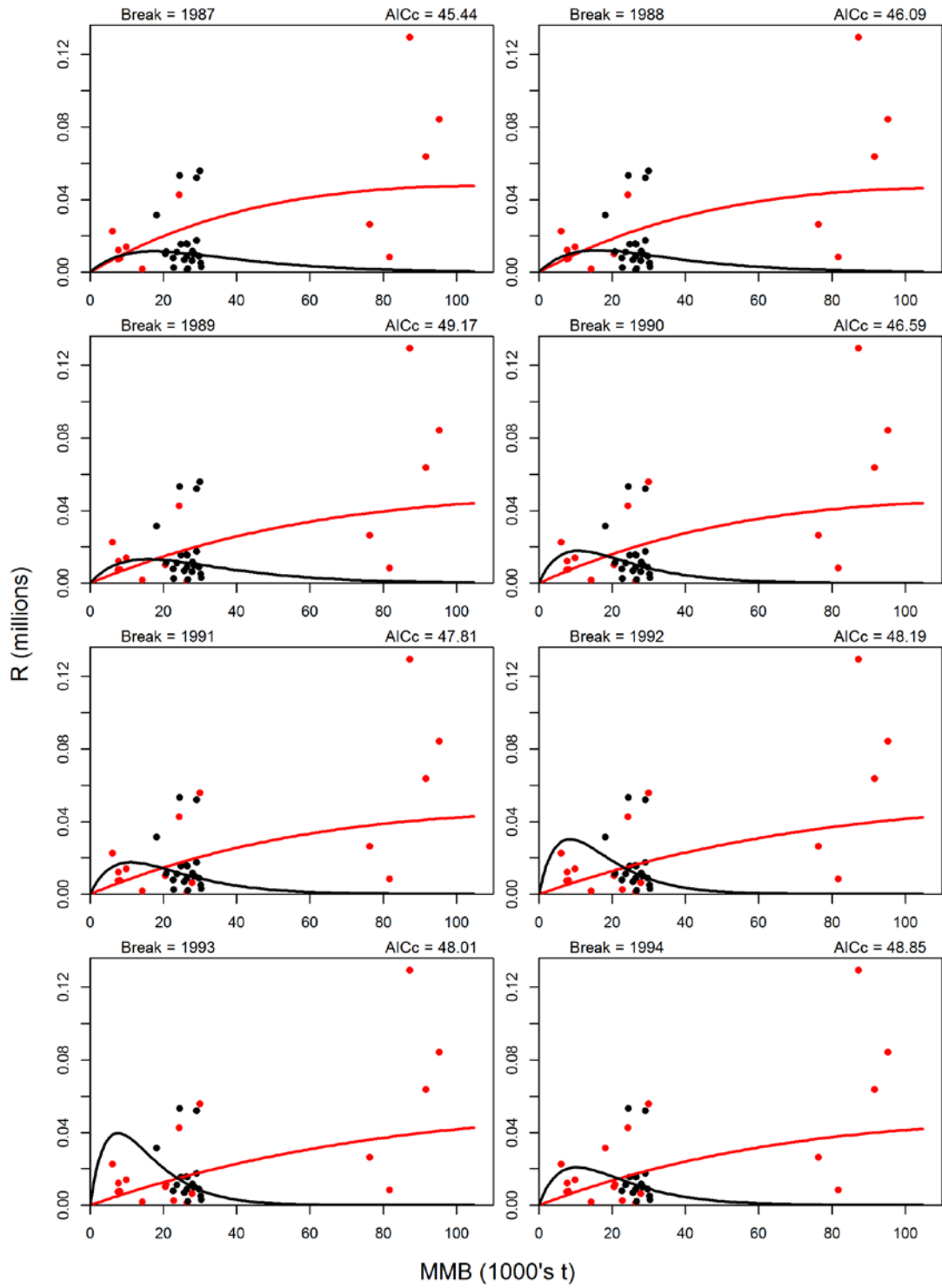


Figure B3. Continue.

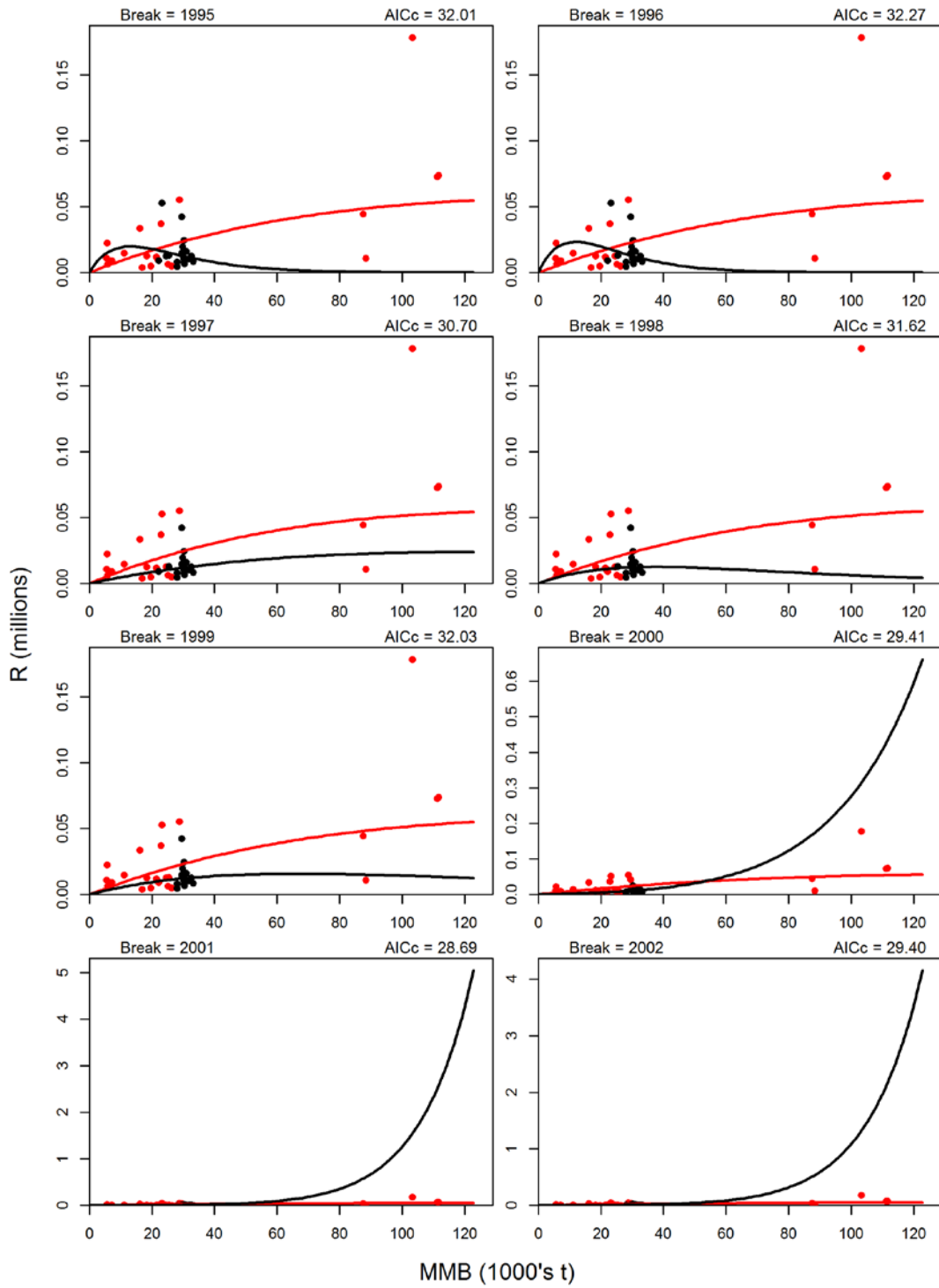
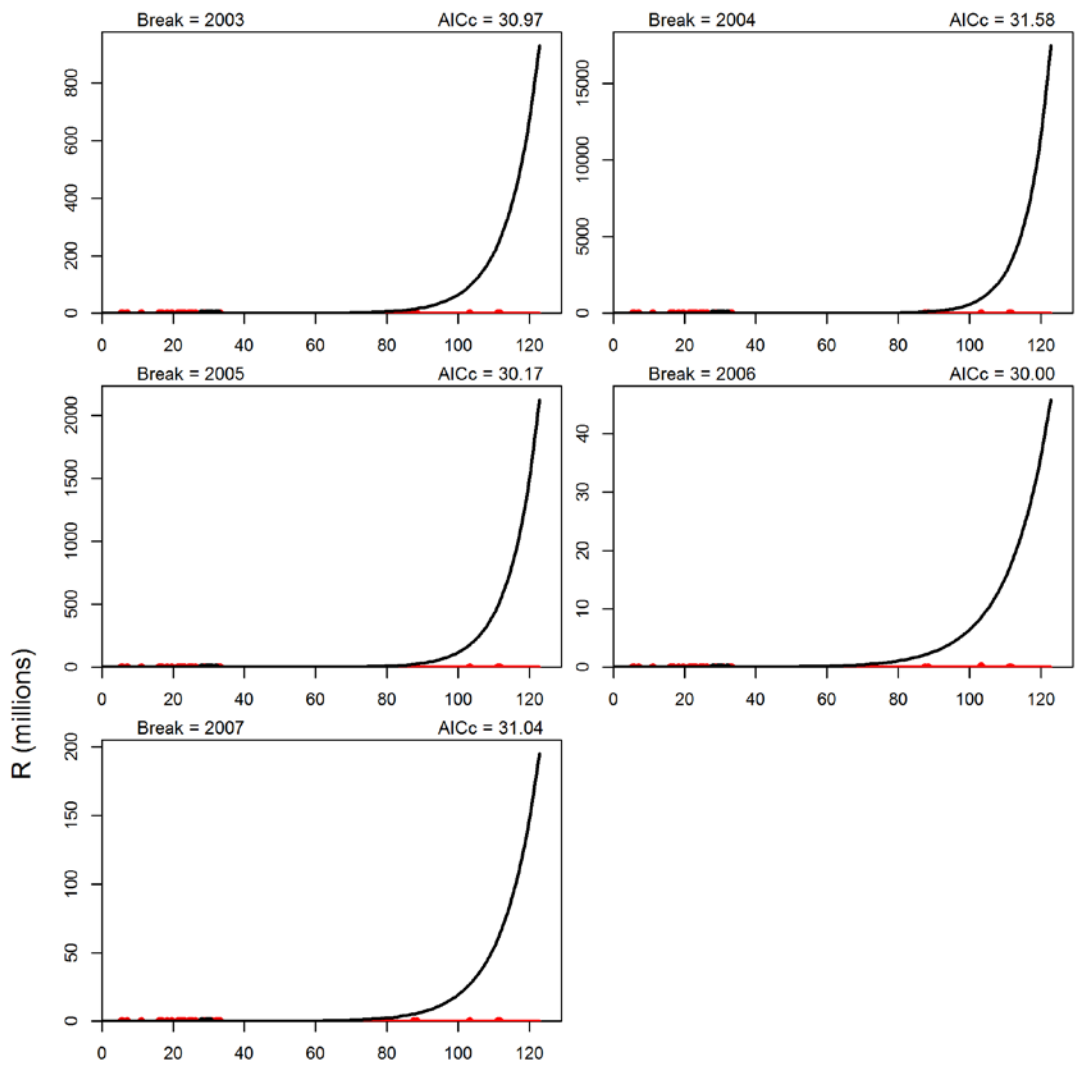


