Appendix A. Recruitment Breakpoint Analysis

Introduction

In 2018 SMBKC was declared overfished and a rebuilding plan was put into motion. On examination, it was clear that recruitment for SMBKC has been consistently lower in recent years. Thus, the crab Plan Team requested that the authors conduct a recruitment breakpoint analysis similar to that conducted for Bristol Bay red king crab in 2017 (Zheng et al. 2017) and eastern Bering Sea Tanner crab in 2013 (Stockhausen 2013). The R code based on these studies was adapted for this study (Jie Zheng, Buck Stockhausen pers. Comm.). The goal of this analysis was to objectively identify a change in stock productivity based on the recruitment time series. This could then be used to develop alternative rebuilding scenarios and also provide alternative B_{MSY} proxies. Results from assessment model 3 from 2018 (Ianelli and Zheng 2018) were used for this analysis.

Methods

The methods were the same as used for BBKRC (Zheng et al. 2017) which followed 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 $y_t = \ln(R/MMB)$ as estimated directly from the stock assessment model and fit externally to stock-recruitment relationships (with predictions as $\hat{y}_t$). For the Ricker stock-recruitment models,

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

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

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

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

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

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

where Ω contains observation and process error as

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

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

For each candidate breakpoint year b, the negative log likelihood value of equation (3) was minimized with respect to the six model parameters: α_1, β_1, α_2, β_2, $\ln(\sigma)$ and $\tan(\rho)$. The minimum time span considered as a potential regime was 5 years. Each brood year from 1983 to 2005 was evaluated as a potential breakpoint b using time series of ln(R/MMB) and MMB for brood years 1978-2010. A model with no breakpoint was also evaluated. Models with different breakpoints were then ranked using AICc (AIC corrected for small sample size; Burnham and Anderson 2004),

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

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

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

Results

Results are summarized in Tables A1-A4 and Figures A1-A6. Both Ricker and Beverton-Holt (B-H) models resulted in the same breakpoint brood year of 1989, which corresponded to recruitment year of 1996. The model without a breakpoint (i.e., a single period) was about 26 times less probable than the 1989 breakpoint model for the Ricker stock-recruitment relationship and 4 times less probable than the Beverton-Holt, which suggested a possible change in stock productivity from the early high period to the recent low period. Alternative breakpoint brood years of 1984-1988 for the Ricker model and of 1990 for Beverton-Holt model were also reasonably reported with relative odds less than 10.

Both Ricker and Beverton-Holt stock-recruitment models fitted the data poorly. Additionally, the fit to the breakpoint group with fewer data points was extremely poor for both models, especially the Ricker model. For example, the Ricker model with a breakpoint year of 1983 (Figure A1) fits the larger data group well (black line) but the fit to the smaller data group (red line) is poor, with an estimated intercept (α_1) that appears to be lower than the expected fit. This was the case for all breakpoint years with the data group (pre or post breakpoint) that had fewer data points. A sensitivity analysis was performed to determine the source of this lack of fit for both the Ricker and B-H models. For the Ricker model a breakpoint analysis that produced two independent regression (where the covariance matrix and ρ were set to 0) produced model fits that fit both data groups well, additionally this analysis produced the same breakpoint year of 1989, but suggested that 1990 was also a possibility. The poor model fit is primarily due to covariance and estimation of ρ in the analysis. The same analysis with the B-H model was performed but only the Ricker results are presented here for simplicity (Figures A8-A10).

Sensitivity analyses suggest that error within the model, specifically autocorrelation (ρ), produce poor fits to the stock-recruit relationships when the sample size for the data set is low. However, the resulting breakpoint year is still the same, suggesting strong evidence for a brood year breakpoint in 1989. The only other likely breakpoint year is 1990, with relative odds < 2 compared to 1989. These breakpoint brood years would produce breaks in recruitment in either 1996 or 1997.

Discussion

A recruitment breakpoint analysis was conducted on St Matthews blue king crab by Punt et al. (2014) with data from 1978 to 2010 to estimate a breakpoint brood year of 1993, corresponding to recruitment year of 1998, but this model used a 5-year lag and incorporated smaller size classes (20 - 90mm) than the current assessment model. The projections for recruitment from the Punt et al. (2014) model are substantially higher in the late 2000s than the current assessment model, which would greatly influence the breakpoint analysis results. The different time series of data may also explain the differences; however, both suggest a break in recruitment in the mid to late 1990s.

Time series of estimated mature male biomass during 1978-2017 (the entire time series) has been used to compute a B_{MSY} proxy. Using the 2018 assessment model the B_{MSY} proxy for 2018 is 3,478 t. The B_{MSY} proxy for the recent recruitment period (based on the break point analysis; 1996-2017) using the same model is 2,030 t (Table A5). The is approximately a 42% reduction (Figure A7). If the estimated breakpoint year is used to set the new recruitment time series, the estimated B_{MSY} 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 A1. 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. Years are brood year.

Year	AICc	Odds
NA	1.474	26.124
1983	-0.187	11.384
1984	-1.498	5.913
1985	-0.975	7.679
1986	-1.449	6.059
1987	-1.141	7.066
1988	-1.784	5.124
1989	-5.052	1.000
1990	0.141	13.413
1991	2.586	45.564
1992	4.658	128.335
1993	4.621	125.992
1994	2.479	43.172
1995	5.339	180.461
1996	5.266	173.990
1997	4.137	98.931
1998	4.950	148.548
1999	7.258	471.115
2000	7.234	465.383
2001	5.509	196.408
2002	6.186	275.605
2003	4.537	120.830
2004	2.989	55.723
2005	6.716	359.120

Table A2. Parameter estimates and standard deviations for the Ricker stock-recruitment model with no breakpoint (first row) and the single breakpoint models (by year of breakpoint). The "best" model is shaded. Years are brood year.

Year	α_1	std.dev.	α_2	std.dev.	β_1	std.dev.	β_2	std.dev.	ln(σ)	std.dev.	tan(ρ)	std.dev.
			5.488	0.624			0.155	0.068	-0.099	0.373	6.493	5.311
1983	4.456	1.224	6.770	1.096	0.062	0.078	0.546	0.127	0.180	0.610	22.813	29.838
1984	4.834	0.989	6.862	0.970	0.080	0.058	0.632	0.138	0.064	0.570	20.324	24.984
1985	5.199	0.845	6.764	0.859	0.100	0.054	0.634	0.142	-0.044	0.523	15.556	17.804
1986	5.510	0.743	6.615	0.764	0.104	0.055	0.617	0.149	-0.166	0.474	11.401	12.175
1987	5.193	0.856	6.794	0.883	0.101	0.054	0.645	0.145	-0.031	0.530	15.858	18.137
1988	5.356	0.779	6.667	0.814	0.103	0.053	0.621	0.147	-0.131	0.520	13.543	15.341
1989	5.819	0.625	6.080	0.698	0.098	0.052	0.475	0.183	-0.521	0.495	6.231	7.556
1990	5.818	0.874	5.790	1.116	0.101	0.058	0.358	0.292	-0.594	0.654	3.776	7.050
1991	5.918	0.703	5.606	0.820	0.124	0.064	0.294	0.194	-0.581	0.433	2.791	3.540
1992	5.270	1.008	6.317	1.232	0.134	0.062	0.439	0.262	-0.031	0.696	10.149	15.757
1993	5.288	1.009	6.262	1.282	0.137	0.063	0.424	0.275	-0.040	0.691	9.514	15.029
1994	5.632	0.812	5.994	1.089	0.138	0.066	0.420	0.245	-0.289	0.512	5.086	6.549
1995	4.886	1.189	6.705	1.340	0.136	0.063	0.500	0.227	0.255	0.621	17.185	22.680
1996	4.949	1.110	6.683	1.273	0.136	0.063	0.513	0.236	0.208	0.597	15.375	20.228
1997	4.720	1.295	6.554	1.437	0.135	0.061	0.381	0.252	0.367	0.600	22.852	29.149
1998	4.997	1.047	5.658	1.435	0.141	0.062	0.068	0.427	0.201	0.551	15.742	19.015
1999	5.533	0.687	5.493	1.665	0.156	0.069	0.179	0.798	-0.129	0.438	6.011	6.144
2000	5.443	0.719	5.636	1.740	0.155	0.069	0.198	0.805	-0.067	0.472	6.998	7.404
2001	5.717	0.537	4.613	1.775	0.156	0.066	-0.078	0.803	-0.261	0.334	4.720	3.589
2002	5.657	0.553	4.553	1.799	0.156	0.066	-0.142	0.800	-0.239	0.366	5.149	4.225
2003	5.767	0.492	4.785	1.705	0.159	0.063	0.062	0.779	-0.343	0.323	4.474	3.254
2004	5.814	0.468	4.685	1.664	0.160	0.062	0.099	0.758	-0.384	0.301	4.213	2.864
2005	5.607	0.555	5.195	1.790	0.155	0.067	0.141	0.826	-0.227	0.378	5.190	4.365

Table A3. 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	-1.533	4.232
1983	4.103	70.852
1984	3.986	66.809
1985	4.005	67.459
1986	2.860	38.062
1987	3.925	64.830
1988	2.563	32.810
1989	-4.418	1.000
1990	-0.741	6.288
1991	0.740	13.187
1992	2.859	38.028
1993	2.630	33.923
1994	0.854	13.956
1995	4.237	75.741
1996	4.267	76.888
1997	1.905	23.605
1998	2.075	25.703
1999	3.956	65.817
2000	4.112	71.165
2001	2.937	39.540
2002	3.116	43.263
2003	0.877	14.121
2004	-0.855	5.939
2005	3.579	54.527

Table A4. Parameter estimates and standard deviations for the Beverton-Holt stock-recruitment model with no breakpoint (first row) and the single breakpoint models (by year of breakpoint). The “best” model is shaded. Years are brood year.

Year	α_1	std.dev.	α_2	std.dev.	β_1	std.dev.	β_2	std.dev.	ln(σ)	std.dev.	tan(ρ)	std.dev.
			11.908	34.104			5.800	34.131	-0.009	0.437	9.869	9.284
1983	11.694	NA	12.970	47.627	5.444	NA	6.914	47.639	-0.064	0.440	8.852	8.394
1984	5.572	2.004	16.904	327.946	-0.995	2.787	10.826	327.948	-0.048	0.461	9.257	9.254
1985	6.345	3.335	13.895	71.302	-0.097	4.202	7.862	71.309	-0.040	0.568	9.453	11.707
1986	7.533	NA	13.399	63.519	0.973	NA	7.500	63.531	-0.261	0.335	6.145	5.013
1987	5.981	1.683	16.024	219.692	-0.666	2.487	10.011	219.695	-0.134	0.472	7.647	7.894
1988	6.262	1.538	13.277	68.643	-0.711	2.287	7.383	68.656	-0.350	0.425	5.155	5.008
1989	7.068	1.875	11.864	69.327	-0.295	2.416	6.194	69.377	-0.751	0.300	2.896	2.154
1990	12.339	NA	11.704	NA	5.363	NA	5.993	NA	-0.722	0.336	2.646	2.383
1991	12.304	38.041	11.711	NA	5.419	38.076	5.985	NA	-0.653	0.356	2.588	2.578
1992	12.200	33.709	11.752	NA	5.608	33.730	5.917	NA	-0.420	0.496	4.429	5.120
1993	12.881	44.794	11.465	NA	6.344	44.807	5.636	NA	-0.369	0.430	4.791	4.774
1994	13.348	51.252	11.695	233.066	6.642	51.264	6.049	233.257	-0.446	0.310	3.715	2.753
1995	11.988	36.396	11.863	111.774	5.817	36.408	5.805	111.874	-0.058	0.518	8.939	9.881
1996	11.966	37.397	11.882	93.181	5.842	37.411	5.790	93.266	-0.020	0.527	9.588	11.563
1997	13.744	105.672	7.696	5.406	8.060	105.672	1.102	5.906	0.337	0.621	24.517	32.501
1998	12.980	58.869	5.748	1.618	7.151	58.870	-2.250	6.036	0.229	0.584	19.852	25.260
1999	13.405	47.136	11.393	NA	7.144	47.143	5.452	NA	-0.137	0.447	7.230	7.396
2000	14.297	98.747	5.732	1.989	8.272	98.752	-1.652	6.425	0.074	0.552	12.085	14.354
2001	12.041	31.917	11.731	NA	5.698	31.953	5.946	NA	-0.230	0.398	6.243	5.598
2002	13.694	52.456	5.888	NA	7.486	52.464	-0.604	NA	-0.162	0.425	7.790	7.064
2003	13.209	40.983	11.292	NA	6.789	40.995	5.706	NA	-0.349	0.371	5.920	4.824
2004	13.213	39.232	11.330	NA	6.749	39.244	5.911	NA	-0.392	0.349	5.678	4.409
2005	14.402	93.698	10.309	NA	8.150	93.706	4.447	NA	-0.158	0.432	7.808	7.191

Table A5. Estimates of B_{MSY} proxy using the entire time series and model suggested breakpoint years for recruitment.

