Saint Matthew Island Blue King Crab Stock Assesssment 2019

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Executive Summary

1. **Stock**: Blue king crab, *Paralithodes platypus*, Saint Matthew Island (SMBKC), Alaska.
2. **Catches**: Peak historical harvest was 4,288 t (9.454 million pounds) in 1983/84[1]. The fishery was closed for 10 years after the stock was declared overfished in 1999. Fishing resumed in 2009/10 with a fishery-reported retained catch of 209 t (0.461 million pounds), less than half the 529.3 t (1.167 million pound) TAC. Following three more years of modest harvests supported by a fishery catch per unit effort (CPUE) of around 10 crab per pot lift, the fishery was again closed in 2013/14 due to declining trawl-survey estimates of abundance and concerns about the health of the stock. The directed fishery resumed again in 2014/15 with a TAC of 300 t (0.655 million pounds), but the fishery performance was relatively poor with a retained catch of 140 t (0.309 million pounds). The retained catch in 2015/16 was even lower at 48 t (0.105 million pounds) and the fishery has remained closed since 2016/17.
3. **Stock biomass**: The 1978-2019 NMFS trawl survey mean biomass is 5,605 t with the 2019 value being the 15th lowest (3,170 t; the tenth lowest since 2000). This 2019 biomass of $\geq$ 90 mm carapace length (CL) male crab is 57% of the long term mean at 6.99 million pounds (with a CV of 34%), and an 83% increase from the 2018 biomass. The most recent 3-year average of the NMFS survey is 40% of the mean value, indicating a decline in biomass compared to historical survey estimates, notably in 2010 and 2011 that were over four times the current average. However, the 2019 value is substantially larger than the two previous years (3,170 t compared to 1,731 t in 2018 and 1,794 t in 2017). The ADFG pot survey did not occur in 2019, but in 2018 the relative biomass in this index was the lowest in the time series (12% of the mean from the 11 surveys conducted since 1995). The assessment model estimates tempers this increase and suggests that the stock (in survey biomass units) is presently at about 27% of the long term model-predicted survey biomass average, similar to the last two years. The trend from these values suggests a steady state in the last few years, which does not fit the 2019 observed survey data point well.
4. **Recruitment**: Recruitment is based on estimated number of male crab within the 90-104 mm CL size class in each year. The 2019 trawl-survey area-swept estimate of 0.403 million male SMBKC in this size class is the twelfth lowest in the 42 years since 1978 and follows two of the lowest previously observed values in 2017 and 2018. The recent six-year (2014 - 2019) average recruitment is only 47% of the long-term mean. In the pot-survey, the abundance of this size group in 2017 was also the second-lowest in the time series (22% of the mean for the available pot-survey data) whereas in 2018 the value was the lowest observed at only 10% of the mean value.
5. **Management performance**: In this assessment, estimated total male catch is the sum of fishery-reported retained catch, estimated male discard mortality in the directed fishery, and estimated male bycatch mortality in the groundfish fisheries. Based on the reference model for SMBKC, the estimate for mature male biomass was below the minimum stock-size threshold (MSST) in 2018/19 and is in an "overfished" condition, despite fishery closures in the last three years (and hence overfishing has not occurred) (Tables 1, 3, and 4). Computations which indicate the relative impact of fishing (i.e., the

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[1] 1983/84 refers to a fishing year that extends from 1 July 1983 to 30 June 1984.

"dynamic B_0") suggests, that the current spawning stock biomass has been reduced to 52% of what it would have been in the absence of fishing, assuming the same level of recruitment as estimated.

Table 1: Status and catch specifications (1000 t) for the reference model. Alternative reference point time frame included for comparison for projection year (alt).

Year	MSST	Biomass (MMB_{mating})	TAC	Retained catch	Total male catch	OFL	ABC
2014/15	1.86	2.48	0.30	0.14	0.15	0.43	0.34
2015/16	1.84	2.11	0.19	0.05	0.053	0.28	0.22
2016/17	1.97	2.23	0.00	0.00	0.001	0.14	0.11
2017/18	1.85	1.29	0.00	0.00	0.003	0.12	0.10
2018/19	1.74	1.15	0.00	0.00	0.001	0.04	0.03
2019/20		1.08				0.04	0.03
2019/20alt		1.04				0.08	0.07

Table 2: Status and catch specifications (million pounds) for the reference model.Alternative reference point time frame included for comparison for projection year (alt).

Year	MSST	Biomass (MMB_{mating})	TAC	Retained catch	Total male catch	OFL	ABC
2014/15	4.1	5.47	0.655	0.309	0.332	0.94	0.75
2015/16	4.1	4.65	0.419	0.110	0.117	0.62	0.49
2016/17	4.3	4.91	0.000	0.000	0.002	0.31	0.25
2017/18	4.1	2.85	0.000	0.000	0.007	0.27	0.22
2018/19	3.84	2.54	0.00	0.00	0.002	0.08	0.07
2019/20		2.38				0.096	0.08
2019/20alt		2.299				0.18	0.15

6. **Basis for the OFL**: Estimated mature-male biomass (MMB) on 15 February is used as the measure of biomass for this Tier 4 stock, with males measuring ≥ 105 mm CL considered mature. The B_{MSY} proxy is obtained by averaging estimated MMB over a specific reference period, and current CPT/SSC guidance recommends using the full assessment time frame as the default reference period. Both the full time frame and the current regime are presented here for consideration for 2019/20.

Table 3: Basis for the OFL (1000 t) from the reference model.

Year	Tier	B_{MSY}	Biomass (MMB_{mating})	B/B_{MSY}	F_{OFL}	γ	Basis for B_{MSY}	Natural mortality
2014/15	4b	3.28	2.71	0.82	0.14	1	1978-2014	0.18
2015/16	4b	3.71	2.45	0.66	0.11	1	1978-2015	0.18
2016/17	4b	3.67	2.23	0.61	0.09	1	1978-2016	0.18
2017/18	4b	3.86	2.05	0.53	0.08	1	1978-2017	0.18
2018/19	4b	3.7	1.15	0.35	0.043	1	1978-2017	0.18
2019/20	4b	3.48	1.08	0.31	0.042	1	1978-2018	0.18
2019/20	4b	2.05	1.04	0.51	0.082	1	1996-2018	0.18

A. Summary of Major Changes

Changes in Management of the Fishery

There are no new changes in management of the fishery.

Changes to the Input Data

Data used in this assessment have been updated to include the most recently available fishery and survey numbers. This assessment includes of one new survey data point - the 2019 NMFS trawl-survey estimate of abudance. The triennial ADF&G pot survey was not conducted in 2019. The NMFS trawl-surveys have associated size compositon data. The assessment also uses updated 2010-2018 groundfish and fixed gear bycatch estimates based on NMFS Alaska Regional Office (AKRO) data. The directed fishery has been closed since 2016/17, so no recent fishery data are available.

Changes in Assessment Methodology

This assessment uses the General model for Alasks crab stocks (Gmacs) framework. The model is configured to track three stages of length categories and was first presented in May 2011 by W.Gaeuman, ADF&G, per.com. and accepted by the CPT in May 2012. A difference from the original approach and that used here is that natural and fishing mortalities are continuous within 5 discrete seasons (using the appropriate catch equation rather than assuming an applied pulse removal). Season length in Gmacs is controlled by changing the proportion of natural mortality that is applied each season. Diagnostic output includes estimates of the "dynamic B_0" which simply computes the ratio of the estimated spawning biomass relative to the spawning biomass that would have occurred had there been no historical fishing mortality. Details of this implementation and other model details are provided in Appendix A.

Changes in Assessment Results

Both surveys indicate a decline over the past few years. The "reference" model is that which was selected for use in 2018. There is only one new data set to be included this year so this becomes the updated reference model. Two alternative models are presented to assess sensitivity to the model, while another is provided for alternative reference point calculations (Table 3) using a recent regime time frame. The **fit survey** configuration simply adds emphasis on the design-based survey data (by assuming a lower input variance). The **add CV pot** configuration estimates an additional CV on the pot survey data, which in turn allows the model to fit the trawl-survey estimates better.

B. Responses to SSC and CPT

CPT and SSC Comments on Assessments in General

Comment: *Regarding general code development, the SSC and CPT outstanding requests continue to be as follows:*

1. *add the ability to conduct retrospective analyses*

   Progress was limited in implementing this feature. We will conduct a retrospective analysis within the next year.

2. *Continued exploration of data weighting (Francis and other approaches) and evaluation of models with and without the 1998 natural mortality spike. The authors are encouraged to bring other models forward for CPT and SSC consideration*

   We continued with the iterative re-weighting for composition data.

Comment: *Breakpoint analysis for reference point time frames that does not rely on stock-recruit relationship*

We applied the STARS method to the recruitment time series, Appendix C.

Comment: *Regarding rebuilding projection specifications and options, the SSC and CPT requests are:*

1. *bring forth reference points for status determination for both regim time frames*

   See reference point table (Table 3). Completed

2. *bring forth projections 1 and 5 from the May CPT, both with mean recruitment 1) current time frame (1978-2018) and 2) breakpt time period (1996-2018)*

   Completed. Refer to Appendix C.

C. Introduction

Scientific Name

The blue king crab is a lithodid crab, *Paralithodes platypus* (Brant 1850).

Distribution

Blue king crab are sporadically distributed throughout the North Pacific Ocean from Hokkaido, Japan, to southeastern Alaska (Figure 1). In the eastern Bering Sea small populations are distributed around St. Matthew Island, the Pribilof Islands, St. Lawrence Island, and Nunivak Island. Isolated populations also exist in some other cold water areas of the Gulf of Alaska (NPFMC 1998). The St. Matthew Island Section for blue king crab is within Area Q2 (Figure 2), which is the Northern District of the Bering Sea king crab registration area and includes the waters north of Cape Newenham (58°39’ N. lat.) and south of Cape Romanzof (61°49’ N. lat.).

Stock Structure

The Alaska Department of Fish and Game (ADF&G) Gene Conservation Laboratory, has detected regional population differences between blue king crab collected from St. Matthew Island and the Pribilof Islands[2]. The NMFS tag-return data from studies on blue king crab in the Pribilof Islands and St. Matthew Island support the idea that legal-sized males do not migrate between the two areas (Otto and Cummiskey 1990). St. Matthew Island blue king crab tend to be smaller than their Pribilof conspecifics, and the two stocks are managed separately.

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[2] NOAA grant Bering Sea Crab Research II, NA16FN2621, 1997.

Life History

Like the red king crab, *Paralithodes camtshaticus*, the blue king crab is considered a shallow water species by comparison with other lithodids such as golden king crab, *Lithodes aequispinus*, and the scarlet king crab, *Lithodes couesi* (Donaldson and Byersdorfer 2005). Adult male blue king crab are found at an average depth of 70 m (NPFMC 1998). The reproductive cycle appears to be annual for the first two reproductive cycles and biennial thereafter (Jensen and Armstrong 1989), and mature crab seasonally migrate inshore where they molt and mate. Unlike red king crab, juvenile blue king crab do not form pods, but instead rely on cryptic coloration for protection from predators and require suitable habitat such as cobble and shell hash. Somerton and MacIntosh (1983) estimated SMBKC male size at sexual maturity to be 77 mm carapace length (CL). Paul et al. (1991) found that spermatophores were present in the vas deferens of 50% of the St. Matthew Island blue king crab males examined with sizes of 40-49 mm CL and in 100% of the males at least 100 mm CL. Spermataphore diameter also increased with increasing CL with an asymptote at ~ 100 mm CL. It was noted, however, that although spermataphore presence indicates physiological sexual maturity, it may not be an indicator of functional sexual maturity. For purposes of management of the St. Matthew Island blue king crab fishery, the State of Alaska uses 105 mm CL to define the lower size bound of functionally mature males (Pengilly and Schmidt 1995). Otto and Cummiskey (1990) report an average growth increment of 14.1 mm CL for adult SMBKC males.

Management History

The SMBKC fishery developed subsequent to baseline ecological studies associated with oil exploration (Otto 1990). Ten U.S. vessels harvested 545 t (1.202 million pounds) in 1977, and harvests peaked in 1983 when 164 vessels landed 4,288 t (9.454 million pounds) (Fitch et al. 2012; Table 7).

The fishing seasons were generally short, often lasting only a few days. The fishery was declared overfished and closed in 1999 when the stock biomass estimate was below the minimum stock-size threshold (MSST) of 4,990 t (11.0 million pounds) as defined by the Fishery Management Plan (FMP) for the Bering Sea/Aleutian Islands King and Tanner crabs (NPFMC 1999). Zheng and Kruse (2002) hypothesized a high level of SMBKC natural mortality from 1998 to 1999 as an explanation for the low catch per unit effort (CPUE) in the 1998/99 commercial fishery and the low numbers across all male crab size groups caught in the annual NMFS eastern Bering Sea trawl survey from 1999 to 2005 (see survey data in next section). In November 2000, Amendment 15 to the FMP for Bering Sea/Aleutian Islands king and Tanner crabs was approved to implement a rebuilding plan for the SMBKC stock (NPFMC 2000). The rebuilding plan included a State of Alaska regulatory harvest strategy (*5 AAC 34.917*), area closures, and gear modifications. In addition, commercial crab fisheries near St. Matthew Island were scheduled in fall and early winter to reduce the potential for bycatch mortality of vulnerable molting and mating crab.

NMFS declared the stock rebuilt on 21 September 2009, and the fishery was reopened after a 10-year closure on 15 October 2009 with a TAC of 529 t (1.167 million pounds), closing again by regulation on 1 February 2010. Seven participating vessels landed a catch of 209 t (0.461 million pounds) with a reported effort of 10,697 pot lifts and an estimated CPUE of 9.9 retained individual crab per pot lift. The fishery remained open the next three years with modest harvests and similar CPUE, but large declines in the NMFS trawl-survey estimate of stock abundance raised concerns about the health of the stock. This prompted ADF&G to close the fishery again for the 2013/14 season. The fishery was reopened for the 2014/15 season with a low TAC of 297 t (0.655 million pounds) and in 2015/16 the TAC was further reduced to 186 t (0.411 million pounds) then completely closed the 2016/17 season.

Although historical observer data are limited due to low sampling effort, bycatch of female and sublegal male crab from the directed blue king crab fishery off St. Matthew Island was relatively high historically, with estimated total bycatch in terms of number of crab captured sometimes more than twice as high as the catch of legal crab (Moore et al. 2000; ADF&G Crab Observer Database). Pot-lift sampling by ADF&G crab observers (Gaeuman 2013; ADF&G Crab Observer Database) indicates similar bycatch rates of discarded male crab since the reopening of the fishery (Table 5), with total male discard mortality in the 2012/13 directed fishery estimated at about 12% (88 t or 0.193 million pounds) of the reported retained catch weight, assuming 20% handling mortality.

These data suggest a reduction in the bycatch of females, which may be attributable to the later timing of the contemporary fishery and the more offshore distribution of fishery effort since reopening in 2009/10[3]. Some bycatch of discarded blue king crab has also been observed historically in the eastern Bering Sea snow crab fishery, but in recent years it has generally been negligible. The St. Matthew Island golden king crab fishery, the third commercial crab fishery to have taken place in the area, typically occurred in areas with depths exceeding blue king crab distribution. The NMFS observer data suggest that variable, but mostly limited, SMBKC bycatch has also occurred in the eastern Bering Sea groundfish fisheries (Table 6).

D. Data

Summary of New Information

Data used in this assessment were updated to include the most recently available fishery and survey numbers. This assessment uses one new survey data point, which is the 2019 NMFS trawl-survey estimate of abudance, and its associated size compositon data. The assessment also uses updated 1993-2018 groundfish and fixed gear bycatch estimates based on AKRO data. The fishery was closed in 2018/19 so no directed fishery catch data were available. The data used in each of the new models is shown in Figure 3.

Major Data Sources

Major data sources used in this assessment include annual directed-fishery retained-catch statistics from fish tickets (1978/79-1998/99, 2009/10-2012/13, and 2014/15-2015/16; Table 7); results from the annual NMFS eastern Bering Sea trawl survey (1978-2019; Table 8); results from the ADF&G SMBKC pot survey (every third year during 1995-2013, then 2015-2018; Table 9); mean somatic mass given length category by year (Table 10); size-frequency information from ADF&G crab-observer pot-lift sampling (1990/91-1998/99, 2009/10-2012/13, and 2014/15-2016/17; Table 5); and the NMFS groundfish-observer bycatch biomass estimates (1992/93-2018/19; Table 6).

Figure 4 maps stations from which SMBKC trawl-survey and pot-survey data were obtained. Further information concerning the NMFS trawl survey as it relates to commercial crab species is available in Daly et al. (2014); see Gish et al. (2012) for a description of ADF&G SMBKC pot-survey methods. It should be noted that the two surveys cover different geographic regions and that each has in some years encountered proportionally large numbers of male blue king crab in areas not covered by the other survey (Figure 5). Crab-observer sampling protocols are detailed in the crab-observer training manual (ADF&G 2013). Groundfish SMBKC bycatch data come from the NMFS Regional office and have been compiled to coincide with the SMBKC management area.

Other Data Sources

The growth transition matrix used is based on Otto and Cummiskey (1990), as in the past. Other relevant data sources, including assumed population and fishery parameters, are presented in Appendix A, which also provides a detailed description of the model configuration used for this assessment.

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[3] D. Pengilly, ADF&G, pers. comm.

E. Analytic Approach

History of Modeling Approaches for this Stock

A four-stage catch-survey-analysis (CSA) assessment model was used before 2011 to estimate abundance and biomass and prescribe fishery quotas for the SMBKC stock. The four-stage CSA is similar to a full length-based analysis, the major difference being coarser length groups, which are more suited to a small stock with consistently low survey catches. In this approach, the abundance of male crab with a CL $\geq$ 90 mm is modeled in terms of four crab stages: stage 1: 90-104 mm CL; stage 2: 105-119 mm CL; stage 3: newshell 120-133 mm CL; and stage 4: oldshell $\geq$ 120 mm CL and newshell $\geq$ 134 mm CL. Motivation for these stage definitions comes from the fact that for management of the SMBKC stock, male crab measuring $\geq$ 105 mm CL are considered mature, whereas 120 mm CL is considered a proxy for the legal size of 5.5 in carapace width, including spines. Additional motivation for these stage definitions comes from an estimated average growth increment of about 14 mm per molt for SMBKC (Otto and Cummiskey 1990).

Concerns about the pre-2011 assessment model led to the CPT and SSC recommendations that included development of an alternative model with provisional assessment based on survey biomass or some other index of abundance. An alternative 3-stage model was proposed to the CPT in May 2011, but a survey-based approach was requested for the Fall 2011 assessment. In May 2012 the CPT approved a slightly revised and better documented version of the alternative model for assessment. Subsequently, the model developed and used since 2012 was a variant of the previous four-stage SMBKC CSA model and similar in complexity to that described by Collie et al. (2005). Like the earlier model, it considered only male crab $\geq$ 90 mm in CL, but combined stages 3 and 4 of the earlier model, resulting in three stages (male size classes) defined by CL measurements of (1) 90-104 mm, (2) 105-119 mm, and (3) 120 mm+ (i.e., 120 mm and above). This consolidation was driven by concern about the accuracy and consistency of shell-condition information, which had been used in distinguishing stages 3 and 4 of the earlier model.

In 2016 the accepted SMBKC assessment model made use of the modeling framework Gmacs (Webber et al. 2016). In that assessment, an effort was made to match the 2015 SMBKC stock assessment model to bridge a framework which provided greater flexibility and opportunity to evaluate model assumptions more fully.

Assessment Methodology

This assessment model again uses the modeling framework Gmacs and is detailed in Appendix A.

Model Selection and Evaluation

Four models are presented with the reference model being the same configuration as approved last year (Ianelli et al. 2018), two sensitivities are considered, one which weights the survey data more heavily and one that adds an additional CV on the ADF&G pot survey data. In addition to these sensitivities, we evaluated the impacts of adding new data to the reference model. In summary, the following lists the models presented and the naming convention used:

1. **18.0 - 2018 Model**: the 2018 recommended model without any new data
2. **19.0 - 2019 Reference Model**: new data for 2019: NMFS trawl-survey and bycatch updates for groundfish
3. **19.0a - 2019 Model - alt reference pts**: model 19.0 with alternative time frames for reference points and projections
4. **19.1 - fit survey**: an exploratory scenario that's the same as the reference model except the NMFS trawl survey is up-weighted by $\lambda^{\mathrm{NMFS}} = 1.5$ and the ADF&G pot survey is up-weighted by $\lambda^{\mathrm{ADFG}} = 2$.

5. **19.2 - add CV pot**: includes an estimated additional CV on the ADF&G pot survey

Note that SSC convention would label these (item 2 above) as model 16.0 (the model first developed in that year). Since only a few models are presented here, for simplicity we labeled model 16.0 as "reference" and for the others, we used the simple naming convention presented above.

Results

a. Sensitivity to new data

Results for scenarios are provided with comparisons to the 2018 model and sensitivity to new 2019 data are shown in Figures 6 and 7 with recruitment and spawning biomass shown in Figures 8 and 9, respectively. The fits to survey CPUEs and spawning biomass show that the addition of new data results in a slight increase compared to the 2018 assessment. However, neither last years or this years reference model capture the recent survey declines in the ADF&G pot survey, or fit post 2005 trawl survey data points well.

b. Effective sample sizes and weighting factors

Observed and estimated effective sample sizes are compared in Table 11. Data weighting factors, standard deviation of normalized residuals (SDNRs), and median absolute residual (MAR) are presented in Table 16. The SDNR for the trawl survey is acceptable at 1.66 in the reference model. Francis (2011) weighting was applied in 2017 but given the relatively few size bins in this assessment, this application was suspended this year.
The SDNRs for the pot surveys show a similar pattern in each of the scenarios, but are much higher suggesting an inconsistency between the pot survey data and the model structure and other data components. Rather than re-weighting, we chose to retain the values as specified, noting that down-weighting these data would effectively exclude the signal from this series. The MAR values for the trawl and pot surveys shows the same pattern among each of the scenarios as the SDNR. The MAR values for the trawl survey and pot survey size compositions were relatively good, ranging from 0.60 to 0.65 for the reference case. The SDNRs for the directed pot fishery and other size compositions were similar to previous estimates.

c. Parameter estimates

Model parameter estimates for each of the Gmacs scenarios are summarized in Tables 12, 13, and 14. These parameter estimates are compared in Table 15. Negative log-likelihood values and management measures for each of the model configurations are compared in Tables 4 through 17.

There are some differences in parameter estimates among models as reflected in the log-likelihood components and the management quantities. The parameter estimates in the "fit survey" and "add CV pot" scenarios differ the most, as expected, particularly the estimate of the ADF&G pot survey catchability (q) (see Table 15). Also, the residuals for recruitment in the first size group are large for these model runs, presumably because higher estimates of recruits in some years are required by the model to match the observed biomass trends.

Selectivity estimates show some variability between models (Figure 10). Estimated recruitment is variable over time for all models and in recent years is well below average (Figure 11). Estimated mature male biomass on 15 February also fluctuates considerably (Figure 12). Estimated natural mortality each year (M_t) is presented in Figure 13.

Estimates of fishing morality, from the reference model, are shown to assist with the rebuilding and reference point time frame discussions (Figure 26). Fishing mortality can not be ruled out as being an influential factor in the current stock status.

d. Evaluation of the fit to the data.

The model fits to total male ($\geq$ 90 mm CL) trawl survey biomass tend to miss the recent peak around 2010, and fits recent survey data points on the lower end of their error bars (Figures 14). These fits are most likely being pulled down by the recent decline in the ADF&G pot survey data points, since the **add CV pot** model captures the upward error bars for these data points when it is allowed to fit the ADF&G pot survey data very poorly. All of the models fit the pot survey CPUE poorly (Figure 15), with the **add CV pot** model having the worst fit due to the addition of variability (Figure 16). For the trawl survey the standardized residuals have similar patterns with the exception of recent years for the **add CV pot** model (19.2), generally poor fit to the last 15 years of data (Figure 17). The standardized residuals for the ADF&G pot survey have similar patterns but are much larger for the “add CV pot” model than the others, for obvious reasons (Figure 18).

Fits to the size compositions for trawl survey, pot survey, and commercial observer data are reasonable but miss the largest size category in some years (Figures 19, 20, and 21) for all scenarios. Representative residual plots of the composition data fits are generally poor (Figures 22, 23 and 24). The model fits to different types of retained and discarded catch values performed as expected given the assumed levels of uncertainty on the input data (Figure 25).

Unsurprisingly, the **fit surveys** model fits the the NMFS survey biomass and ADF&G pot survey CPUE data better but still has a similar residual pattern (Figures 14 and 15). It is worth noting that that this scenario (included for exploratory purposes) resulted in worse SDNR and MAR values for the two abundance indices.

e. Retrospective and historical analyses

This is only the third year a formal assessment model developed for this stock. As such, retrospective patterns and historical analyses relative to fisheries impacts are limited.

f. Uncertainty and sensitivity analyses.

Estimated standard deviations of parameters and selected management measures for the models are summarized in Tables 12, 13, and 14 (compiled in Table 15). Probabilities for mature male biomass and OFL in 2019 are presented in Section F.

g. Comparison of alternative model scenarios.

The estimates of mature male biomass (Figure 12), for the **fit survey** sensitivity differs from the other models due to a low value for pot survey catchability being estimated (which tends to scale the population estimate). Difference in the mature male biomass since 2010 in the **add CV pot** model are due to the model following the trajectory of the trawl survey and downweighting the declines in the pot survey. The **fit Survey** scenario upweights both the trawl and pot surveys abundance indices and represents a model run that places greater emphasis on the abundance indices. The **add CV pot** scenario places more emphasis on the trawl survey, essentially ignoring the pot survey results in more recent years (since 2010).

In summary, the use of the reference model for management purposes is preferred since it provides the best fit to all of the data and is consistent with previous model specifications. Research on alternative model specifications (e.g., natural mortality variability) was limited this year since the authors were focused on the time frame to estimate reference points and rebuilding projections (Appendix C). Consequently, the reference model appears reasonable and appropriate for ABC and OFL determinations for this stock in 2019. Additionally, the **fit surveys** and the **add CV pot** models provide conflicting conditions of this stock depending on which survey results are more believable. These conflicting results, in addition to the stock being in a overfished state, should highlight the caution needed providing management advice.

F. Calculation of the OFL and ABC

The overfishing level (OFL) is the fishery-related mortality biomass associated with fishing mortality F_{OFL}. The SMBKC stock is currently managed as Tier 4, and only a Tier 4 analysis is presented here. Thus, given stock estimates or suitable proxy values of B_{MSY} and F_{MSY}, along with two additional parameters α and β, F_{OFL} is determined by the control rule

$$F_{OFL} = \begin{cases} F_{MSY}, & \text{when } B/B_{MSY} > 1 \\ F_{MSY}\frac{(B/B_{MSY}-\alpha)}{(1-\alpha)}, & \text{when } \beta < B/B_{MSY} \leq 1 \end{cases} \tag{1}$$

$$F_{OFL} < F_{MSY} \text{ with directed fishery } F = 0 \text{ when } B/B_{MSY} \leq \beta$$

where B is quantified as mature-male biomass (MMB) at mating with time of mating assigned a nominal date of 15 February. Note that as B itself is a function of the fishing mortality F_{OFL} (therefore numerical approximation of F_{OFL} is required). As implemented for this assessment, all calculations proceed according to the model equations given in Appendix A. F_{OFL} is taken to be full-selection fishing mortality in the directed pot fishery and groundfish trawl and fixed-gear fishing mortalities set at their model geometric mean values over years for which there are data-based estimates of bycatch-mortality biomass.

The currently recommended Tier 4 convention is to use the full assessment period, currently 1978- 2018, to define a B_{MSY} proxy in terms of average estimated MMB and to set $\gamma = 1.0$ with assumed stock natural mortality $M = 0.18$ yr^{-1} in setting the F_{MSY} proxy value γM. The parameters α and β are assigned their default values $\alpha = 0.10$ and $\beta = 0.25$. The F_{OFL}, OFL, ABC, and MMB in 2019 for all scenarios are summarized in Table 4. The ABC is 80% of the OFL.

Table 4: Comparisons of management measures for the model scenarios. Biomass and OFL are in tons.

Component	model 19.0 (ref)	model 19.1 (fit survey)	model 19.2 (add CV pot)	model 19.0a (alt regime)
MMB_{2019}	1151.299	2537.418	3430.487	1151.299
B_{MSY}	3484.398	7645.093	3709.633	2052.737
MMB/B_{MSY}	0.310	0.285	0.834	0.508
F_{OFL}	0.042	0.000	0.147	0.082
OFL_{2019}	43.736	0.911	427.429	82.314
ABC_{2019}	34.989	0.729	341.943	65.852

G. Rebuilding Analysis

This stock was declared overfished in fall of 2018 and a rebuilding plan is being constructed concurrent to the 2019 stock assessment (Appendix C). Model scenarios presented here all suggest the stock is still overfished.

H. Data Gaps and Research Priorities

The following topics have been listed as areas where more research on SMBKC is needed:

1. Growth increments and molting probabilities as a function of size.
2. Trawl survey catchability and selectivities.
3. Temporal changes in spatial distributions near the island.
4. Natural mortality.

I. Projections and outlook

The outlook for recruitment is pessimistic and the abundance relative to the proxy B_{MSY} is low. The NMFS survey results in 2018 noted ocean conditions warmer than normal with an absence of a "cold pool" in the region. This could have detrimental effects on the SMBKC stocks and should be carefully monitored. Relative to the impact of historical fishing, we again conducted a "dynamic-B_0" analysis. This procedure simply projects the population based on estimated recruitment but removes the effect of fishing. For the reference case, this suggests that the impact of fishing has reduced the stock to about 52% of what it would have been in the absence of fishing (Figure 27). The other non-fishing contributors to the observed depleted stock trend (ignoring stock-recruit relationship) may reflect variable survival rates due to environmental conditions and also range shifts.