Figure B3. Continue.



MMB (1000's t)

Figure B3. Continue.

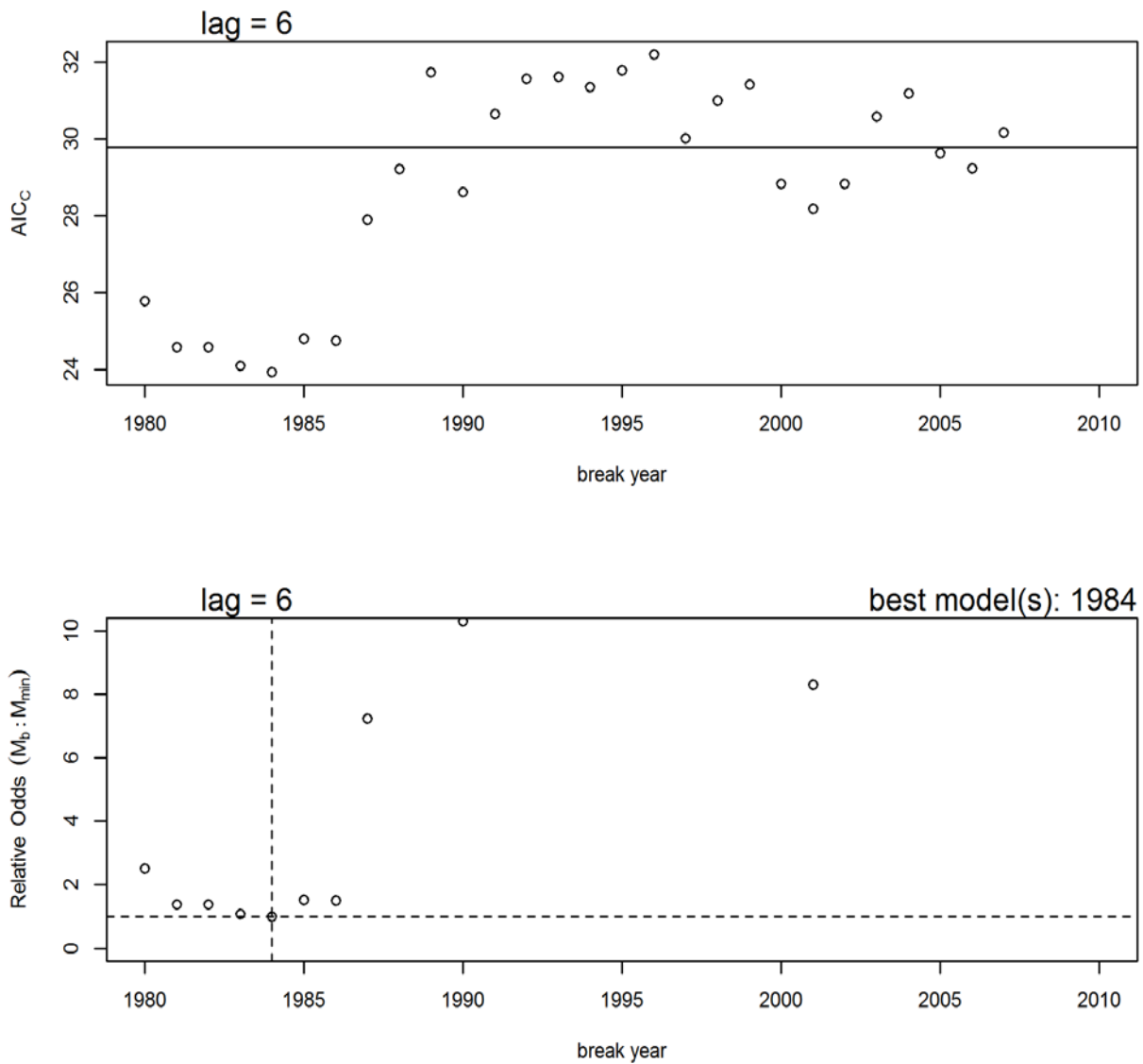


Figure B4. Results from the B-H stock-recruit breakpoint analysis. Upper graph: AICc vs. year of breakpoint for the 1-breakpoint models (circles) and AICc for the model with no breakpoint (horizontal line). Lower graph: probabilistic odds for all 1-breakpoint models (circles) and the no breakpoint model (horizontal solid line) relative to the model with the smallest AICc score. The dashed lines indicate the value for the model with the lowest AICc score (breakpoint in 1984). Not shown are 1-breakpoint models with high odds (>10) of being incorrect.