Year	Basis for B_{MSY}	B_{MSY} proxy	MSST	Biomass (MMB_{mating})	B/B_{MSY}
2018/19	1978-2017	3.48	1.74	1.09	0.31
2018/19	1996-2017	2.03	1.015	1.08	0.53

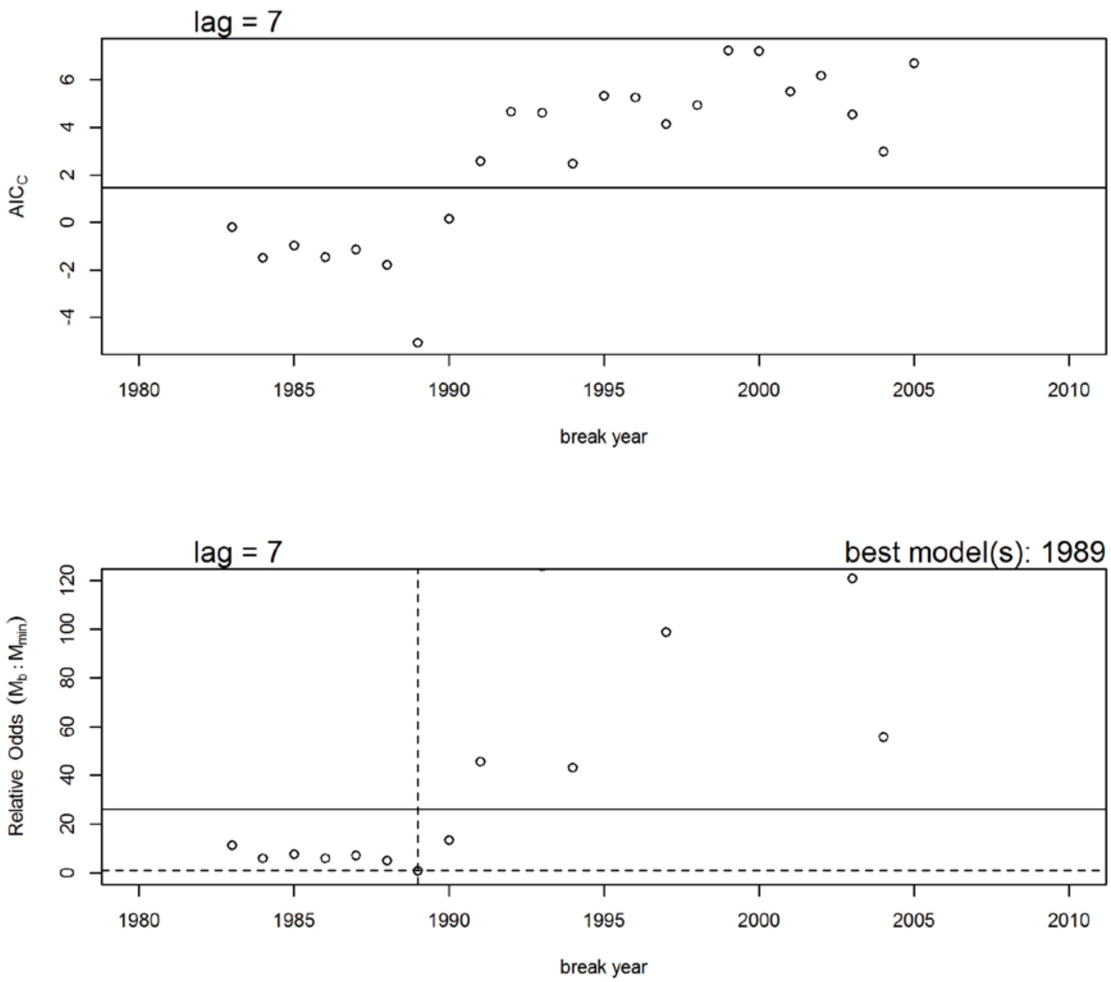


Figure A1. Results from the Ricker stock-recruit breakpoint analysis. Upper graph: AICc vs. year of breakpoint for the 1-breakpoint models (circles) and AICc for the model with no breakpoint (horizontal line). Lower graph: probabilistic odds for all 1-breakpoint models (circles) and the no breakpoint model (horizontal solid line) relative to the model with the smallest AICc score. The dashed lines indicate the value for the model with the lowest AICc score (breakpoint in 1989). Not shown are 1-breakpoint models with high odds (>120) of being incorrect.

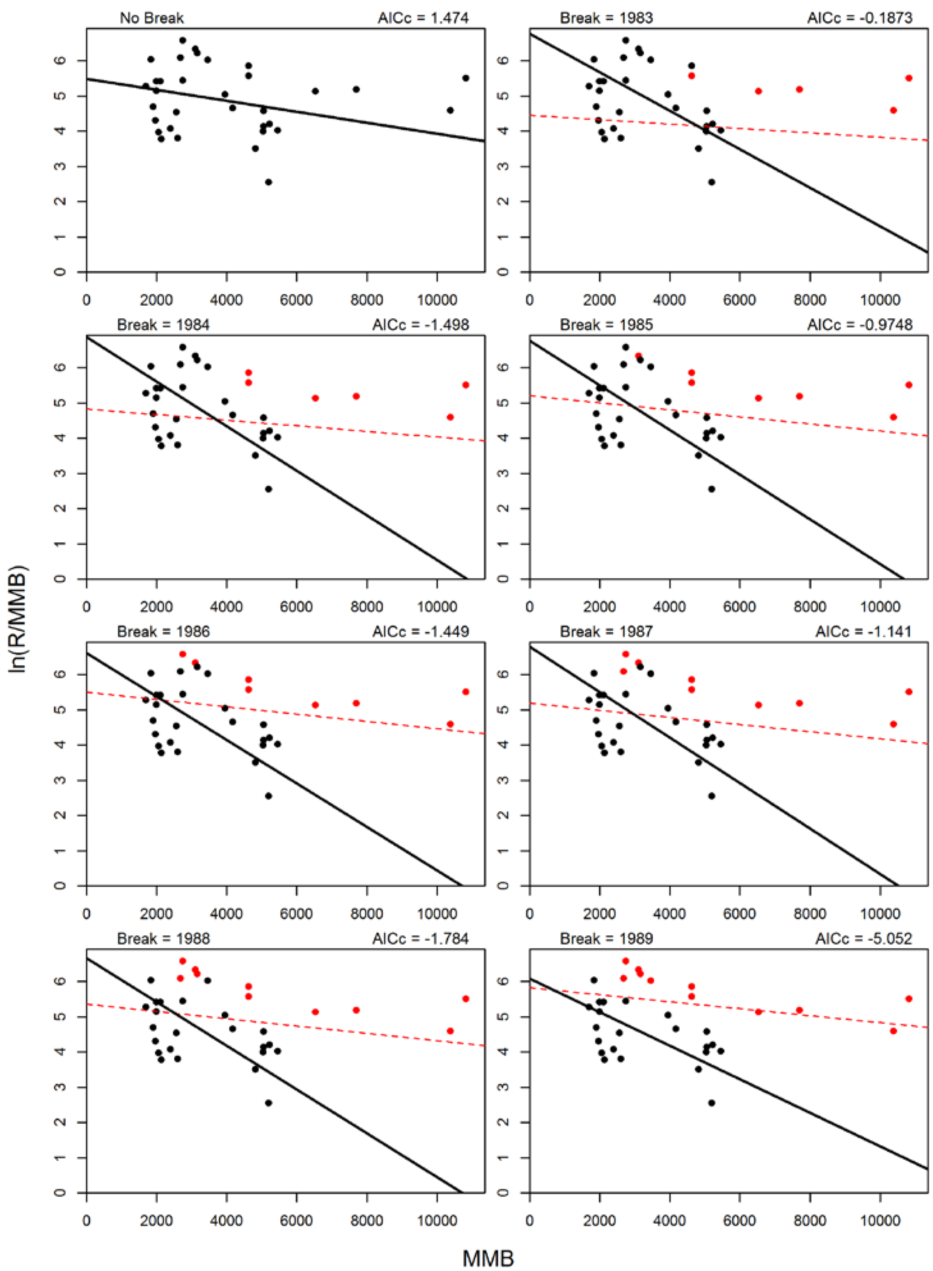
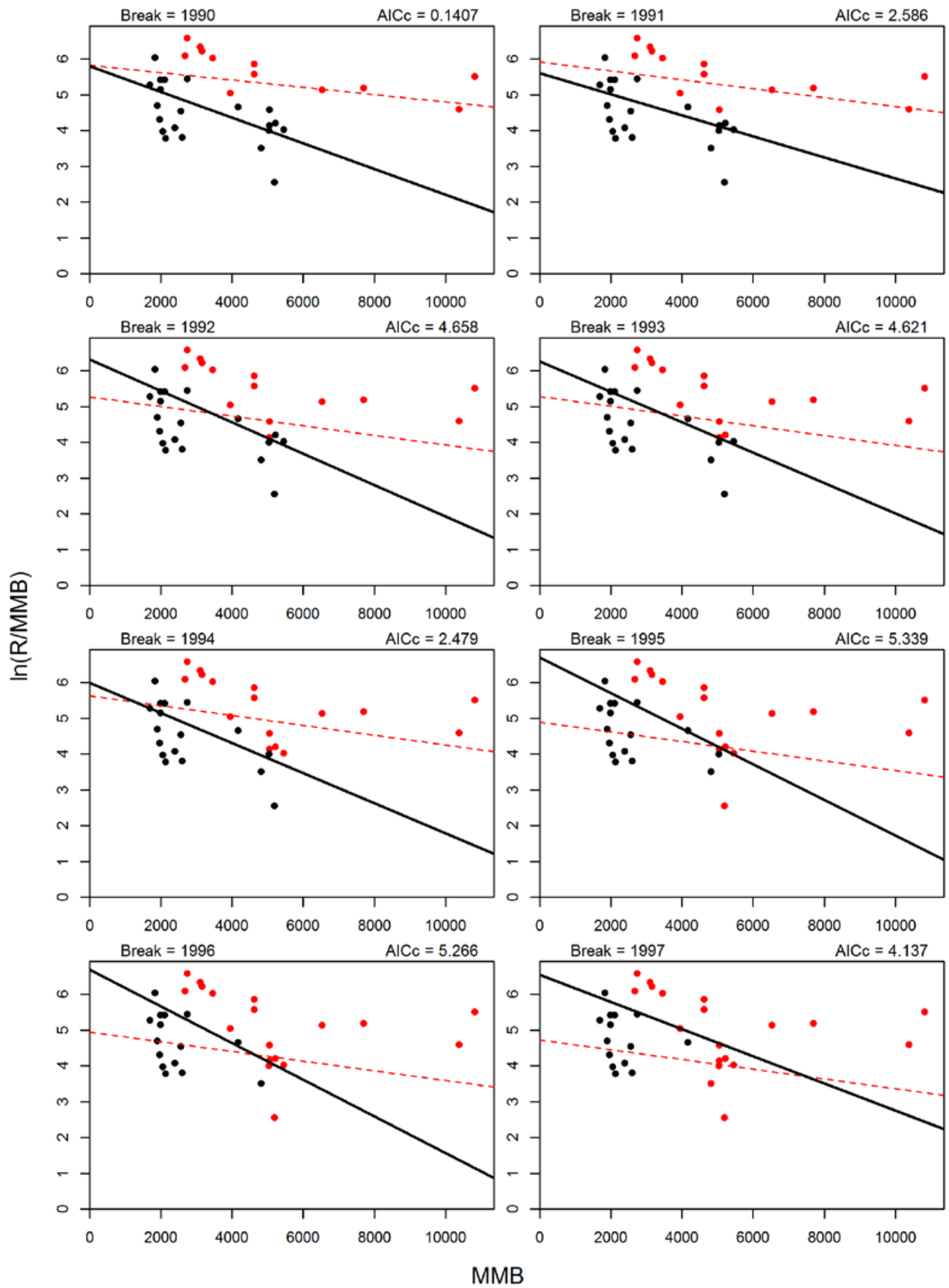


Figure A2. Fits for Ricker models with no breakpoint (upper left graph) and with 1-breakpoint for break years 1978-2005. For 1-breakpoint models, the pre-break data (circles) and model fit (line) are shown in red, whereas the post-break data and fit are shown in black.