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Tables

Table 5: Observed proportion of crab by size class during the ADF&G crab observer pot-lift sampling. Source: ADF&G Crab Observer Database.

Year	Total pot lifts	Pot lifts sampled	Number of crab (90 mm+ CL)	Stage 1	Stage 2	Stage 3
1990/91	26,264	10	150	0.113	0.393	0.493
1991/92	37,104	125	3,393	0.133	0.177	0.690
1992/93	56,630	71	1,606	0.191	0.268	0.542
1993/94	58,647	84	2,241	0.281	0.210	0.510
1994/95	60,860	203	4,735	0.294	0.271	0.434
1995/96	48,560	47	663	0.148	0.212	0.640
1996/97	91,085	96	489	0.160	0.223	0.618
1997/98	81,117	133	3,195	0.182	0.205	0.613
1998/99	91,826	135	1.322	0.193	0.216	0.591
1999/00 - 2008/09			FISHERY CLOSED			
2009/10	10,484	989	19,802	0.141	0.324	0.535
2010/11	29,356	2,419	45,466	0.131	0.315	0.553
2011/12	48,554	3,359	58,666	0.131	0.305	0.564
2012/13	37,065	2,841	57,298	0.141	0.318	0.541
2013/14			FISHERY CLOSED			
2014/15	10,133	895	9,906	0.094	0.228	0.679
2015/16	5,475	419	3,248	0.115	0.252	0.633
2016/17 - 2018/19			FISHERY CLOSED			

Table 6: Groundfish SMBKC male bycatch biomass (t) estimates. Trawl includes pelagic trawl and non-pelagic trawl types. Source: J. Zheng, ADF&G, and author estimates based on data from R. Foy, NMFS. Estimates used after 2008/09 are from NMFS Alaska Regional Office.

Year	Trawl bycatch	Fixed gear bycatch
1978	0.000	0.000
1979	0.000	0.000
1980	0.000	0.000
1981	0.000	0.000
1982	0.000	0.000
1983	0.000	0.000
1984	0.000	0.000
1985	0.000	0.000
1986	0.000	0.000
1987	0.000	0.000
1988	0.000	0.000
1989	0.000	0.000
1990	0.000	0.000
1991	3.538	0.045
1992	1.996	2.268
1993	1.542	0.500
1994	0.318	0.091
1995	0.635	0.136
1996	0.500	0.045
1997	0.500	0.181
1998	0.500	0.907
1999	0.500	1.361
2000	0.500	0.500
2001	0.500	0.862
2002	0.726	0.408
2003	0.998	1.134
2004	0.091	0.635
2005	0.500	0.590
2006	2.812	1.451
2007	0.045	69.717
2008	0.272	6.622
2009	0.638	7.522
2010	0.360	9.564
2011	0.170	0.796
2012	0.011	0.739
2013	0.163	0.341
2014	0.010	0.490
2015	0.010	0.711
2016	0.229	1.633
2017	0.052	6.032
2018	0.001	1.281

Table 7: Fishery characteristics and update. Columns include the 1978/79 to 2015/16 directed St. Matthew Island blue king crab pot fishery. The Guideline Harvest Level (GHL) and Total Allowable Catch (TAC) are in millions of pounds. Harvest includes deadloss. Catch per unit effort (CPUE) in this table is simply the harvest number / pot lifts. The average weight is the harvest weight / harvest number in pounds. The average CL is the average of retained crab in mm from dockside sampling of delivered crab. Source: Fitch et al 2012; ADF&G Dutch Harbor staff, pers. comm. Note that management (GHL) units are in pounds, for conserving space, conversion to tons is ommitted.

			Harvest					
Year	Dates	GHL/TAC	Crab	Pounds	Pot lifts	CPUE	avg wt	avg CL
1978/79	07/15 - 09/03		436,126	1,984,251	43,754	10	4.5	132.2
1979/80	07/15 - 08/24		52,966	210,819	9,877	5	4.0	128.8
1980/81	07/15 - 09/03			CONFIDENTIAL				
1981/82	07/15 - 08/21		1,045,619	4,627,761	58,550	18	4.4	NA
1982/83	08/01 - 08/16		1,935,886	8,844,789	165,618	12	4.6	135.1
1983/84	08/20 - 09/06	8.0	1,931,990	9,454,323	133,944	14	4.9	137.2
1984/85	09/01 - 09/08	2.0-4.0	841,017	3,764,592	73,320	11	4.5	135.5
1985/86	09/01 - 09/06	0.9-1.9	436,021	2,175,087	46,988	9	5.0	139.0
1986/87	09/01 - 09/06	0.2-0.5	219,548	1,003,162	22,073	10	4.6	134.3
1987/88	09/01 - 09/05	0.6-1.3	227,447	1,039,779	28,230	8	4.6	134.1
1988/89	09/01 - 09/05	0.7-1.5	280,401	1,236,462	21,678	13	4.4	133.3
1989/90	09/01 - 09/04	1.7	247,641	1,166,258	30,803	8	4.7	134.6
1990/91	09/01 - 09/07	1.9	391,405	1,725,349	26,264	15	4.4	134.3
1991/92	09/16 - 09/20	3.2	726,519	3,372,066	37,104	20	4.6	134.1
1992/93	09/04 - 09/07	3.1	545,222	2,475,916	56,630	10	4.5	134.1
1993/94	09/15 - 09/21	4.4	630,353	3,003,089	58,647	11	4.8	135.4
1994/95	09/15 - 09/22	3.0	827,015	3,764,262	60,860	14	4.9	133.3
1995/96	09/15 - 09/20	2.4	666,905	3,166,093	48,560	14	4.7	135.0
1996/97	09/15 - 09/23	4.3	660,665	3,078,959	91,085	7	4.7	134.6
1997/98	09/15 - 09/22	5.0	939,822	4,649,660	81,117	12	4.9	139.5
1998/99	09/15 - 09/26	4.0	635,370	2,968,573	91,826	7	4.7	135.8
1999/00 - 2008/09				FISHERY CLOSED				
2009/10	10/15 - 02/01	1.17	103,376	460,859	10,697	10	4.5	134.9
2010/11	10/15 - 02/01	1.60	298,669	1,263,982	29,344	10	4.2	129.3
2011/12	10/15 - 02/01	2.54	437,862	1,881,322	48,554	9	4.3	130.0
2012/13	10/15 - 02/01	1.63	379,386	1,616,054	37,065	10	4.3	129.8
2013/14				FISHERY CLOSED				
2014/15	10/15 - 02/05	0.66	69,109	308,582	10,133	7	4.5	132.3
2015/16	10/19 - 11/28	0.41	24,076	105,010	5,475	4	4.4	132.6
2016/17				FISHERY CLOSED				
2017/18				FISHERY CLOSED				
2018/19				FISHERY CLOSED				

Table 8: NMFS EBS trawl-survey area-swept estimates of male crab abundance (10^6 crab) and male (≥ 90 mm CL) biomass (10^6 lbs). Total number of captured male crab ≥ 90 mm CL is also given. Source: R. Foy, NMFS. The "+" refer to plus group.

	Abundance					Biomass		
Year	Stage-1 (90-104 mm)	Stage-2 (105-119 mm)	Stage-3 (120+ mm)	Total	CV	Total (90+ mm CL)	CV	Number of crabs
1978	2.213	1.991	1.521	5.726	0.411	15.064	0.394	157
1979	3.061	2.281	1.808	7.150	0.472	17.615	0.463	178
1980	2.856	2.563	2.541	7.959	0.572	22.017	0.507	185
1981	0.483	1.213	2.263	3.960	0.368	14.443	0.402	140
1982	1.669	2.431	5.884	9.984	0.401	35.763	0.344	271
1983	1.061	1.651	3.345	6.057	0.332	21.240	0.298	231
1984	0.435	0.497	1.452	2.383	0.175	8.976	0.179	105
1985	0.379	0.376	1.117	1.872	0.216	6.858	0.210	93
1986	0.203	0.447	0.374	1.025	0.428	3.124	0.388	46
1987	0.325	0.631	0.715	1.671	0.302	5.024	0.291	71
1988	0.410	0.816	0.957	2.183	0.285	6.963	0.252	81
1989	2.169	1.154	1.786	5.109	0.314	13.974	0.271	208
1990	1.053	1.031	2.338	4.422	0.302	14.837	0.274	170
1991	1.147	1.665	2.233	5.046	0.259	15.318	0.248	197
1992	1.074	1.382	2.291	4.746	0.206	15.638	0.201	220
1993	1.521	1.828	3.276	6.626	0.185	21.051	0.169	324
1994	0.883	1.298	2.257	4.438	0.187	14.416	0.176	211
1995	1.025	1.188	1.741	3.953	0.187	12.574	0.178	178
1996	1.238	1.891	3.064	6.193	0.263	20.746	0.241	285
1997	1.165	2.228	3.789	7.182	0.367	24.084	0.337	296
1998	0.660	1.661	2.849	5.170	0.373	17.586	0.355	243
1998	0.223	0.222	0.558	1.003	0.192	3.515	0.182	52
2000	0.282	0.285	0.740	1.307	0.303	4.623	0.310	61
2001	0.419	0.502	0.938	1.859	0.243	6.242	0.245	91
2002	0.111	0.230	0.640	0.981	0.311	3.820	0.320	38
2003	0.449	0.280	0.465	1.194	0.399	3.454	0.336	65
2004	0.247	0.184	0.562	0.993	0.369	3.360	0.305	48
2005	0.319	0.310	0.501	1.130	0.403	3.620	0.371	42
2006	0.917	0.642	1.240	2.798	0.339	8.585	0.334	126
2007	2.518	2.020	1.193	5.730	0.420	14.266	0.385	250
2008	1.352	0.801	1.457	3.609	0.289	10.261	0.284	167
2009	1.573	2.161	1.410	5.144	0.263	13.892	0.256	251
2010	3.937	3.253	2.458	9.648	0.544	24.539	0.466	388
2011	1.800	3.255	3.207	8.263	0.587	24.099	0.558	318
2012	0.705	1.970	1.808	4.483	0.361	13.669	0.339	193
2013	0.335	0.452	0.807	1.593	0.215	5.043	0.217	74
2014	0.723	1.627	1.809	4.160	0.503	13.292	0.449	181
2015	0.992	1.269	1.979	4.240	0.774	12.958	0.770	153
2016	0.535	0.660	1.178	2.373	0.447	7.685	0.393	108
2017	0.091	0.323	0.663	1.077	0.657	3.955	0.600	42
2018	0.154	0.232	0.660	1.047	0.298	3.816	0.281	62
2019	0.403	0.482	1.170	2.056	0.352	6.990	0.337	105

Table 9: Size-class and total CPUE (90+ mm CL) with estimated CV and total number of captured crab (90+ mm CL) from the 96 common stations surveyed during the ADF&G SMBKC pot surveys. Source: ADF&G.

Year	Stage-1 (90-104 mm)	Stage-2 (105-119 mm)	Stage-3 (120+ mm)	Total CPUE	CV	Number of crabs
1995	1.919	3.198	6.922	12.042	0.13	4624
1998	0.964	2.763	8.804	12.531	0.06	4812
2001	1.266	1.737	5.487	8.477	0.08	3255
2004	0.112	0.414	1.141	1.667	0.15	640
2007	1.086	2.721	4.836	8.643	0.09	3319
2010	1.326	3.276	5.607	10.209	0.13	3920
2013	0.878	1.398	3.367	5.643	0.19	2167
2015	0.198	0.682	1.924	2.805	0.18	1077
2016	0.198	0.456	1.724	2.378	0.19	777
2017	0.177	0.429	1.083	1.689	0.25	643
2018	0.076	0.161	0.508	0.745	0.14	286

Table 10: Mean weight (kg) by stage in used in all of the models (provided as a vector of weights at length each year to Gmacs).

Year	Stage-1	Stage-2	Stage-3
1978	0.7	1.2	1.9
1979	0.7	1.2	1.7
1980	0.7	1.2	1.9
1981	0.7	1.2	1.9
1982	0.7	1.2	1.9
1983	0.7	1.2	2.1
1984	0.7	1.2	1.9
1985	0.7	1.2	2.1
1986	0.7	1.2	1.9
1987	0.7	1.2	1.9
1988	0.7	1.2	1.9
1989	0.7	1.2	2.0
1990	0.7	1.2	1.9
1991	0.7	1.2	2.0
1992	0.7	1.2	1.9
1993	0.7	1.2	2.0
1994	0.7	1.2	1.9
1995	0.7	1.2	2.0
1996	0.7	1.2	2.0
1997	0.7	1.2	2.1
1998	0.7	1.2	2.0
1999	0.7	1.2	1.9
2000	0.7	1.2	1.9
2001	0.7	1.2	1.9
2002	0.7	1.2	1.9
2003	0.7	1.2	1.9
2004	0.7	1.2	1.9
2005	0.7	1.2	1.9
2006	0.7	1.2	1.9
2007	0.7	1.2	1.9
2008	0.7	1.2	1.9
2009	0.7	1.2	1.9
2010	0.7	1.2	1.8
2011	0.7	1.2	1.8
2012	0.7	1.2	1.8
2013	0.7	1.2	1.9
2014	0.7	1.2	1.9
2015	0.7	1.2	1.9
2016	0.7	1.2	1.9
2017	0.7	1.2	1.9
2018	0.7	1.2	1.9

Table 11: Observed and input sample sizes for observer data from the directed pot fishery, the NMFS trawl survey, and the ADF&G pot survey.

	Number measured			Input sample sizes		
Year	Observer pot	NMFS trawl	ADF&G pot	Observer pot	NMFS trawl	ADF&G pot
1978		157			50	
1979		178			50	
1980		185			50	
1981		140			50	
1982		271			50	
1983		231			50	
1984		105			50	
1985		93			46.5	
1986		46			23	
1987		71			35.5	
1988		81			40.5	
1989		208			50	
1990	150	170		15	50	
1991	3393	197		25	50	
1992	1606	220		25	50	
1993	2241	324		25	50	
1994	4735	211		25	50	
1995	663	178	4624	25	50	100
1996	489	285		25	50	
1997	3195	296		25	50	
1998	1323	243	4812	25	50	100
1999		52			26	
2000		61			30.5	
2001		91	3255		45.5	100
2002		38			19	
2003		65			32.5	
2004		48	640		24	100
2005		42			21	
2006		126			50	
2007		250	3319		50	100
2008		167			50	
2009	19802	251		50	50	
2010	45466	388	3920	50	50	100
2011	58667	318		50	50	
2012	57282	193		50	50	
2013		74	2167		37	100
2014	9906	181		50	50	
2015	3248	153	1077	50	50	100
2016		108	777		50	100
2017		42	643		21	100
2018		62	286		31	100
2019		105			50	

Table 12: Model parameter estimates, selected derived quantities, and their standard deviations (SD) for the reference (19.0) model.

Parameter	Estimate	SD
Natural mortality deviation in 1998/99 (δ^M_{1998})	1.582	0.137
$\log(\bar{R})$	13.912	0.045
$\log(n^0_1)$	14.963	0.175
$\log(n^0_2)$	14.532	0.210
$\log(n^0_3)$	14.349	0.206
q_{pot}	3.733	0.248
$\log(\bar{F}^{\text{df}})$	-2.159	0.052
$\log(\bar{F}^{\text{tb}})$	-9.457	0.074
$\log(\bar{F}^{\text{fb}})$	-8.154	0.074
log Stage-1 directed pot selectivity 1978-2008	-0.804	0.179
log Stage-2 directed pot selectivity 1978-2008	-0.436	0.128
log Stage-1 directed pot selectivity 2009-2017	-0.470	0.161
log Stage-2 directed pot selectivity 2009-2017	-0.000	0.000
log Stage-1 NMFS trawl selectivity	-0.309	0.065
log Stage-2 NMFS trawl selectivity	-0.000	0.000
log Stage-1 ADF&G pot selectivity	-0.713	0.125
log Stage-2 ADF&G pot selectivity	-0.000	0.000
F_{OFL}	0.042	0.005
OFL	43.736	9.254

Table 13: Model parameter estimates, selected derived quantities, and their standard deviations (SD) for the 'fit surveys' (19.1) model.

Parameter	Estimate	SD
Natural mortality deviation in 1998/99 (δ^M_{1998})	1.746	0.088
$\log(\bar{R})$	14.233	0.048
$\log(n^0_1)$	15.288	0.179
$\log(n^0_2)$	15.065	0.201
$\log(n^0_3)$	14.844	0.204
q_{pot}	1.399	0.058
$\log(\bar{F}^{\text{df}})$	-2.921	0.039
$\log(\bar{F}^{\text{tb}})$	-10.000	0.000
$\log(\bar{F}^{\text{fb}})$	-8.993	0.066
log Stage-1 directed pot selectivity 1978-2008	-0.485	0.172
log Stage-2 directed pot selectivity 1978-2008	-0.091	0.123
log Stage-1 directed pot selectivity 2009-2017	-0.000	0.000
log Stage-2 directed pot selectivity 2009-2017	-0.000	0.000
log Stage-1 NMFS trawl selectivity	-0.068	0.067
log Stage-2 NMFS trawl selectivity	-0.000	0.000
log Stage-1 ADF&G pot selectivity	-0.000	0.000
log Stage-2 ADF&G pot selectivity	-0.000	0.000
F_{OFL}	0.000	0.000
OFL	0.911	0.175

Table 14: Model parameter estimates, selected derived quantities, and their standard deviations (SD) for the 'add CV pot' (19.2) model.

Parameter	Estimate	SD
Natural mortality deviation in 1998/99 (δ^M_{1998})	1.860	0.206
$\log(\bar{R})$	14.216	0.053
$\log(n^0_1)$	14.962	0.174
$\log(n^0_2)$	14.482	0.211
$\log(n^0_3)$	14.313	0.205
q_{pot}	2.135	0.445
$\log(\bar{F}^{\mathrm{df}})$	-2.359	0.055
$\log(\bar{F}^{\mathrm{tb}})$	-9.656	0.079
$\log(\bar{F}^{\mathrm{fb}})$	-8.355	0.079
log Stage-1 directed pot selectivity 1978-2008	-0.784	0.179
log Stage-2 directed pot selectivity 1978-2008	-0.423	0.130
log Stage-1 directed pot selectivity 2009-2017	-0.902	0.178
log Stage-2 directed pot selectivity 2009-2017	-0.000	0.000
log Stage-1 NMFS trawl selectivity	-0.369	0.063
log Stage-2 NMFS trawl selectivity	-0.000	0.000
log Stage-1 ADF&G pot selectivity	-1.064	0.122
log Stage-2 ADF&G pot selectivity	-0.134	0.074
log add CV_{pot}	-0.351	0.144
F_{OFL}	0.147	0.018
OFL	427.429	99.801

Table 15: Comparisons of parameter estimates for the model scenarios.

Parameter	Ref	FitSurvey	addCVpot
$\log(\bar{F}^{\mathrm{df}})$	-2.159	-2.921	-2.359
$\log(\bar{F}^{\mathrm{fb}})$	-8.154	-8.993	-8.355
$\log(\bar{F}^{\mathrm{tb}})$	-9.457	-10.000	-9.656
$\log(\bar{R})$	13.912	14.233	14.216
$\log(n^0_1)$	14.963	15.288	14.962
$\log(n^0_2)$	14.532	15.065	14.482
$\log(n^0_3)$	14.349	14.844	14.313
F_{OFL}	0.050	0.000	0.147
q_{pot}	3.733	1.399	2.135
log Stage-1 ADF&G pot selectivity	-0.713	-0.000	-1.064
log Stage-1 directed pot selectivity 1978-2008	-0.804	-0.485	-0.784
log Stage-1 directed pot selectivity 2009-2017	-0.470	-0.000	-0.902
log Stage-1 NMFS trawl selectivity	-0.309	-0.068	-0.369
log Stage-2 ADF&G pot selectivity	-0.000	-0.000	-0.134
log Stage-2 directed pot selectivity 1978-2008	-0.436	-0.091	-0.423
log Stage-2 directed pot selectivity 2009-2017	-0.000	-0.000	-0.000
log Stage-2 NMFS trawl selectivity	-0.000	-0.000	-0.000
Natural mortality deviation in 1998/99 (δ^M_{1998})	1.582	1.746	1.860
OFL	57.464	0.911	427.429

Table 16: Comparisons of data weights, SDNR and MAR (standard deviation of normalized residuals and median absolute residual) values for the model scenarios.

Component	model 19.0 (ref)	model 19.1 (fit survey)	model 19.2 (add CV pot)
NMFS trawl survey weight	1.00	1.50	1.00
ADF&G pot survey weight	1.00	2.00	1.00
Directed pot LF weight	1.00	1.00	1.00
NMFS trawl survey LF weight	1.00	1.00	1.00
ADF&G pot survey LF weight	1.00	1.00	1.00
SDNR NMFS trawl survey	1.66	2.24	1.42
SDNR ADF&G pot survey	4.36	6.64	8.32
SDNR directed pot LF	0.70	1.03	0.64
SDNR NMFS trawl survey LF	1.30	1.80	1.03
SDNR ADF&G pot survey LF	0.95	2.83	0.67
MAR NMFS trawl survey	1.35	1.52	1.18
MAR ADF&G pot survey	2.76	3.42	4.07
MAR directed pot LF	0.52	0.64	0.36
MAR NMFS trawl survey LF	0.60	0.84	0.51
MAR ADF&G pot survey LF	0.65	1.99	0.56

Table 17: Comparisons of negative log-likelihood values for the selected model scenarios. It is important to note that comparisons among models may be limited since the assumed variances are modified (e.g., **Fit surveys** model).

Component	19.0 (ref)	19.1 (fit survey)	19.2 (add CV pot)
Pot Retained Catch	-68.46	-66.12	-69.56
Pot Discarded Catch	5.15	30.71	3.20
Trawl bycatch Discarded Catch	-7.71	5.29	-7.71
Fixed bycatch Discarded Catch	-7.67	-7.68	-7.70
NMFS Trawl Survey	10.56	66.22	-7.87
ADF&G Pot Survey CPUE	85.62	219.49	6.30
Directed Pot LF	-103.93	-93.25	-105.46
NMFS Trawl LF	-252.96	-189.41	-276.80
ADF&G Pot LF	-91.09	-39.04	-97.37
Recruitment deviations	58.10	69.65	52.25
F penalty	9.66	9.66	9.66
M penalty	6.46	6.46	6.46
Prior	13.71	13.71	16.20
Total	-342.55	25.71	-478.40
Total estimated parameters	144.00	144.00	145.00

Table 18: Population abundances ($\boldsymbol{n}$) by crab stage in numbers of crab at the time of the survey and mature male biomass (MMB) in tons on 15 February for the **model configuration used in 2017**.

Year	n_1	n_2	n_3	MMB	CV MMB
1978	3149901	2026113	1691808	4627	0.177
1979	4406952	2386335	2320120	6531	0.123
1980	3777269	3285078	3513392	10382	0.083
1981	1439121	3229331	4921922	10816	0.063
1982	1622786	1836080	4944197	7698	0.072
1983	821366	1450607	3510769	4623	0.099
1984	671941	865303	2019469	3097	0.124
1985	943457	630172	1441282	2736	0.143
1986	1387169	717248	1221156	2678	0.139
1987	1347381	1004912	1314785	3161	0.127
1988	1251503	1076403	1524571	3450	0.123
1989	2889898	1044524	1679883	3943	0.118
1990	1869765	1956051	1979670	5042	0.093
1991	1933011	1669653	2453269	5049	0.094
1992	2082017	1589639	2406643	5216	0.086
1993	2341075	1662864	2511682	5447	0.078
1994	1585169	1823739	2578928	5186	0.073
1995	1852864	1441917	2463118	5033	0.074
1996	1740308	1479903	2356653	4813	0.076
1997	902302	1427751	2278132	4172	0.096
1998	639111	928069	1850726	2741	0.112
1999	372911	318597	713616	1693	0.105
2000	414886	317064	791944	1838	0.087
2001	376659	340465	860780	1993	0.079
2002	131970	326484	926346	2099	0.074
2003	297533	182946	950670	1982	0.075
2004	213183	229387	914205	1968	0.074
2005	475801	196960	899501	1903	0.075
2006	721959	335307	895860	2051	0.077
2007	456687	520406	985267	2397	0.077
2008	852808	425832	1113937	2560	0.062
2009	597966	624587	1225354	2600	0.058
2010	574487	535464	1292414	2136	0.060
2011	436291	474745	1108376	1500	0.073
2012	214022	361716	768850	913	0.115
2013	241596	206596	463647	1049	0.103
2014	151449	205539	514426	983	0.111
2015	167400	149336	481170	936	0.112
2016	268617	142863	469732	991	0.109
2017	163496	199675	489663	1086	0.108
2018	122409	158548	524010	1053	0.105

Table 19: Population abundances ($\boldsymbol{n}$) by crab stage in numbers of crab at the time of the survey (1 July, season 1) and mature male biomass (MMB) in tons on 15 February for the reference model.

Year	n_1	n_2	n_3	MMB	CV MMB
1978	3151217	2048032	1704813	4676	0.176
1979	4405644	2394327	2341979	6576	0.122
1980	3774514	3287008	3535569	10427	0.083
1981	1435061	3228410	4941160	10851	0.062
1982	1622665	1833539	4959495	7725	0.072
1983	826815	1449709	3522402	4646	0.099
1984	673504	867978	2029459	3119	0.123
1985	940551	631919	1451162	2759	0.143
1986	1398609	716293	1230084	2694	0.139
1987	1351732	1011045	1322901	3183	0.127
1988	1256200	1080852	1534825	3474	0.123
1989	2919885	1048636	1691144	3969	0.119
1990	1888479	1974231	1993985	5088	0.093
1991	1953255	1686052	2476052	5111	0.094
1992	2112699	1606335	2435840	5290	0.085
1993	2392964	1685630	2547439	5543	0.077
1994	1638537	1860336	2625259	5314	0.070
1995	1766633	1483754	2525427	5201	0.073
1996	1804613	1446768	2421768	4904	0.075
1997	941521	1454055	2323563	4296	0.094
1998	618296	958642	1906137	2860	0.109
1999	381326	315898	737767	1735	0.102
2000	421648	320952	811560	1879	0.084
2001	383990	345593	879772	2034	0.076
2002	134380	332345	945496	2142	0.071
2003	302039	186255	969851	2022	0.072
2004	191454	233042	932326	2006	0.072
2005	479484	185831	914401	1919	0.072
2006	718464	333716	903047	2062	0.072
2007	409910	517899	990132	2402	0.069
2008	844891	398703	1112005	2526	0.061
2009	692584	611117	1209302	2557	0.055
2010	634017	586098	1281337	2168	0.058
2011	509421	528796	1129162	1588	0.072
2012	239665	425751	819051	1062	0.109
2013	264030	246289	539320	1227	0.098
2014	216047	231419	599794	1160	0.104
2015	171673	195187	571890	1140	0.106
2016	178308	160859	568985	1187	0.103
2017	138175	154391	572956	1186	0.101
2018	147990	129272	568274	1151	0.101
2019	262671	126752	553209	1081	0.103

Figures

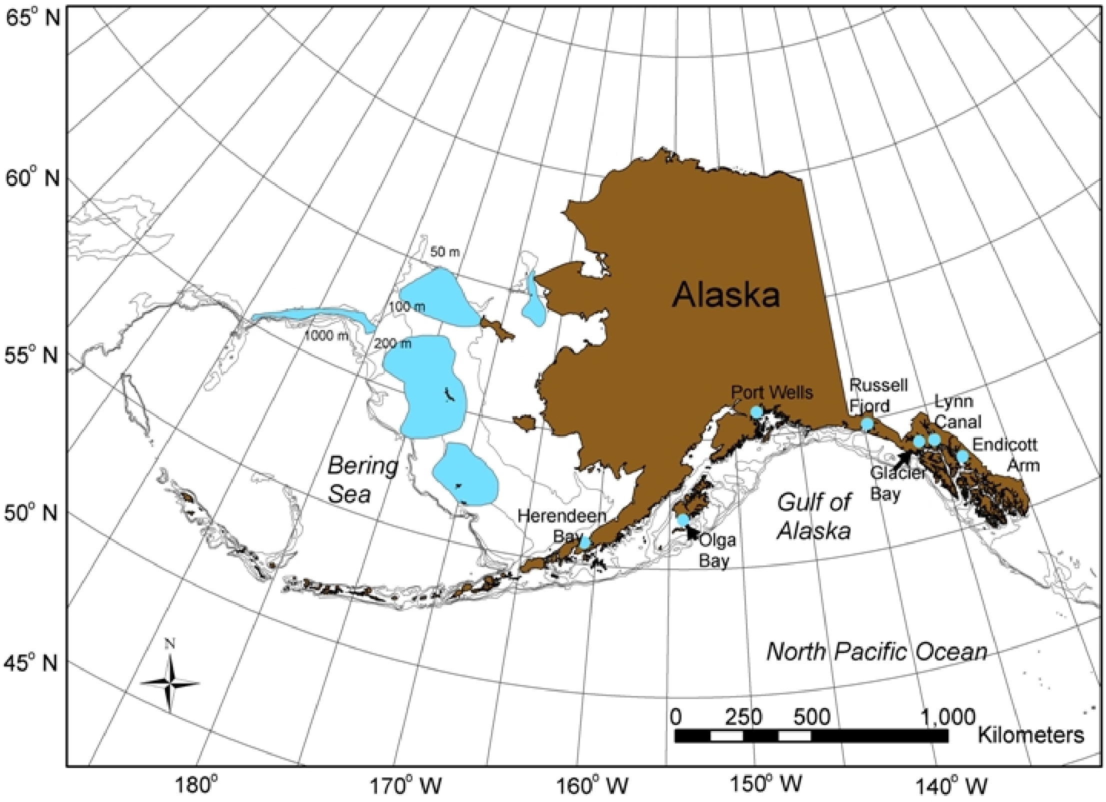

Figure 1: Distribution of blue king crab (Paralithodes platypus) in the Gulf of Alaska, Bering Sea, and Aleutian Islands waters (shown in blue).