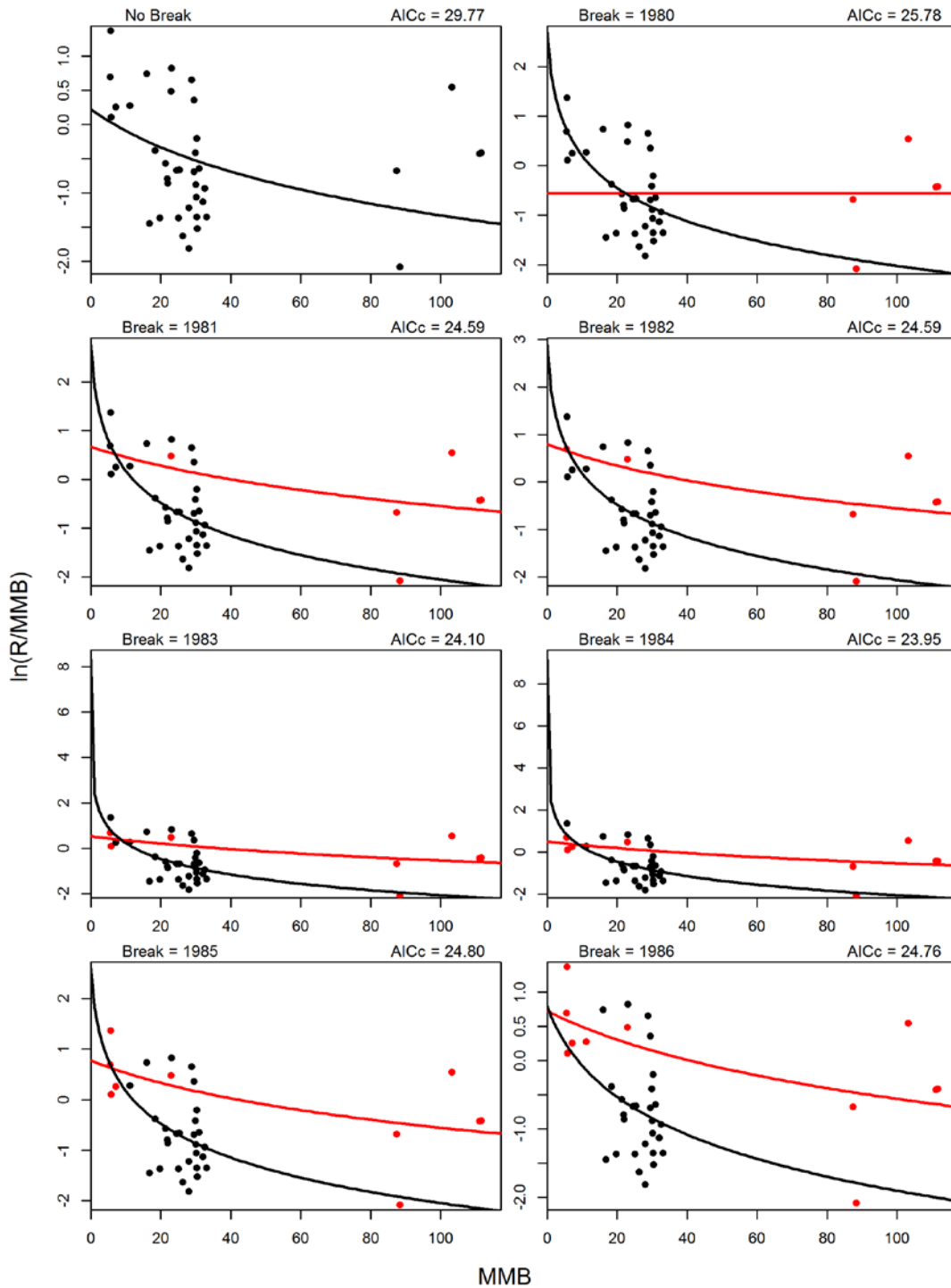


Figure B5. Fits for B-H models with no breakpoint (upper left graph) and with 1-breakpoint for break years 1975-2007. For 1-breakpoint models, the pre-break data (circles) and model fit (line) are shown in red, whereas the post-break data and fit are shown in black.

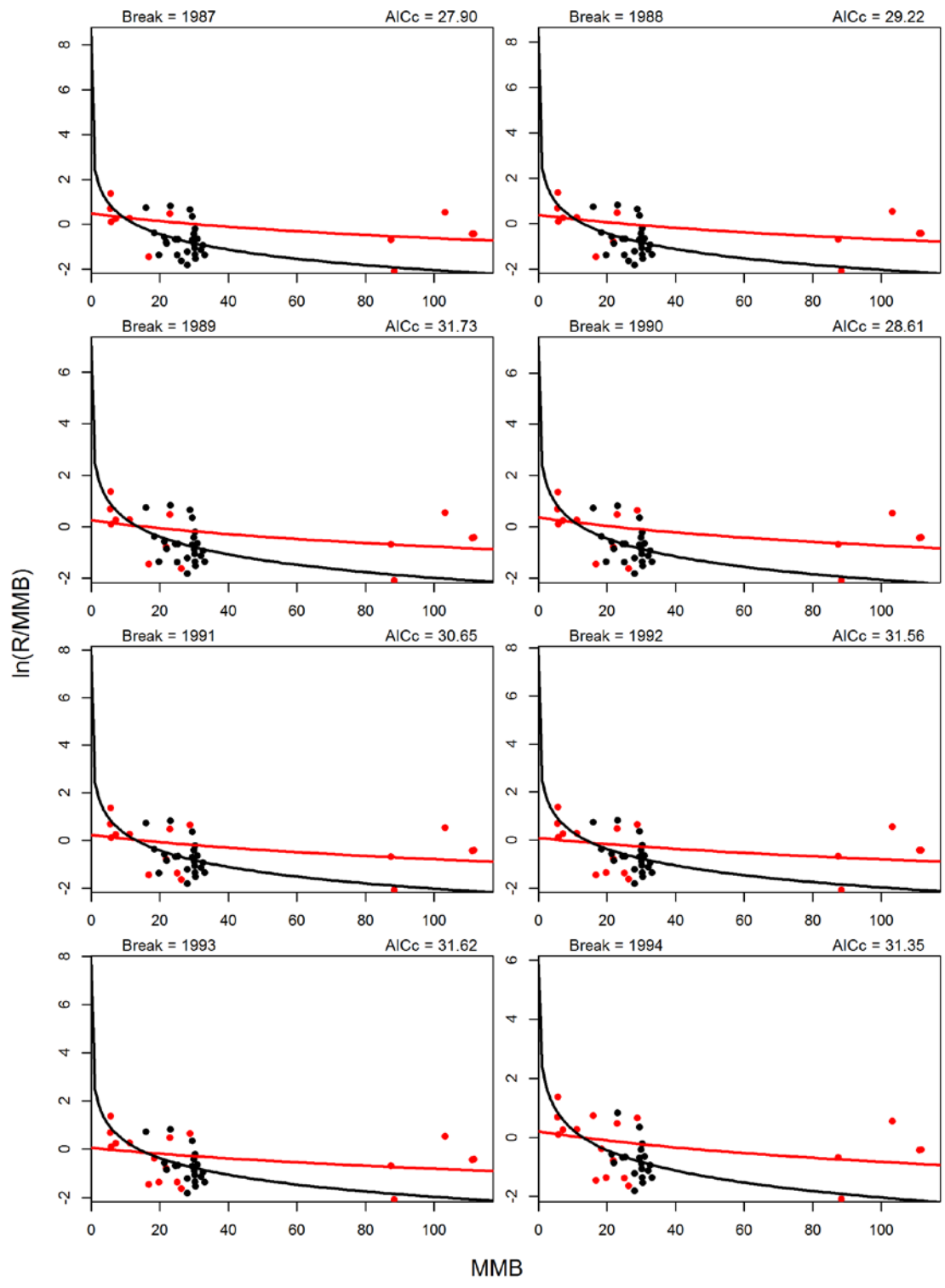


Figure B5. Continue.