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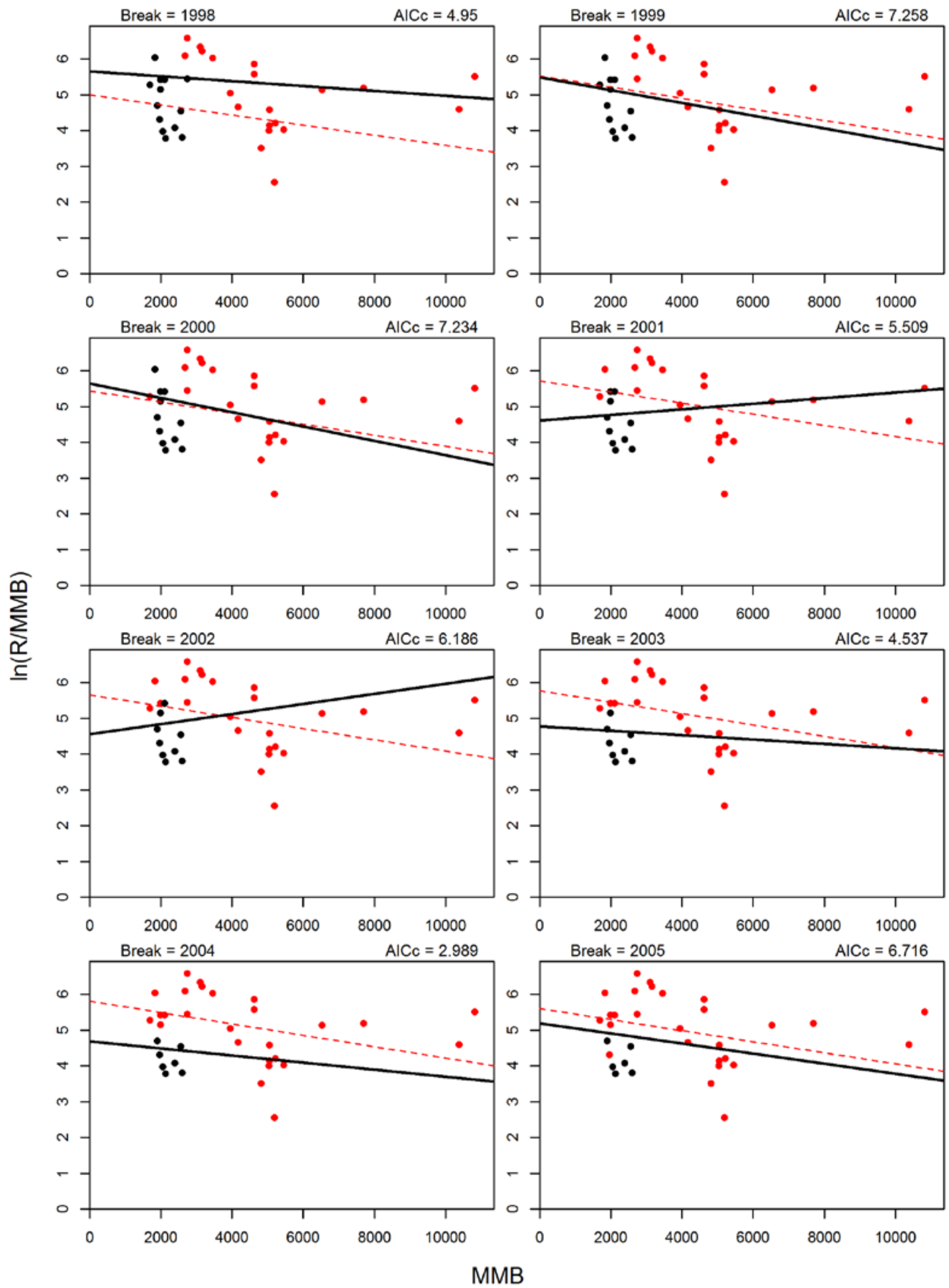

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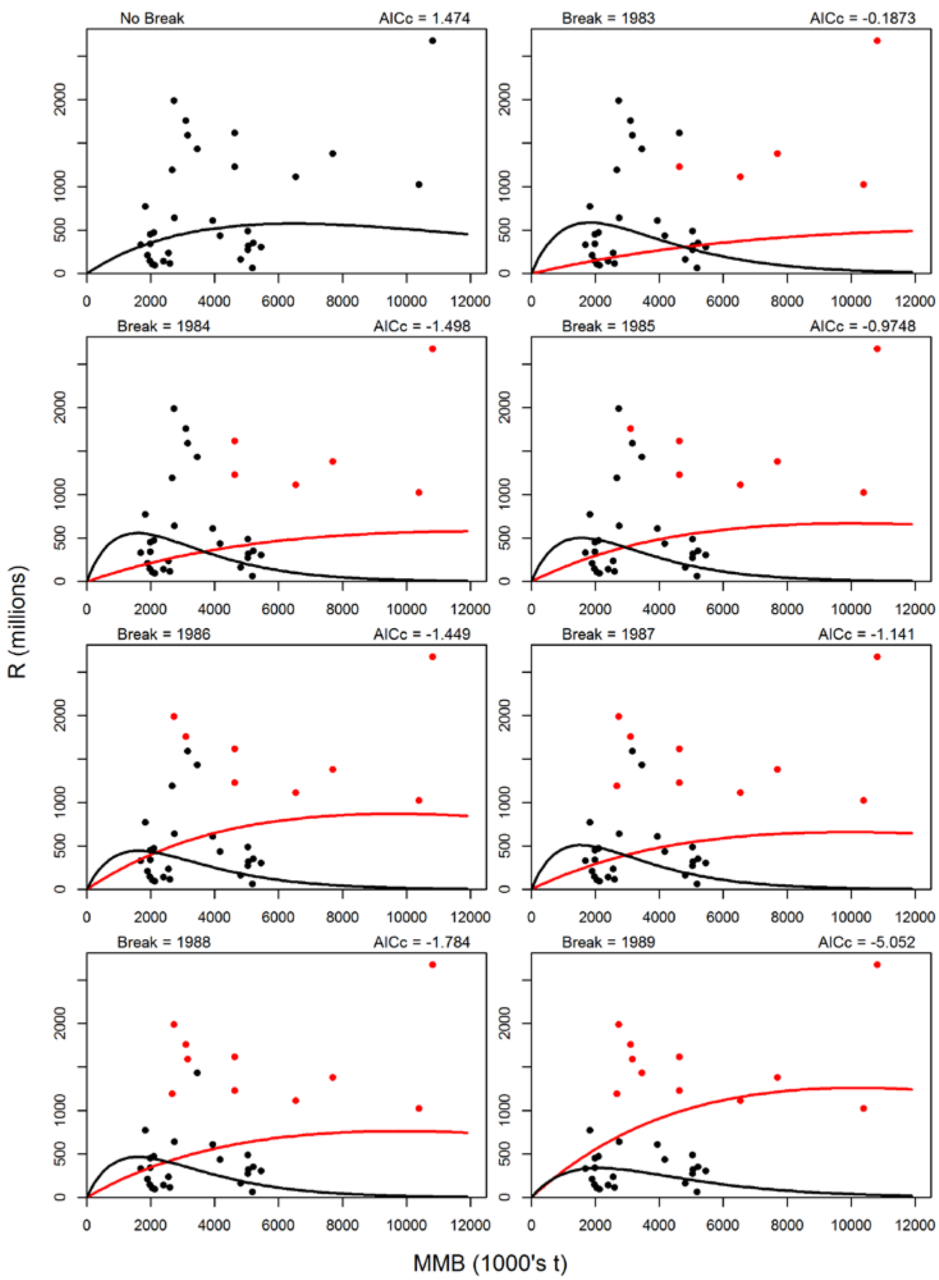
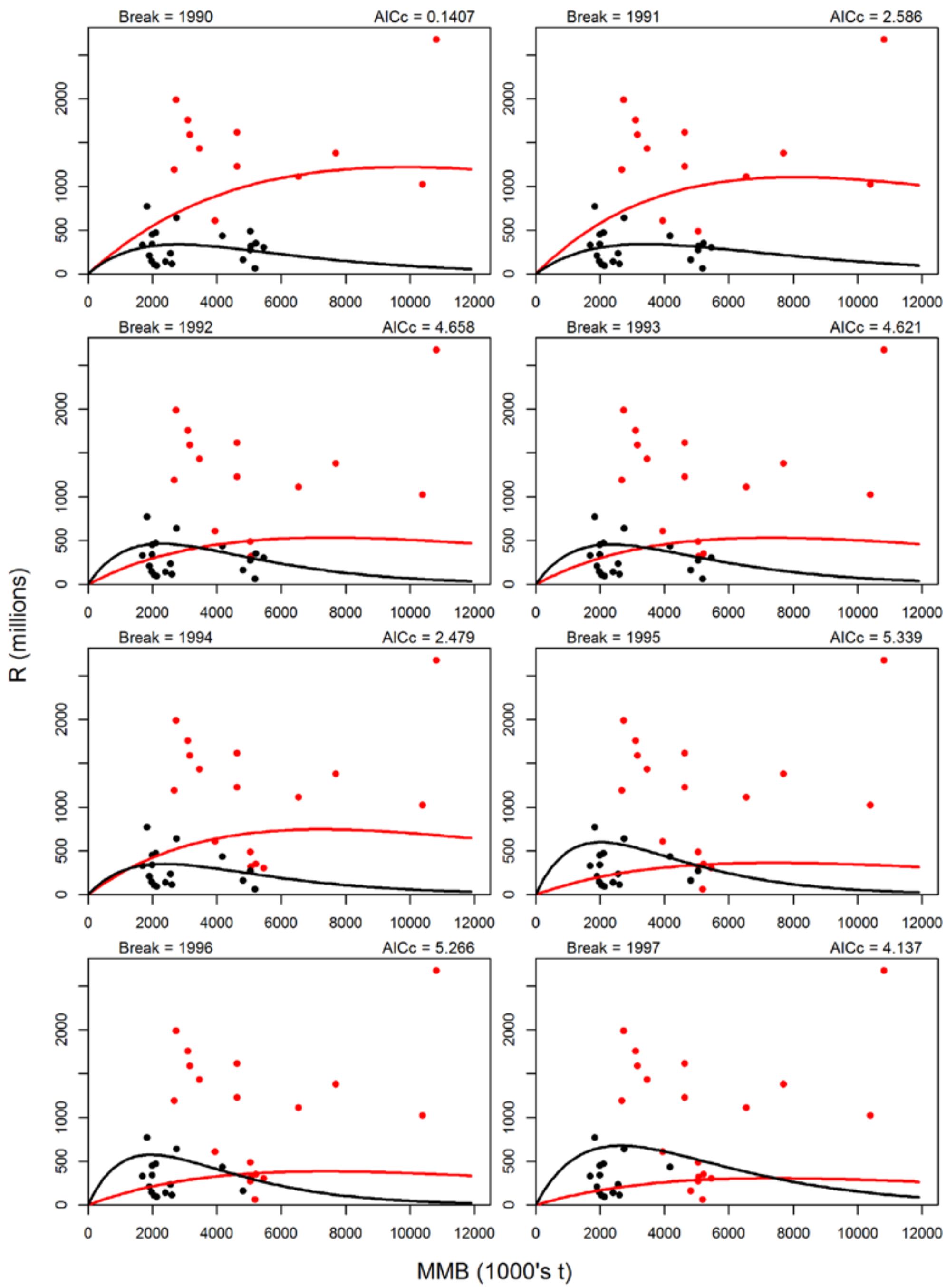


Figure A3. Fits on the arithmetic scale for Ricker models with no breakpoint (upper left graph) and with 1-breakpoint for break years 1978-2005. For 1-breakpoint models, the pre-break data (circles) and model fit (line) are shown in red, whereas the post-break data and fit are shown in black.