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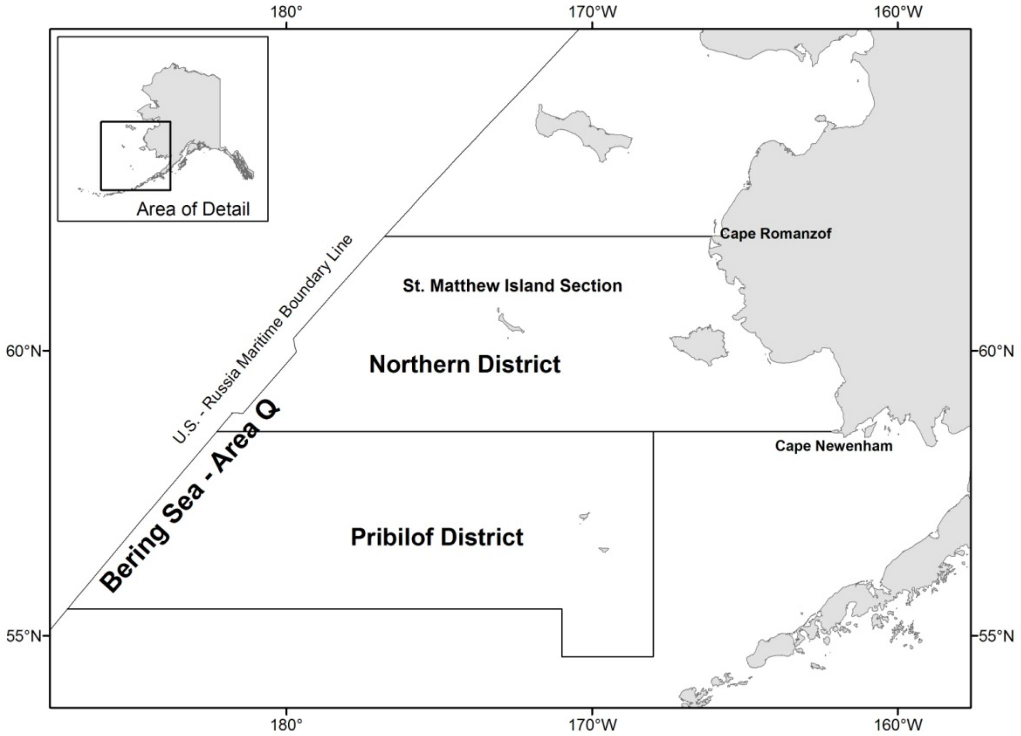

Figure 2: Blue king crab Registration Area Q (Bering Sea)

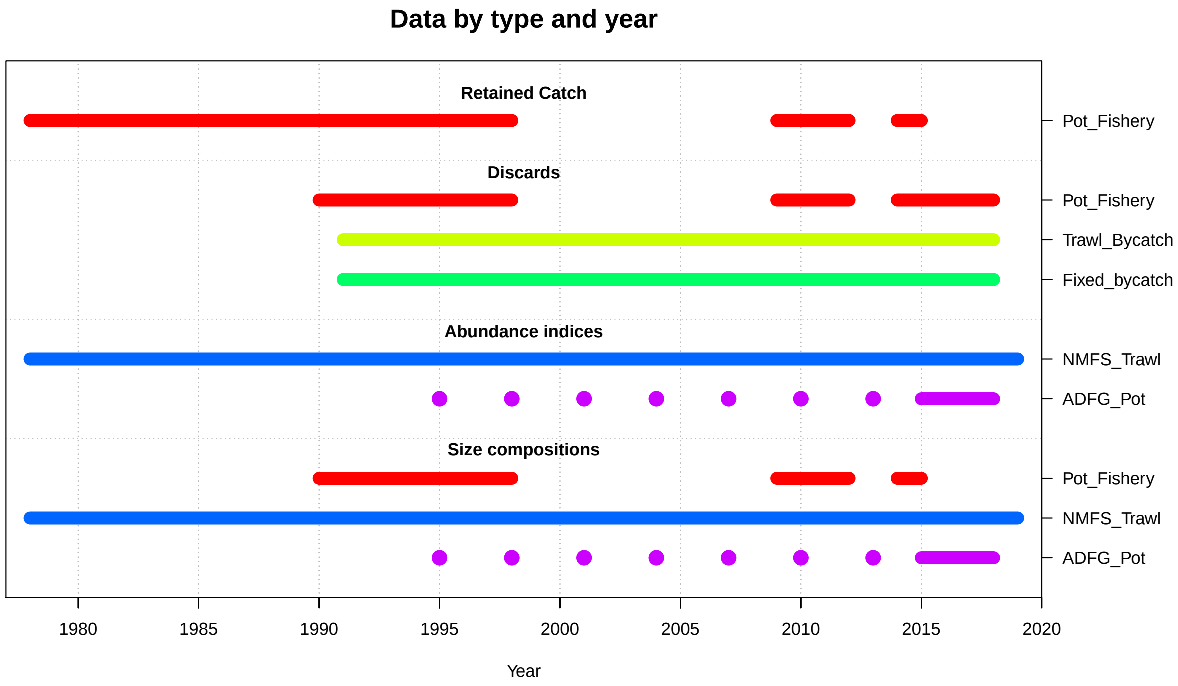

Figure 3: Data extent for the SMBKC assessment.

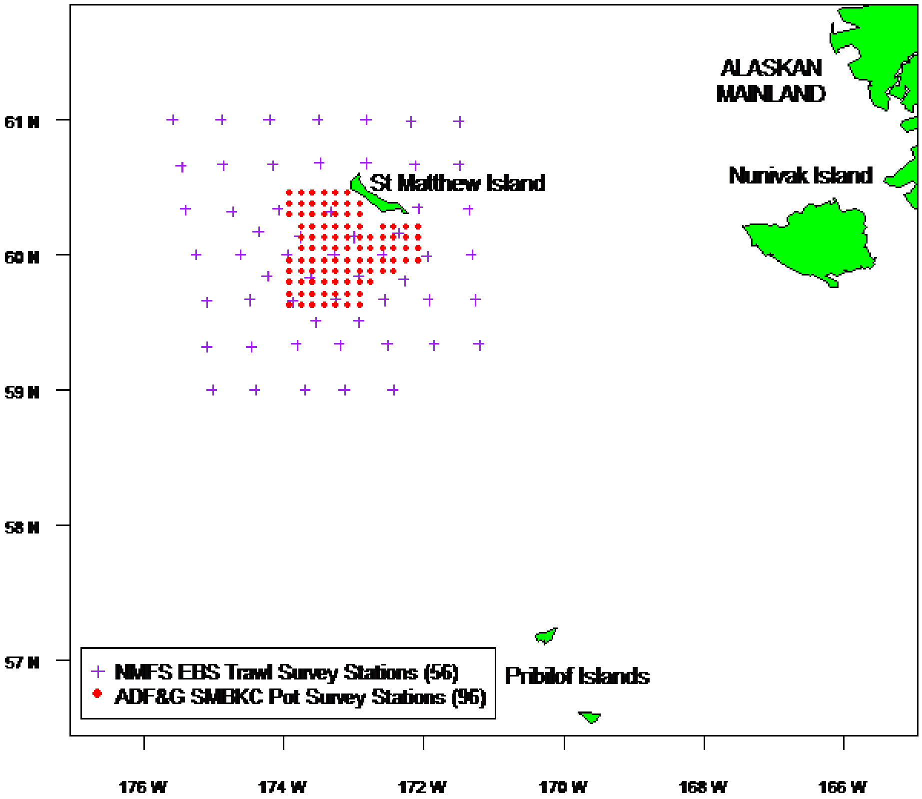

Figure 4: Trawl and pot-survey stations used in the SMBKC stock assessment.

Figure 5: Catches (in numbers) of male blue king crab > 90mm CL from the 2011-2019 NMFS trawl-survey at the 56 stations used to assess the SMBKC stock.

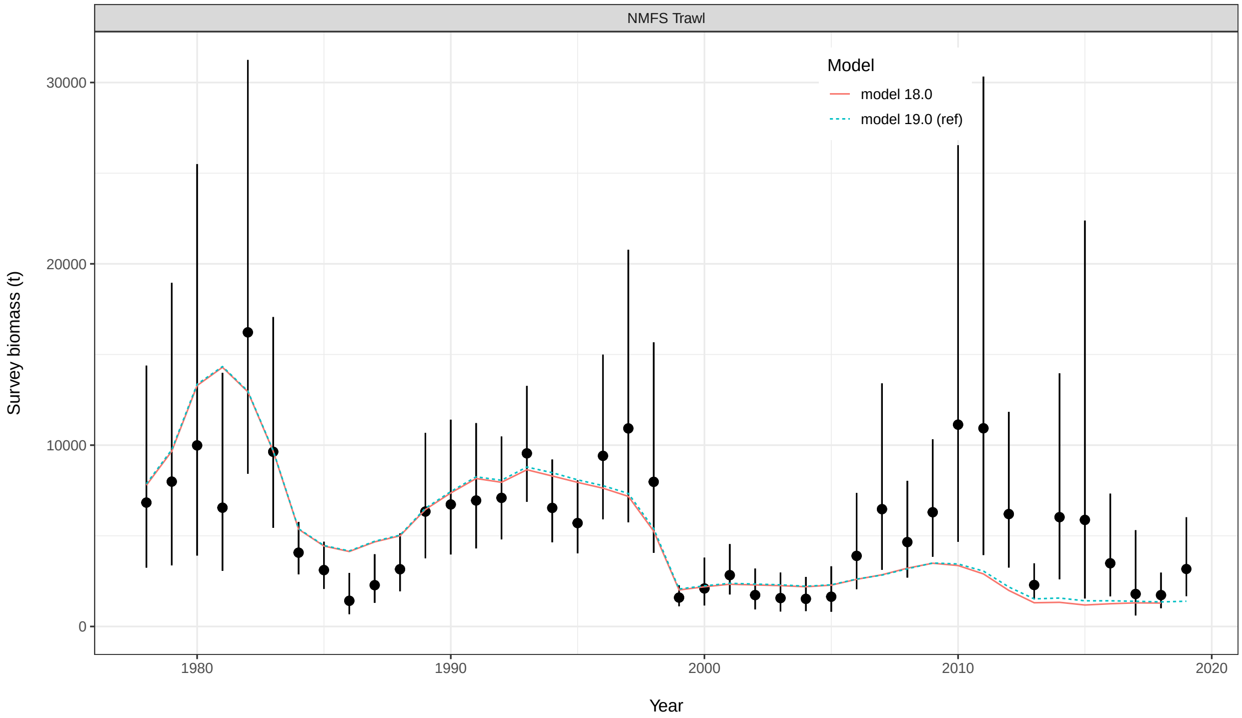

Figure 6: Fits to NMFS area-swept trawl estimates of total (/*ge* 90mm) male survey biomass with the addition of new data (the Reference Model is with new data, 2018 Model is last year's accepted model). Error bars are plus and minus 2 standard deviations.

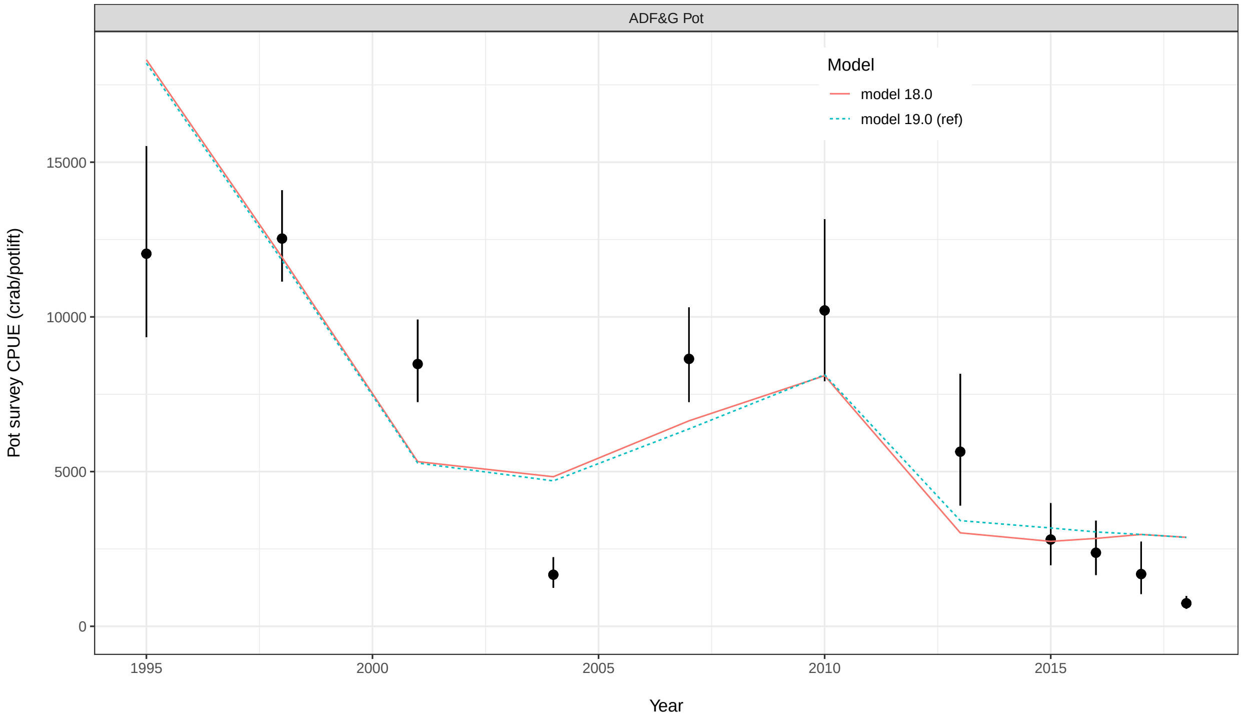

Figure 7: Comparisons of fits to CPUE from the ADF&G pot surveys with the addition of new data (note that there is no new pot data for 2019). Error bars are plus and minus 2 standard deviations.

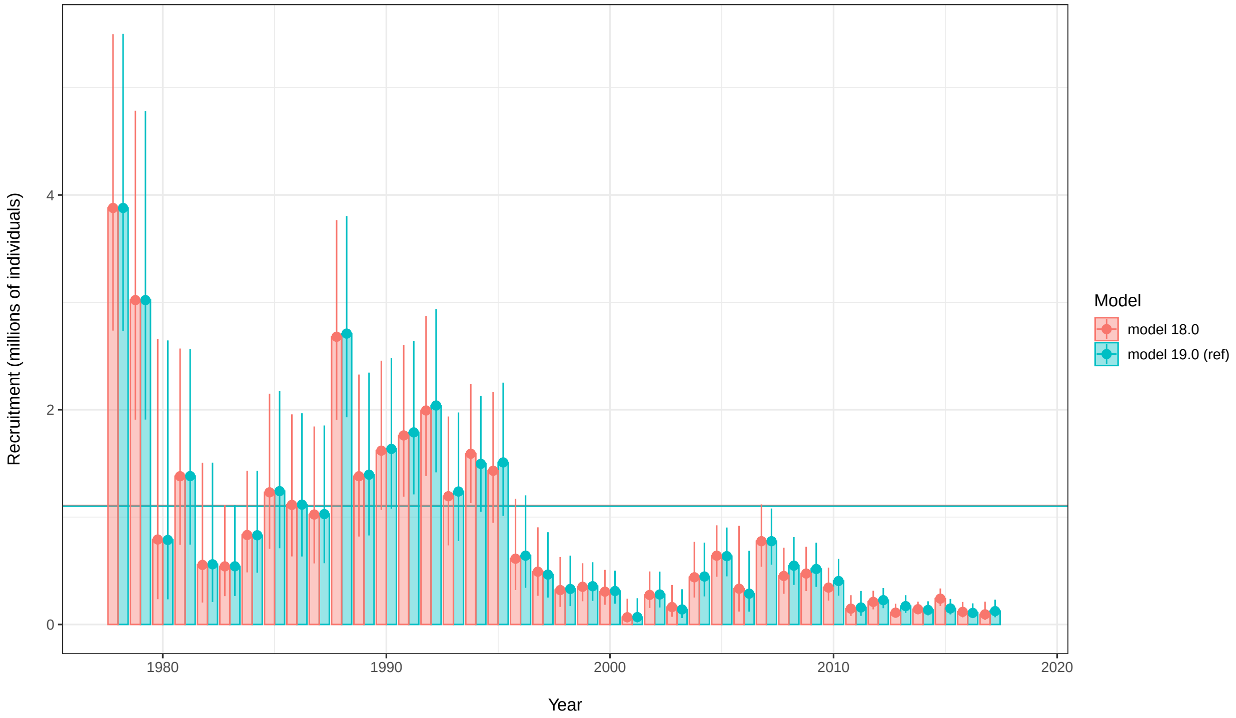

Figure 8: Sensitivity of new data in 2019 on estimated recruitment ; 1978-2017.

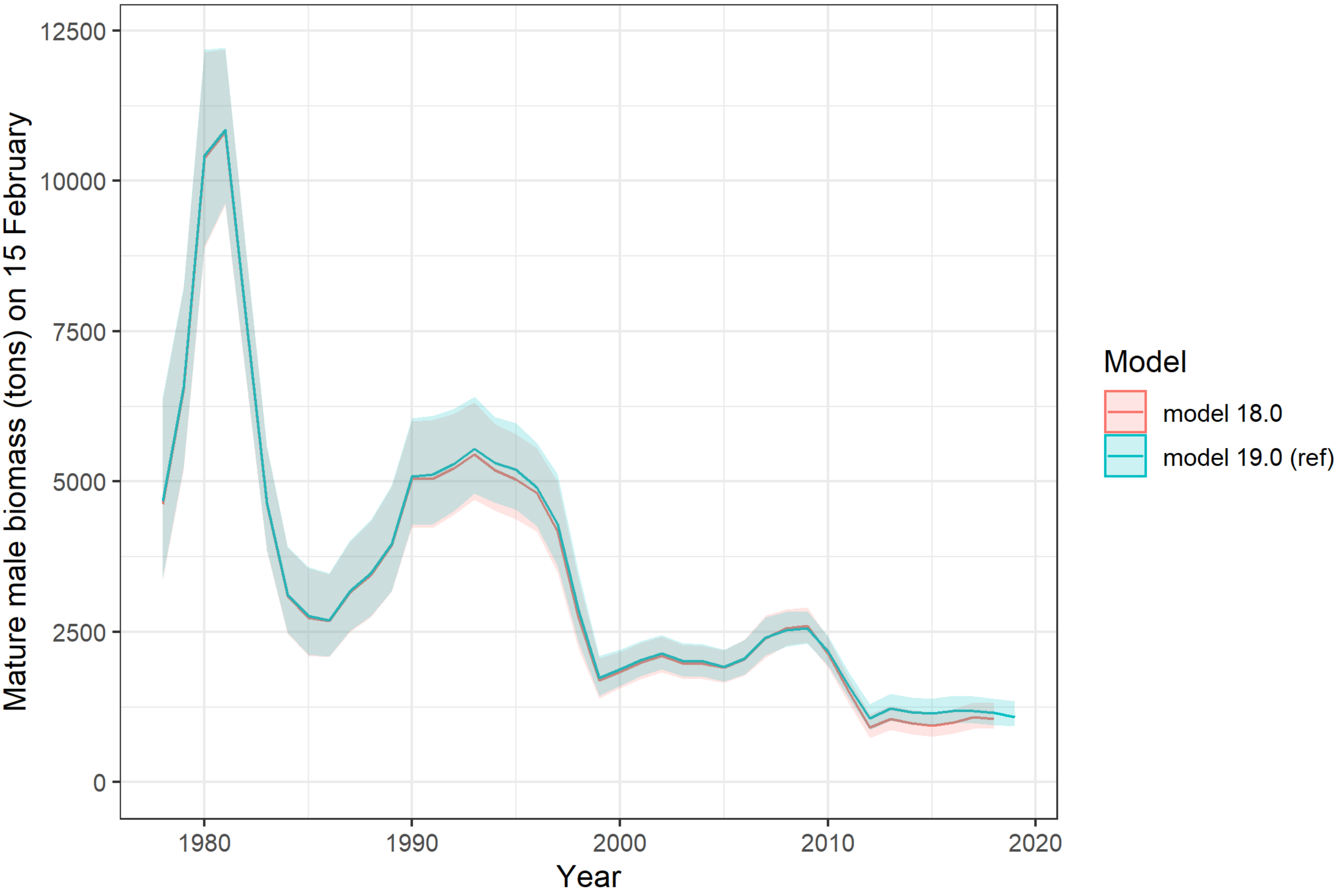

Figure 9: Sensitivity of new data in 2019 on estimated mature male biomass (MMB); 1978-2019.

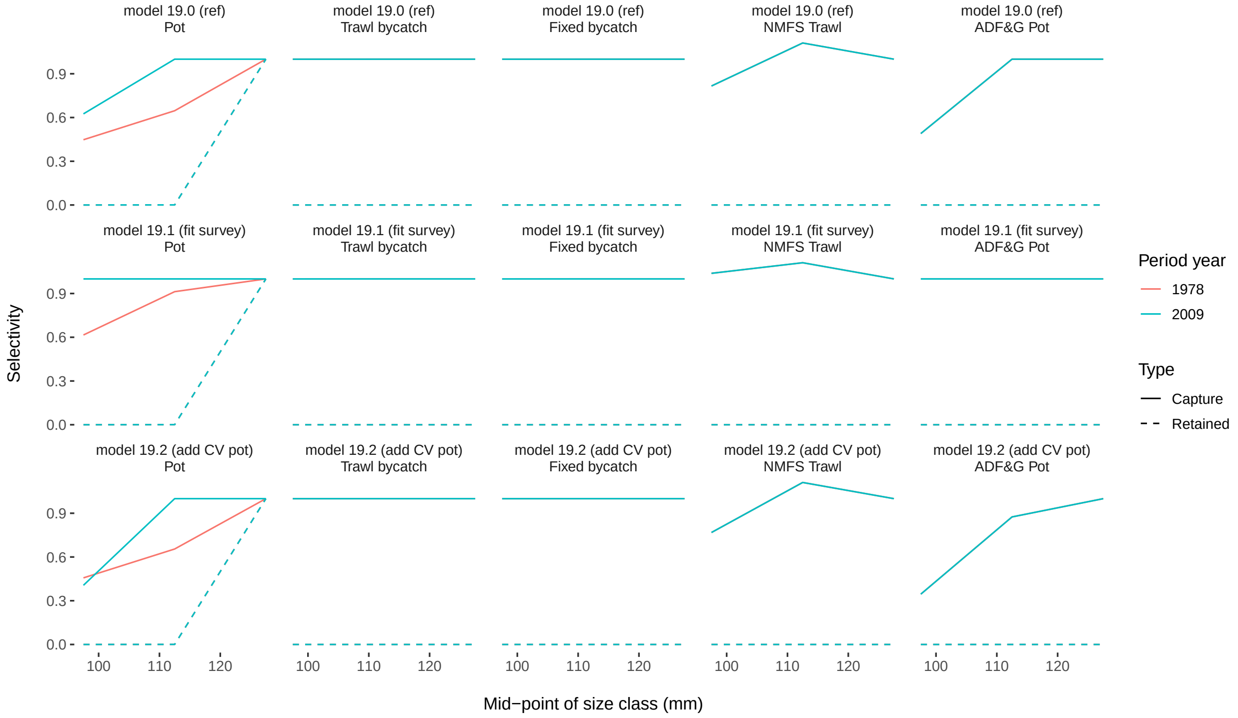

Figure 10: Comparisons of the estimated stage-1 and stage-2 selectivities for the different model scenarios (the stage-3 selectivities are all fixed at 1). Estimated selectivities are shown for the directed pot fishery, the trawl bycatch fishery, the fixed bycatch fishery, the NMFS trawl survey, and the ADF&G pot survey. Two selectivity periods are estimated in the directed pot fishery, from 1978-2008 and 2009-2018.

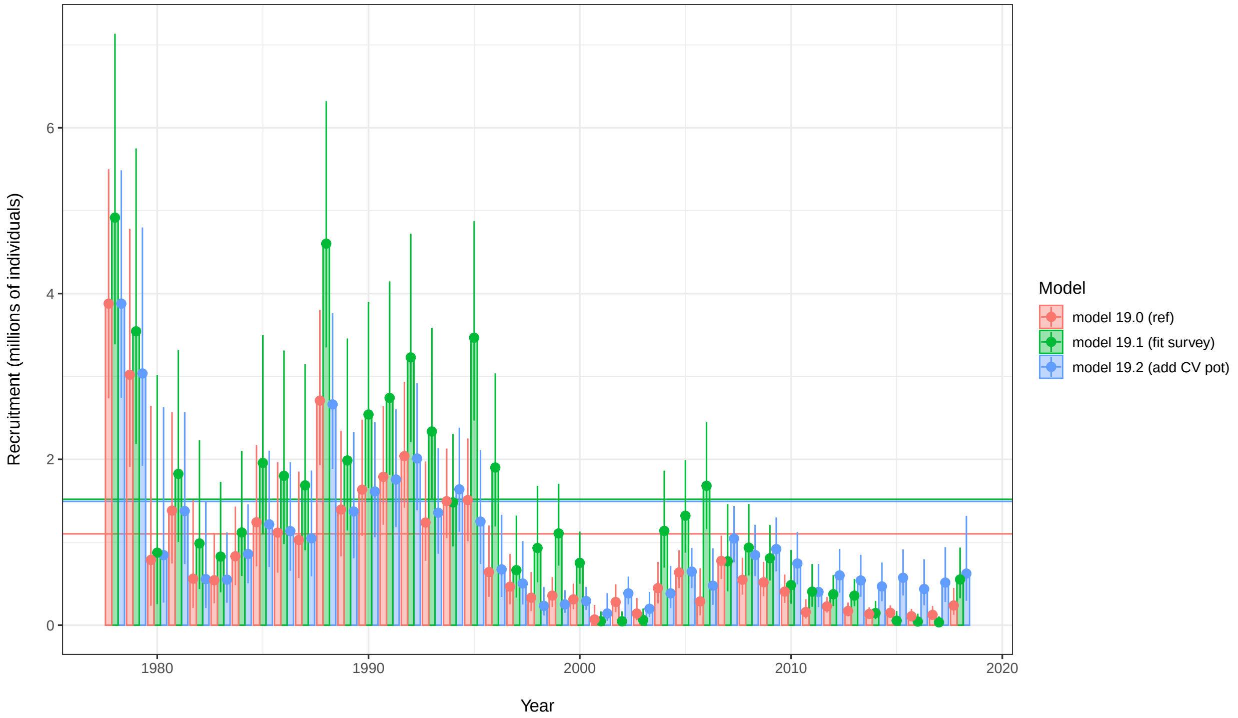

Figure 11: Estimated recruitment 1979-2018 comparing model alternatives. The solid horizontal lines in the background represent the estimate of the average recruitment parameter ($\bar{R}$) in each model scenario.

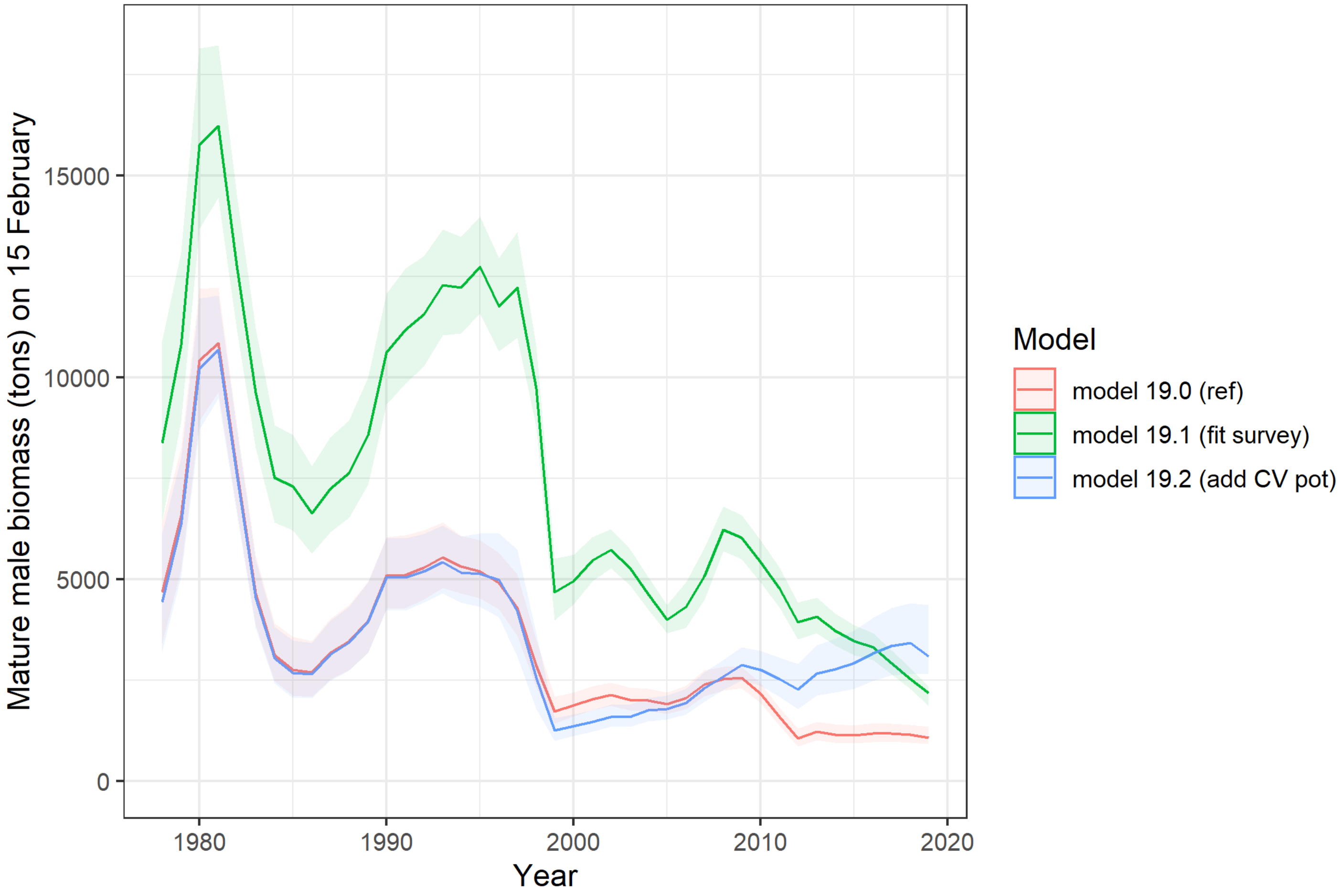

Figure 12: Comparisons of estimated mature male biomass (MMB) time series on 15 February during 1978-2019 for each of the model scenarios.