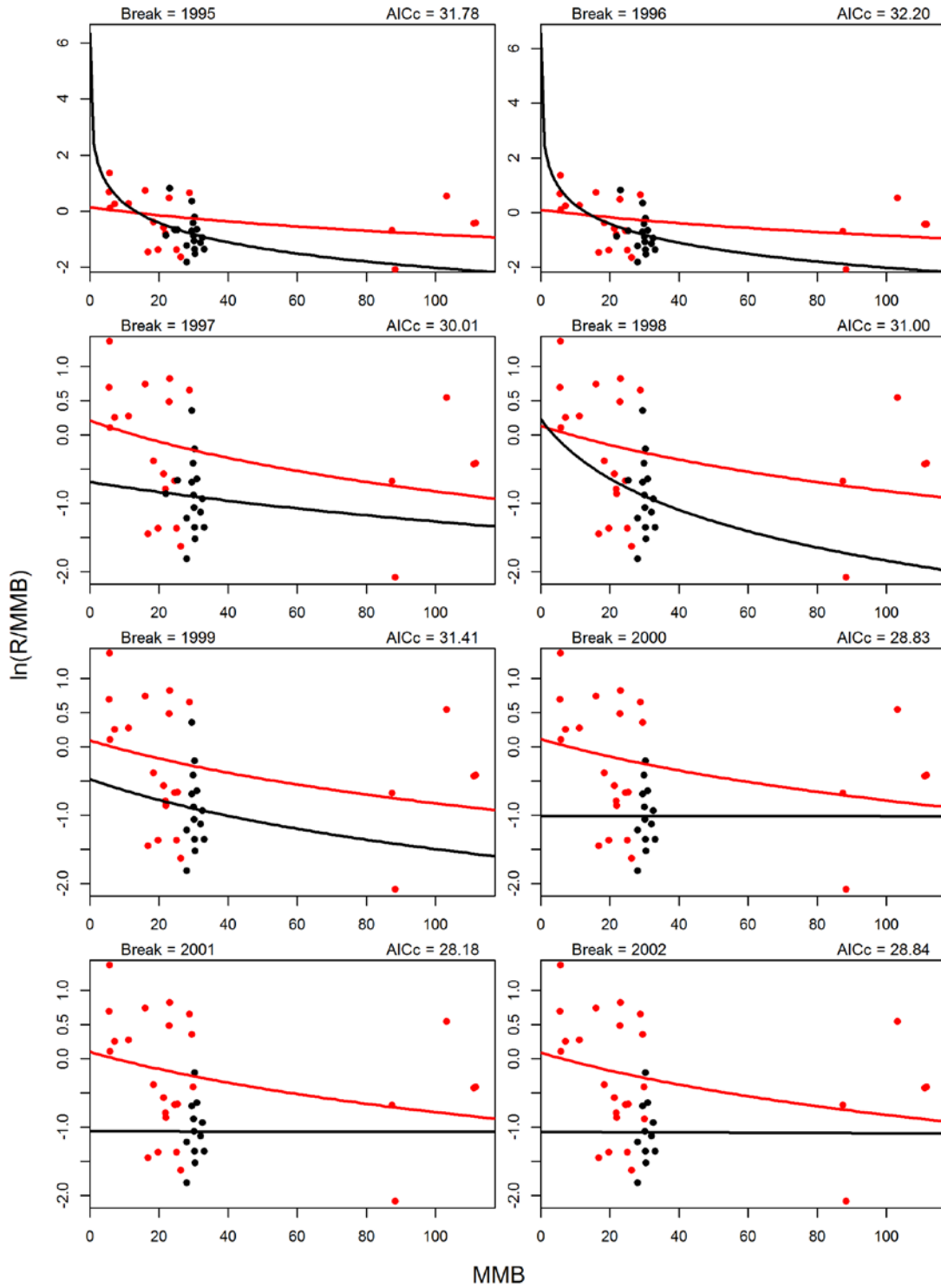
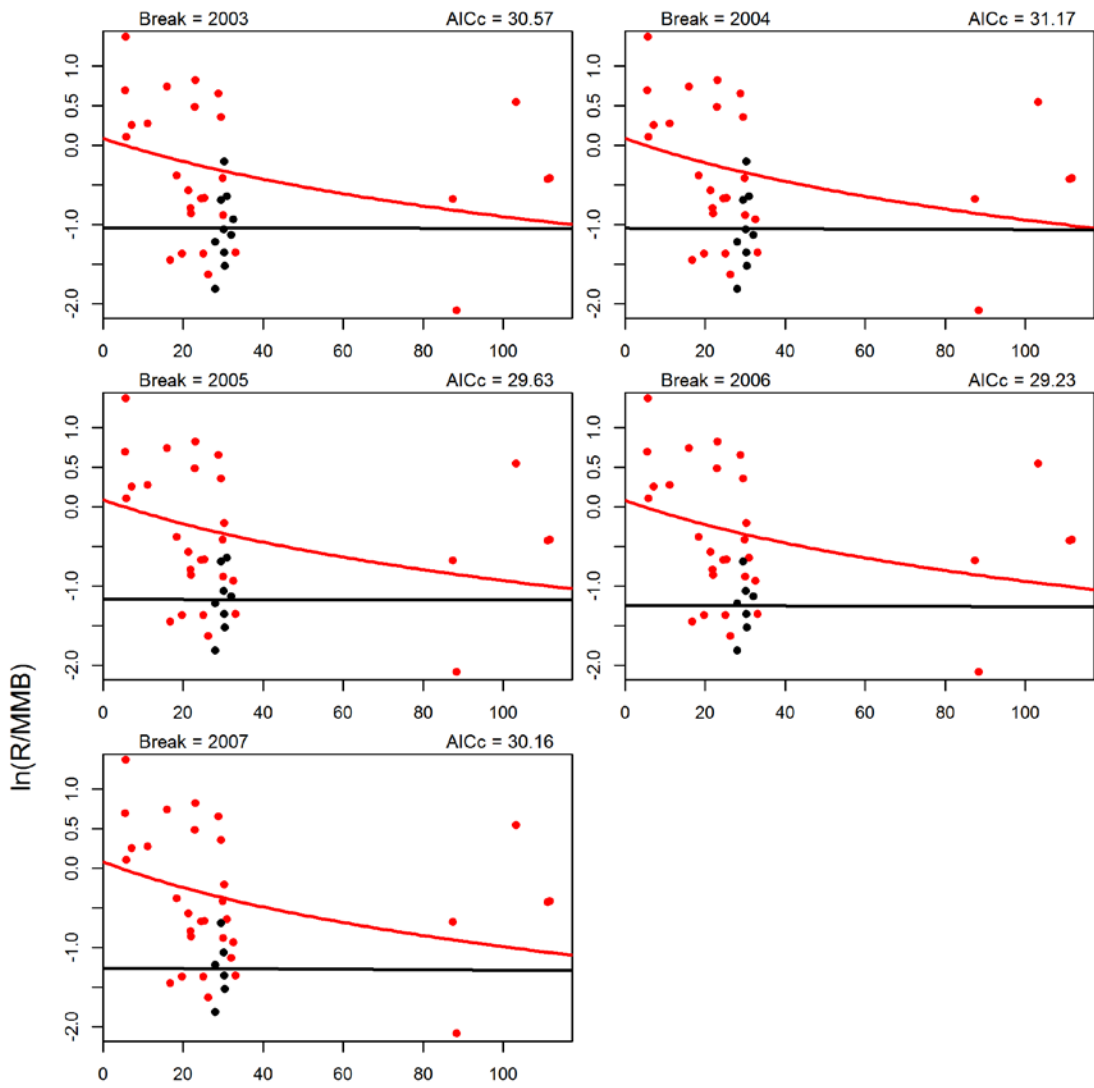


Figure B5. Continue.



MMB

Figure B5. Continue.

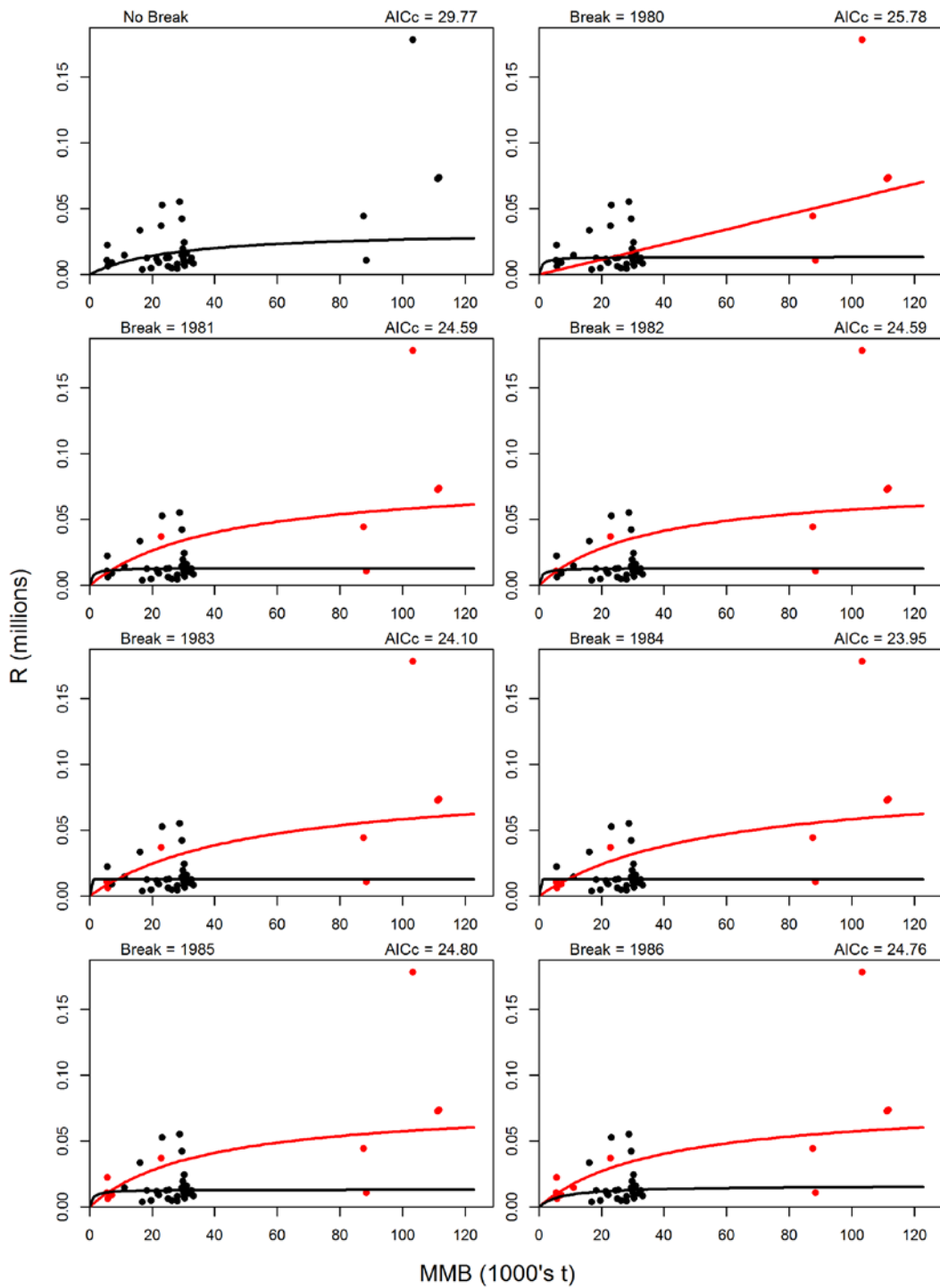


Figure B6. Fits on the arithmetic scale for B-H models with no breakpoint (upper left graph) and with 1-breakpoint for break years 1975-2007. For 1-breakpoint models, the pre-break data (circles) and model fit (line) are shown in red, whereas the post-break data and fit are shown in black.