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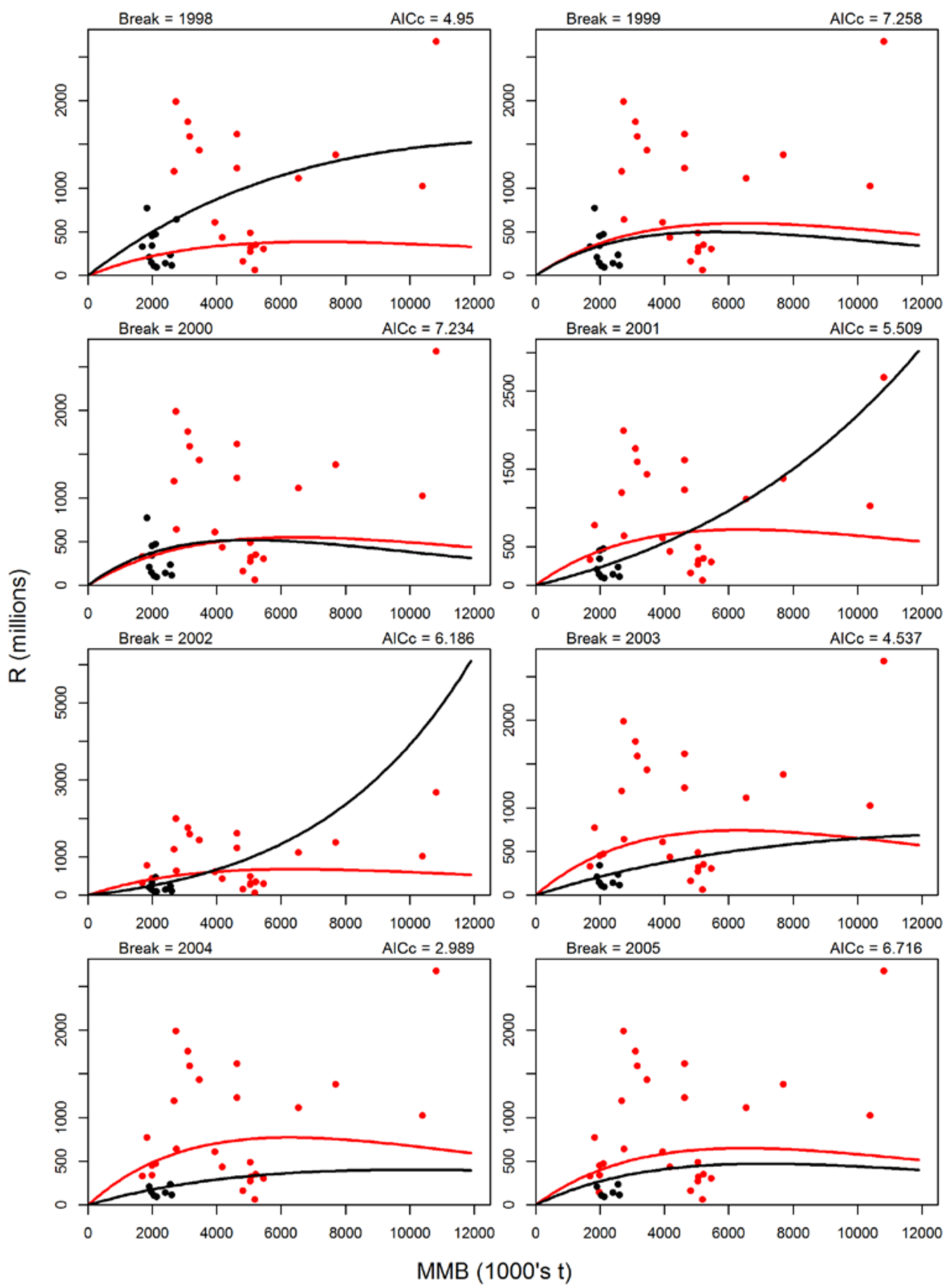

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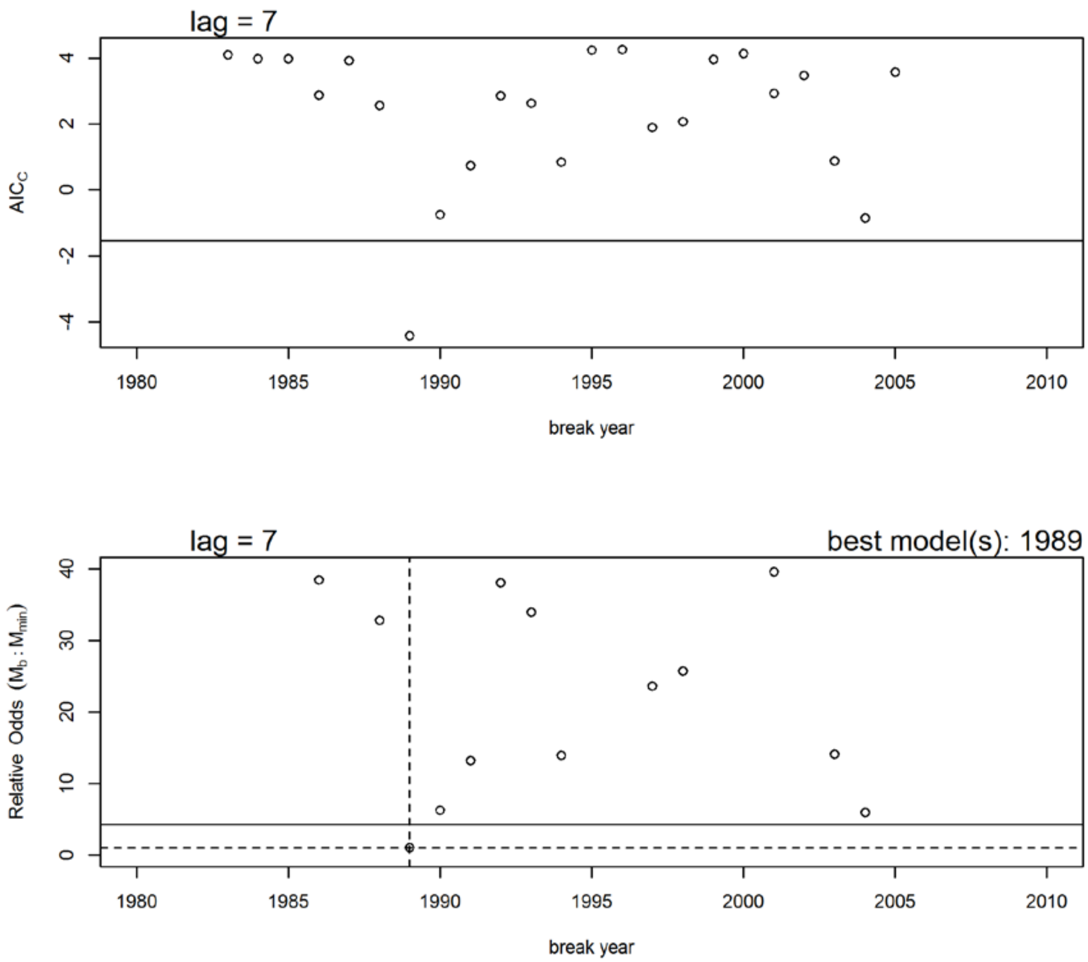


Figure A4. Results from the B-H stock-recruit breakpoint analysis. Upper graph: AICc vs. year of breakpoint for the 1-breakpoint models (circles) and AICc for the model with no breakpoint (horizontal line). Lower graph: probabilistic odds for all 1-breakpoint models (circles) and the no breakpoint model (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 1989). Not shown are 1-breakpoint models with high odds (>40) of being incorrect.

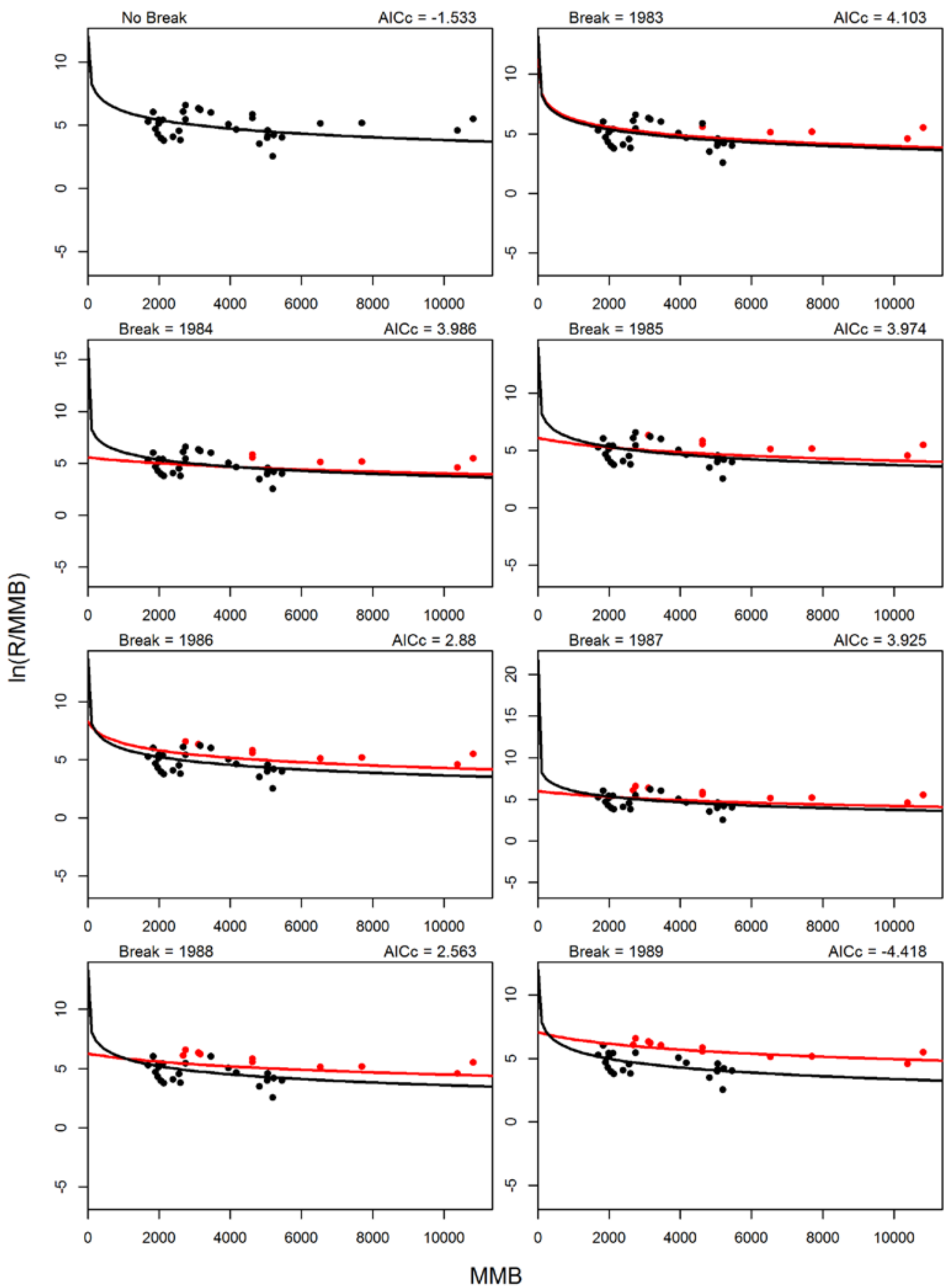
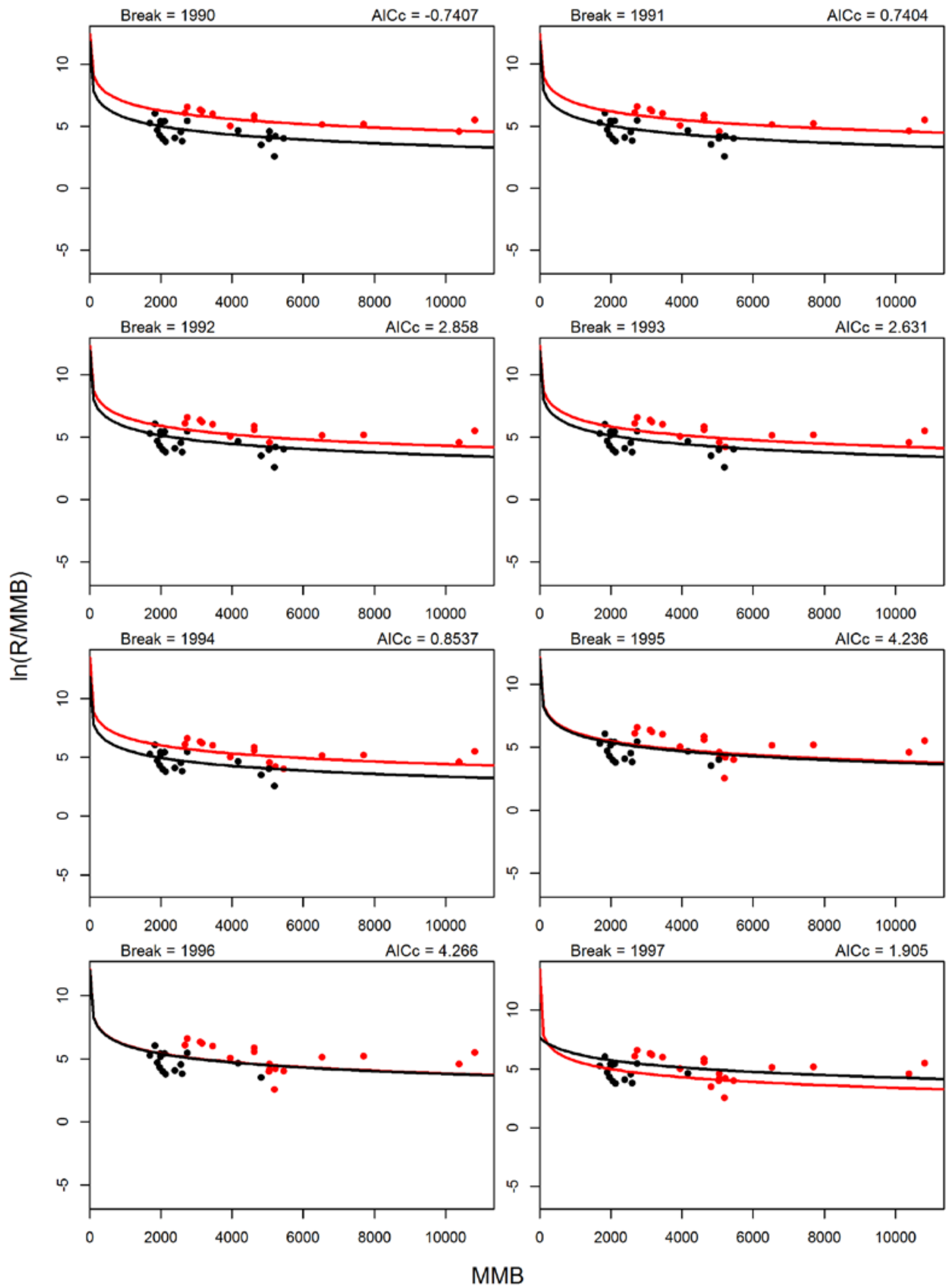