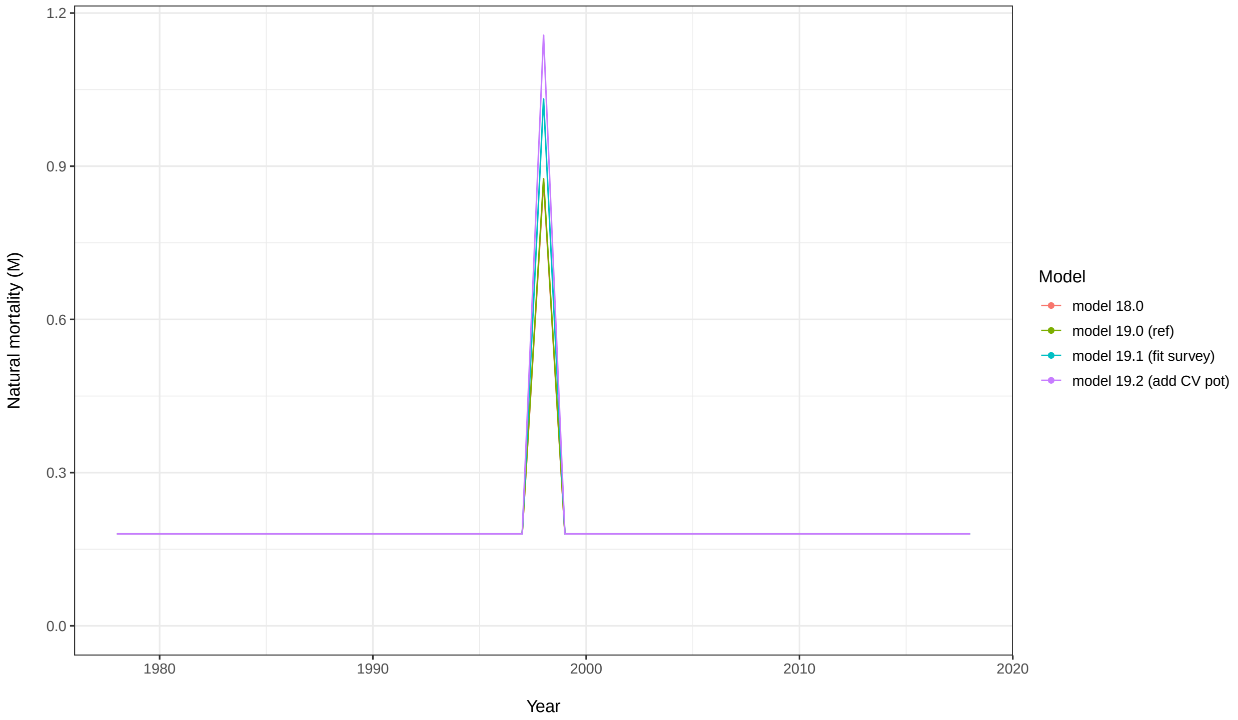

Figure 13: Time-varying natural mortality (M_t). Estimated pulse period occurs in 1998/99 (i.e. M_{1998}).

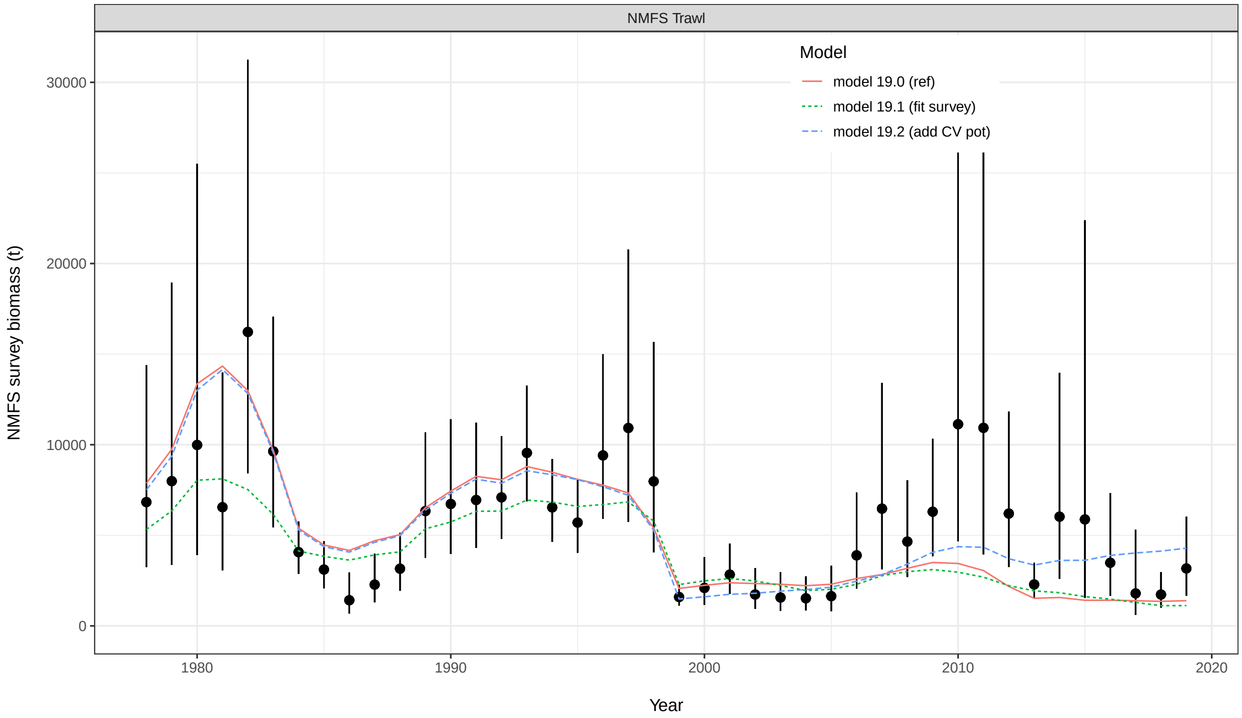

Figure 14: Comparisons of area-swept estimates of total (90+ mm CL) male survey biomass (tons) and model predictions for the model scenarios. The error bars are plus and minus 2 standard deviations.

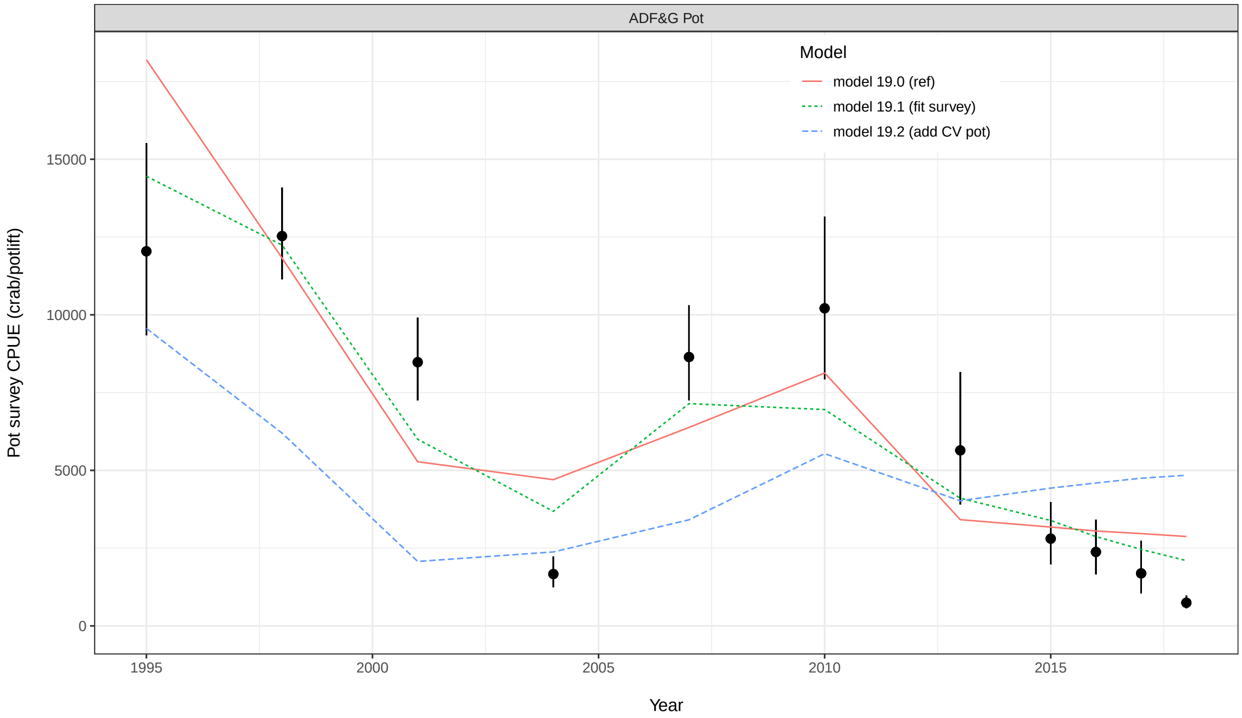

Figure 15: Comparisons of total (90+ mm CL) male pot survey CPUEs and model predictions for the model scenarios. The error bars are plus and minus 2 standard deviations.

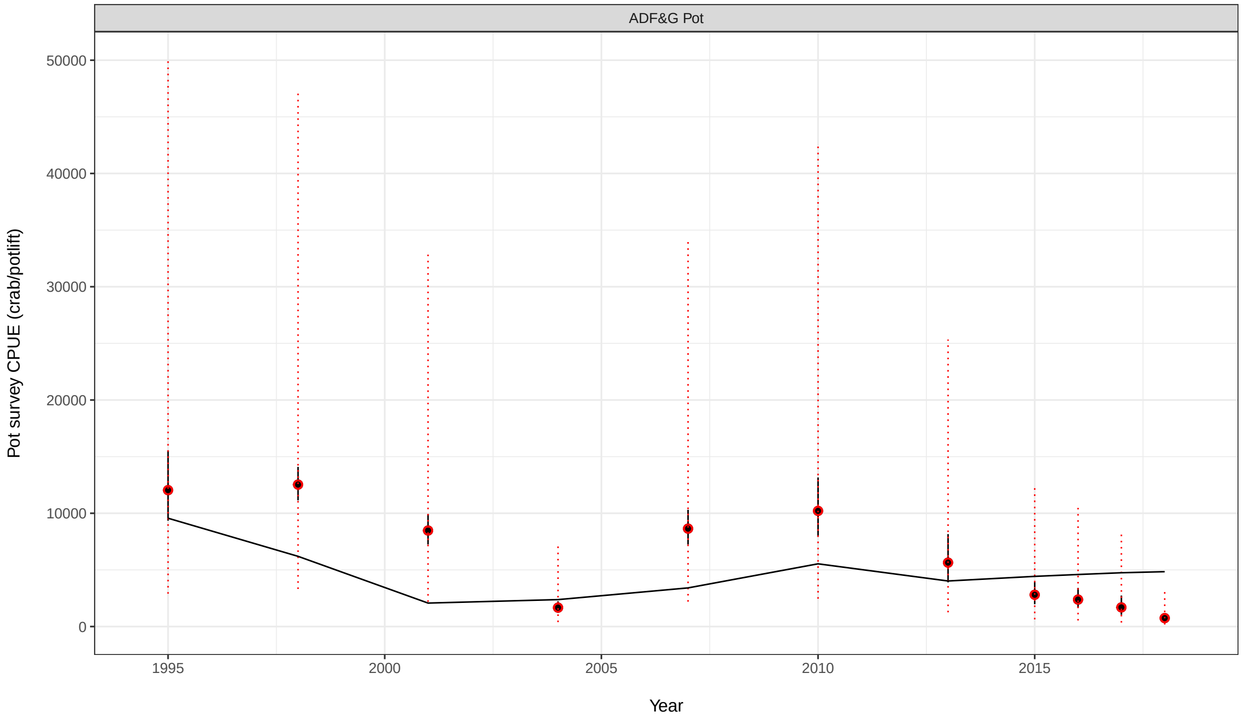

Figure 16: Comparisons of total (90+ mm CL) male pot survey CPUEs and model predictions for the ‘add CV pot’ scenario. The black error bars are plus and minus 2 standard deviations, while the red ones incorporate the additional variability .

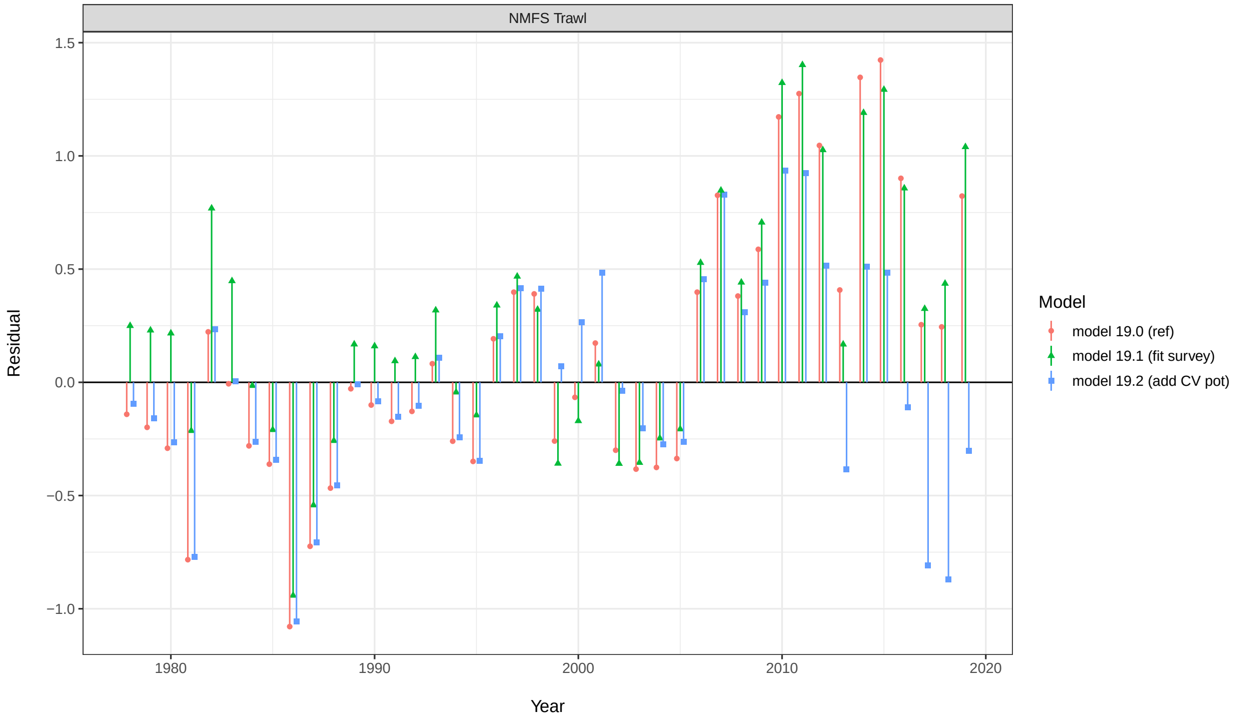

Figure 17: Standardized residuals for area-swept estimates of total male survey biomass for the model scenarios.

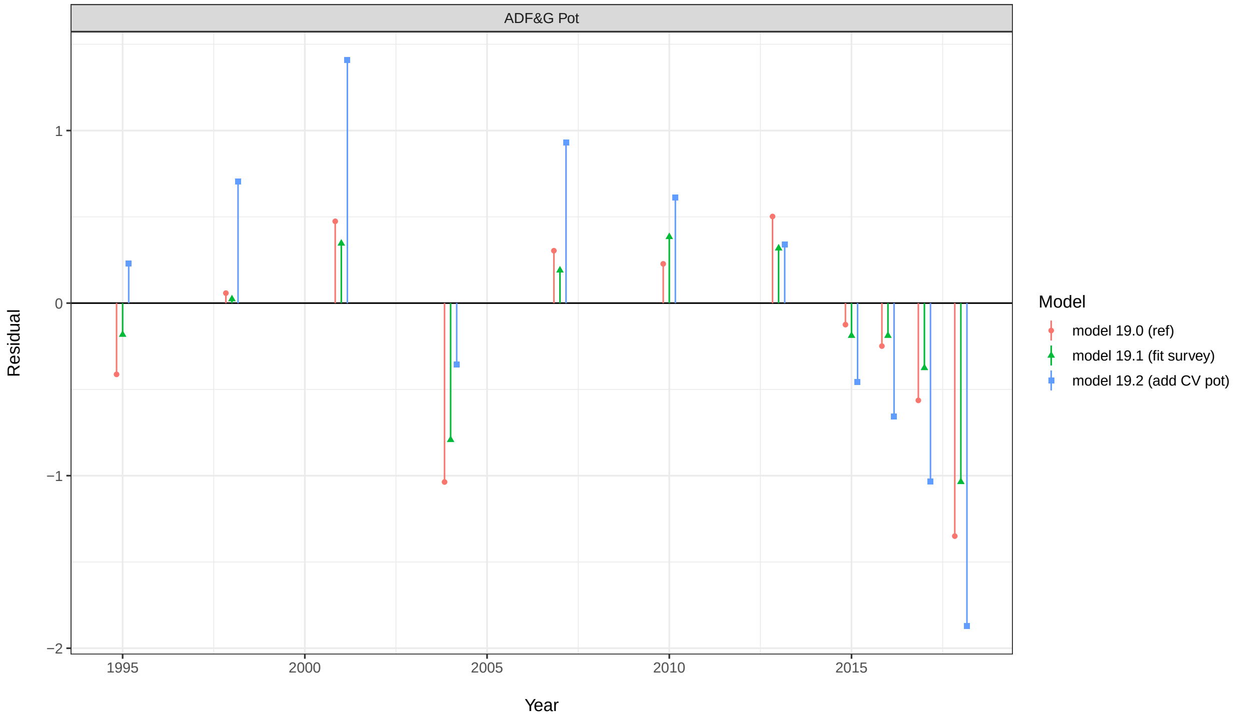

Figure 18: Standardized residuals for total male pot survey CPUEs for each of the Gmacs model scenarios.

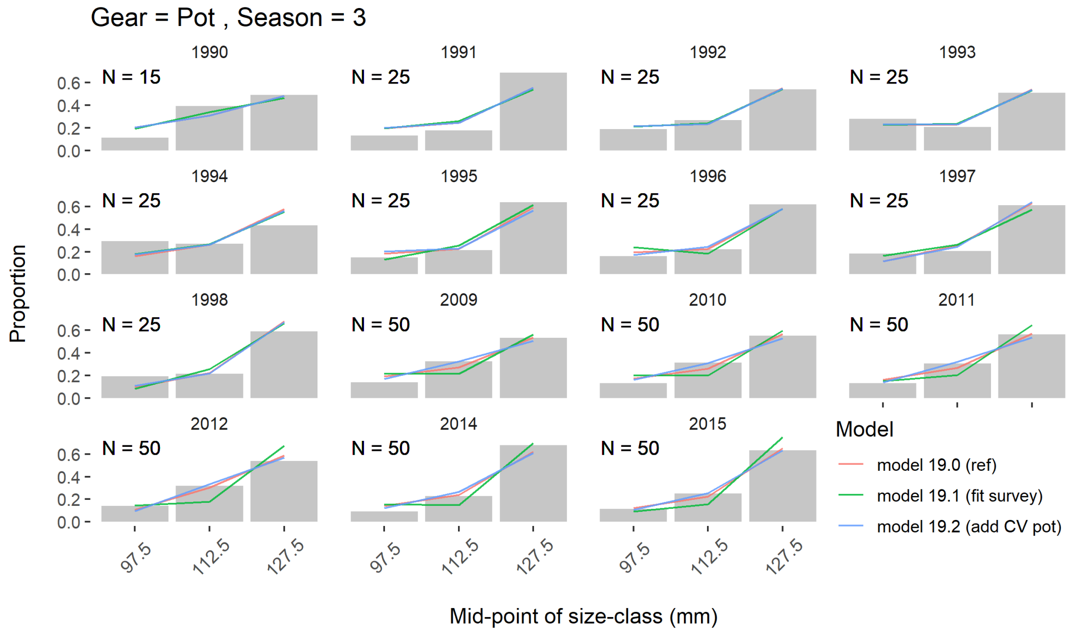

Figure 19: Observed and model estimated size-frequencies of SMBKC by year retained in the directed pot fishery for the model scenarios.

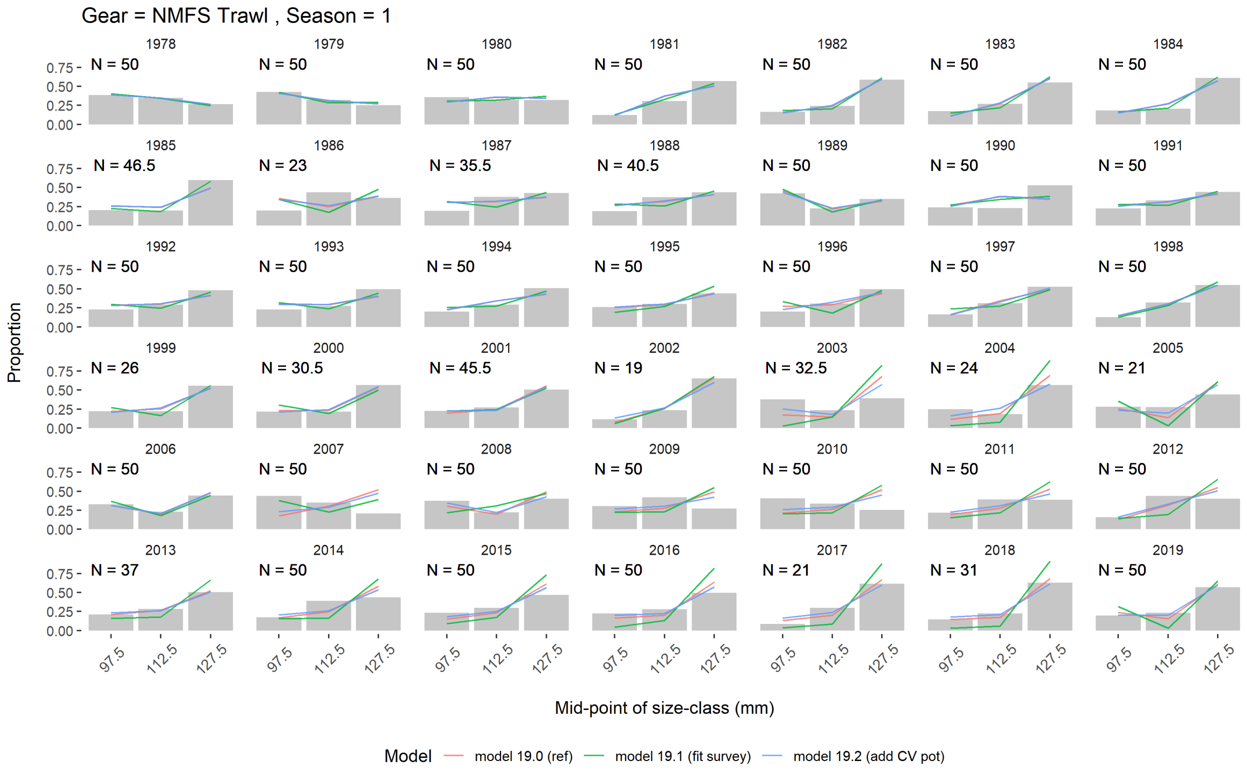

Figure 20: Observed and model estimated size-frequencies of discarded male SMBKC by year in the NMFS trawl survey for the model scenarios.

Figure 21: Observed and model estimated size-frequencies of discarded SMBKC by year in the ADFG pot survey for the model scenarios.

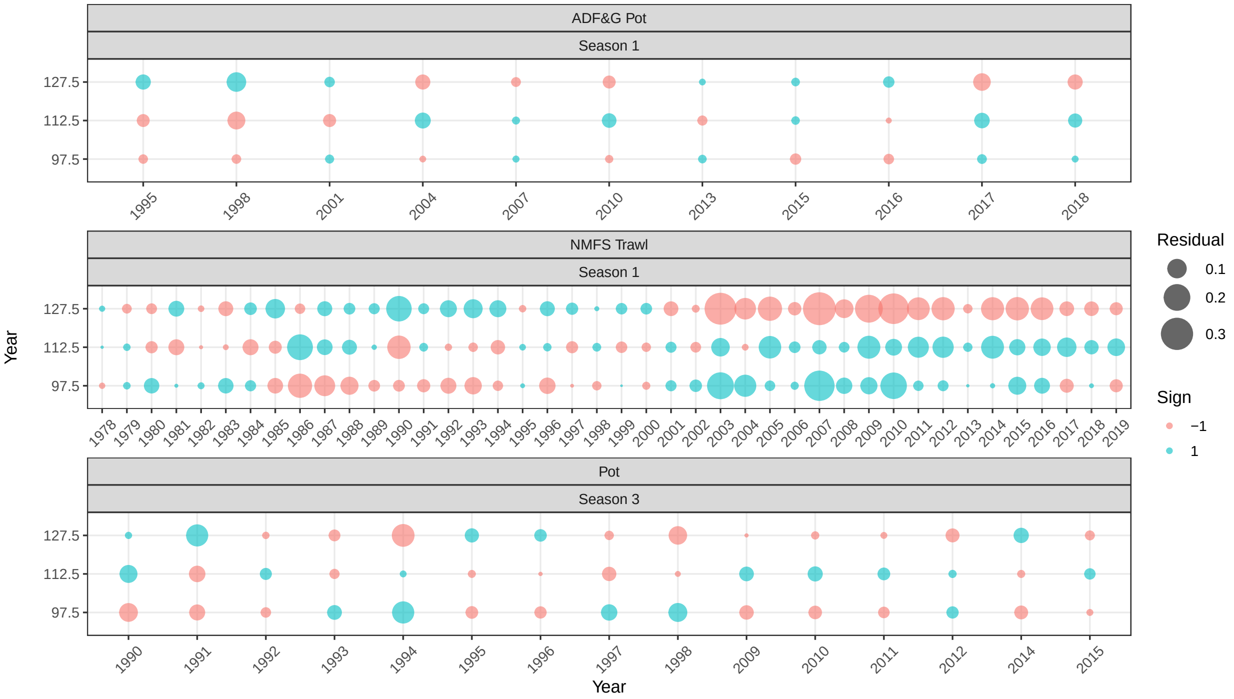

Figure 22: Bubble plots of residuals by stage and year for the all the size composition data sets (ADF&G pot survey, NMFS trawl survey, and the directed pot fishery) for SMBKC in the **reference** model (19.0).

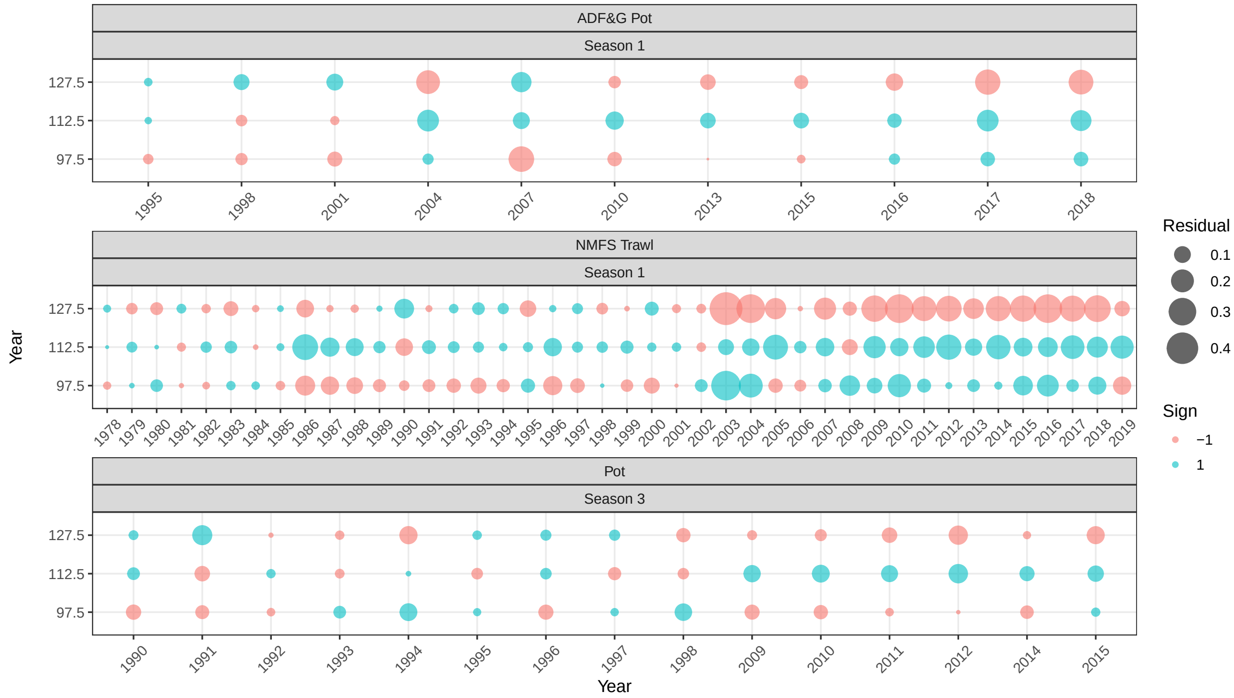

Figure 23: Bubble plots of residuals by stage and year for the all the size composition data sets (ADF&G pot survey, NMFS trawl survey, and the directed pot fishery) for SMBKC in the **fit surveys** model (19.1).