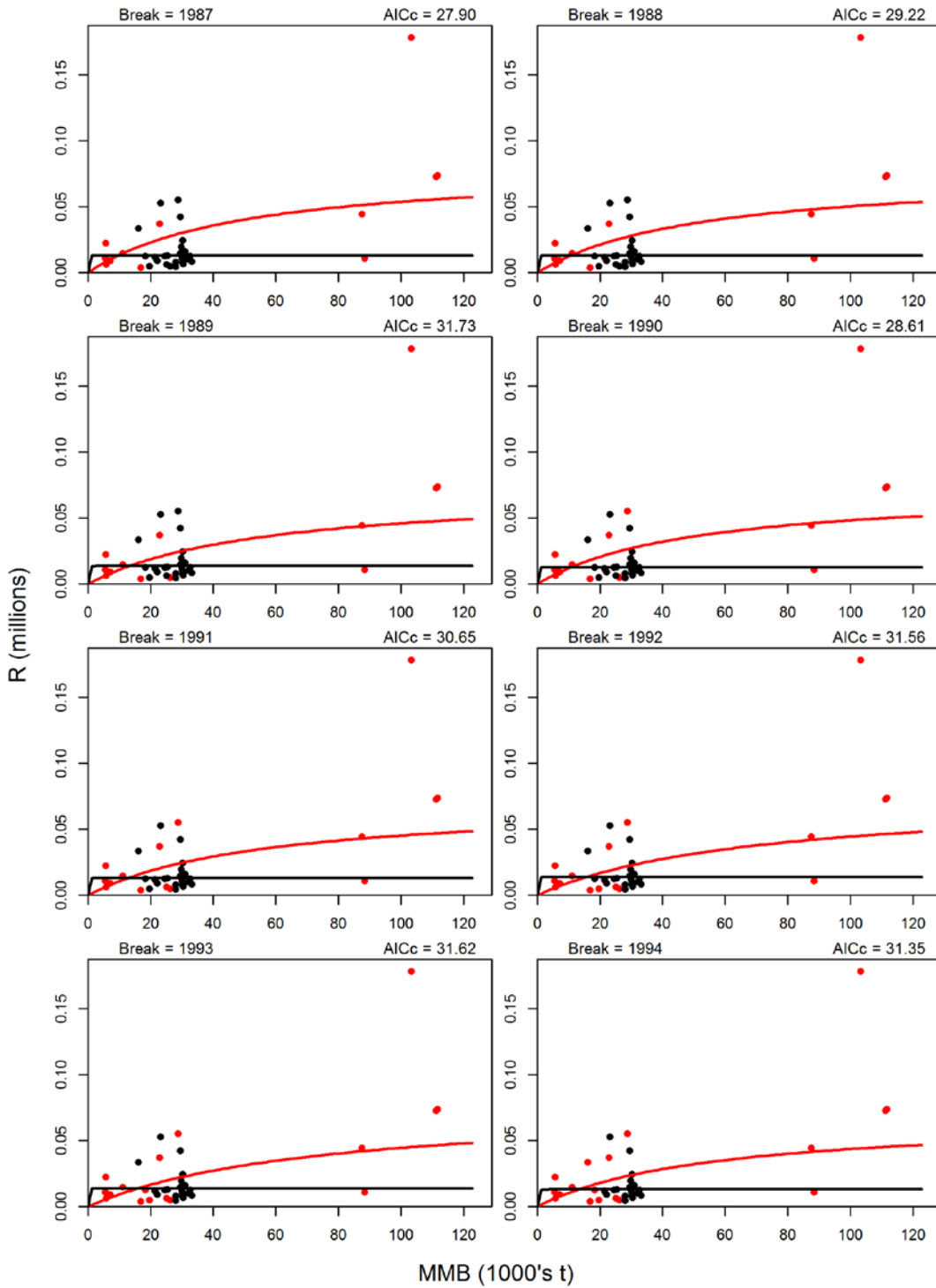


Figure B6. Continue.

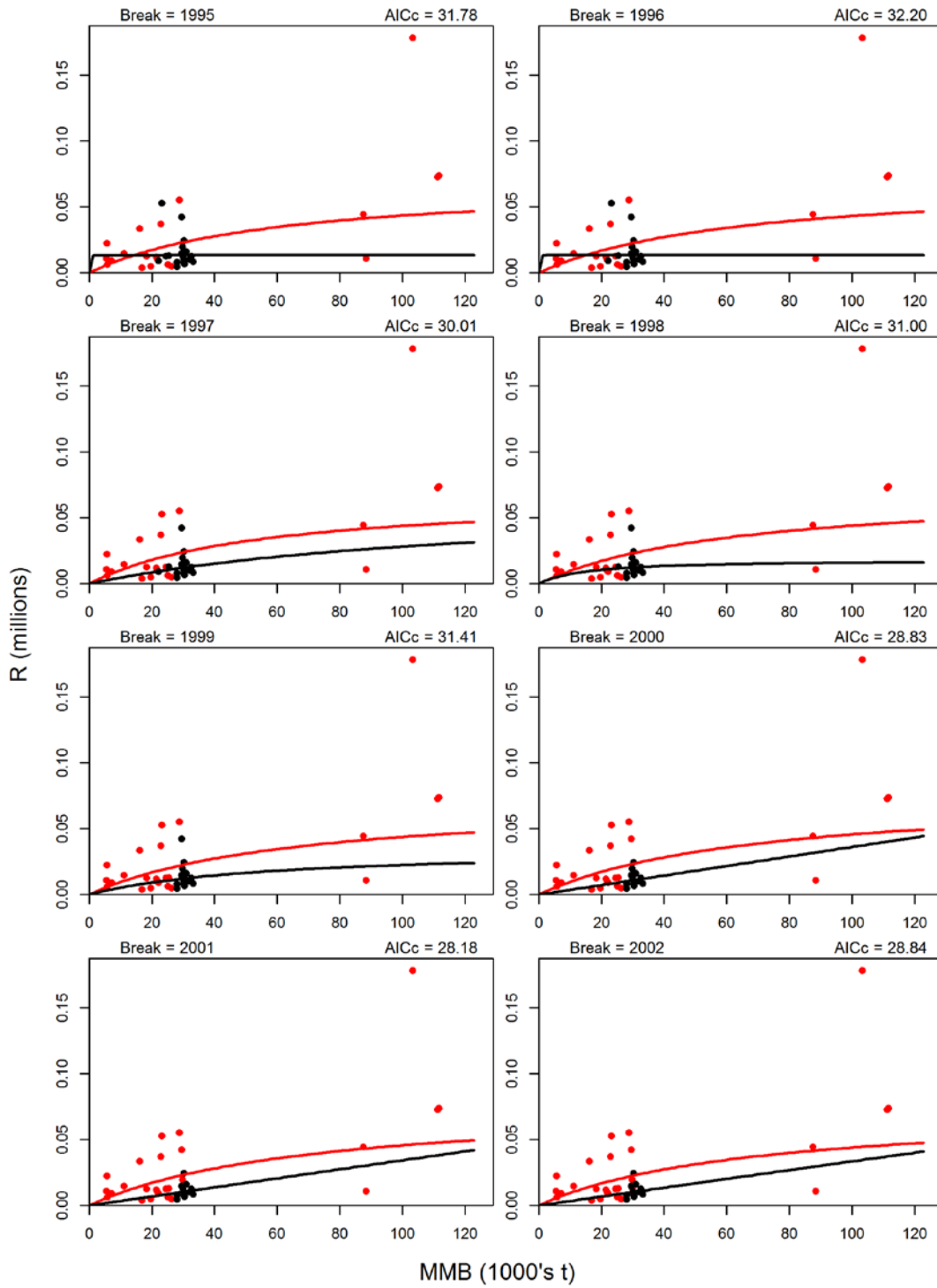
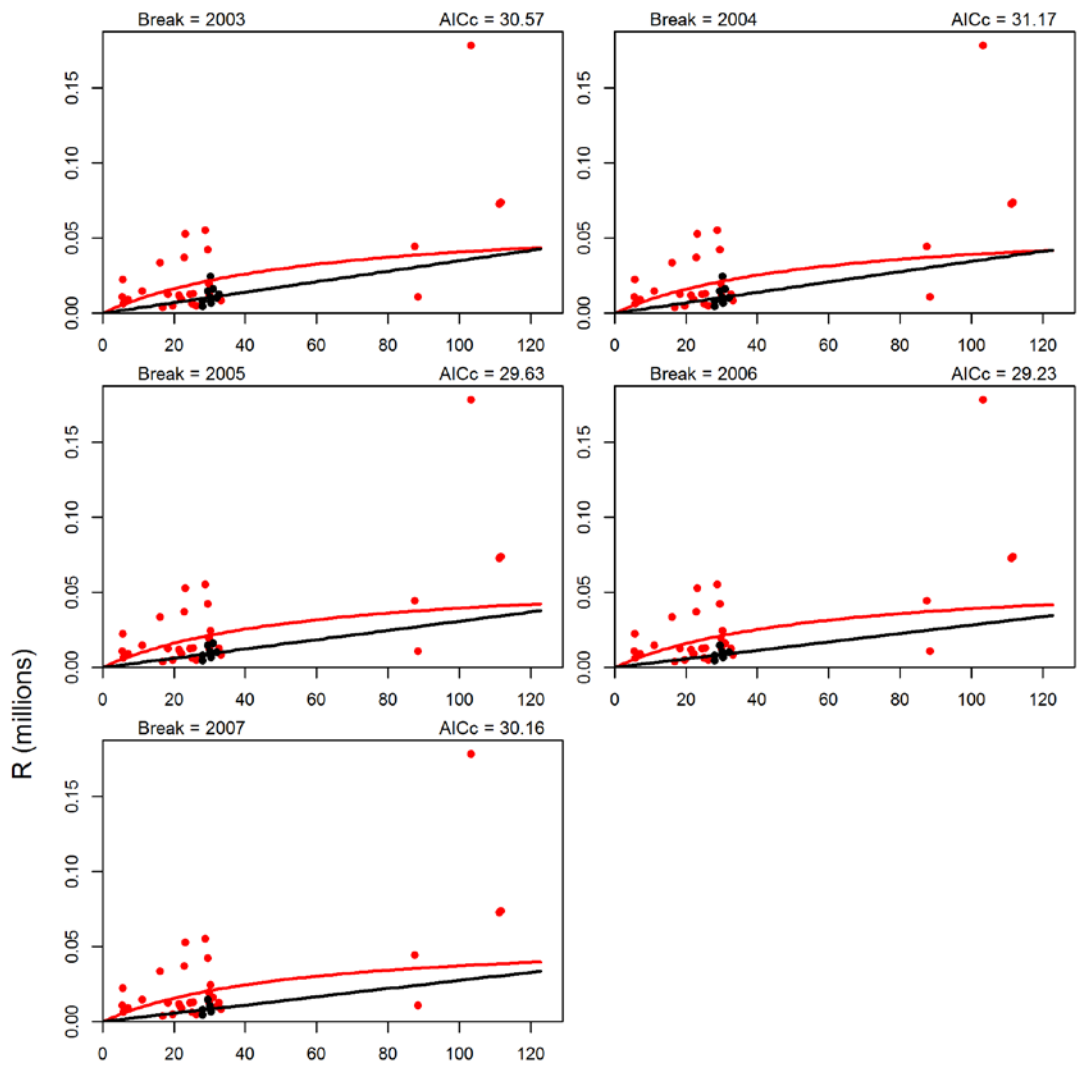


Figure B6. Continue.