Figure A5. Fits for B-H models with no breakpoint (upper left graph) and with 1-breakpoint for break years 1978-2005. For 1-breakpoint models, the pre-break data (circles) and model fit (line) are shown in red, whereas the post-break data and fit are shown in black.



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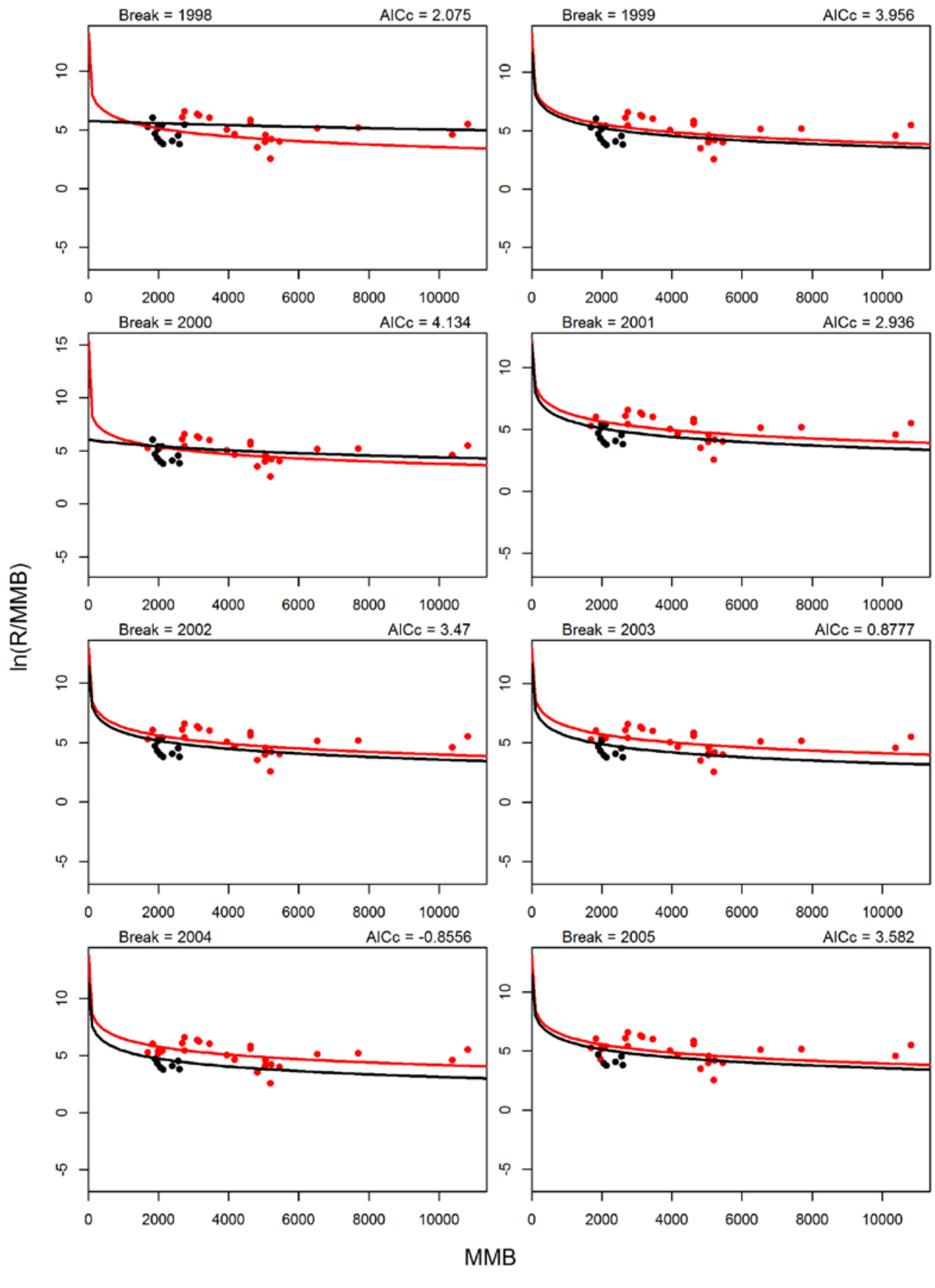

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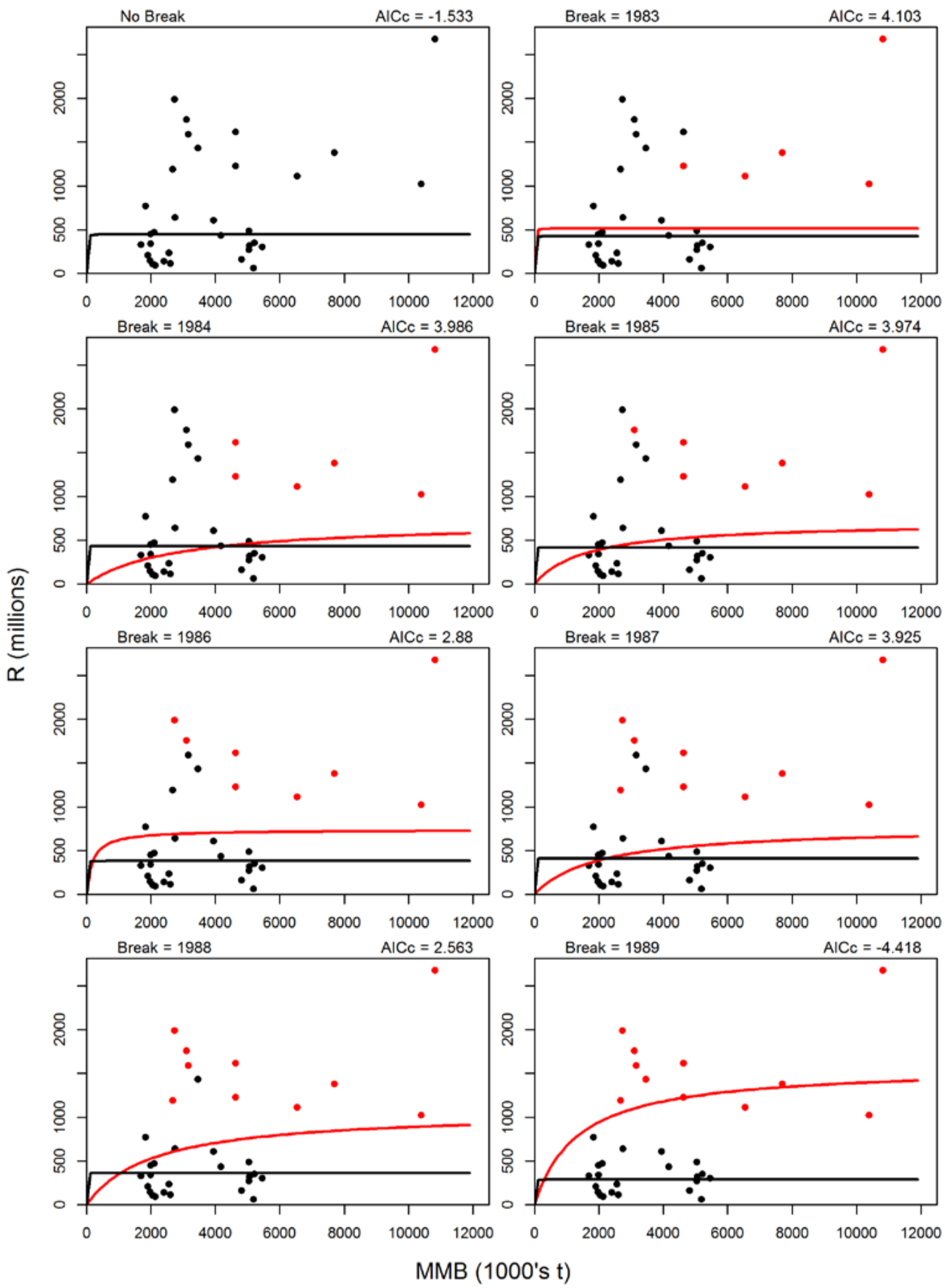
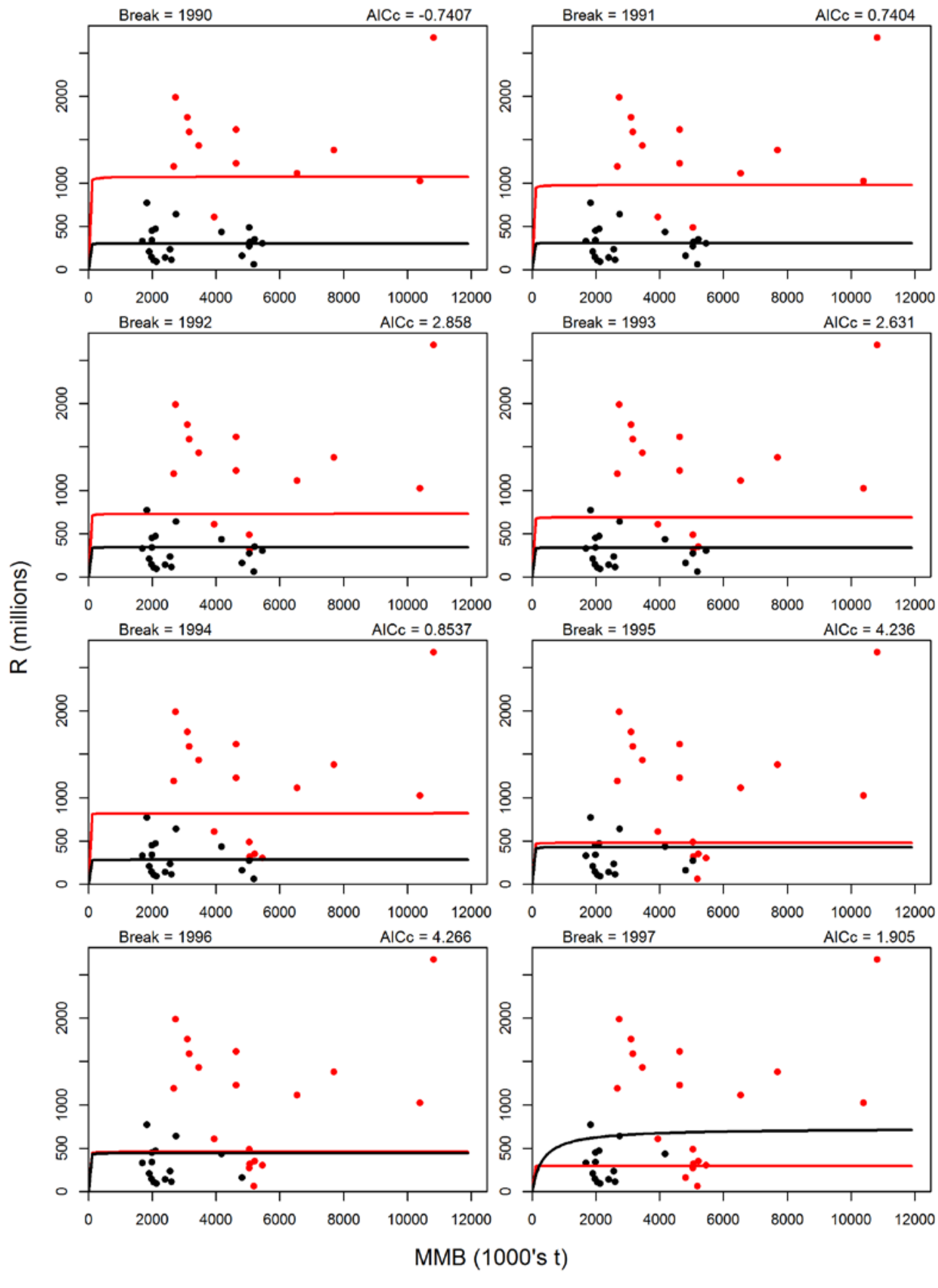