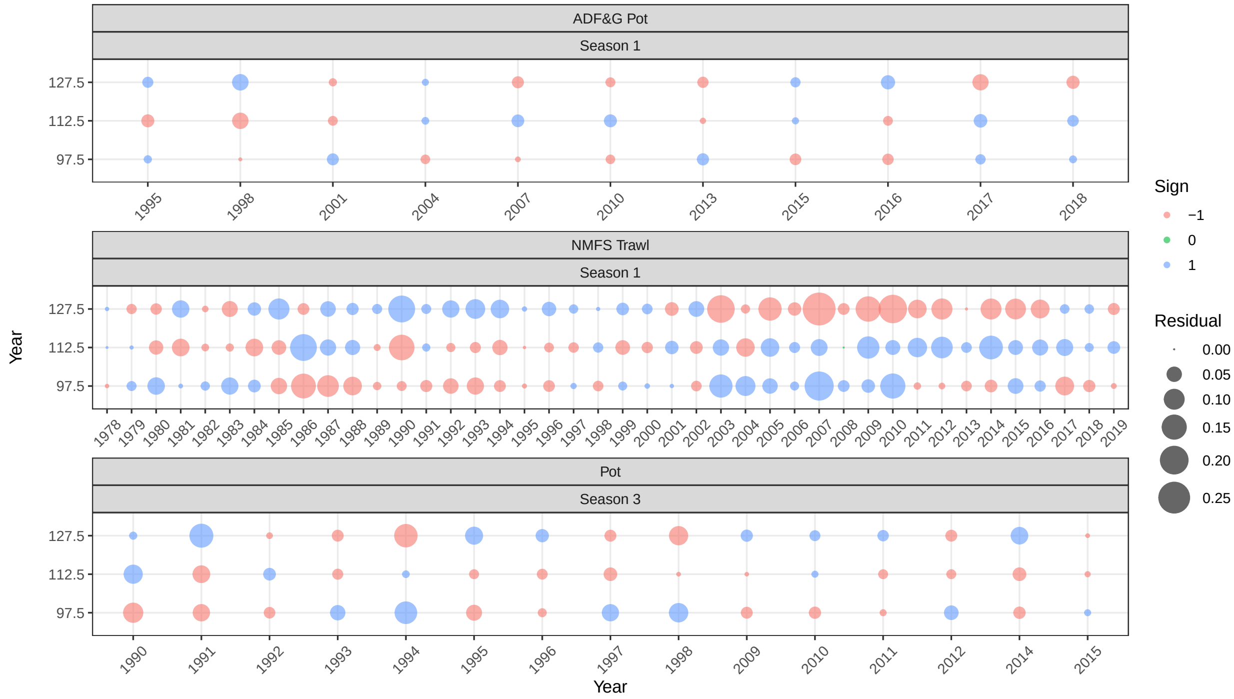

Figure 24: Bubble plots of residuals by stage and year for the all the size composition data sets (ADF&G pot survey, NMFS trawl survey, and the directed pot fishery) for SMBKC in the **add CV pot** model (19.2).

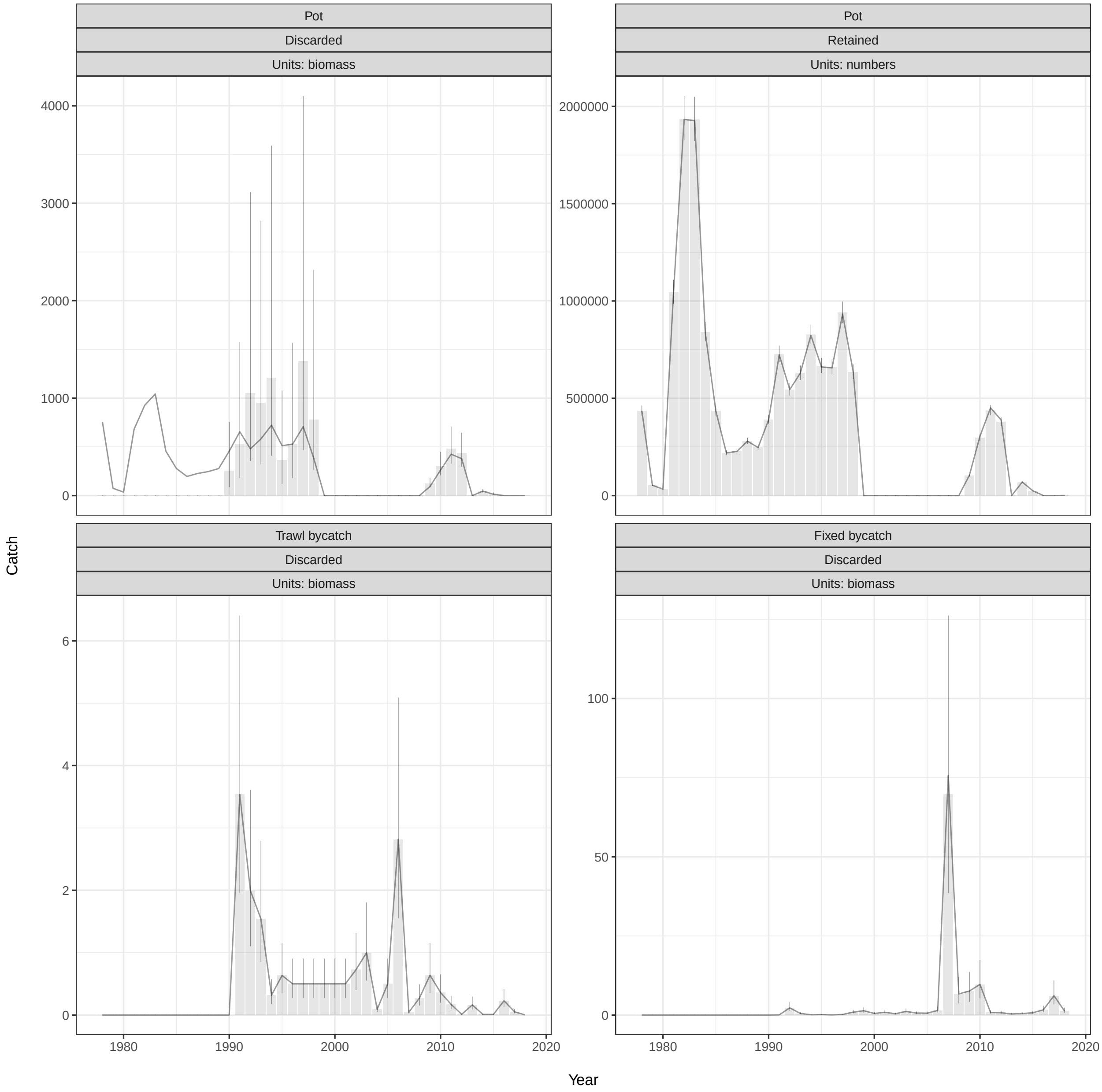

Figure 25: Comparison of observed and model predicted retained catch and bycatches in each of the Gmacs models. Note that difference in units between each of the panels, some panels are expressed in numbers of crab, some as biomass (tons).

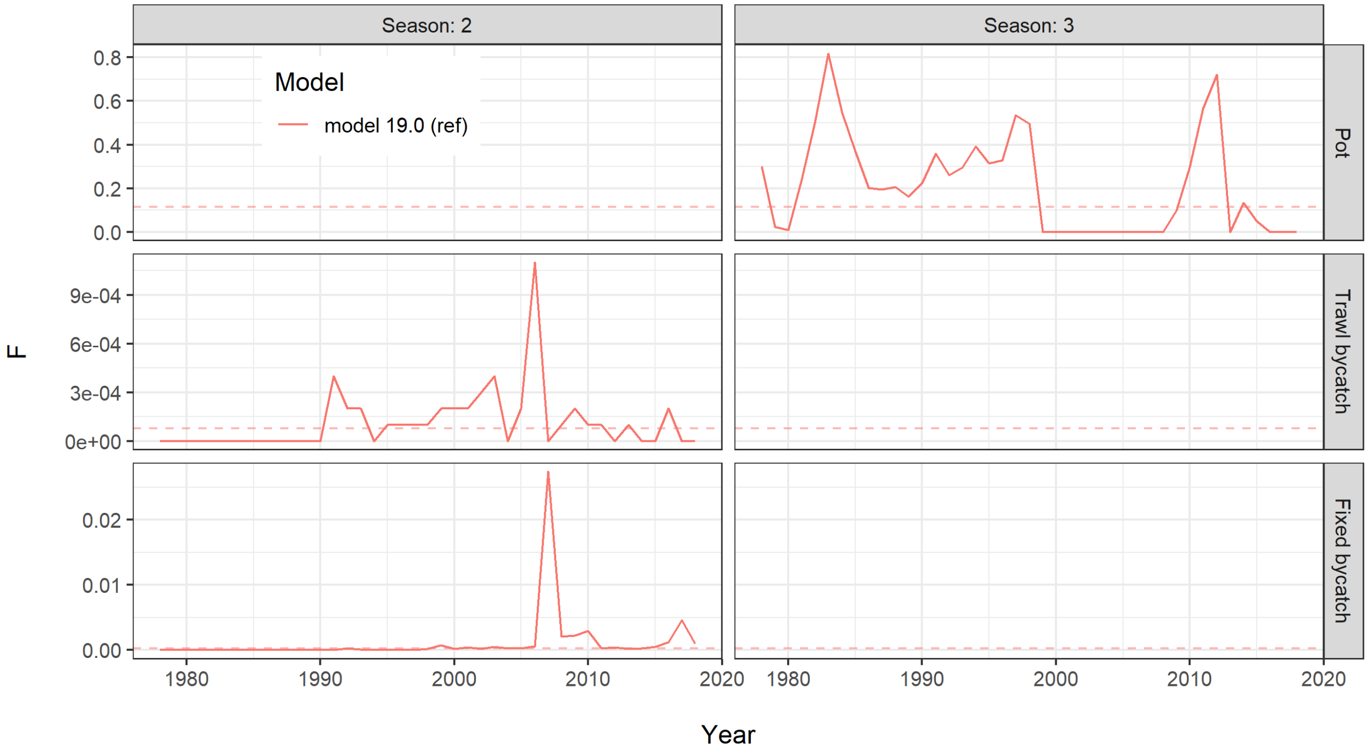

Figure 26: Fishing mortality estimates from the reference model (19.0) for directed and bycatch fleets

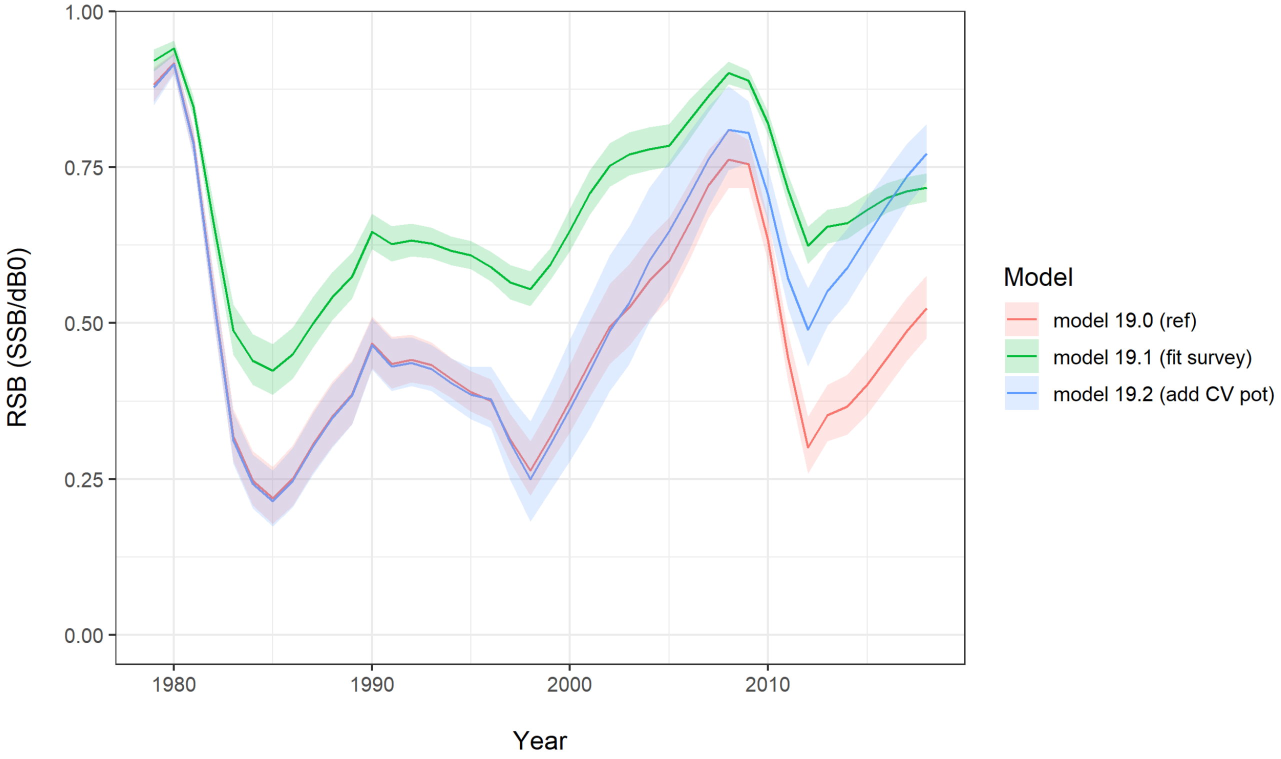

Figure 27: Comparison of mature male biomass relative to the dynamic B zero value, (15 February, 1978-2018) for each of the model scenarios.

Appendix A: SMBKC Model Description

1. Introduction

The Gmacs model has been specified to account only for male crab $\geq$ 90 mm in carapace length (CL). These are partitioned into three stages (size- classes) determined by CL measurements of (1) 90-104 mm, (2) 105-119 mm, and (3) 120+ mm. For management of the St. Matthew Island blue king crab (SMBKC) fishery, 120 mm CL is used as the proxy value for the legal measurement of 5.5 inch carapace width (CW), whereas 105 mm CL is the management proxy for mature-male size (state regulation *5 AAC 34.917 (d)*). Accordingly, within the model only stage-3 crab are retained in the directed fishery, and stage-2 and stage-3 crab together comprise the collection of mature males. Some justification for the 105 mm value is presented in Pengilly and Schmidt (1995), who used it in developing the current regulatory SMBKC harvest strategy. The term “recruit” here designates recruits to the model, i.e., annual new stage-1 crab, rather than recruits to the fishery. The following description of model structure reflects the Gmacs base model configuration.

2. Model Population Dynamics

Within the model, the beginning of the crab year is assumed contemporaneous with the NMFS trawl survey, nominally assigned a date of 1 July. Although the timing of the fishery is different each year, MMB is estimated at 15 February, which is the reference date for calculation of federal management biomass quantities. To accommodate this, each model year is split into 5 seasons (t) and a proportion of the natural mortality (τ_t), scaled relative to the portions of the year, is applied in each of these seasons where $\sum_{t=1}^{t=5} \tau_t = 1$. Each model year consists of the following processes with time-breaks denoted here by “Seasons.” However, it is important to note that actual seasons are survey-to-fishery, fishery-to Feb 15, and Feb 15 to July 1. The following breakdown accounts for events and fishing mortality treatments:

1. Season 1 (survey period)
    - Beginning of the SMBKC fishing year (1 July)
    - $\tau_1 = 0$
    - Surveys
2. Season 2 (natural mortality until pulse fishery)
    - τ_2 ranges from 0.05 to 0.44 depending on the time of year the fishery begins each year (i.e., a higher value indicates the fishery begins later in the year; see Table reftab:smbkc-fishery)
3. Season 3 (pulse fishery)
    - $\tau_3 = 0$
    - fishing mortality applied
4. Season 4 (natural mortality until spawning)
    - $\tau_4 = 0.63 - \sum_{i=1}^{i=4} \tau_i$
    - Calculate MMB (15 February)
5. Season 5 (natural mortality and somatic growth through to June 30th)
    - $\tau_5 = 0.37$
    - Growth and molting
    - Recruitment (all to stage-1)

The proportion of natural mortality (τ_t) applied during each season in the model is provided in Table 20. The beginning of the year (1 July) to the date that MMB is measured (15 February) is 63% of the year. Therefore 63% of the natural mortality must be applied before the MMB is calculated. Because the timing of the fishery is different each year, τ_2 varies and thus τ_4 varies also.

With boldface lower-case letters indicating vector quantities we designate the vector of stage abundances during season t and year y as

$$\boldsymbol{n}_{t,y} = n_{l,t,y} = \left[n_{1,t,y}, n_{2,t,y}, n_{3,t,y}\right]^\top . \tag{2}$$

The number of new crab, or recruits, of each stage entering the model each season t and year y is represented as the vector $\boldsymbol{r}_{t,y}$. The SMBKC formulation of Gmacs specifies recruitment to stage-1 only during season $t = 5$, thus the recruitment size distribution is

$$\phi_l = \left[1, 0, 0\right]^\top , \tag{3}$$

and the recruitment is

$$\boldsymbol{r}_{t,y} = \begin{cases} 0 & \text{for} \quad t < 5 \\ \bar{R}\phi_l \delta_y^R & \text{for} \quad t = 5. \end{cases} \tag{4}$$

where $\bar{R}$ is the average annual recruitment and δ_y^R are the recruitment deviations each year y

$$\delta_y^R \sim \mathcal{N}\left(0, \sigma_R^2\right) . \tag{5}$$

Using boldface upper-case letters to indicate a matrix, we describe the size transition matrix $\boldsymbol{G}$ as

$$\boldsymbol{G} = \left[\begin{array}{ccc} 1 - \pi_{12} - \pi_{13} & \pi_{12} & \pi_{13} \\ 0 & 1 - \pi_{23} & \pi_{23} \\ 0 & 0 & 1 \end{array} \right] , \tag{6}$$

with π_{jk} equal to the proportion of stage-j crab that molt and grow into stage-k within a season or year.

The natural mortality each season t and year y is

$$M_{t,y} = \bar{M}\tau_t + \delta_y^M \text{ where } \delta_y^M \sim \mathcal{N}\left(0, \sigma_M^2\right) \tag{7}$$

Fishing mortality by year y and season t is denoted $F_{t,y}$ and calculated as

$$F_{t,y} = F_{t,y}^{\text{df}} + F_{t,y}^{\text{tb}} + F_{t,y}^{\text{fb}} \tag{8}$$

where $F_{t,y}^{\text{df}}$ is the fishing mortality associated with the directed fishery, $F_{t,y}^{\text{tb}}$ is the fishing mortality associated with the trawl bycatch fishery, $F_{t,y}^{\text{fb}}$ is the fishing mortality associated with the fixed bycatch fishery. Each of these are derived as

$$\begin{aligned} F_{t,y}^{\text{df}} &= \bar{F}^{\text{df}} + \delta_{t,y}^{\text{df}} \quad \text{where} \quad \delta_{t,y}^{\text{df}} \sim \mathcal{N}\left(0, \sigma_{\text{df}}^2\right) , \\ F_{t,y}^{\text{tb}} &= \bar{F}^{\text{tb}} + \delta_{t,y}^{\text{tb}} \quad \text{where} \quad \delta_{t,y}^{\text{df}} \sim \mathcal{N}\left(0, \sigma_{\text{tb}}^2\right) , \\ F_{t,y}^{\text{fb}} &= \bar{F}^{\text{fb}} + \delta_{t,y}^{\text{fb}} \quad \text{where} \quad \delta_{t,y}^{\text{df}} \sim \mathcal{N}\left(0, \sigma_{\text{fb}}^2\right) , \end{aligned} \tag{9}$$

where $\delta_{t,y}^{\text{df}}$, $\delta_{t,y}^{\text{tb}}$, and $\delta_{t,y}^{\text{fb}}$ are the fishing mortality deviations for each of the fisheries, each season t during each year y, $\bar{F}^{\text{df}}$, $\bar{F}^{\text{tb}}$, and $\bar{F}^{\text{fb}}$ are the average fishing mortalities for each fishery. The total mortality $Z_{l,t,y}$ represents the combination of natural mortality $M_{t,y}$ and fishing mortality $F_{t,y}$ during season t and year y

$$\boldsymbol{Z}_{t,y} = Z_{l,t,y} = M_{t,y} + F_{t,y}. \tag{10}$$

The survival matrix $\boldsymbol{S}_{t,y}$ during season t and year y is

$$\boldsymbol{S}_{t,y} = \left[\begin{array}{ccc} 1 - e^{-Z_{1,t,y}} & 0 & 0 \\ 0 & 1 - e^{-Z_{2,t,y}} & 0 \\ 0 & 0 & 1 - e^{-Z_{3,t,y}} \end{array} \right] . \tag{11}$$

The basic population dynamics underlying Gmacs can thus be described as

$$\begin{aligned} \boldsymbol{n}_{t+1,y} &= \boldsymbol{S}_{t,y}\boldsymbol{n}_{t,y}, && \text{if } t < 5 \\ \boldsymbol{n}_{t,y+1} &= \boldsymbol{G}\boldsymbol{S}_{t,y}\boldsymbol{n}_{t,y} + \boldsymbol{r}_{t,y} && \text{if } t = 5. \end{aligned} \tag{12}$$

3. Model Data

Data inputs used in model estimation are listed in Table 21.

4. Model Parameters

Table 22 lists fixed (externally determined) parameters used in model computations. In all scenarios, the stage-transition matrix is

$$\boldsymbol{G} = \begin{bmatrix} 0.2 & 0.7 & 0.1 \\ 0 & 0.4 & 0.6 \\ 0 & 0 & 1 \end{bmatrix} \tag{13}$$

which is the combination of the growth matrix and molting probabilities.

Estimated parameters are listed in Table 23 and include an estimated natural mortality deviation parameter in 1998/99 (δ^M_{1998}) assuming an anomalous mortality event in that year, as hypothesized by Zheng and Kruse (2002), with natural mortality otherwise fixed at 0.18 yr^{-1}.

5. Model Objective Function and Weighting Scheme

The objective function consists of the sum of several "negative log-likelihood" terms characterizing the hypothesized error structure of the principal data inputs (Table 17). A lognormal distribution is assumed to characterize the catch data and is modelled as

$$\sigma^{\text{catch}}_{t,y} = \sqrt{\log\left(1 + \left(CV^{\text{catch}}_{t,y}\right)^2\right)} \tag{14}$$

$$\delta^{\text{catch}}_{t,y} = \mathcal{N}\left(0, \left(\sigma^{\text{catch}}_{t,y}\right)^2\right) \tag{15}$$

where $\delta^{\text{catch}}_{t,y}$ is the residual catch. The relative abudance data is also assumed to be lognormally distributed

$$\sigma^{\text{I}}_{t,y} = \frac{1}{\lambda}\sqrt{\log\left(1 + \left(CV^{\text{I}}_{t,y}\right)^2\right)} \tag{16}$$

$$\delta^{\text{I}}_{t,y} = \log\left(I^{\text{obs}}/I^{\text{pred}}\right)/\sigma^{\text{I}}_{t,y} + 0.5\sigma^{\text{I}}_{t,y} \tag{17}$$

and the likelihood is

$$\sum \log\left(\delta^{\text{I}}_{t,y}\right) + \sum 0.5\left(\sigma^{\text{I}}_{t,y}\right)^2 \tag{18}$$

Gmacs calculates standard deviation of the normalised residual (SDNR) values and median of the absolute residual (MAR) values for all abundance indices and size compositions to help the user come up with resonable likelihood weights. For an abundance data set to be well fitted, the SDNR should not be much greater than 1 (a value much less than 1, which means that the data set is fitted better than was expected, is not a cause for concern). What is meant by "much greater than 1" depends on m (the number of years in the data set). Francis (2011) suggests upper limits of 1.54, 1.37, and 1.26 for m = 5, 10, and 20, respectively. Although an SDNR not much greater than 1 is a necessary condition for a good fit, it is not sufficient. It is important to plot the observed and expected abundances to ensure that the fit is good.

Gmacs also calculates Francis weights for each of the size composition data sets supplied (Francis 2011). If the user wishes to use the Francis iterative re-weighting method, first the weights applied to the abundance indices should be adjusted by trial and error until the SDNR (and/or MAR) are adequte. Then the Francis weights supplied by Gmacs should be used as the new likelihood weights for each of the size composition data sets the next time the model is run. The user can then iteratively adjust the abudance index and size composition weights until adequate SDNR (and/or MAR) values are achieved, given the Francis weights.

6. Estimation

The model was implemented using the software AD Model Builder (Fournier et al. 2012), with parameter estimation by minimization of the model objective function using automatic differentiation. Parameter estimates and standard deviations provided in this document are AD Model Builder reported values assuming maximum likelihood theory asymptotics.

Table 20: Proportion of the natural mortality (τ_t) that is applied during each season (t) in the model.

Year	Season 1	Season 2	Season 3	Season 4	Season 5
1978	0.00	0.07	0.00	0.56	0.37
1979	0.00	0.06	0.00	0.57	0.37
1980	0.00	0.07	0.00	0.56	0.37
1981	0.00	0.05	0.00	0.58	0.37
1982	0.00	0.07	0.00	0.56	0.37
1983	0.00	0.12	0.00	0.51	0.37
1984	0.00	0.10	0.00	0.53	0.37
1985	0.00	0.14	0.00	0.49	0.37
1986	0.00	0.14	0.00	0.49	0.37
1987	0.00	0.14	0.00	0.49	0.37
1988	0.00	0.14	0.00	0.49	0.37
1989	0.00	0.14	0.00	0.49	0.37
1990	0.00	0.14	0.00	0.49	0.37
1991	0.00	0.18	0.00	0.45	0.37
1992	0.00	0.14	0.00	0.49	0.37
1993	0.00	0.18	0.00	0.45	0.37
1994	0.00	0.18	0.00	0.45	0.37
1995	0.00	0.18	0.00	0.45	0.37
1996	0.00	0.18	0.00	0.45	0.37
1997	0.00	0.18	0.00	0.45	0.37
1998	0.00	0.18	0.00	0.45	0.37
1999	0.00	0.18	0.00	0.45	0.37
2000	0.00	0.18	0.00	0.45	0.37
2001	0.00	0.18	0.00	0.45	0.37
2002	0.00	0.18	0.00	0.45	0.37
2003	0.00	0.18	0.00	0.45	0.37
2004	0.00	0.18	0.00	0.45	0.37
2005	0.00	0.18	0.00	0.45	0.37
2006	0.00	0.18	0.00	0.45	0.37
2007	0.00	0.18	0.00	0.45	0.37
2008	0.00	0.18	0.00	0.45	0.37
2009	0.00	0.44	0.00	0.19	0.37
2010	0.00	0.44	0.00	0.19	0.37
2011	0.00	0.44	0.00	0.19	0.37
2012	0.00	0.44	0.00	0.19	0.37
2013	0.00	0.44	0.00	0.19	0.37
2014	0.00	0.44	0.00	0.19	0.37
2015	0.00	0.44	0.00	0.19	0.37
2016	0.00	0.44	0.00	0.19	0.37
2017	0.00	0.44	0.00	0.19	0.37
2018	0.00	0.44	0.00	0.19	0.37

Table 21: Data inputs used in model estimation.

Data	Years	Source
Directed pot-fishery retained-catch number (not biomass)	1978/79 - 1998/99 2009/10 - 2015/16	Fish tickets (fishery closed 1999/00 - 2008/09 and 2016/17 - 2018/19)
Groundfish trawl bycatch biomass	1992/93 - 2018/19	NMFS groundfish observer program
Groundfish fixed-gear bycatch biomass	1992/93 - 2018/19	NMFS groundfish observer program
NMFS trawl-survey biomass index (area-swept estimate) and CV	1978-2019	NMFS EBS trawl survey
ADF&G pot-survey abundance index (CPUE) and CV	1995-2018	ADF&G SMBKC pot survey
NMFS trawl-survey stage proportions and total number of measured crab	1978-2019	NMFS EBS trawl survey
ADF&G pot-survey stage proportions and total number of measured crab	1995-2018	ADF&G SMBKC pot survey
Directed pot-fishery stage proportions and total number of measured crab	1990/91 - 1998/99 2009/10 - 2015/16	ADF&G crab observer program (fishery closed 1999/00 - 2008/09 and 2016/17 - 2018/19)

Table 22: Fixed model parameters for all scenarios.