MMB (1000's t)

Figure B6. Continue.

Appendix C. Simple B0 Analysis

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

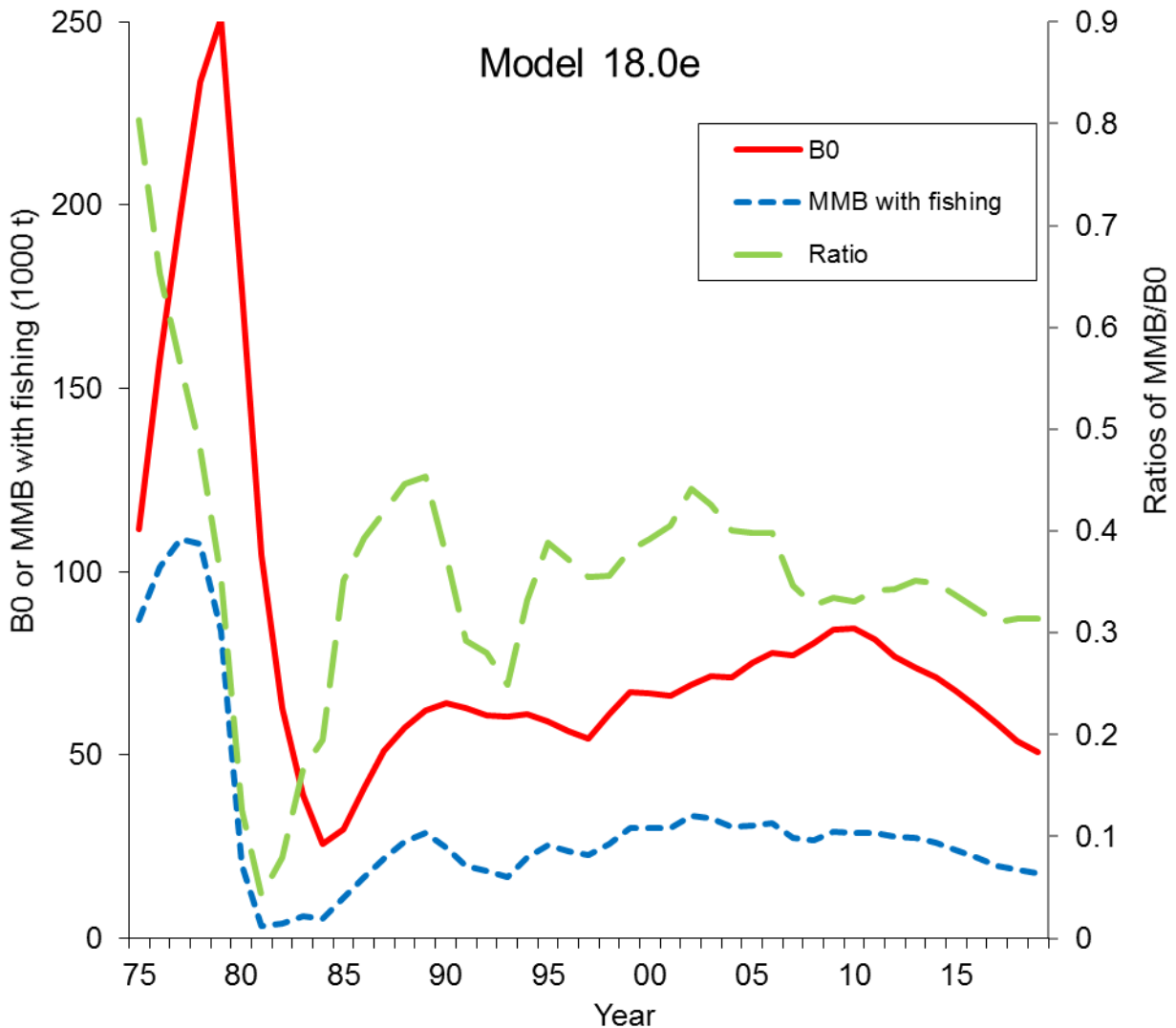


Figure C1. Estimated B0, MMB with fishing, and ratios of MMB/B0 from 1975 to 2019 for model 18.0e for Bristol Bay red king crab.

Appendix D. Control File for Model 19.0 (GMACS)

```

##                                     ##
## LEADING PARAMETER CONTROLS                                     ##
## Controls for leading parameter vector (theta)                 ##
## LEGEND                                                         ##
## prior: 0 = uniform, 1 = normal, 2 = lognormal, 3 = beta, 4 = gamma ##
##                                                                 ##
## ntheta
91
## ----- ##
## ival   lb   ub   phz  prior  p1   p2   # parameter  ##
## ----- ##
0.18   0.15  0.2   -4   2   0.18  0.04   # M
0.18   0.15  0.2   -4   2   0.18  0.04   # M
16.5  -10   18   -2   0  -10.0  20.0   # logR0
19.5  -10   25   3    0  10.0  25.0   # logRini, to estimate if NOT initialized at unfished (n68)
16.5  -10   25   1    0  10.0  20.0 #1   # logRbar, to estimate if NOT initialized at unfished #1
72.5  55   100  -4   1  72.5  7.25   # recruitment expected value (males or combined)
0.726149 0.32  1.64  3    0  0.1   5.0   # recruitment scale (variance component) (males or combined)
0.00   -5    5    -4   0  0.0   20.00  # recruitment expected value (females)
0.00  -1.69  0.40  3    0  0.0   20.0   # recruitment scale (variance component) (females)
-0.10536 -10   0.75  -4   0  -10.0  0.75   # ln(sigma_R)
0.75   0.20  1.00  -2   3   3.0   2.00   # steepness
0.01   0.00  1.00  -3   3   1.01  1.01   # recruitment autocorrelation
# 0.00  -10   4    2    0  10.0  20.00  # Deviation for size-class 1 (normalization class)
1.107962885630 -10   4    9    0  10.0  20.00  # Deviation for size-class 2
0.563229168219 -10   4    9    0  10.0  20.00  # Deviation for size-class 3
0.681928313426 -10   4    9    0  10.0  20.00  # Deviation for size-class 4
0.491057364532 -10   4    9    0  10.0  20.00  # Deviation for size-class 5
0.407911777560 -10   4    9    0  10.0  20.00  # Deviation for size-class 6
0.436516142684 -10   4    9    0  10.0  20.00  # Deviation for size-class 7
0.40612675395550 -10   4    9    0  10.0  20.00  # Deviation for size-class 8
0.436145974880 -10   4    9    0  10.0  20.00  # Deviation for size-class 9
0.40494522852708 -10   4    9    0  10.0  20.00  # Deviation for size-class 10
0.30401970466854 -10   4    9    0  10.0  20.00  # Deviation for size-class 11
0.2973752673022 -10   4    9    0  10.0  20.00  # Deviation for size-class 12
0.1746800712364 -10   4    9    0  10.0  20.00  # Deviation for size-class 13
0.0845298456942 -10   4    9    0  10.0  20.00  # Deviation for size-class 14
0.0107462399193 -10   4    9    0  10.0  20.00  # Deviation for size-class 15
-0.190468322904 -10   4    9    0  10.0  20.00  # Deviation for size-class 16
-0.376312503735 -10   4    9    0  10.0  20.00  # Deviation for size-class 17
-0.699162895473 -10   4    9    0  10.0  20.00  # Deviation for size-class 18
-1.15881771530 -10   4    9    0  10.0  20.00  # Deviation for size-class 19
-1.17311583316 -10   4    9    0  10.0  20.00  # Deviation for size-class 20
-100.00 -101  5    -2   0  10.0  20.00  # Deviation for size-class 1
-100.00 -101  5    -2   0  10.0  20.00  # Deviation for size-class 2
-100.00 -101  5    -2   0  10.0  20.00  # Deviation for size-class 3
-100.00 -101  5    -2   0  10.0  20.00  # Deviation for size-class 4
-100.00 -101  5    -2   0  10.0  20.00  # Deviation for size-class 5
-100.00 -101  5    -2   0  10.0  20.00  # Deviation for size-class 6
-100.00 -101  5    -2   0  10.0  20.00  # Deviation for size-class 7
-100.00 -101  5    -2   0  10.0  20.00  # Deviation for size-class 8