Figure A6. Fits on the arithmetic scale for B-H models with no breakpoint (upper left graph) and with 1-breakpoint for break years 1978-2005. For 1-breakpoint models, the pre-break data (circles) and model fit (line) are shown in red, whereas the post-break data and fit are shown in black.



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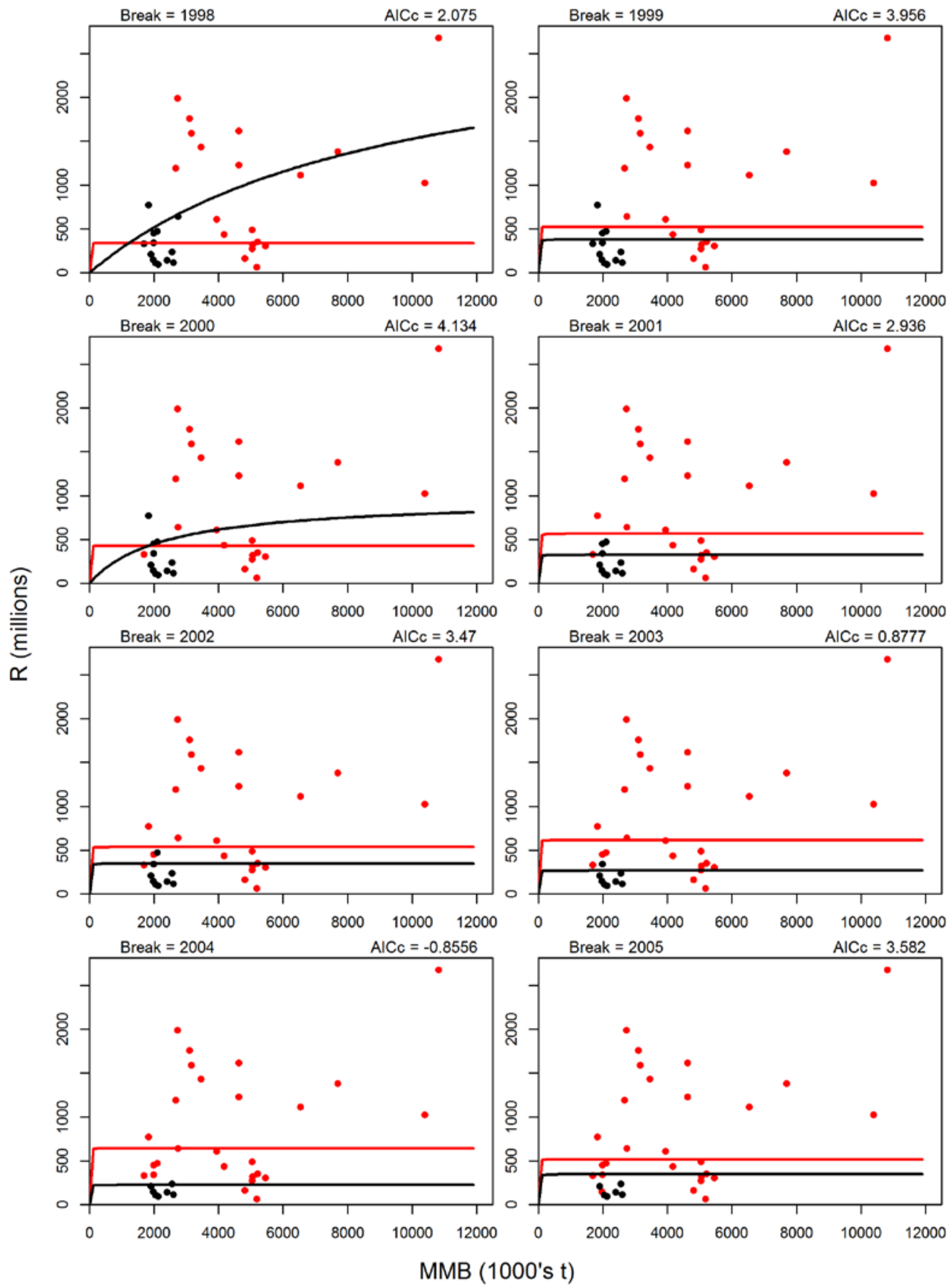

Figure A6. Continued.

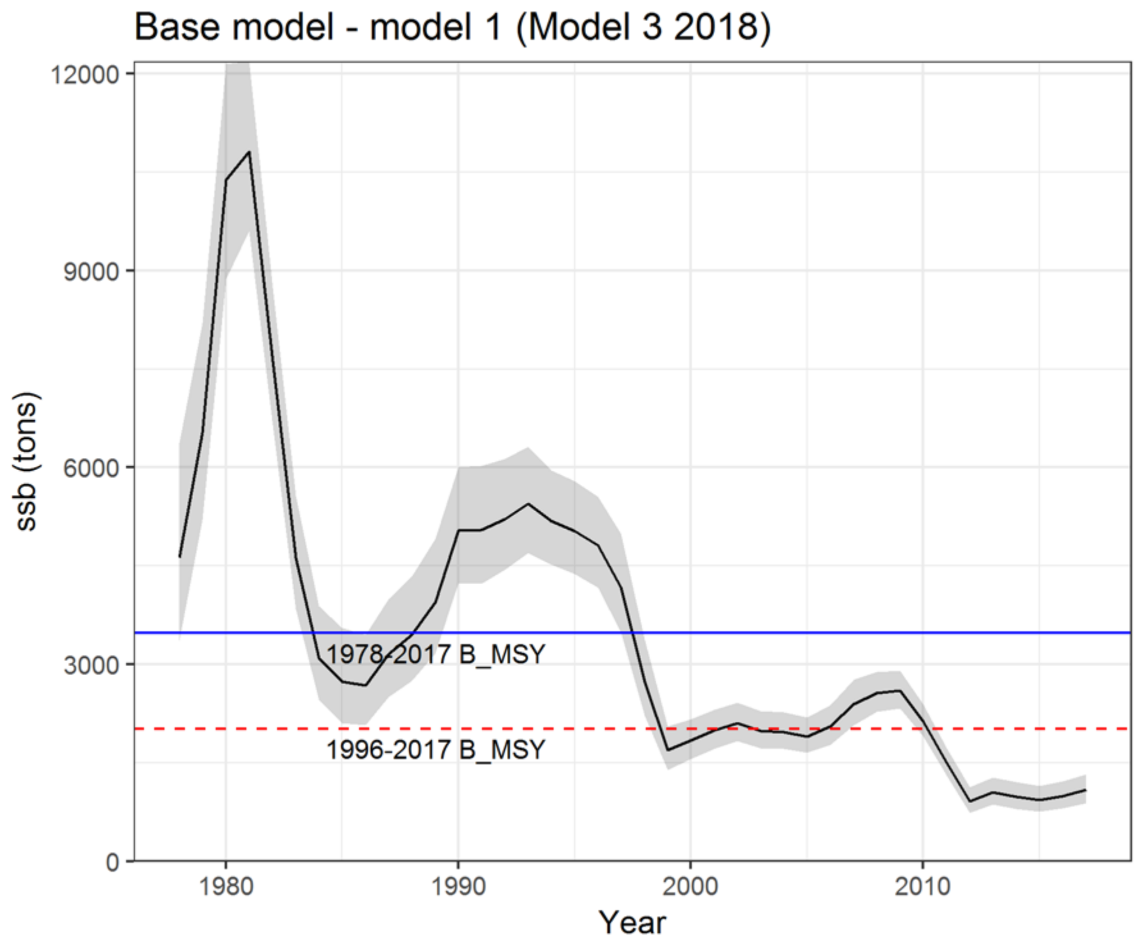

Figure A7. Computed B_{MSY} proxy (average mature male biomass) for the corresponding year ranges based on the 2018 assessment model with GMACS code updates.

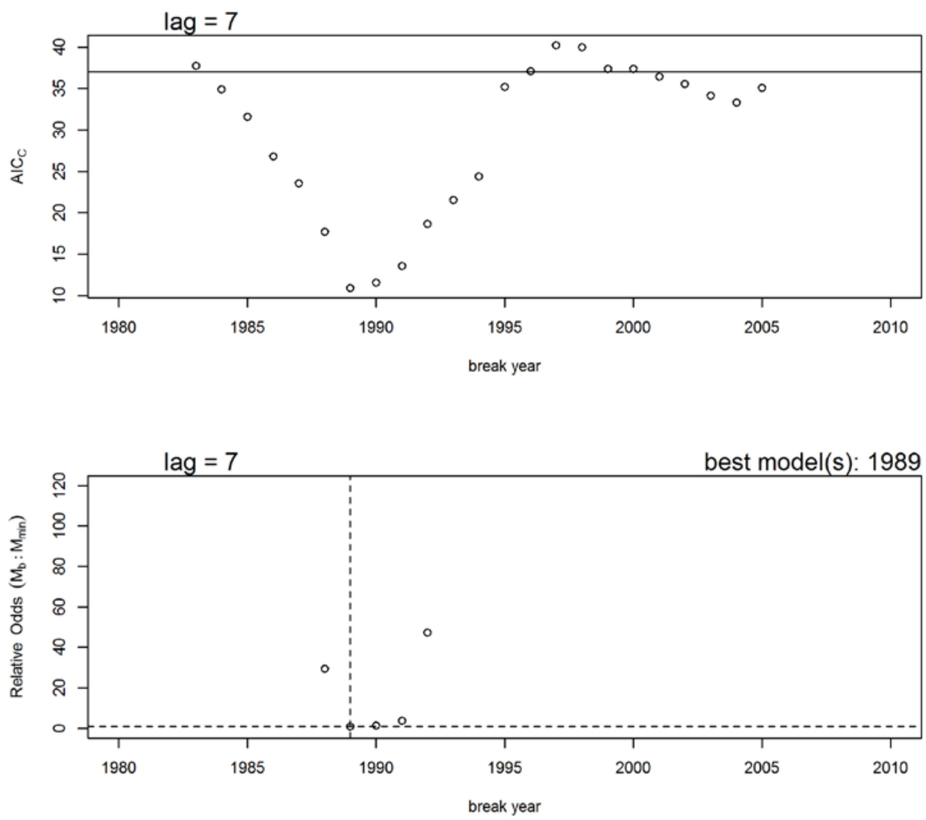

Figure A8. Results from the sensitivity analysis for Ricker stock-recruit breakpoint analysis. Upper graph: AICc vs. year of breakpoint for the 1-breakpoint models (circles) and AICc for the model with no breakpoint (horizontal line). Lower graph: probabilistic odds for all 1-breakpoint models (circles) and the no breakpoint model (horizontal solid line) relative to the model with the smallest AICc score. The dashed lines indicate the value for the model with the lowest AICc score (breakpoint in 1989). Not shown are 1-breakpoint models with high odds (>120) of being incorrect.