Parameter	Symbol	Value	Source/rationale
Trawl-survey catchability	q	1.0	Default
Natural mortality	M	0.18 yr^{-1}	NPFMC (2007)
Size transition matrix	$\boldsymbol{G}$	Equation 13	Otto and Cummiskey (1990)
Stage-1 and stage-2 mean weights	w_1, w_2	0.7, 1.2 kg	Length-weight equation (B. Foy, NMFS) applied to stage midpoints
Stage-3 mean weight	$w_{3,y}$	Depends on year	Fishery reported average retained weight from fish tickets, or its average, and mean weights of legal males
Recruitment SD	σ_R	1.2	High value
Natural mortality SD	σ_M	10.0	High value (basically free parameter)
Directed fishery handling mortality		0.2	2010 Crab SAFE
Groundfish trawl handling mortality		0.8	2010 Crab SAFE
Groundfish fixed-gear handling mortality		0.5	2010 Crab SAFE

Table 23: The lower bound (LB), upper bound (UB), initial value, prior, and estimation phase for each estimated model parameter.

Parameter	LB	Initial value	UB	Prior	Phase
Average recruitment $\log(\bar{R})$	-7	10.0	20	Uniform(-7,20)	1
Stage-1 initial numbers $\log(n_1^0)$	5	14.5	20	Uniform(5,20)	1
Stage-2 initial numbers $\log(n_2^0)$	5	14.0	20	Uniform(5,20)	1
Stage-3 initial numbers $\log(n_3^0)$	5	13.5	20	Uniform(5,20)	1
ADF&G pot survey catchability q	0	3.0	5	Uniform(0,5)	1
Stage-1 directed fishery selectivity 1978-2008	0	0.4	1	Uniform(0,1)	3
Stage-2 directed fishery selectivity 1978-2008	0	0.7	1	Uniform(0,1)	3
Stage-1 directed fishery selectivity 2009-2017	0	0.4	1	Uniform(0,1)	3
Stage-2 directed fishery selectivity 2009-2017	0	0.7	1	Uniform(0,1)	3
Stage-1 NMFS trawl survey selectivity	0	0.4	1	Uniform(0,1)	4
Stage-2 NMFS trawl survey selectivity	0	0.7	1	Uniform(0,1)	4
Stage-1 ADF&G pot survey selectivity	0	0.4	1	Uniform(0,1)	4
Stage-2 ADF&G pot survey selectivity	0	0.7	1	Uniform(0,1)	4
Natural mortality deviation during 1998 δ_{1998}^M	-3	0.0	3	Normal(0, σ_M^2)	4
Recruitment deviations δ_y^R	-7	0.0	7	Normal(0, σ_R^2)	3
Average directed fishery fishing mortality $\bar{F}^{\mathrm{df}}$	-	0.2	-	-	1
Average trawl bycatch fishing mortality $\bar{F}^{\mathrm{tb}}$	-	0.001	-	-	1
Average fixed gear bycatch fishing mortality $\bar{F}^{\mathrm{fb}}$	-	0.001	-	-	1

Appendix B. Data files for the reference model (16.0)

The reference model (16.0) data file for 2019

```
#========================================================================================================
# Gmacs Main  Data  File  Version 1.1:  SM18 with all new data
# GEAR_INDEX  DESCRIPTION
#   1      : Pot fishery retained catch.
#   1      : Pot fishery with discarded catch.
#   2      : Trawl bycatch
#   3      : Fixed bycatch
#   4      : Trawl survey
#   5      : Pot survey
#========================================================================================================
# Fisheries:  1 Pot Fishery,  2 Pot Discard,  3 Trawl by-catch, 3 Fixed by-catch
# Surveys:   4 NMFS Trawl Survey, 5 Pot Survey
#========================================================================================================
1978  # Start year
2018  # End year (updated) last year of fishery does NOT include current survey year
5    # Number of seasons
5    # Number of fleets (fisheries and surveys)
1    # Number of sexes
1    # Number of shell condition types
1    # Number of maturity types
3    # Number of size-classes in the model
5    # Season recruitment occurs
5    # Season molting and growth occurs
4    # Season to calculate SSB
1    # Season for N output
# size_breaks (a vector giving the break points between size intervals with dimension nclass+1)
90  105  120  135
# Natural mortality per season input type (1 = vector by season, 2 = matrix by season/year)
2
# Proportion of the total natural mortality to be applied each season (each row must add to 1)
0.000   0.070   0.000   0.560   0.370
0.000   0.060   0.000   0.570   0.370
0.000   0.070   0.000   0.560   0.370
0.000   0.050   0.000   0.580   0.370
0.000   0.070   0.000   0.560   0.370
0.000   0.120   0.000   0.510   0.370
0.000   0.100   0.000   0.530   0.370
0.000   0.140   0.000   0.490   0.370
0.000   0.140   0.000   0.490   0.370
0.000   0.140   0.000   0.490   0.370
0.000   0.140   0.000   0.490   0.370
0.000   0.140   0.000   0.490   0.370
0.000   0.140   0.000   0.490   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.140   0.000   0.490   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.440   0.000   0.190   0.370
0.000   0.440   0.000   0.190   0.370
0.000   0.440   0.000   0.190   0.370
0.000   0.440   0.000   0.190   0.370
0.000   0.440   0.000   0.190   0.370
```

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0.000   0.440   0.000   0.190   0.370
0.000   0.440   0.000   0.190   0.370
0.000   0.440   0.000   0.190   0.370
0.000   0.440   0.000   0.190   0.370
0.000   0.440   0.000   0.190   0.370 # (updated)
#0  0.0025  0  0.6245  0.373
# Fishing fleet names (delimited with : no spaces in names)
Pot_Fishery:Trawl_Bycatch:Fixed_bycatch
# Survey names (delimited with : no spaces in names)
NMFS_Trawl:ADFG_Pot
# Are the fleets instantaneous (0) or continuous (1)
1 1 1 1 1
# Number  of  catch data  frames
4
# Number  of  rows  in  each  data  frame
27  18 28  28 #(updated - all should increase 1 placeholder for direct fishery if closed)
##  CATCH DATA
##  Type of catch: 1 = retained, 2 = discard
##  Units of catch: 1 = biomass, 2 = numbers
##  for SMBKC Units are in number of crab for landed & 1000 kg for discards.
##  Male Retained
# year  seas   fleet  sex   obs    cv type  units mult effort  discard_mortality
1978   3     1     1     436126  0.03   1     2     1     0     0.2
1979   3     1     1     52966   0.03   1     2     1     0     0.2
1980   3     1     1     33162   0.03   1     2     1     0     0.2
1981   3     1     1     1045619 0.03   1     2     1     0     0.2
1982   3     1     1     1935886 0.03   1     2     1     0     0.2
1983   3     1     1     1931990 0.03   1     2     1     0     0.2
1984   3     1     1     841017  0.03   1     2     1     0     0.2
1985   3     1     1     436021  0.03   1     2     1     0     0.2
1986   3     1     1     219548  0.03   1     2     1     0     0.2
1987   3     1     1     227447  0.03   1     2     1     0     0.2
1988   3     1     1     280401  0.03   1     2     1     0     0.2
1989   3     1     1     247641  0.03   1     2     1     0     0.2
1990   3     1     1     391405  0.03   1     2     1     0     0.2
1991   3     1     1     726519  0.03   1     2     1     0     0.2
1992   3     1     1     545222  0.03   1     2     1     0     0.2
1993   3     1     1     630353  0.03   1     2     1     0     0.2
1994   3     1     1     827015  0.03   1     2     1     0     0.2
1995   3     1     1     666905  0.03   1     2     1     0     0.2
1996   3     1     1     660665  0.03   1     2     1     0     0.2
1997   3     1     1     939822  0.03   1     2     1     0     0.2
1998   3     1     1     635370  0.03   1     2     1     0     0.2
2009   3     1     1     103376  0.03   1     2     1     0     0.2
2010   3     1     1     298669  0.03   1     2     1     0     0.2
2011   3     1     1     437862  0.03   1     2     1     0     0.2
2012   3     1     1     379386  0.03   1     2     1     0     0.2
2014   3     1     1     69109   0.03   1     2     1     0     0.2
2015   3     1     1     24407   0.03   1     2     1     0     0.2
#2016   3     1     1     10.000  0.03   1     2     1     0     0.2
#2017   3     1     1     10.000  0.03   1     2     1     0     0.2
#2018   3     1     1     10.000  0.03   1     2     1     0     0.2 # placeholder no fishery
# Male  discards  Pot fishery
1990   3     1     1    254.9787861    0.6    2     1     1     0     0.2
1991   3     1     1    531.4483252    0.6    2     1     1     0     0.2
1992   3     1     1    1050.387026    0.6    2     1     1     0     0.2
1993   3     1     1    951.4626128    0.6    2     1     1     0     0.2
1994   3     1     1    1210.764588    0.6    2     1     1     0     0.2
1995   3     1     1    363.112032     0.6    2     1     1     0     0.2
1996   3     1     1    528.5244687    0.6    2     1     1     0     0.2
1997   3     1     1    1382.825328    0.6    2     1     1     0     0.2
1998   3     1     1    781.1032977    0.6    2     1     1     0     0.2
2009   3     1     1    123.3712279    0.2    2     1     1     0     0.2
2010   3     1     1    304.6562225    0.2    2     1     1     0     0.2
2011   3     1     1    481.3572126    0.2    2     1     1     0     0.2
2012   3     1     1    437.3360731    0.2    2     1     1     0     0.2
2014   3     1     1    45.4839749     0.2    2     1     1     0     0.2
2015   3     1     1    21.19378597    0.2    2     1     1     0     0.2
2016   3     1     1    0.021193786    0.2    2     1     1     0     0.2
2017   3     1     1    0.021193786    0.2    2     1     1     0     0.2
2018   3     1     1    0.214868020    0.2    2     1     1     0     0.2  # (updated)
#   Trawl   fishery discards
```

```
1991    2   2   1   3.538   0.31    2   1   1   0   0.8
1992    2   2   1   1.996   0.31    2   1   1   0   0.8
1993    2   2   1   1.542   0.31    2   1   1   0   0.8
1994    2   2   1   0.318   0.31    2   1   1   0   0.8
1995    2   2   1   0.635   0.31    2   1   1   0   0.8
1996    2   2   1   0.500   0.31    2   1   1   0   0.8
1997    2   2   1   0.500   0.31    2   1   1   0   0.8
1998    2   2   1   0.500   0.31    2   1   1   0   0.8
1999    2   2   1   0.500   0.31    2   1   1   0   0.8
2000    2   2   1   0.500   0.31    2   1   1   0   0.8
2001    2   2   1   0.500   0.31    2   1   1   0   0.8
2002    2   2   1   0.726   0.31    2   1   1   0   0.8
2003    2   2   1   0.998   0.31    2   1   1   0   0.8
2004    2   2   1   0.091   0.31    2   1   1   0   0.8
2005    2   2   1   0.500   0.31    2   1   1   0   0.8
2006    2   2   1   2.812   0.31    2   1   1   0   0.8
2007    2   2   1   0.045   0.31    2   1   1   0   0.8
2008    2   2   1   0.272   0.31    2   1   1   0   0.8
2009    2   2   1   0.638   0.31    2   1   1   0   0.8
2010    2   2   1   0.360   0.31    2   1   1   0   0.8
2011    2   2   1   0.170   0.31    2   1   1   0   0.8
2012    2   2   1   0.011   0.31    2   1   1   0   0.8
2013    2   2   1   0.163   0.31    2   1   1   0   0.8
2014    2   2   1   0.010   0.31    2   1   1   0   0.8
2015    2   2   1   0.010   0.31    2   1   1   0   0.8
2016    2   2   1   0.229   0.31    2   1   1   0   0.8
2017    2   2   1   0.052   0.31    2   1   1   0   0.8
2018    2   2   1   0.001   0.31    2   1   1   0   0.8 # (updated - data is 0 but small value for placeholder)
#   Fixed   fishery discards
1991    2   3   1   0.045   0.31    2   1   1   0   0.5
1992    2   3   1   2.268   0.31    2   1   1   0   0.5
1993    2   3   1   0.500   0.31    2   1   1   0   0.5
1994    2   3   1   0.091   0.31    2   1   1   0   0.5
1995    2   3   1   0.136   0.31    2   1   1   0   0.5
1996    2   3   1   0.045   0.31    2   1   1   0   0.5
1997    2   3   1   0.181   0.31    2   1   1   0   0.5
1998    2   3   1   0.907   0.31    2   1   1   0   0.5
1999    2   3   1   1.361   0.31    2   1   1   0   0.5
2000    2   3   1   0.500   0.31    2   1   1   0   0.5
2001    2   3   1   0.862   0.31    2   1   1   0   0.5
2002    2   3   1   0.408   0.31    2   1   1   0   0.5
2003    2   3   1   1.134   0.31    2   1   1   0   0.5
2004    2   3   1   0.635   0.31    2   1   1   0   0.5
2005    2   3   1   0.590   0.31    2   1   1   0   0.5
2006    2   3   1   1.451   0.31    2   1   1   0   0.5
2007    2   3   1   69.717  0.31    2   1   1   0   0.5
2008    2   3   1   6.622   0.31    2   1   1   0   0.5
2009    2   3   1   7.522   0.31    2   1   1   0   0.5
2010    2   3   1   9.564   0.31    2   1   1   0   0.5
2011    2   3   1   0.796   0.31    2   1   1   0   0.5
2012    2   3   1   0.739   0.31    2   1   1   0   0.5
2013    2   3   1   0.341   0.31    2   1   1   0   0.5
2014    2   3   1   0.490   0.31    2   1   1   0   0.5
2015    2   3   1   0.711   0.31    2   1   1   0   0.5
2016    2   3   1   1.633   0.31    2   1   1   0   0.5
2017    2   3   1   6.032   0.31    2   1   1   0   0.5
2018    2   3   1   1.281   0.31    2   1   1   0   0.5 # (updated - bycatch_groundfish.R)
##  RELATIVE  ABUNDANCE DATA
##  Units of abundance: 1 = biomass, 2 = numbers
##  for SMBKC Units are in  crabs for Abundance.
##  Number  of  relative  abundance indicies
2
##  Number  of  rows  in  each  index
42  11
# Survey data (abundance indices, units are mt for trawl survey and crab/potlift for pot survey)
# Year, Seas, Fleet,  Sex,  Abundance,  CV    units
1978  1 4 1 6832.819  0.394 1
1979  1 4 1 7989.881  0.463 1
1980  1 4 1 9986.830  0.507 1
1981  1 4 1 6551.132  0.402 1
1982  1 4 1 16221.933 0.344 1
1983  1 4 1 9634.250  0.298 1
```

```
1984  1 4 1 4071.218  0.179 1
1985  1 4 1 3110.541  0.210 1
1986  1 4 1 1416.849  0.388 1
1987  1 4 1 2278.917  0.291 1
1988  1 4 1 3158.169  0.252 1
1989  1 4 1 6338.622  0.271 1
1990  1 4 1 6730.130  0.274 1
1991  1 4 1 6948.184  0.248 1
1992  1 4 1 7093.272  0.201 1
1993  1 4 1 9548.459  0.169 1
1994  1 4 1 6539.133  0.176 1
1995  1 4 1 5703.591  0.178 1
1996  1 4 1 9410.403  0.241 1
1997  1 4 1 10924.107 0.337 1
1998  1 4 1 7976.839  0.355 1
1999  1 4 1 1594.546  0.182 1
2000  1 4 1 2096.795  0.310 1
2001  1 4 1 2831.440  0.245 1
2002  1 4 1 1732.599  0.320 1
2003  1 4 1 1566.675  0.336 1
2004  1 4 1 1523.869  0.305 1
2005  1 4 1 1642.017  0.371 1
2006  1 4 1 3893.875  0.334 1
2007  1 4 1 6470.773  0.385 1
2008  1 4 1 4654.473  0.284 1
2009  1 4 1 6301.470  0.256 1
2010  1 4 1 11130.898 0.466 1
2011  1 4 1 10931.232 0.558 1
2012  1 4 1 6200.219  0.339 1
2013  1 4 1 2287.557  0.217 1
2014  1 4 1 6029.220  0.449 1
2015  1 4 1 5877.433  0.770 1
2016  1 4 1 3485.909  0.393 1
2017  1 4 1 1793.760  0.599 1
2018  1 4 1 1730.742  0.281 1
2019  1 4 1 3170.467  0.337 1 # (updated - EBSsurvey_analysis.R)
1995  1 5 1 12042.000 0.130 2
1998  1 5 1 12531.000 0.060 2
2001  1 5 1 8477.000  0.080 2
2004  1 5 1 1667.000  0.150 2
2007  1 5 1 8643.000  0.090 2
2010  1 5 1 10209.000 0.130 2
2013  1 5 1 5643.000  0.190 2
2015  1 5 1 2805.000  0.180 2
2016  1 5 1 2378.000  0.186 2
2017  1 5 1 1689.000  0.250 2
2018  1 5 1  745.000  0.140 2 # no smbkc pot survey in 2019
##  Number  of  length  frequency matrices
3
##  Number  of  rows  in  each  matrix
15  42  11 # (updated)
##  Number  of  bins  in  each  matrix  (columns  of  size  data)
3  3  3
##  SIZE  COMPOSITION DATA  FOR ALL FLEETS
##  SIZE  COMP  LEGEND
##  Sex:  1 = male, 2 = female, 0 = both  sexes combined
##  Type  of  composition:  1 = retained, 2 = discard,  0 = total composition
##  Maturity  state:  1 = immature, 2 = mature, 0 = both  states  combined
##  Shell condition:  1 = new shell,  2 = old shell,  0 = both  shell types combined
##length  proportions of  pot discarded males
##Year, Seas, Fleet,  Sex,  Type, Shell,  Maturity, Nsamp,  DataVec
  1990  3 1 1 0 0 0 15  0.1133  0.3933  0.4933
  1991  3 1 1 0 0 0 25  0.1329  0.1768  0.6902
  1992  3 1 1 0 0 0 25  0.1905  0.2677  0.5417
  1993  3 1 1 0 0 0 25  0.2807  0.2097  0.5096
  1994  3 1 1 0 0 0 25  0.2942  0.2714  0.4344
  1995  3 1 1 0 0 0 25  0.1478  0.2127  0.6395
  1996  3 1 1 0 0 0 25  0.1595  0.2229  0.6176
  1997  3 1 1 0 0 0 25  0.1818  0.2053  0.6128
  1998  3 1 1 0 0 0 25  0.1927  0.2162  0.5911
  2009  3 1 1 0 0 0 50  0.1413  0.3235  0.5352
  2010  3 1 1 0 0 0 50  0.1314  0.3152  0.5534
```

```
  2011  3 1 1 0 0 0 50  0.1314  0.3051  0.5636
  2012  3 1 1 0 0 0 50  0.1417  0.3178  0.5406
  2014  3 1 1 0 0 0 50  0.0939  0.2275  0.6786
  2015  3 1 1 0 0 0 50  0.1148  0.2518  0.6333 #no fishery so not updated
##length  proportions of  trawl survey  males
##Year, Seas, Fleet,  Sex,  Type, Shell,  Maturity, Nsamp,  DataVec
  1978  1 4 1 0 0 0 50  0.3865  0.3478  0.2657
  1979  1 4 1 0 0 0 50  0.4281  0.3190  0.2529
  1980  1 4 1 0 0 0 50  0.3588  0.3220  0.3192
  1981  1 4 1 0 0 0 50  0.1219  0.3065  0.5716
  1982  1 4 1 0 0 0 50  0.1671  0.2435  0.5893
  1983  1 4 1 0 0 0 50  0.1752  0.2726  0.5522
  1984  1 4 1 0 0 0 50  0.1823  0.2085  0.6092
  1985  1 4 1 0 0 0 46.5 0.2023  0.2010  0.5967
  1986  1 4 1 0 0 0 23  0.1984  0.4364  0.3652
  1987  1 4 1 0 0 0 35.5 0.1944  0.3779  0.4277
  1988  1 4 1 0 0 0 40.5 0.1879  0.3737  0.4384
  1989  1 4 1 0 0 0 50  0.4246  0.2259  0.3496
  1990  1 4 1 0 0 0 50  0.2380  0.2332  0.5288
  1991  1 4 1 0 0 0 50  0.2274  0.3300  0.4426
  1992  1 4 1 0 0 0 50  0.2263  0.2911  0.4826
  1993  1 4 1 0 0 0 50  0.2296  0.2759  0.4945
  1994  1 4 1 0 0 0 50  0.1989  0.2926  0.5085
  1995  1 4 1 0 0 0 50  0.2593  0.3005  0.4403
  1996  1 4 1 0 0 0 50  0.1998  0.3054  0.4948
  1997  1 4 1 0 0 0 50  0.1622  0.3102  0.5275
  1998  1 4 1 0 0 0 50  0.1276  0.3212  0.5511
  1999  1 4 1 0 0 0 26  0.2224  0.2214  0.5562
  2000  1 4 1 0 0 0 30.5 0.2154  0.2180  0.5665
  2001  1 4 1 0 0 0 45.5 0.2253  0.2699  0.5048
  2002  1 4 1 0 0 0 19  0.1127  0.2346  0.6527
  2003  1 4 1 0 0 0 32.5 0.3762  0.2345  0.3893
  2004  1 4 1 0 0 0 24  0.2488  0.1848  0.5663
  2005  1 4 1 0 0 0 21  0.2825  0.2744  0.4431
  2006  1 4 1 0 0 0 50  0.3276  0.2293  0.4431
  2007  1 4 1 0 0 0 50  0.4394  0.3525  0.2081
  2008  1 4 1 0 0 0 50  0.3745  0.2219  0.4036
  2009  1 4 1 0 0 0 50  0.3057  0.4202  0.2741
  2010  1 4 1 0 0 0 50  0.4081  0.3371  0.2548
  2011  1 4 1 0 0 0 50  0.2179  0.3940  0.3881
  2012  1 4 1 0 0 0 50  0.1573  0.4393  0.4034
  2013  1 4 1 0 0 0 37  0.2100  0.2834  0.5065
  2014  1 4 1 0 0 0 50  0.1738  0.3912  0.4350
  2015  1 4 1 0 0 0 50  0.2340  0.2994  0.4666
  2016  1 4 1 0 0 0 50  0.2255  0.2780  0.4965
  2017  1 4 1 0 0 0 21  0.0849  0.2994  0.6157
  2018  1 4 1 0 0 0 31  0.1475  0.2219  0.6306
  2019  1 4 1 0 0 0 50  0.1961  0.2346  0.5692
  ##length  proportions of  pot survey
  ##Year, Seas, Fleet,  Sex,  Type, Shell,  Maturity, Nsamp,  DataVec
  1995  1 5 1 0 0 0 100 0.1594  0.2656  0.5751
  1998  1 5 1 0 0 0 100  0.0769  0.2205  0.7026
  2001  1 5 1 0 0 0 100  0.1493  0.2049  0.6457
  2004  1 5 1 0 0 0 100  0.0672  0.2484  0.6845
  2007  1 5 1 0 0 0 100  0.1257  0.3148  0.5595
  2010  1 5 1 0 0 0 100  0.1299  0.3209  0.5492
  2013  1 5 1 0 0 0 100  0.1556  0.2477  0.5967
  2015  1 5 1 0 0 0 100  0.0706  0.2431  0.6859
  2016  1 5 1 0 0 0 100  0.0832  0.1917  0.7251
  2017  1 5 1 0 0 0 100  0.1048  0.2540  0.6412
  2018  1 5 1 0 0 0 100  0.10201 0.21611 0.68188
##  Growth data (increment)
# Type of growth increment (0=ignore;1=growth increment with a CV;2=size-at-release; size-at)
0
# nobs_growth
0
#3
# MidPoint Sex Increment CV
# 97.5  1  14.1  0.2197
#112.5  1  14.1  0.2197
#127.5  1  14.1  0.2197
#  97.5  1 13.8 0.2197
```

```
#  112.5  1 14.1 0.2197
#  127.5  1 14.4 0.2197
## eof
9999
```

The reference model (16.0) control file for 2019

```
## ==================================================================================== ##
## LEADING PARAMETER CONTROLS                                                           ##
# Controls for leading parameter vector theta
# LEGEND FOR PRIOR:
#                 0 -> uniform #                 1 -> normal #                 2 -> lognormal
#                 3 -> beta
#                 4 -> gamma
# ntheta
  12
## ==================================================================================== ##
# ival        lb        ub        phz   prior     p1      p2         # parameter         #
  0.18      0.01         1        -4       2   0.18    0.02          # M
  14.3      -7.0        30        -2       0    -7       30          # log(R0)
  10.0      -7.0        20        -1       1   -10.0     20          # log(Rini)
  13.39     -7.0        20         1       0    -7       20          # log(Rbar) (MUST be PHASE 1)
  80.0      30.0       310        -2       1    72.5    7.25         # Recruitment size distribution expected value
  0.25       0.1         7        -4       0    0.1     9.0          # Recruitment size scale (variance component)
  0.2      -10.0      0.75        -4       0  -10.0    0.75          # log(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
 14.5       5.00     20.00         1       0    5.00  20.00          # logN0 vector of initial numbers at length
 14.0       5.00     20.00         1       0    5.00  20.00          # logN0 vector of initial numbers at length
 13.5       5.00     20.00         1       0    5.00  20.00          # logN0 vector of initial numbers at length

#  Use custom natural mortality  (0=no,  1=yes,  by  sex  and  year)
0

# weight-at-length input method (1 = allometry i.e. w_l = a*l^b, 2 = vector by sex, 3 = matrix by sex)
3
# Male weight-at-length
0.000748427    0.001165731    0.001930510
0.000748427    0.001165731    0.001688886
0.000748427    0.001165731    0.001922246
0.000748427    0.001165731    0.001877957
0.000748427    0.001165731    0.001938634
0.000748427    0.001165731    0.002076413
0.000748427    0.001165731    0.001899330
0.000748427    0.001165731    0.002116687
0.000748427    0.001165731    0.001938784
0.000748427    0.001165731    0.001939764
0.000748427    0.001165731    0.001871067
0.000748427    0.001165731    0.001998295
0.000748427    0.001165731    0.001870418
0.000748427    0.001165731    0.001969415
0.000748427    0.001165731    0.001926859
0.000748427    0.001165731    0.002021492
0.000748427    0.001165731    0.001931318
0.000748427    0.001165731    0.002014407
0.000748427    0.001165731    0.001977471
0.000748427    0.001165731    0.002099246
0.000748427    0.001165731    0.001982478
0.000748427    0.001165731    0.001930932
0.000748427    0.001165731    0.001930932
0.000748427    0.001165731    0.001930932
0.000748427    0.001165731    0.001930932
0.000748427    0.001165731    0.001930932
0.000748427    0.001165731    0.001930932
0.000748427    0.001165731    0.001930932
0.000748427    0.001165731    0.001930932
0.000748427    0.001165731    0.001930932
0.000748427    0.001165731    0.001930932
0.000748427    0.001165731    0.001891628
```

```
0.000748427    0.001165731    0.001795721
0.000748427    0.001165731    0.001823113
0.000748427    0.001165731    0.001807433
0.000748427    0.001165731    0.001930932
0.000748427    0.001165731    0.001894627
0.000748427    0.001165731    0.001850611
0.000748427    0.001165731    0.001930932
0.000748427    0.001165731    0.001930932
0.000748427    0.001165731    0.001930932
0.000748427    0.001165731    0.001930932 # (updated - should this change?)
# Proportion mature by sex
0 1 1
# Proportion legal by sex
0 0 1

## GROWTH PARAM CONTROLS                                                           ##
# Use custom transition matrix (0=no, 1=growth matrix, 2=transition matrix, i.e. growth and molting)
1
# growth increment model (0=prespecified;1=alpha/beta; 2=estimated by size-class;3=pre-specified/emprical)
0
# molt probability function (0=pre-specified; 1=flat;2=declining logistic)
2
# maximum size-class (males then females)
3
# Maximum size-class for recruitment(males then females)
1
## number of size-increment periods
1
## Two lines for each parameter if split sex, one line if not                        ##
## number of molt periods
1
## Year(s) molt period changes (blank if no changes)
## Beta parameters are relative (1=Yes;0=no)
1
## ================================================================================ ##
# ival        lb        ub         phz  prior     p1      p2        # parameter         #
#  14.1      10.0      30.0         -3       0    0.0   999.0        # alpha males or combined
#   0.0001    0.0       0.01        -3       0    0.0   999.0        # beta males or combined
#   0.45      0.01      1.0         -3       0    0.0   999.0        # gscale males or combined
 121.5      65.0     145.0         -4       0    0.0   999.0        # molt_mu males or combined
   0.060     0.0       1.0         -3       0    0.0   999.0        # molt_cv males or combined

# The custom growth matrix (if not using just fill with zeros)
# Alternative TM (loosely) based on Otto and Cummiskey (1990)
   0.1761   0.0000   0.0000
   0.7052   0.2206   0.0000
   0.1187   0.7794   1.0000
#   0.1761   0.7052   0.1187
#   0.0000   0.2206   0.7794
#   0.0000   0.0000   1.0000

# custom molt probability matrix


## ================================================================================ ##
## SELECTIVITY CONTROLS                                                             ##
##     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, 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                           ##
## ================================================================================ ##
## ivector for number of year periods or nodes                                      ##
## POT       TBycatch FBycatch  NMFS_S   ADFG_pot
## Gear-1    Gear-2   Gear-3    Gear-4   Gear-5
   2         1        1         1        1         # Selectivity periods
   0         0        0         0        0         # sex specific selectivity
   0         3        3         0        0         # male selectivity type
   0         0        0         0        0         # within another gear
```