```

-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 9
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 10
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 11
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 12
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 13
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 14
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 15
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 16
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 17
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 18
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 19
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 20
0.425704202053	-10	4	9	0	10.0	20.00	# Deviation for size-class 1
2.268408592660	-10	4	9	0	10.0	20.00	# Deviation for size-class 2
1.810451373080	-10	4	9	0	10.0	20.00	# Deviation for size-class 3
1.37035725111	-10	4	9	0	10.0	20.00	# Deviation for size-class 4
1.158258087990	-10	4	9	0	10.0	20.00	# Deviation for size-class 5
0.596196784439	-10	4	9	0	10.0	20.00	# Deviation for size-class 6
0.225756761257	-10	4	9	0	10.0	20.00	# Deviation for size-class 7
-0.0247857565368	-10	4	9	0	10.0	20.00	# Deviation for size-class 8
-0.214045895269	-10	4	9	0	10.0	20.00	# Deviation for size-class 9
-0.560539577780	-10	4	9	0	10.0	20.00	# Deviation for size-class 10
-0.974218300021	-10	4	9	0	10.0	20.00	# Deviation for size-class 11
-1.24580072031	-10	4	9	0	10.0	20.00	# Deviation for size-class 12
-1.49292897450	-10	4	9	0	10.0	20.00	# Deviation for size-class 13
-1.94135821253	-10	4	9	0	10.0	20.00	# Deviation for size-class 14
-2.05101560679	-10	4	9	0	10.0	20.00	# Deviation for size-class 15
-1.94956606430	-10	4	9	0	10.0	20.00	# Deviation for size-class 16
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 17
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 18
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 19
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 20
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 1
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 2
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 3
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 4
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 5
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 6
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 7
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 8
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 9
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 10
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 11
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 12
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 13
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 14
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 15
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 16
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 17
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 18
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 19
-100.00	-101	5	-2	0	10.0	20.00	# Deviation for size-class 20

```

# Use custom natural mortality (0=no, 1=yes, by sex and year)
0
# weight-at-length input method (1 = allometry [w_1 = a*I^b], 2 = vector by sex)
2
## Males
0.000224781 0.000281351 0.000346923 0.000422209 0.000507927 0.000604802 0.000713564
0.00083495 0.0009697 0.00111856 0.00128229 0.00146163 0.00165736
0.00187023 0.00210101 0.00235048 0.00261942 0.00290861 0.00321882
0.0039059
## Females
0.0002151 0.00026898 0.00033137 0.00040294 0.00048437 0.00062711 0.0007216
0.00082452 0.00093615 0.00105678 0.00118669 0.00132613 0.00147539
0.00163473 0.00180441 0.00218315 0.00218315 0.00218315 0.00218315
0.0021831
# Proportion mature by sex
0 0 0 0 0 0 0 0 0 0 0 1 1
1 1 1 1 1 1 1 1 1 1 1 1 1
0 0 0 0 0 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1 1 1 1
# Proportion legal by sex
0 0 0 0 0 0 0 0 0 0 0 1 1
1 1 1 1 1 1 1 1 1 1 1 1 1
0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0
## ----- ##
## ----- ##
## GROWTH PARAMETER CONTROLS ##
## Two lines for each parameter if split sex, one line if not ##
## ----- ##
# Use growth transition matrix option (1=read in growth-increment matrix; 2=read in size-transition; 3=gamma
distribution for size-increment; 4=gamma distribution for size after increment)
3
# growth increment model (1=alpha/beta; 2=estimated by size-class;3=pre-specified/emprical)
3
# molt probability function (0=pre-specified; 1=flat;2=declining logistic)
2
# maximum size-class (males then females)
20 16
# Maximum size-class for recruitment(males then females)
7 5
## number of size-increment periods
1 3
## Year(s) size-incremnt period changes (blank if no changes)
1983 1994
## number of molt periods
2 2
## Year(s) molt period changes (blank if no changes)
1980 1980
## Beta parameters are relative (1=Yes;0=no)
1
## ----- ##

```

##	ival	lb	ub	phz	prior	p1	p2	# parameter	##
16.5		0	20	-33	0	0	0	999	# Males
16.5		0	20	-33	0	0	0	999	# Males
16.4		0	20	-33	0	0	0	999	# Males
16.3		0	20	-33	0	0	0	999	# Males
16.3		0	20	-33	0	0	0	999	# Males
16.2		0	20	-33	0	0	0	999	# Males
16.2		0	20	-33	0	0	0	999	# Males
16.1		0	20	-33	0	0	0	999	# Males
16.1		0	20	-33	0	0	0	999	# Males
16		0	20	-33	0	0	0	999	# Males
16		0	20	-33	0	0	0	999	# Males
15.9		0	20	-33	0	0	0	999	# Males
15.8		0	20	-33	0	0	0	999	# Males
15.8		0	20	-33	0	0	0	999	# Males
15.7		0	20	-33	0	0	0	999	# Males
15.7		0	20	-33	0	0	0	999	# Males
15.6		0	20	-33	0	0	0	999	# Males
15.6		0	20	-33	0	0	0	999	# Males
15.5		0	20	-33	0	0	0	999	# Males
15.5		0	20	-33	0	0	0	999	# Males
#1.38403	0.5	3.7	7	0	0	0	0	999	# Males (beta)
1.0	0.5	3.0	6	0	0	999	# Males (beta)		
13.8		0	20	-33	0	0	0	999	# Females
12.2		0	20	-33	0	0	0	999	# Females
10.5		0	20	-33	0	0	0	999	# Females
8.4		0	20	-33	0	0	0	999	# Females
7.5		0	20	-33	0	0	0	999	# Females
7		0	20	-33	0	0	0	999	# Females
6.6		0	20	-33	0	0	0	999	# Females
6.1		0	20	-33	0	0	0	999	# Females
5.6		0	20	-33	0	0	0	999	# Females
5.1		0	20	-33	0	0	0	999	# Females
4.6		0	20	-33	0	0	0	999	# Females
4.1		0	20	-33	0	0	0	999	# Females
3.6		0	20	-33	0	0	0	999	# Females
3.2		0	20	-33	0	0	0	999	# Females
2.7		0	20	-33	0	0	0	999	# Females
2.2		0	20	-33	0	0	0	999	# Females
1.7		0	20	-33	0	0	0	999	# Females
1.2		0	20	-33	0	0	0	999	# Females
0.7		0	20	-33	0	0	0	999	# Females
0.4		0	20	-33	0	0	0	999	# Females
#1.38403	0.5	3.0	7	0	0	0	0	999	# Females (beta)
1.5	0.5	3.0	6	0	0	999	# Females (beta)		
15.4		0	20	-33	0	0	0	999	# Females
13.8		0	20	-33	0	0	0	999	# Females
12.2		0	20	-33	0	0	0	999	# Females
10.5		0	20	-33	0	0	0	999	# Females
8.9		0	20	-33	0	0	0	999	# Females
7.9		0	20	-33	0	0	0	999	# Females
7.2		0	20	-33	0	0	0	999	# Females


```

300.0000  5.  500.0  -4  0  0.0  999.0  # molt_mu females (molt every year)
0.01      0.001  9.0  -4  0  0.0  999.0  # molt_cv females (molt every year)
## ----- ##
# The custom growth-increment matrix
# custom molt probability matrix
## ----- ##
## SELECTIVITY CONTROLS ##
## Selectivity P(capture of all sizes). Each gear must have a selectivity and a ##
## retention selectivity. If a uniform prior is selected for a parameter then the ##
## lb and ub are used (p1 and p2 are ignored) ##
## LEGEND ##
## sel type: 0 = parametric, 1 = coefficients (NIY), 2 = logistic, 3 = logistic95, ##
## 4 = double normal (NIY) ##
## gear index: use +ve for selectivity, -ve for retention ##
## sex dep: 0 for sex-independent, 1 for sex-dependent ##
## ----- ##
## Gear-1 Gear-2 Gear-3 Gear-4 Gear-5 Gear-6
## PotFshry TrawlByc TCFshry FixedGr NMFS BSFRF
1 1 1 1 2 1 # selectivity periods
1 0 1 0 1 1 # sex specific selectivity
2 2 2 2 2 2 # male selectivity type
2 2 2 2 2 2 # female selectivity type
0 0 0 0 6 0 #6 # within another gear
## Gear-1 Gear-2 Gear-3 Gear-4 Gear-5 Gear-6
2 1 1 1 1 1 # retention periods
1 0 0 0 0 0 # sex specific retention
2 6 6 6 6 6 # male retention type
6 6 6 6 6 6 # female retention type
1 0 0 0 0 0 # male retention flag (0 = no, 1 = yes)
0 0 0 0 0 0 # female retention flag (0 = no, 1 = yes)

## ----- ##
## gear par sel start end ##
## index index par sex ival lb ub prior p1 p2 phz period period ##
## ----- ##
# Gear-1
1 1 1 1 125.0000 5 190 0 1 999 4 1975 2018 #4
1 2 2 1 8.0 0.1 20 0 1 999 4 1975 2018 #4
1 3 1 2 84.00 5 150 0 1 999 4 1975 2018
1 4 2 2 4.0000 0.1 20 0 1 999 4 1975 2018
# Gear-2
2 5 1 0 165.0 5 190 0 1 999 4 1975 2018
2 6 2 0 15.0000 0.1 25 0 1 999 4 1975 2018
# Gear-3-
3 7 1 1 115.0 5 190 0 1 999 4 1975 2018
3 8 2 1 15.0 0.1 25 0 1 999 4 1975 2018
3 9 1 2 95.0 5 190 0 1 999 4 1975 2018
3 10 2 2 2.5 0.1 25 0 1 999 4 1975 2018
# Gear-4
4 11 1 0 115.0 5 190 0 1 999 4 1975 2018
4 12 2 0 9.0 0.1 25 0 1 999 4 1975 2018
# Gear-5
5 13 1 1 75.0 30 190 0 1 999 5 1975 1981 #5