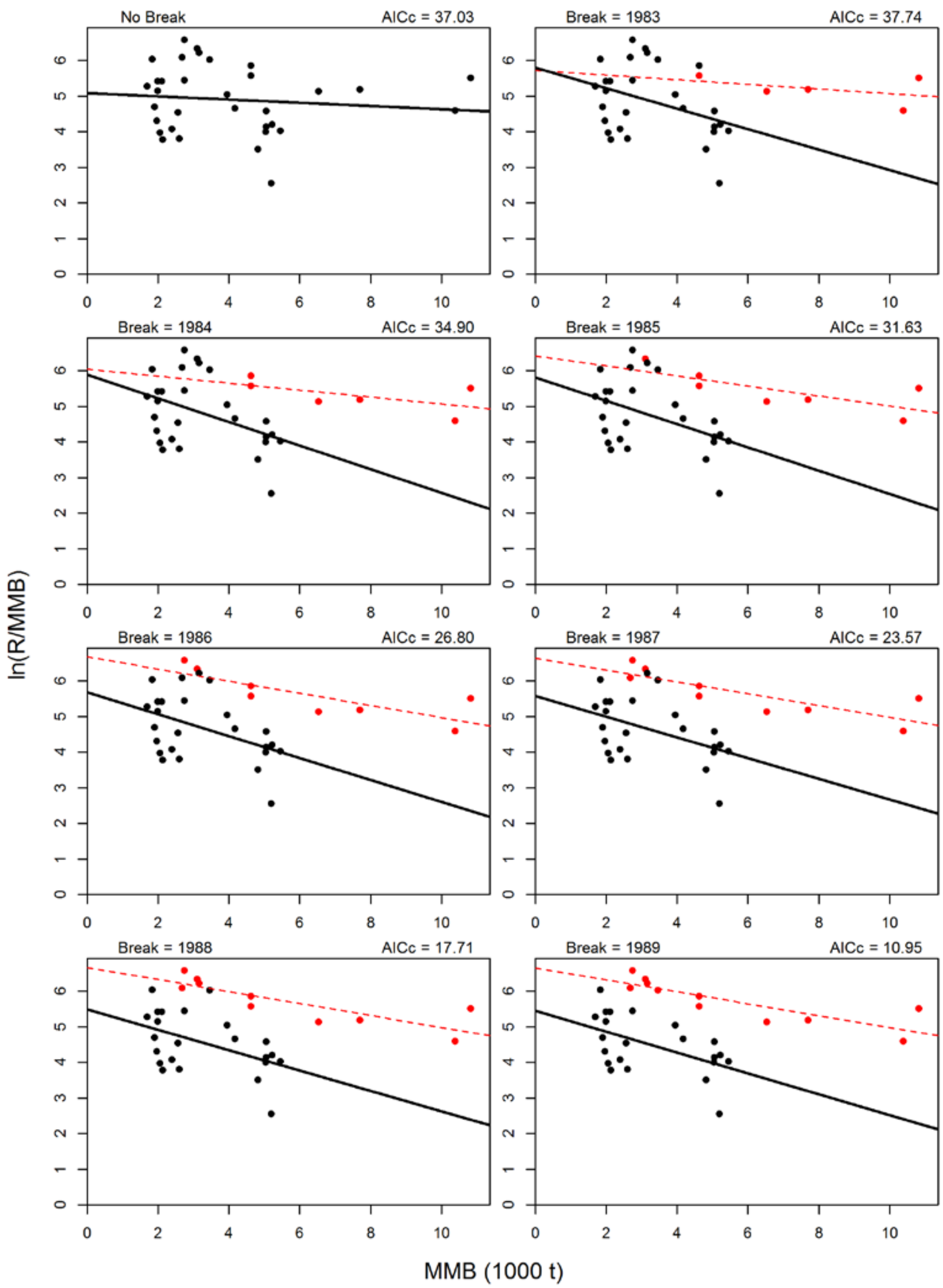

Figure A9. Fits for the sensitivity analysis using the Ricker models with no breakpoint (upper left graph) and with 1-breakpoint for break years 1978-2005. For 1-breakpoint models, the pre-break data (circles) and model fit (line) are shown in red, whereas the post-break data and fit are shown in black.

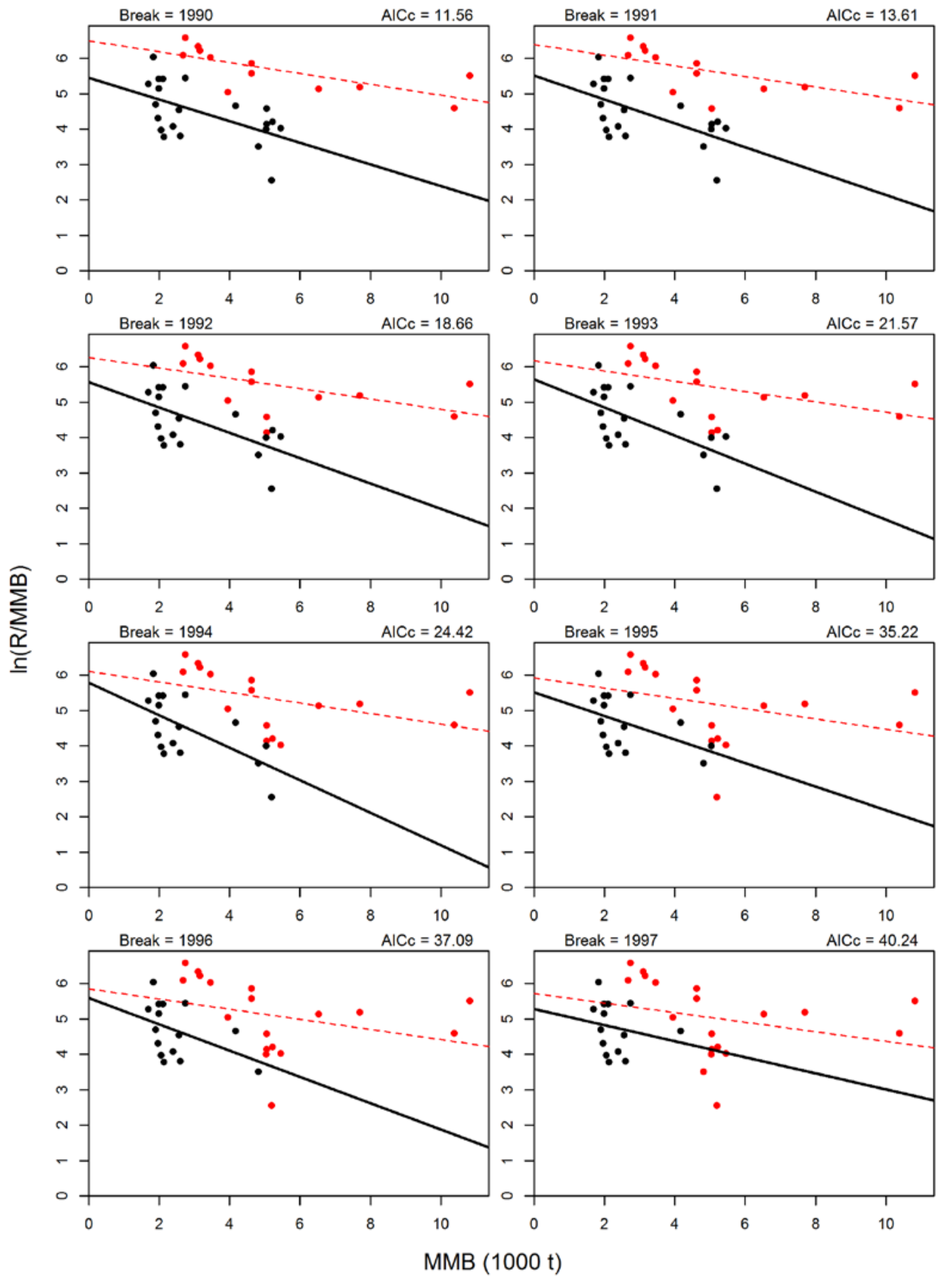

Figure A9. Continued.

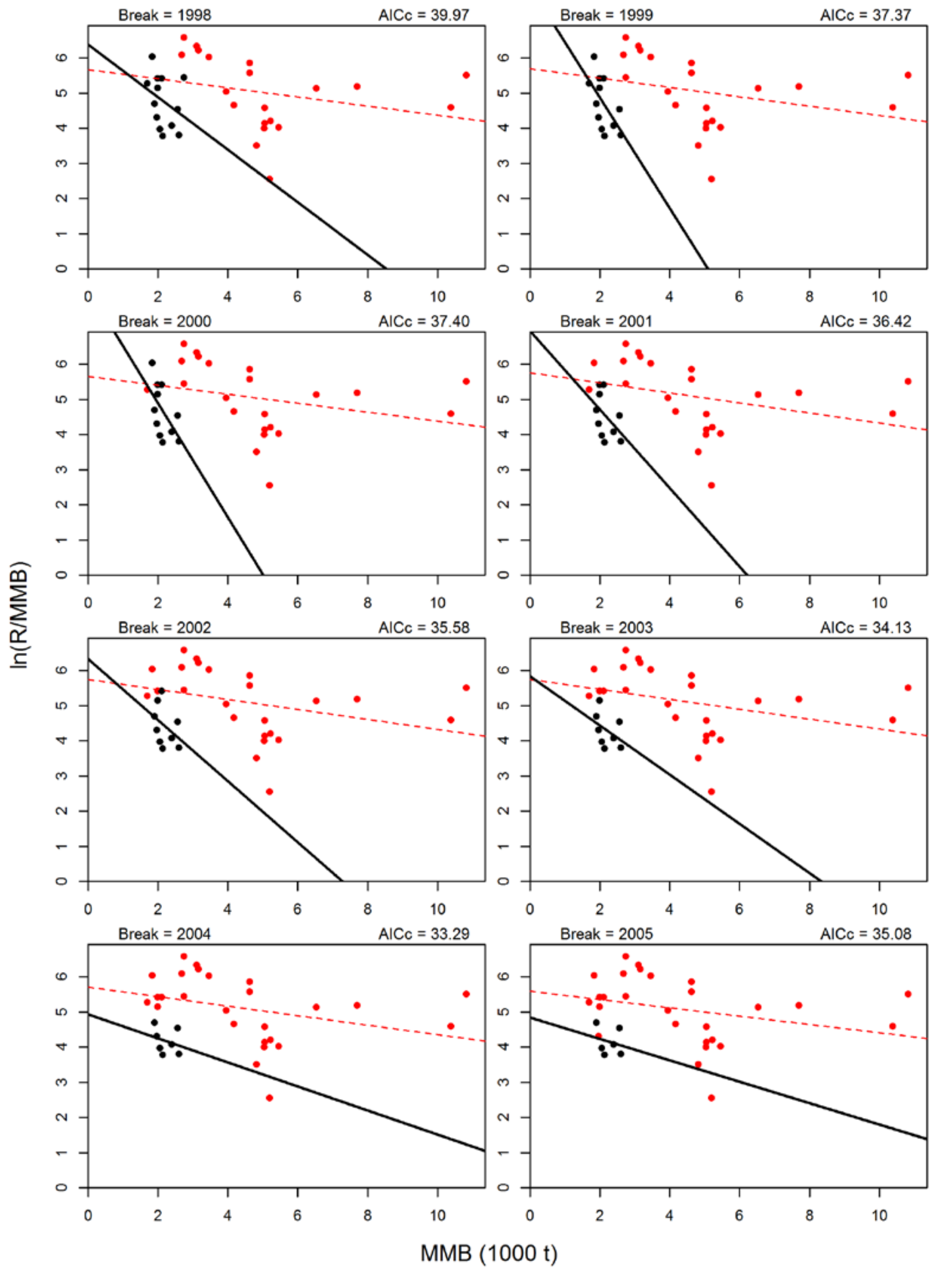

Figure A9. Continued.