```
## Gear-1    Gear-2   Gear-3    Gear-4   Gear-5
   1         1        1         1        1         # Retention periods
   0         0        0         0        0         # sex specific retention
   3         6        6         6        6         # male retention type
   1         0        0         0        0         # male retention flag (0 -> no, 1 -> yes)
## gear  par   sel                                             phz    start  end        ##
## index index par sex  ival  lb    ub     prior p1     p2     mirror period period     ##
# Gear-1
   1     1     1   0    0.4    0.001 1.0    0       0      1    3     1978   2008
   1     2     2   0    0.7    0.001 1.0    0       0      1    3     1978   2008
   1     3     3   0    1.0    0.001 2.0    0       0      1    -2     1978   2008
   1     1     1   0    0.4    0.001 1.0    0       0      1    3     2009   2018
   1     2     2   0    0.4    0.001 1.0    0       0      1    3     2009   2018
   1     3     3   0    1.0    0.001 2.0    0       0      1    -2     2009   2018
# Gear-2
   2     7     1   0    40      10.0  200    0      10    200   -3     1978   2018
   2     8     2   0    60      10.0  200    0      10    200   -3     1978   2018
# Gear-3
   3     9     1   0    40      10.0  200    0      10    200   -3     1978   2018
   3    10     2   0    60      10.0  200    0      10    200   -3     1978   2018
# Gear-4
   4     11    1   0    0.7     0.001 1.0    0       0      1   4     1978   2019
   4     12    2   0    0.7     0.001 1.0    0       0      1   4     1978   2019
   4     13    3   0    0.9     0.001 1.0    0       0      1   -5     1978   2019
# Gear-5
   5     14    1   0    0.4     0.001 1.0    0       0      1   4     1978   2019
   5     15    2   0    0.7     0.001 1.0    0       0      1   4     1978   2019
   5     16    3   0    1.0     0.001 2.0    0       0      1   -2     1978   2019
## Retained
# Gear-1
  -1     17    1   0    120        50 200    0      1    900    -7     1978   2018
  -1     18    2   0    123       110 200    0      1    900    -7     1978   2018
# Gear-2
  -2     19    1   0   595    1    999    0      1    999   -3     1978   2018
# Gear-3
  -3     20    1   0   595    1    999    0      1    999   -3     1978   2018
# Gear-4
  -4     21    1   0   595    1    999    0      1    999   -3     1978   2019
# Gear-5
  -5     22    1   0   595    1    999    0      1    999   -3     1978   2019

# Number of asymptotic parameters
1
# Fleet   Sex     Year       ival  lb   ub    phz
       1     1     1978   0.000001   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               ##
## ==================================================================================== ##
##  LAMBDA: Arbitrary relative weights for each series, 0 = do not fit.
## SURVEYS/INDICES ONLY
## ival    lb       ub    phz   prior   p1       p2    Analytic?   LAMBDA Emphasis
   1.0     0.5      1.2   -4    0       0        9.0   0           1            1 # NMFS trawl
 0.003      0        5     3    0       0        9.0   0           1            1 # ADF&G pot
## ==================================================================================== ##

## ==================================================================================== ##
## 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: 0 = uniform, 1 = normal, 2 = lognormal, 3 = beta, 4 = gamma               ##
## ==================================================================================== ##
## ival        lb        ub        phz   prior     p1      p2
   0.0000001      0.00000001   10.0      -4    4         1.0     100   # NMFS (PHASE -4)
   0.0000001      0.00000001   10.0      -4    4         1.0     100   # ADF&G
## ==================================================================================== ##
```

```
## ==================================================================================== ##
## PENALTIES FOR AVERAGE FISHING MORTALITY RATE FOR EACH GEAR
## ==================================================================================== ##
## Mean_F Female_offset STD_PHZ1  STD_PHZ2  PHZ_M PHZ_F
   0.2              0.0     3.0     50.0        1    -1 # Pot
   0.0001           0.0     4.0     50.0        1    -1 # Trawl
   0.0001           0.0     4.0     50.0        1    -1 # Fixed
   0.00             0.0     2.00     20.00       -1    -1 # NMFS
   0.00             0.0     2.00     20.00       -1    -1 # ADF&G
## ==================================================================================== ##

## ==================================================================================== ##
## OPTIONS FOR SIZE COMPOSTION DATA (COLUMN FOR EACH MATRIX)
## ==================================================================================== ##
## LIKELIHOOD OPTIONS
##   -1) Multinomial with estimated/fixed sample size
##   -2) Robust approximation to multinomial
##   -3) logistic normal (NIY)
##   -4) multivariate-t (NIY)
##   -5) Dirichlet
## AUTOTAIL COMPRESSION
##   pmin is the cumulative proportion used in tail compression.
## ==================================================================================== ##
#  1   1   1  # Type of likelihood
  2   2   2  # Type of likelihood
#  5   5   5   # Type of likelihood
  0   0   0   # Auto tail compression (pmin)
  1   1   1   # Initial value for effective sample size multiplier
 -4  -4  -4   # Phz for estimating effective sample size (if appl.)
  1   2   3   # Composition aggregator
  1   1   1   # LAMBDA
  1   1   1   # Emphasis
## ==================================================================================== ##

## ==================================================================================== ##
## TIME VARYING NATURAL MORTALIIY RATES                                                 ##
## ==================================================================================== ##
## 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
## Phase of estimation (only use if parameters are default)
3
## STDEV in m_dev for Random walk
10.0
## Number of nodes for cubic spline or number of step-changes for option 3
2
## Year position of the knots (vector must be equal to the number of nodes)
1998 1999
## Number of Breakpoints in M by size
0
## Size-class of breakpoint
#3
## Specific initial values for the natural mortality devs (0-no, 1=yes)
1
## =========================================================================================== ##
## ival        lb        ub        phz   extra    prior     p1      p2         # parameter     ##
## =========================================================================================== ##
 1.600000       0          2          3      0                        # Males
 0.000000      -2          2        -99      0                        # Dummy to retun to base value
# 2.000000       0          4         -1      0                        # Size-specific M
## ==================================================================================== ##

## ==================================================================================== ##
## OTHER CONTROLS
## ==================================================================================== ##
1978       # First rec_dev
```

```
2018       # last rec_dev
   3       # Estimated rec_dev phase
  -3       # Estimated rec_ini phase
   0       # VERBOSE FLAG (0 = off, 1 = on, 2 = objective func)
   2       # Initial conditions (0 = Unfished, 1 = Steady-state fished, 2 = Free parameters)
   1       # Lambda (proportion of mature male biomass for SPR reference points)
   0       # Stock-Recruit-Relationship (0 = None, 1 = Beverton-Holt)
  10 # 10       # Maximum phase (stop the estimation after this phase).
  -1       # Maximum number of function calls
## ================================================================================ ##
## EMPHASIS FACTORS (CATCH)
## ================================================================================ ##
#Ret_POT Disc_POT Disc_trawl Disc_fixed
       1        1          1          1