```

```

5 14 2 1 5.0 1 50 0 1 999 5 1975 1981 #5
5 15 1 1 80.0 30 190 0 1 999 5 1982 2019 #5
5 16 2 1 10.0 1 50 0 1 999 5 1982 2019 #5
5 17 1 2 70.0 30 180 0 1 999 5 1975 1981 #5
5 18 2 2 9.0 1 50 0 1 999 5 1975 1981 #5
5 19 1 2 70.0 30 180 0 1 999 5 1982 2019 #5
5 20 2 2 4.00 1.0 50 0 1 999 5 1982 2019 #5
# Gear-6
6 21 1 1 75.0 1 180 0 1 999 5 1975 2019 #5
6 22 2 1 8.5 1 50 0 1 999 5 1975 2019 #5
6 23 1 2 85.0 1 180 0 1 999 5 1975 2019 #5
6 24 2 2 10.0 1 50 0 1 999 5 1975 2019 #5
##-----##
## Retained ##
## gear par sel start end ##
## index index par sex ival lb ub prior p1 p2 phz period period ##
##-----##
# Gear-1
-1 25 1 1 135 1 999 0 1 999 4 1975 2004
-1 26 2 1 2.0 1 20 0 1 999 4 1975 2004
-1 27 1 1 140 1 999 0 1 999 4 2005 2018
-1 28 2 1 2.5 1 20 0 1 999 4 2005 2018
-1 29 1 2 591 1 999 0 1 999 -3 1975 2003
-1 30 1 2 591 1 999 0 1 999 -3 2004 2018
# Gear-2
-2 31 1 0 595 1 999 0 1 999 -3 1975 2018
# Gear-3
-3 32 1 0 595 1 999 0 1 999 -3 1975 2018
# Gear-4
-4 33 1 0 595 1 999 0 1 999 -3 1975 2018
# Gear-5
-5 34 1 0 590 1 999 0 1 999 -3 1975 2019
# Gear-6
-6 35 1 0 580 1 999 0 1 999 -3 1975 2019
##-----##
# Number of asymptotic parameters
1
# Fleet Sex Year ival lb ub phz
# 1 1 1975 0.000001 0 1 -3
# 1 1 2006 0.044000 0 1 -3
# 1 1 2007 0.019700 0 1 -3
# 1 1 2008 0.019875 0 1 -3
# 1 1 2009 0.032750 0 1 -3
# 1 1 2010 0.015320 0 1 -3
# 1 1 2011 0.011250 0 1 -3
# 1 1 2012 0.024045 0 1 -3
# 1 1 2013 0.063200 0 1 -3
# 1 1 2014 0.160500 0 1 -3
# 1 1 2015 0.070950 0 1 -3
# 1 1 2016 0.082600 0 1 -3

```



```

## ----- ##
## PRIORS FOR CATCHABILITY
## If a uniform prior is selected for a parameter then the lb and ub are used (p1 ##
## and p2 are ignored). ival must be > 0 ##
## LEGEND ##
## prior: 0 = uniform, 1 = normal, 2 = lognormal, 3 = beta, 4 = gamma ##
## ----- ##
## ival lb ub phz prior p1 p2 Analytic? LAMBDA Emphasis
0.896 0 2 6 1 0.896 0.03 0 1 1
1.0 0 5 -6 0 0.001 5.00 0 1 1 # BSFRF
## ----- ##
## ----- ##
## ADDITIONAL CV FOR SURVEYS/INDICES ##
## If a uniform prior is selected for a parameter then the lb and ub are used (p1 ##
## and p2 are ignored). ival must be > 0 ##
## LEGEND ##
## prior type: 0 = uniform, 1 = normal, 2 = lognormal, 3 = beta, 4 = gamma ##
## ----- ##
## ival lb ub phz prior p1 p2
0.0001 0.00001 10.0 -4 4 1.0 100 # NMFS
0.25 0.00001 10.0 9 0 0.001 1.00 # BSFRF
## ----- ##
## ----- ##
## PENALTIES FOR AVERAGE FISHING MORTALITY RATE FOR EACH GEAR ##
## ----- ##
## Mean_F Female Offset STD_PHZ1 STD_PHZ2 PHZ_M PHZ_F
0.22313 0.0505 0.5 45.50 1 1 # Pot
0.0183156 1.0 0.5 45.50 1 -1 # Trawl
0.011109 1.0 0.5 45.50 1 1 # Tanner (-1 -5)
0.011109 1.0 0.5 45.50 1 -1 # Fixed
0.00 0.0 2.00 20.00 -1 -1 # NMFS trawl survey (0 catch)
0.00 0.0 2.00 20.00 -1 -1 # BSFRF (0)
2.95 # Upper bound value for male directed fishig mortality deviations
## ----- ##
## ----- ##
## OPTIONS FOR SIZE COMPOSTION DATA ##
## One column for each data matrix ##
## LEGEND ##
## Likelihood: 1 = Multinomial with estimated/fixed sample size ##
## 2 = Robust approximation to multinomial ##
## 3 = logistic normal (NIY) ##
## 4 = multivariate-t (NIY) ##
## 5 = Dirichlet ##
## AUTO TAIL COMPRESSION ##
## pmin is the cumulative proportion used in tail compression ##
## ----- ##
# Pot Trawl Tanner Fixed NMFS BSFRF
2 2 2 2 2 2 2 2 2 2 2 2 2 # Type of likelihood
0 0 0 0 0 0 0 0 0 0 0 0 0 # Auto tail compression (pmin)
1 1 1 1 1 1 1 1 1 1 1 1 1 # Initial value for effective sample size multiplier
-4 -4 -4 -4 -4 -4 -4 -4 -4 -4 -4 -4 -4 # Phz for estimating effective sample size (if appl.)
1 2 3 4 4 5 5 6 6 7 7 8 8 # Composition aggregator
1 1 1 1 1 1 1 1 1 1 1 1 1 # LAMBDA

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1 1 1 1 1 1 1 1 1 1 1 1 1 # Emphasis AEP
## _____ ##
## _____ ##
## TIME VARYING NATURAL MORTALITY RATES ##
## LEGEND ##
## Type: 0 = constant natural mortality ##
## 1 = Random walk (deviates constrained by variance in M) ##
## 2 = Cubic Spline (deviates constrained by nodes & node-placement) ##
## 3 = Blocked changes (deviates constrained by variance at specific knots) ##
## 4 = Time blocks ##
## _____ ##
## Type
6
## M is relative (YES=1; NO=0)
0
## Phase of estimation
3
## STDEV in m_dev for Random walk
0.25
## Number of nodes for cubic spline or number of step-changes for option 3
2
4
## Year position of the knots (vector must be equal to the number of nodes)
1980 1985
1976 1980 1985 1994
# number of breakpoints in M by size
0
## Specific initial values for the natural mortality devs (0=no, 1=yes)
1
## _____ ##
## ival lb ub phz extra prior p1 p2 # parameter ##
## _____ ##
1.5342575 0 2 8 0
0.000000 -2 2 -99 0
0.262792 0 2 8 0
1.780586 0 2 8 0
9.262792 0 2 8 -3
0.000000 -2 2 -99 0
## _____ ##
## _____ ##
## OTHER CONTROLS
## _____ ##
1975 # First rec_dev
2018 # last rec_dev
2 # Estimated rec_dev phase
-3 # Estimated rec_ini phase
1 # VERBOSE FLAG (0 = off, 1 = on, 2 = objective func; 3 diagnostics)
3 # Initial conditions (0 = Unfished, 1 = Steady-state fished, 2 = Free parameters, 3 = Free parameters (revised))
1 # Lambda (proportion of mature male biomass for SPR reference points).
0 # Stock-Recruit-Relationship (0 = none, 1 = Beverton-Holt)
10 # Maximum phase (stop the estimation after this phase).
-1 # Maximum number of function calls

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## ----- ##
## EMPHASIS FACTORS (CATCH)
## ----- ##
#Ret_male Disc_male Disc_female Disc_trawl Disc_Tanner_male Disc_Tanner_female Disc_fixed
   1     1     1     1         1         1     1
## ----- ##
## EMPHASIS FACTORS (Priors)
## ----- ##
# Log_fdevs  meanF    Mdevs Rec_devs Initial_devs Fst_dif_dev Mean_sex-Ratio
  10000     0      1.0     2         0         0         1
## EOF
9999

```