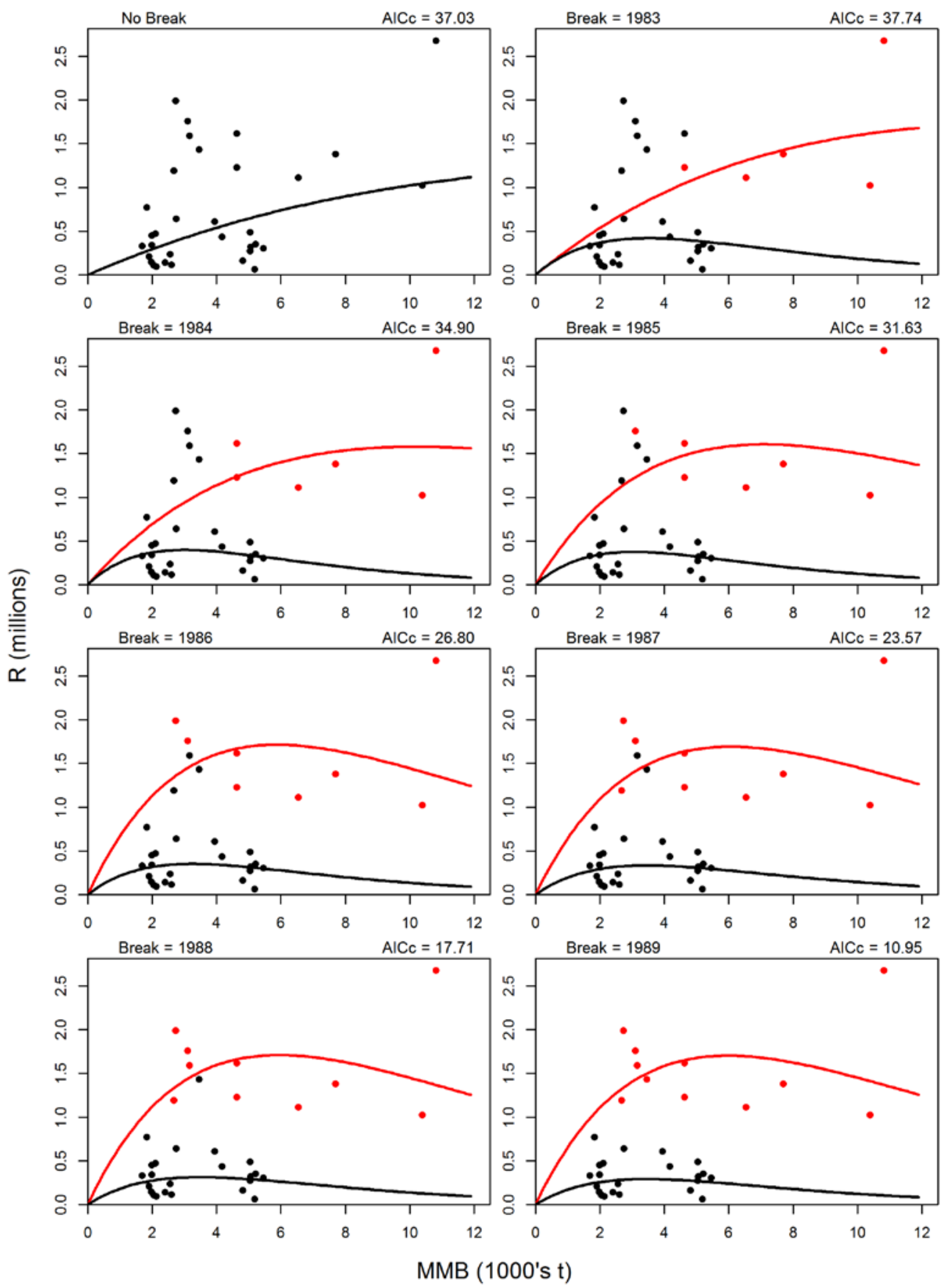

Figure A10. Fits on the arithmetic scale for the sensitivity analysis using the Ricker models with no breakpoint (upper left graph) and with 1-breakpoint for break years 1978-2005. For 1-breakpoint models, the pre-break data (circles) and model fit (line) are shown in red, whereas the post-break data and fit are shown in black.

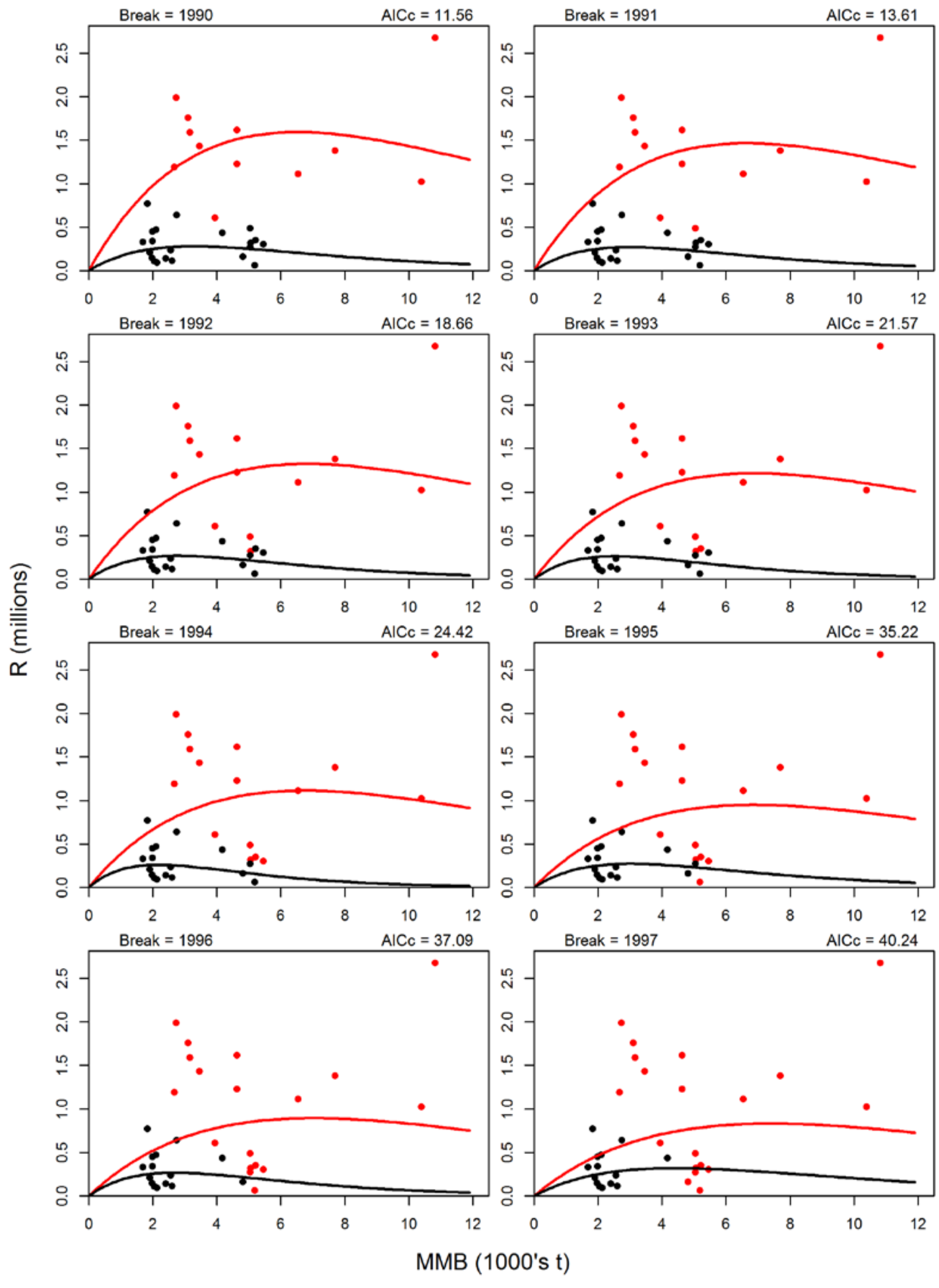

Figure A10. Continued.

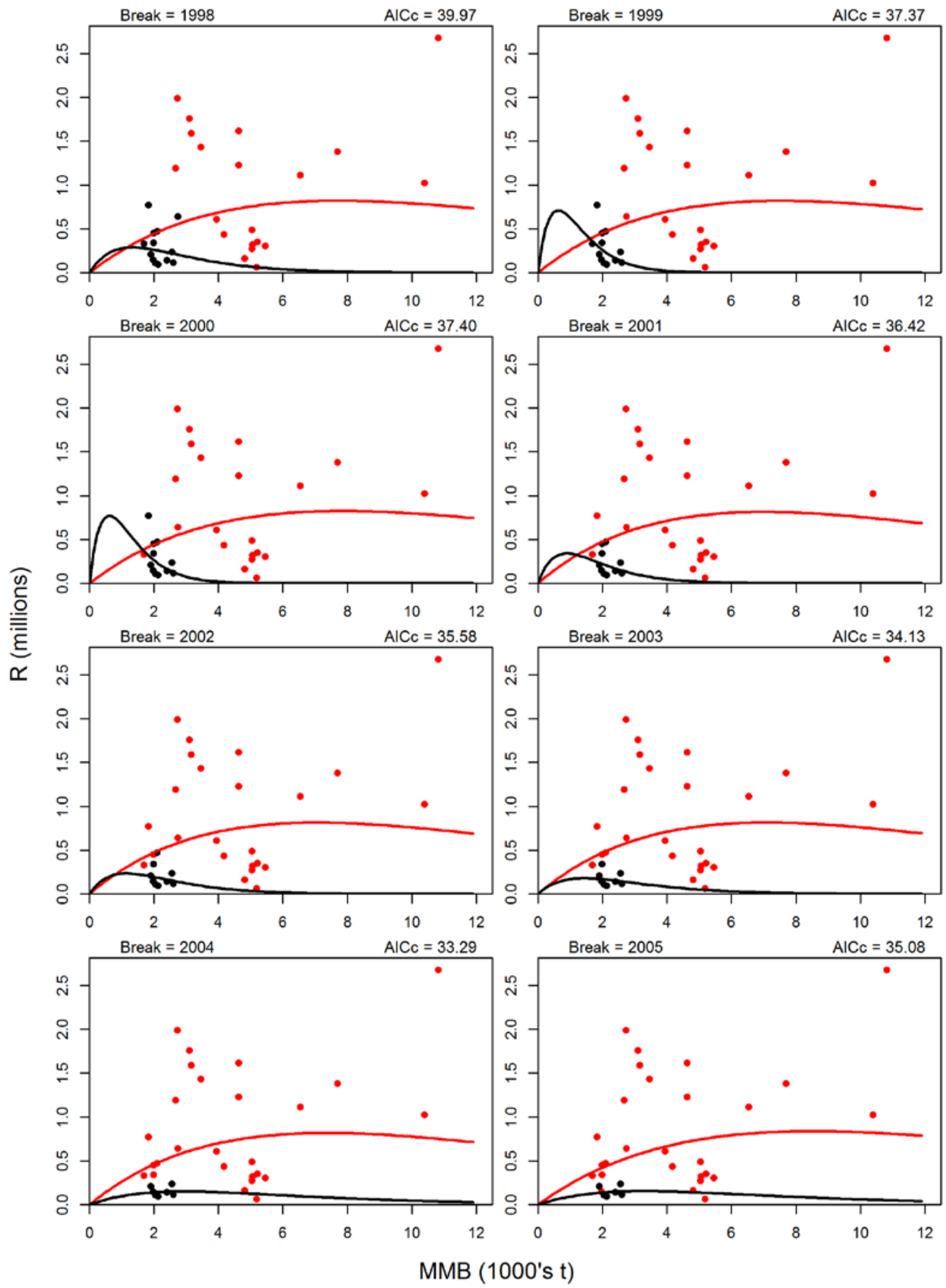

Figure A10. Continued.