## ================================================================================ ##
## EMPHASIS FACTORS (Priors)
## ================================================================================ ##
# Log_fdevs   meanF       Mdevs  Rec_devs Initial_devs Fst_dif_dev Mean_sex-Ratio
      10000       1           1         1            0           0             1             #(10000)
## EOF
9999
```

Appendix C. Rebuilding analysis for St. Matthew blue king crab

Introduction

In 2018 the MMB for SMBKC fell below 50% of the B_{MSY} proxy or the MSST, using average mature male biomass from 1978-2017. The stock was determined to be overfished (but overfishing is not occurring since the fishery has been closes the last two years) and a rebuilding plan is to be implemented within 2 years. This document summarizes the projections performed on the 2019 assessment model and their associated rebuilding probabilities for the stock using the projections module developed for GMACS (A.Punt pers Comm). All projections presented here are performed on the base or reference model with 2019 data, results include projections that look at a alternative regime time frame for reference point calculations.

Regime shifts

Model output in 2018 (using the reference model) of both biomass and recruitment suggest a shift from higher levels in the first have of the time series to lower levels in the recent regime. These trends warranted an examination of the modeled data to determine if a regime shift has occurred.

Recruitment breakpoint analysis

Upon 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 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 BMSY proxies. Results from assessment model 3 from 2018, which is the base or reference model (Ianelli and Zheng 2018), were used for this analysis. These results were presented at the May 2019 crab Plan Team meeting, the details of this analysis can be found in Appendix D.

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.

STARS method

The "Sequential t-Test Analysis of Regime Shifts (STARS)" method was suggested as a alternative analysis that could be used to determine of the St.Matthew blue king crab stock has undergone a regime shift (Rodionov and Overland 2005). The advantage of this method is that it can be performed on any time series and does not rely on a stock recruitment relationship. This method identifies discontinuity in a time-series and allows for early detection of a regime shift and subsequent monitoring of changes in its magnitude over time (Rodionov 2004).

Detection of discontinuity is accomplished by sequentially testing whether a new mean recruitment value within a time-series represents a statistically significant deviation from the mean value of the current 'regime.' As data are added to the time-series, the hypothesis of a new 'regime' (i.e. time block) is either confirmed or rejected based on the Student's t-test (Rodionov and Overland 2005). The STARS method is well documented in the literature and has been applied previously to physical and biological indices (Mueter et al. 2007; Reid et al. 2016; Marty 2008; Conversi et al. 2010; Menberg et al. 2014; Blamey et al. 2012; Lindegren et al. 2010; Howard et al. 2007). An R script (STARS.R; Seddon et al. 2011; http://esapubs.org/archive/ecol/E095/262/suppl-1.php) that is equivalent to the v3-2 excel add-in tool (http://www. beringclimate.noaa.gov/regimes), and references the methods from Rodionov 2004 and 2006, was used to run the STARS method on the recruitment time series from the accepted 2018 model output.

Several parameters within the STARS method need specification prior to application to determine the breaks in the recruitment time series. Two parameters, the p-value (the probability level for significance between ‘regime’ means) and the cutoff length (the approximate minimum number of years within a regime) control the magnitude and scale of the regimes to be detected, or how strong a change in the recruitment needs to be detected. If regimes are longer than the cutoff length, they will be detected. There is a reduced probability of detection for regimes shorter than the cutoff length, but the regimes may still be detected if the shift is of sufficient magnitude (Rodionov 2004). In addition, Huber’s weight parameter determines the weight assigned to outliers and thus the magnitude of the average values of each regime (Huber 1964). Finally, the user determines whether to account for autocorrelation and specifies the associated subsample size needed. For this study, a p-value of 0.05 was chosen, which is well within the range of other studies that have applied the STARS method. A range of cutoff values from 5 to 20 were specified within the STARS method to explore the sensitivity, but all values produced the same significant break year of 1996. The default value of one for Huber’s weight parameter, and autocorrelation were included (Newman et al. 2003). Two frameworks are available within the STARS method to estimate autocorrelation (Rodionov 2004): the MPK (Marriott-Pope and Kendall) and the IPN4 (Inverse Proportionality with 4 corrections). The two frameworks break the time series into subsamples, estimate bias-corrected first-order autocorrelation for each subsample and then use the median value of all estimates. The two frameworks produce very similar results and only in certain instances (small subsample size) does the IPN4 method significantly outperform the MPK method (Rodionov 2004). Therefore, the IPN4 method was used in this analysis with the suggested subsample size of m=(l+1)/3, where l is the cutoff length.

This parameterization resulted in two potential time blocks: 1978-1995 and 1996–2017, corresponding to a break in 1996 which is the same year as the recruitment breakpoint analysis that was performed in May 2019.

Rebuilding projections

The rebuilding projections were performed using the projection module coded into GMACS in early 2019 (A. Punt per Comm). A preliminary analysis of the rebuilding projections performed at the January crab plan team meeting by A.Punt concluded that bycatch mortality in this fishery was minor and that the rebuilding timeline was mostly dependent on assumptions of recruitment for the stock.

Initial rebuilding projections presented at the May CPT meeting (June SSC meeting) included recruitment options of: Ricker, or Beverton-Holt stock recruit relationship and “random” recruitment. Stock-recruitment models (Ricker, Beverton-Holt) typically fit poorly for crab stocks, and this holds true for SMBKC. Projections using these stock recruitment relationships were still provided for initial review since they scale recruitment to the current status of the stock. The “random”" recruitment option resamples historical recruitment estimates randomly, from a designated period for each projection iteration, such as the entire time series 1978 to 2018 as one example. This option assumes that recruitment is unrelated to stock size, but also relies on choosing the random draws from a biologically and environmentally representative time frame of past recruitment.

Projections were performed to look at a range of combinations of recruitment, bycatch mortality, and implementation of the state harvest policy to determine the probability of recovery for each scenario. Rebuilding time under any of the projection combinations is insensitive to the average values for recent (2013 - 2017 or 2014 - 2018) bycatch. As a sensitivity analysis the projections presented here were also performed using the maximum observed bycatch value, corresponding to year 2007. The implementation of the state harvest policy in the projections (version “d”) affected rebuilding times in some projections, but with a much smaller affect of increasing T_{min} than projections at F = M (0.18), therefore the projections presented here use the state of Alaska harvest policy as the upper bound for fishing mortality.

The projections considered in May produced a range of T_{min} values, however, the decision tackled at this meeting was which option is the most biologically and environmentally plausible. The recruitment breakpoint analysis and the STARS method suggested that recent recruitment (1996-2017) differed from the early part of the time series.

Both the CPT and SSC recommendations from the May meeting were to proceed with “random” recruitment projections that drew from two recruitment time periods:

1) the entire time series, 1978 to 2018
2) the current regime, 1996 to 2018

These projections use the state harvest policy as the upper fishing mortality and included average recent bycatch mortality (2014 - 2018). Additionally, sensitivity on T_{min} values to higher bycatch mortality are included to help inform the rebuilding time frame (using maximum observed bycatch in 2007, which is 10 times here than recent bycatch levels).

The important decision points that are needed to move forward with the rebuilding plan are to adapt a consensus on:

- the current state of the stock (reference point time frame),
- the corresponding expectations on future recruitment, and
- the expectations for future bycatch mortality.

Recommendations from the Sept. 2019 CPT meeting were to consider projections that were presented in May in addition to those initially presented in this document. Therefore, this document was updated to also include additional projections: projection 4 - random recruitment from recent years (1996-2018) with the current reference point time frame (1978-2018) and projection 2 - ricker stock-recruit relationship using entire time series (Tables 1 and 2).

Table 1: Projections performed with associated recruitment assumptions.

Projection	recruitment	B_{MSY} proxy	recruitment years
1	random recruitment	1978-2018	1978-2018
2	ricker	1978-2018	
4	random recruitment	1978-2018	1996-2018
5	random recruitment	1996-2018	1996-2018

Table 2: Versions for each of the projections.

Version	Bycatch mortality	SOA harvest policy
d	present (2014-2018)	yes
aa	max value (2007)	yes

Results

Bycatch mortality

Rebuilding time under any of the projection combinations is insensitive to the average values for recent (2014 - 2018) bycatch. A sensitivity analysis to larger bycatch levels was performed using the maximum observed bycatch value, corresponding to year 2007 in the model input (Figures 1 and 2).

Random recruitment entire time series (1978 - 2018)

Projections using "random" recruitment (projection 1) resampled from the entire time series (1978-2018) implied environmental conditions as being equal to this period. Under this hypothesis the probability of recovery produces, under average recent bycatch levels, a $T_{min} = 6.05$ years under no directed fishery mortality (F = 0), and a $T_{min} = 9.0$ years when the state harvest policy is implemented (Figure 3). The recruitment breakpoint analysis performed on this stock (Appendix D) suggested that recruitment conditions equal to the full period are unlikely and overly optimistic.

Random recruitment from current regime (1996 - 2018)

The recruitment breakpoint analysis suggested that a shift occurred in 1996. Both the "random" recruitment time period and the time period to calculate the B_{MSY} proxy should reflect this (Table 3). Projection 5 matches these two time frames, and under average recent bycatch levels, has a $T_{min} = 9.0$ years for the probability of recovery to this new/current B_{MSY} proxy under no directed fishery mortality (F = 0), and a T_{min} a little over 9.0 years under the state harvest policy implementation (Figure 4). The consistencies in these T_{min} values is due to the state harvest policy thresholds being based on past periods rather than having adopted to changes in B_{MSY} proxy years.

Projection 4 uses recruitment from the recent regime but keeps the reference point time frame for the entire time series of data (1978-2018). Although this is a mis-match of the reference point and recruitment time frame it encompasses expectations for the recruitment of the stock with respect to the environment and the current stock status (Figure 5).

Ricker stock-recruit relationship (1978 - 2018)

While the stock-recruit relationship for St. Matt's blue king crab is weak, it still provides an estimate of recruitment potential that responds to the status of the mature male biomass, therefore it is also presented here for comparison (Figure 6). The benefit of this projection is that it incorporates the stock status into the recruitment considerations without changing the time frame to draw either recruitment or the B_{MSY} proxy.

Discussion

The projections initially considered here produced T_{min} values that fell between 6 and a little over 11 years (Tables 4 and 5), however, the question remains which option is the most biologically and environmentally plausible. The recruitment breakpoint analysis (Appendix D) suggested that recent recruitment (1996-2018) differed from the early part of the time series. Recruitment success for SMBKC, as with many crab species, is driven by environmental conditions. In the Bering Sea recent environmental conditions appear to be unfavorable for recruitment success for this stock, which may be due to the longer larval duration of blue king crab.

Projections that include average recent bycatch levels have a T_{min} value less than 10 years under no directed fishing (F = 0). These values increased with maximum bycatch levels, however these projections assume that these high bycatch levels would persist annually throughout the 50 year projection. Even with increased bycatch to higher levels in some years the rebuilding time frame would not be expected to increase dramatically (Table 5).

Assuming that recent trends in recruitment and biomass represent a current environmental "regime", the most biologically and environmental plausible projection would be projection 5, which suggests the stock would rebuild in less than 10 years to a more representative B_{MSY} that is based on current recruitment conditions. However, if adjusting the reference point time frame is not considered valid the projections suggest a rebuilding time frame < 10 years to the current B_{MSY} proxy levels, with large assumptions on upcoming recruitment variability. When the reference point time frame or B_{MSY} proxy years are kept to the entire time series the probability of recovery of the stock ranges from >100 years (assuming recent recruitment) to less than 10 years if recruitment is allowed to be randomly draw from the entire time series. Overall, the CPT and the author feel that these two outlooks are more pessimistic and more optimistic, respectively, than the reality for this stock. Projection 2, which uses a stock-recruit relationship, provides some intermediate reference for T_{min}.

According to the federal rebuilding framework if T_{min} exceeds 10 years, then the method for determining a T_{max} would be defined by one of three options. These are: T_{min} plus one generation time, time to rebuild to B_{msy} if fished at 75% of MFMT, or T_{min} multiplied by two. The rough generation time calculated for this stock, assuming a recruitment age of 7 years, is approximately 14 years. The CPT entertained estimates of T_{max} that reflected these, while also stressing the important of recruitment assumptions for this stock.

Tables

Table 3: B_{MSY} proxy options for 2018 model 3, all Tier 4b.

Year	Basis for B_{MSY}	B_{MSY} proxy	MSST	Biomass(MMB_{mating})	B/B_{MSY}	F_{OFL}	M
2019/20	1978-2018	3.48	1.74	1.08	0.31	0.042	0.18
2019/20	1996-2018	2.05	1.025	1.04	0.51	0.082	0.18

Table 4: T_{min} for each projection version d with no directed fishing (F=0) and average recent bycatch.

Projection	recruitment	B_{MSY} proxy	recruitment yrs	T_{min}
1	random recruitment	1978-2018	1978-2018	6.05 years
2	ricker	1978-2018	1978-2018	14.5 years
4	random recruitment	1978-2018	1996-2018	>100 years
5	random recruitment	1996-2018	1996-2018	9.0 years

Table 5: T_{min} for each projection version aa with maximum observed bycatch.

Projection	recruitment	B_{MSY} proxy	recruitment yrs	F level	T_{min}
1	random recruitment	1978-2018	1978-2018	F = 0	6.5 years
1	random recruitment	1978-2018	1978-2018	F = SHR	11.0 years
5	random recruitment	1996-2018	1996-2018	F = 0	11.25 years
5	random recruitment	1996-2018	1996-2018	F = SHR	13.0 years

Figures

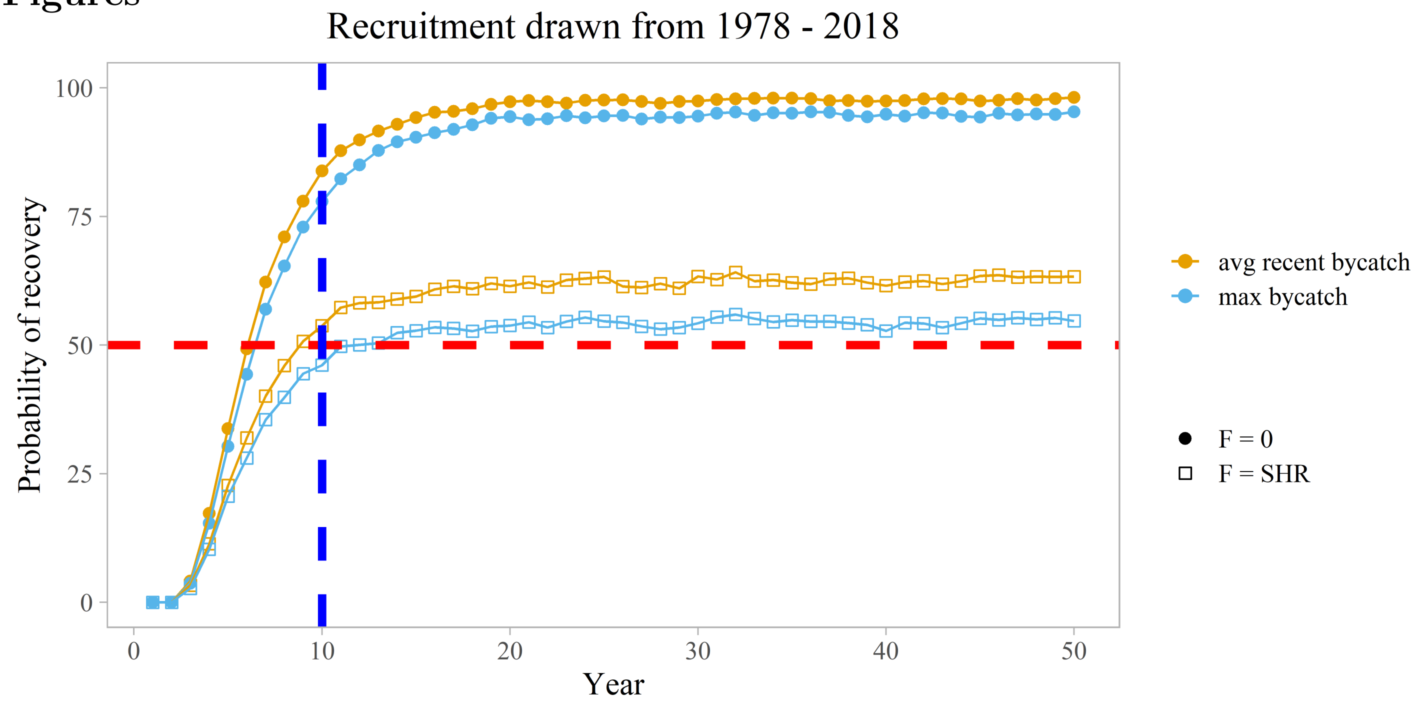

Figure 1: Comparisons of probability of recovery with random recruitment from 1978 to 2018 under different bycatch levels, show as with a min F = 0 and a max F equivalent to the state harvest rate (SHR).

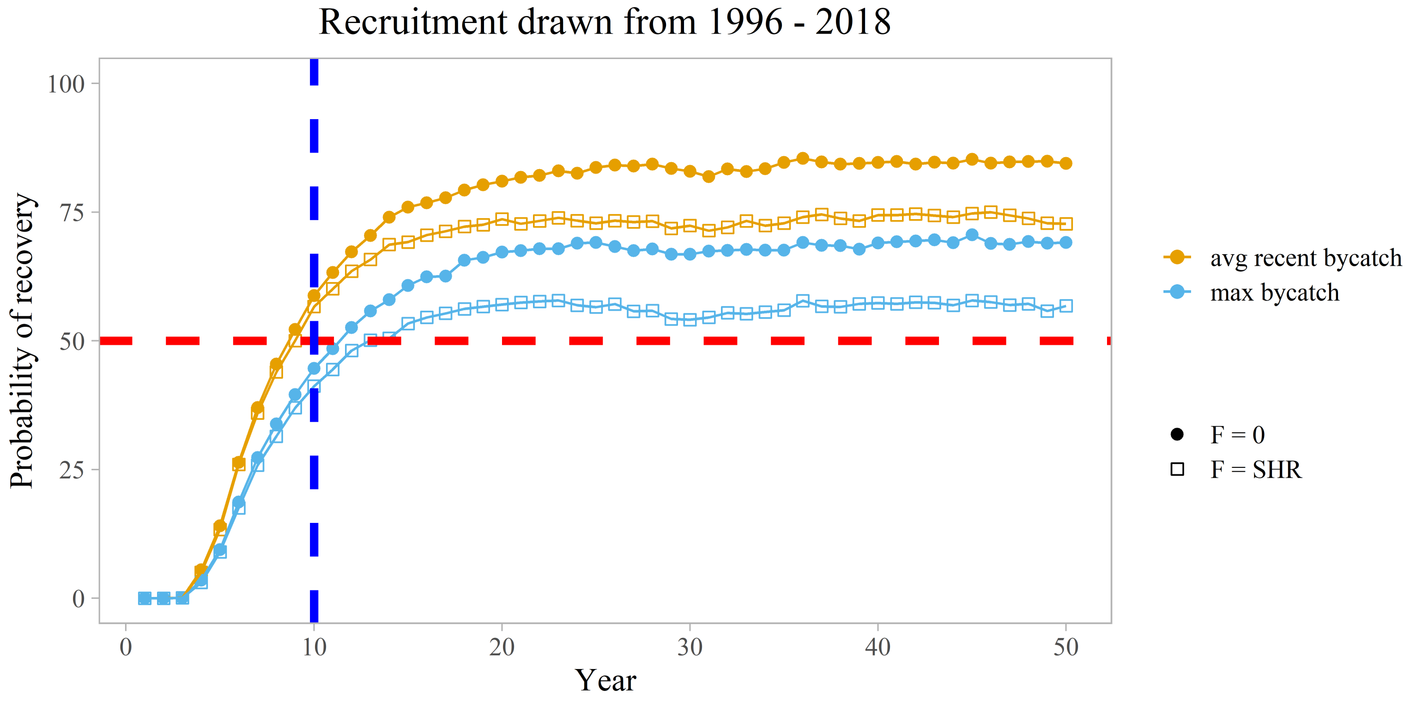

Figure 2: Comparisons of probability of recovery with random recruitment from 1996 to 2018 under different bycatch levels, show as with a min F = 0 and a max F equivalent to the state harvest rate (SHR).

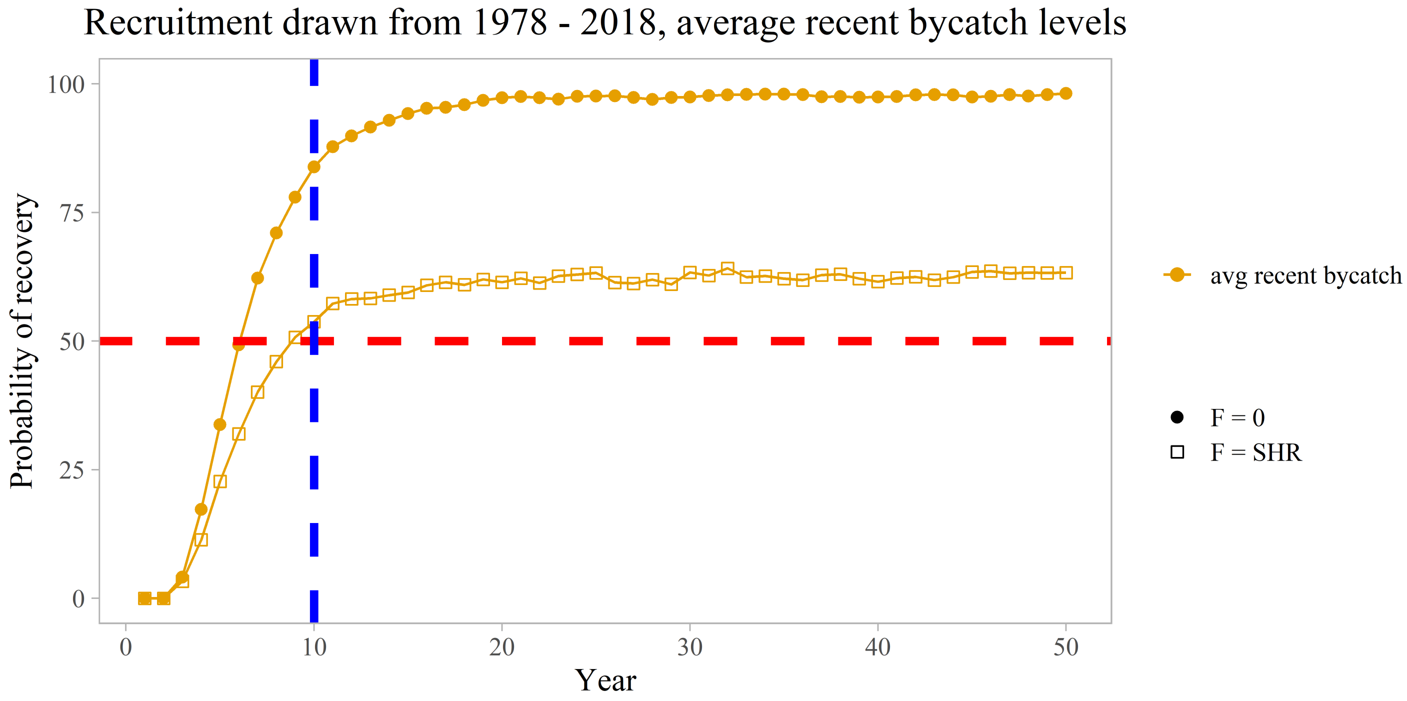

Figure 3: Probability of recovery with random recruitment from 1978 to 2018 under different fishing mortalities, min F = 0 and a max F equivalent to the state harvest rate (SHR). Projection 1.

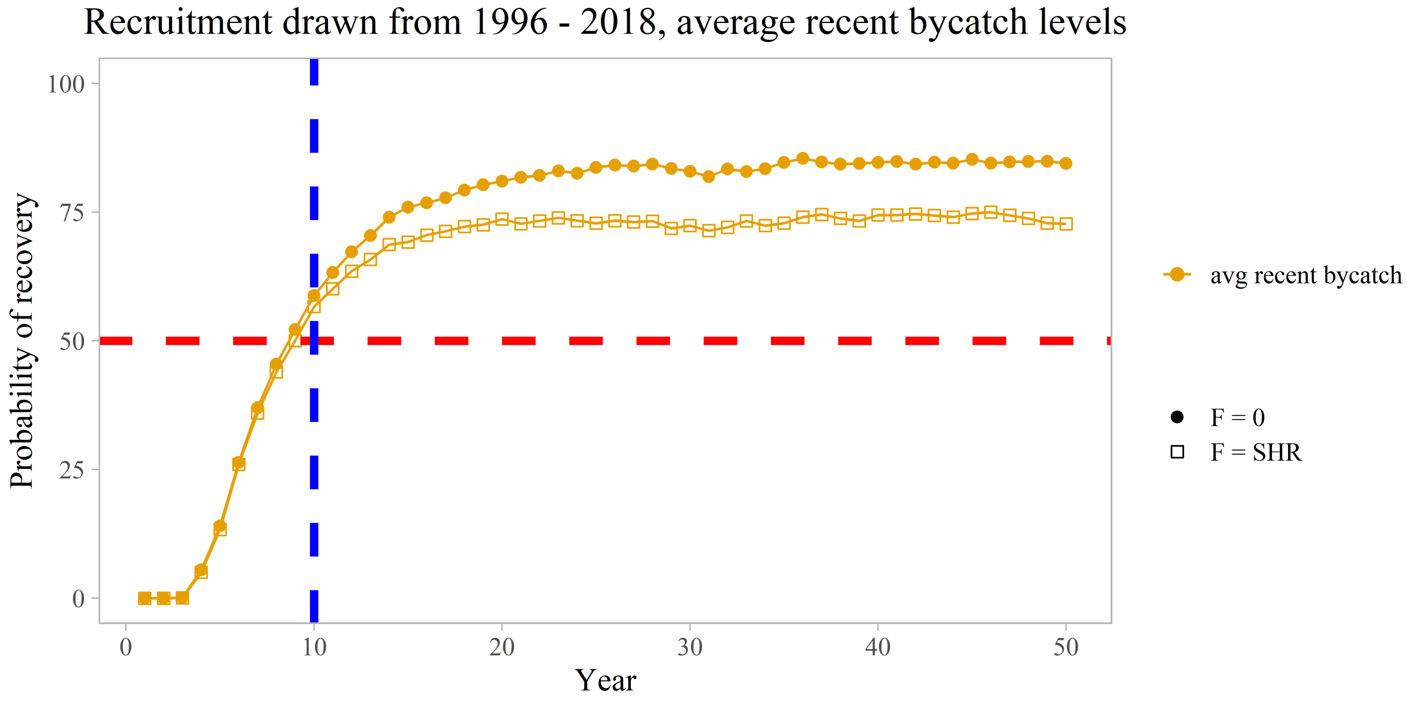

Figure 4: Probability of recovery with random recruitment from 1996 to 2018 under different fishing mortalities, min F = 0 and a max F equivalent to the state harvest rate (SHR). Projection 5.

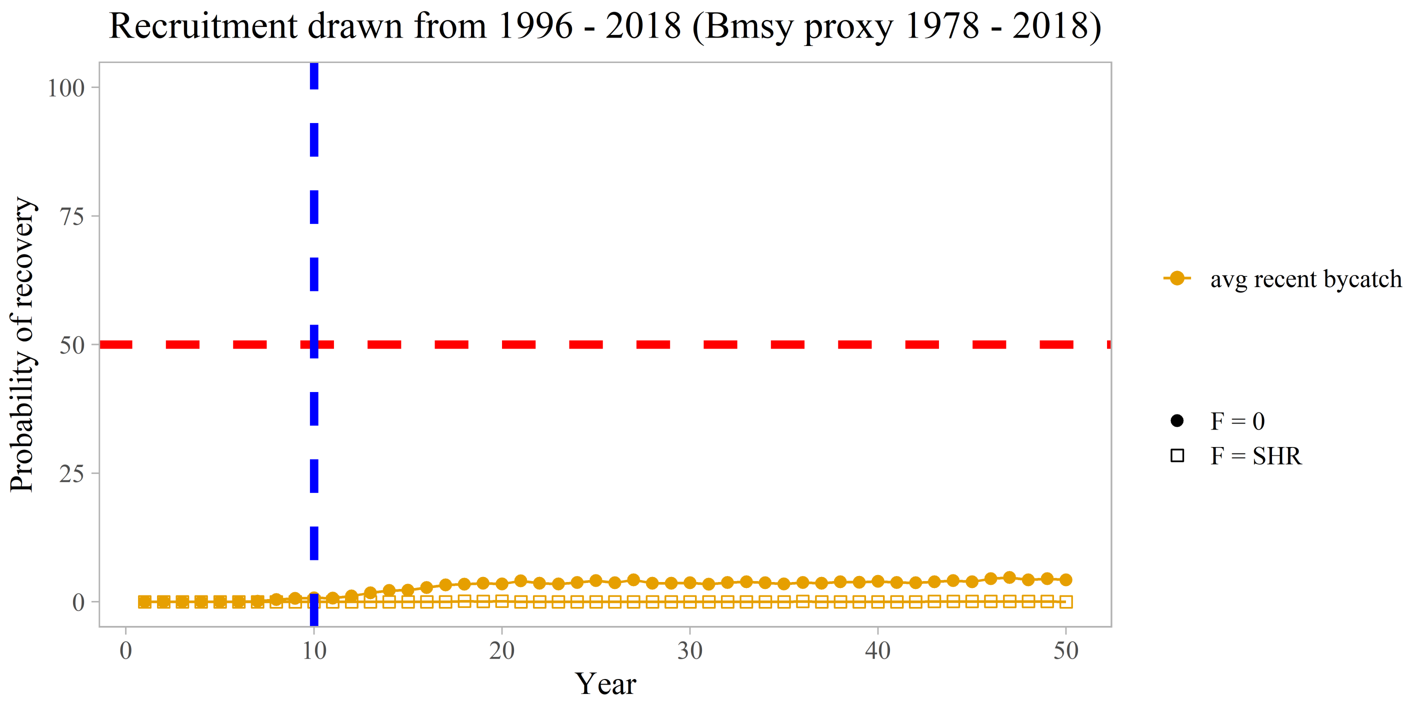

Figure 5: Probability of recovery with random recruitment from 1996 to 2018, while the Bmsy proxy is from 1978 to 2018, under different fishing mortalities, min F = 0 and a max F equivalent to the state harvest rate (SHR). Projection 4

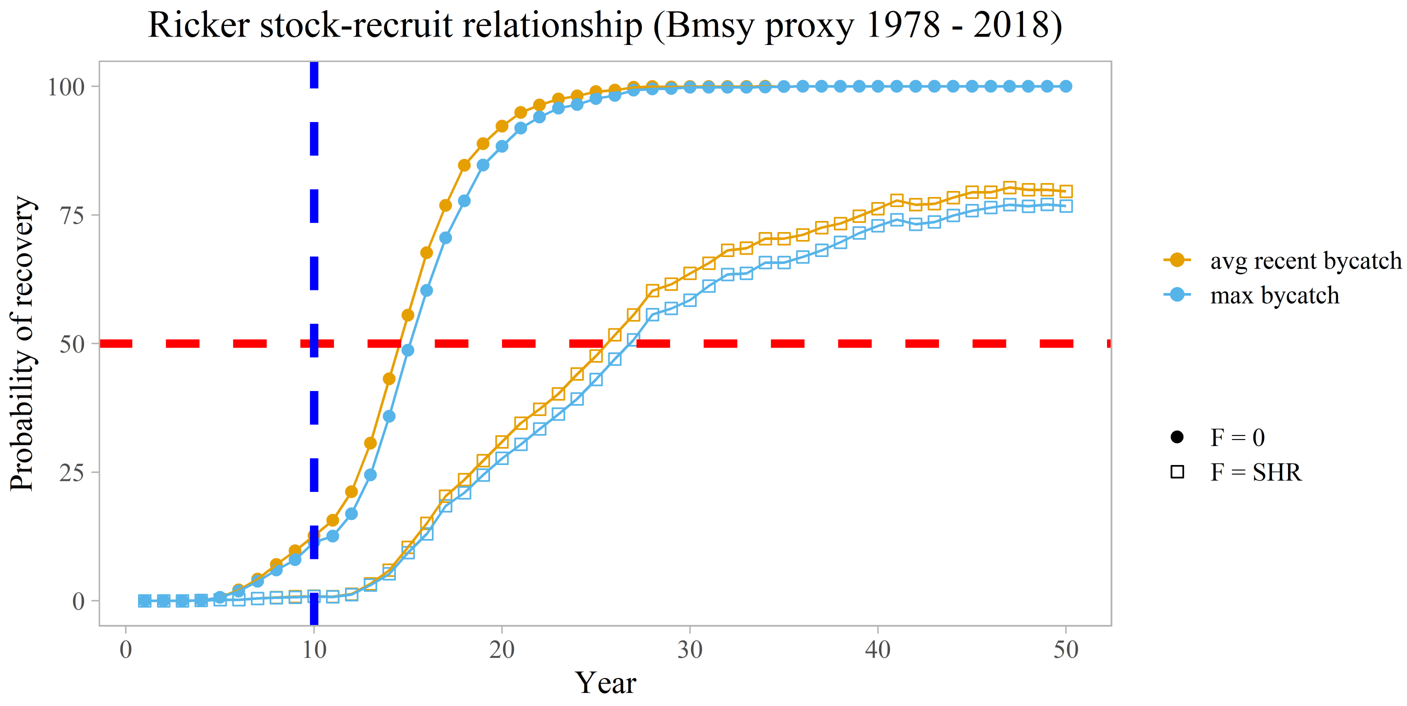

Figure 6: Comparisons of probability of recovery with ricker s-r relationshipusing the entire time series (1978-2018) under different bycatch levels, show as with a min F = 0 and a max F equivalent to the state harvest rate (SHR). Projection 2

Appendix D. 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,

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

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,

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

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(σ) and tan(ρ). 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),

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

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

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

Results

Results are summarized in Tables D1-D4 and Figures D1-D6. 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 D1) 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 D8-D10).

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 D5). The is approximately a 42% reduction (Figure D7). 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

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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 D1. 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 D2. 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 D3. 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 D4. 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 D5. 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

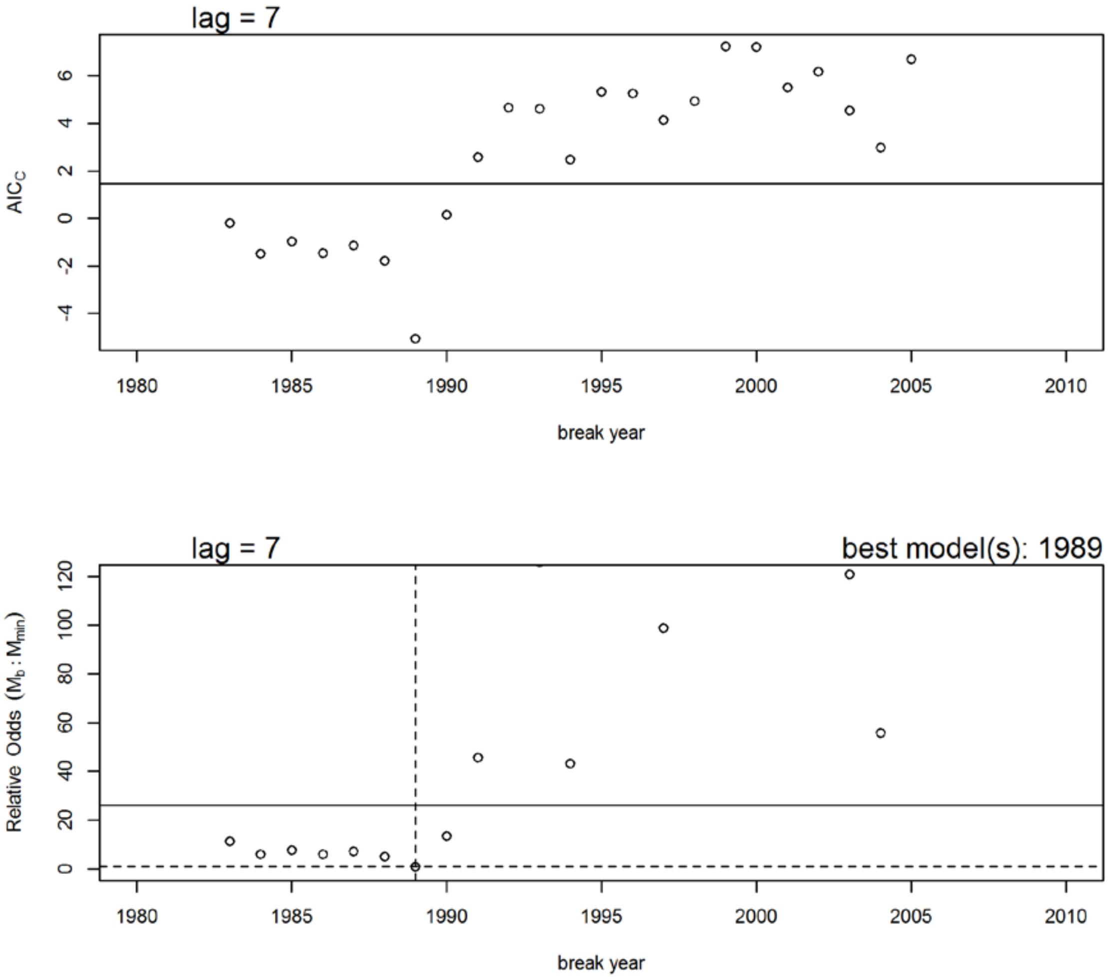


Figure D1. Results from the Ricker stock-recruit breakpoint analysis. Upper graph: AICc vs. year of breakpoint for the 1-breakpoint models (circles) and AICc for the model with no breakpoint (horizontal line). Lower graph: probabilistic odds for all 1-breakpoint models (circles) and the no breakpoint 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.

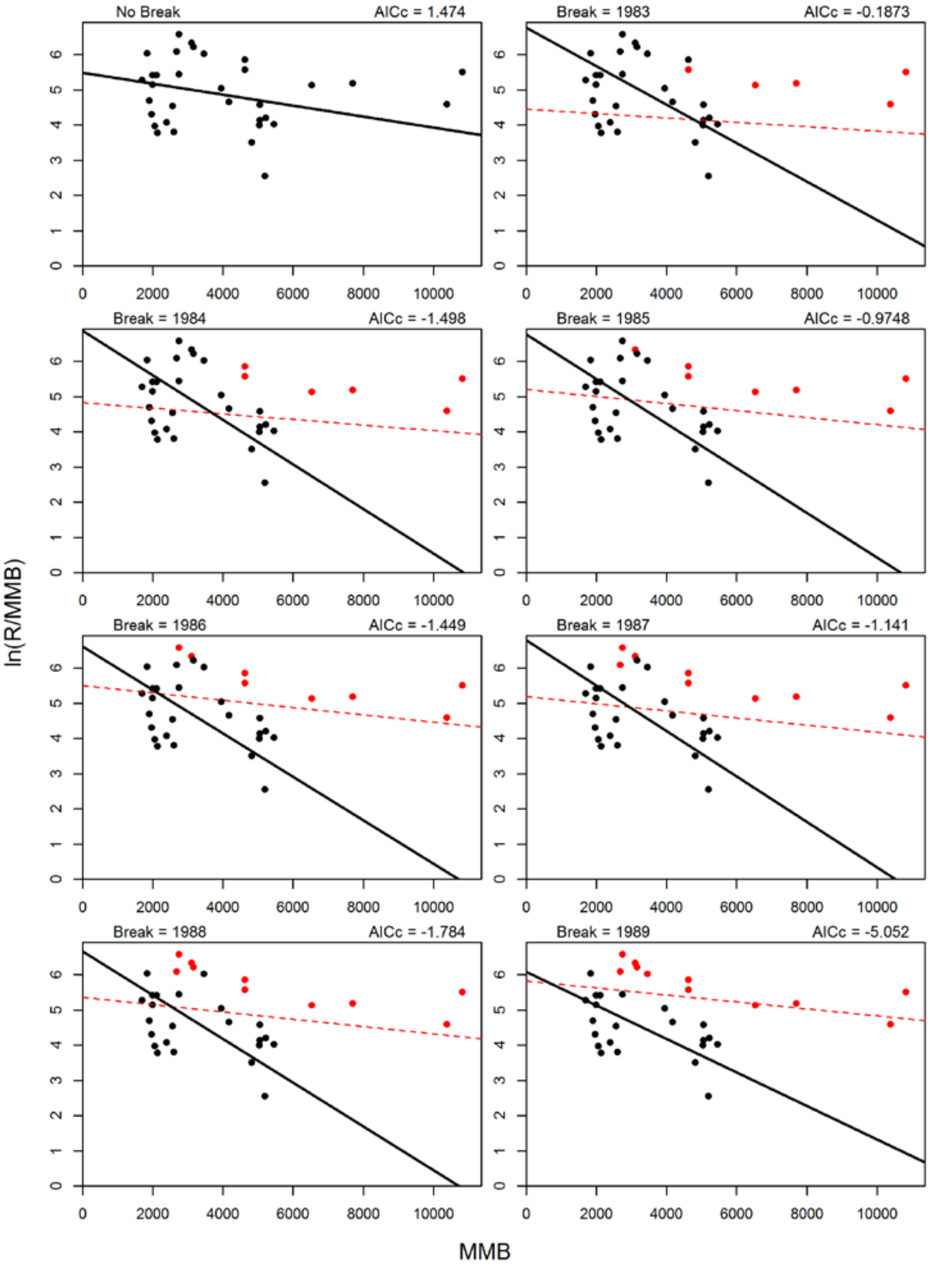
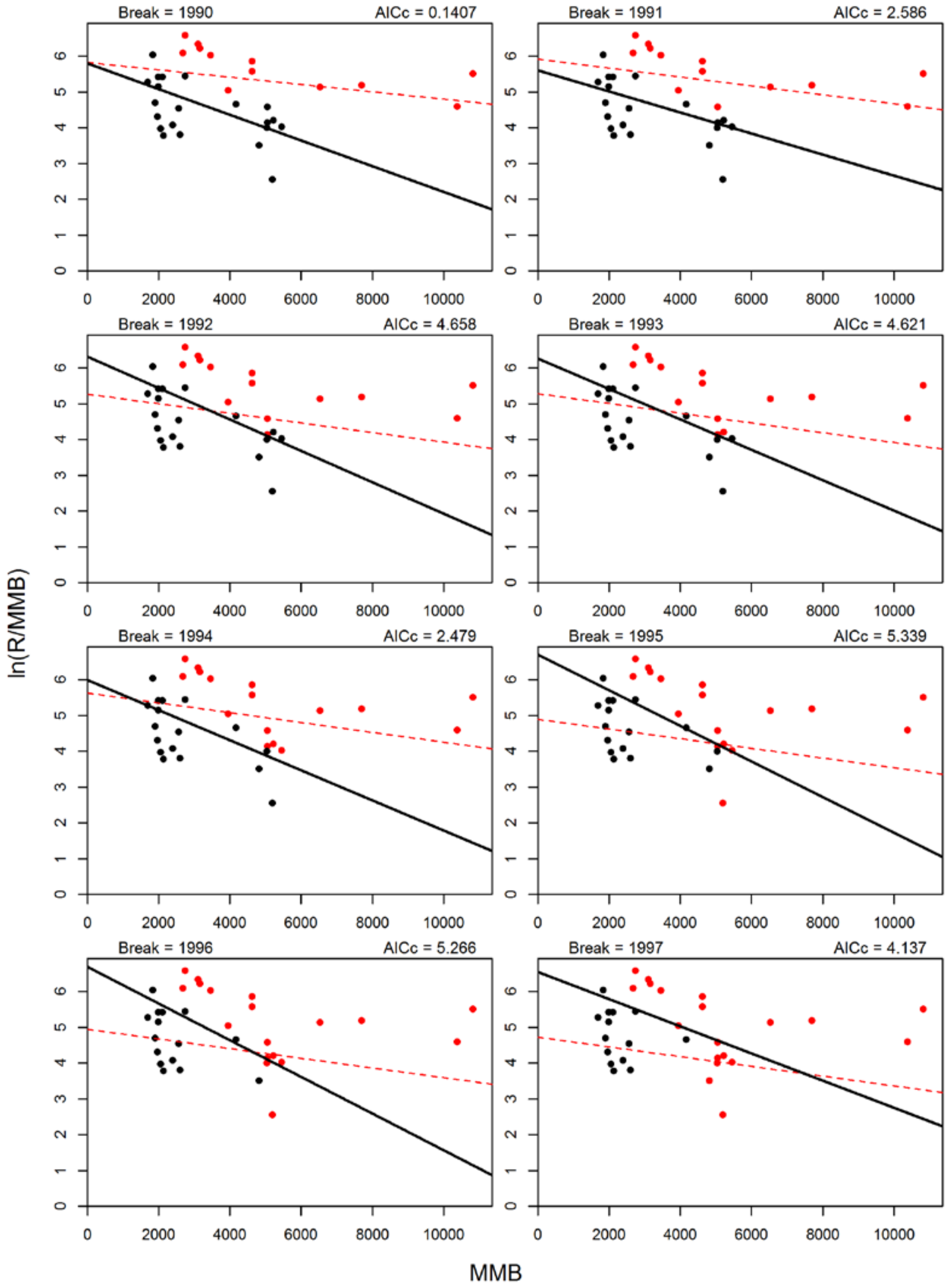


Figure D2. Fits for Ricker models with no breakpoint (upper left graph) and with 1-breakpoint for break years 1978-2005. For 1-breakpoint models, the pre-break data (circles) and model fit (line) are shown in red, whereas the post-break data and fit are shown in black.



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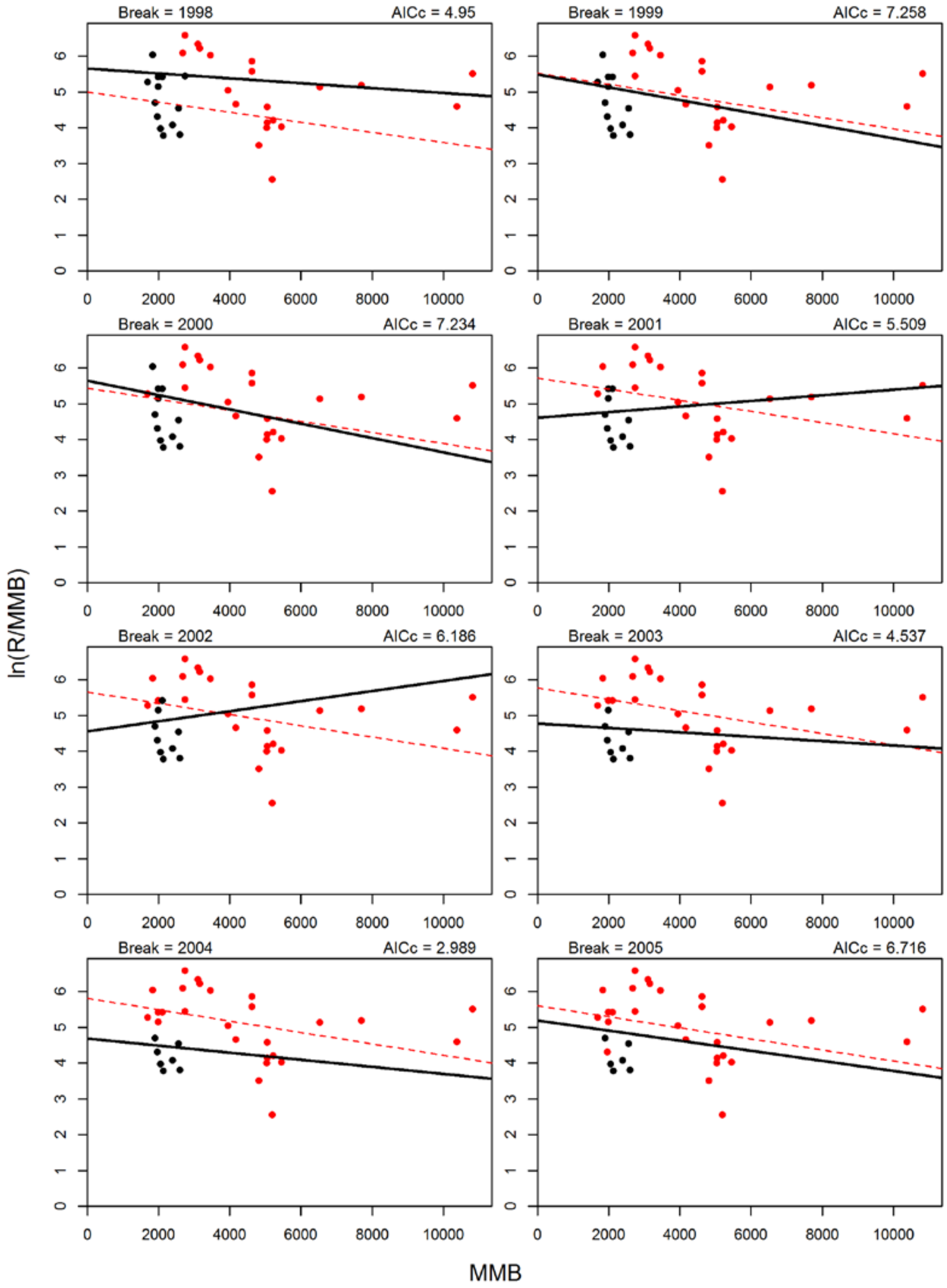

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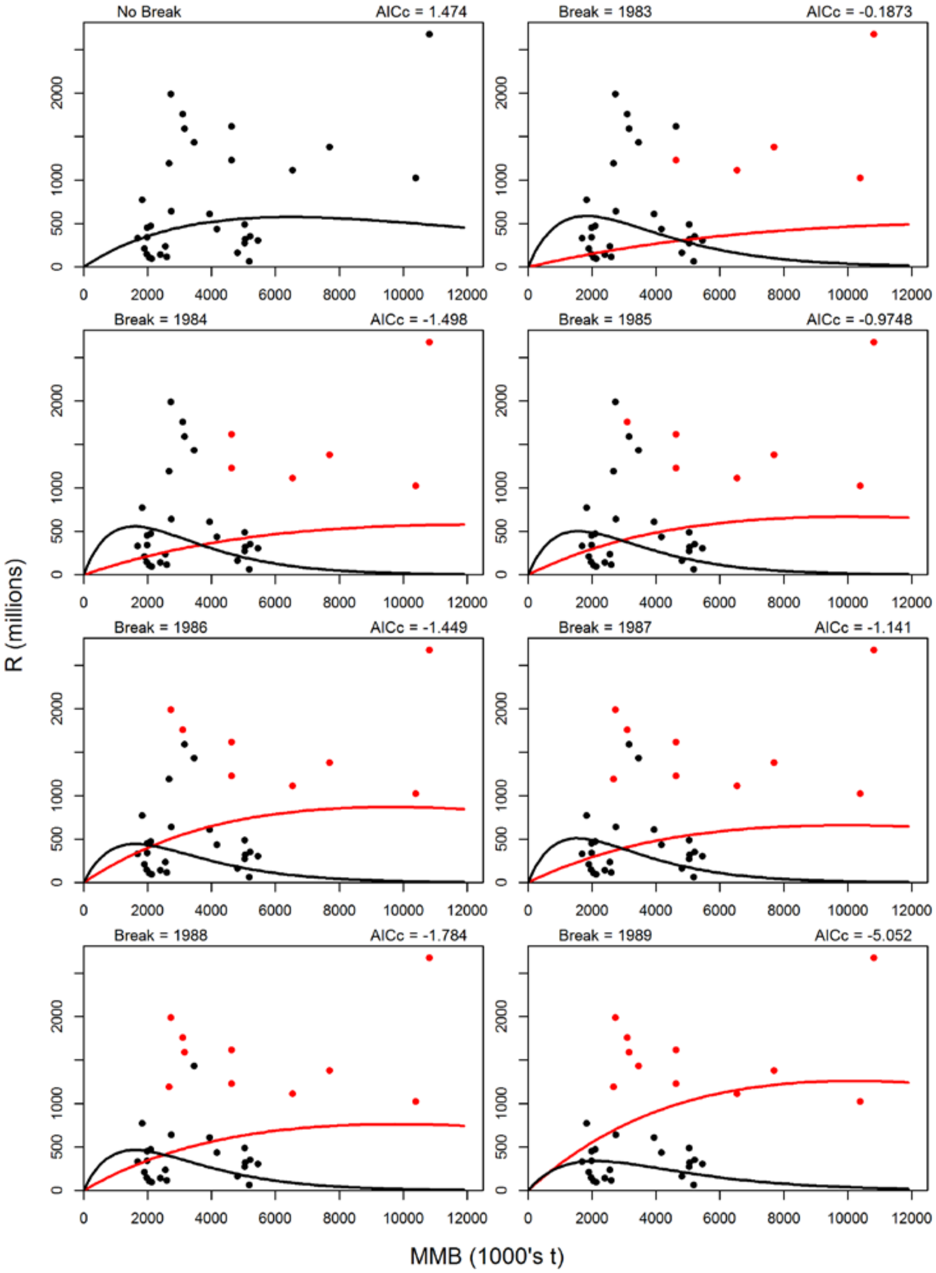
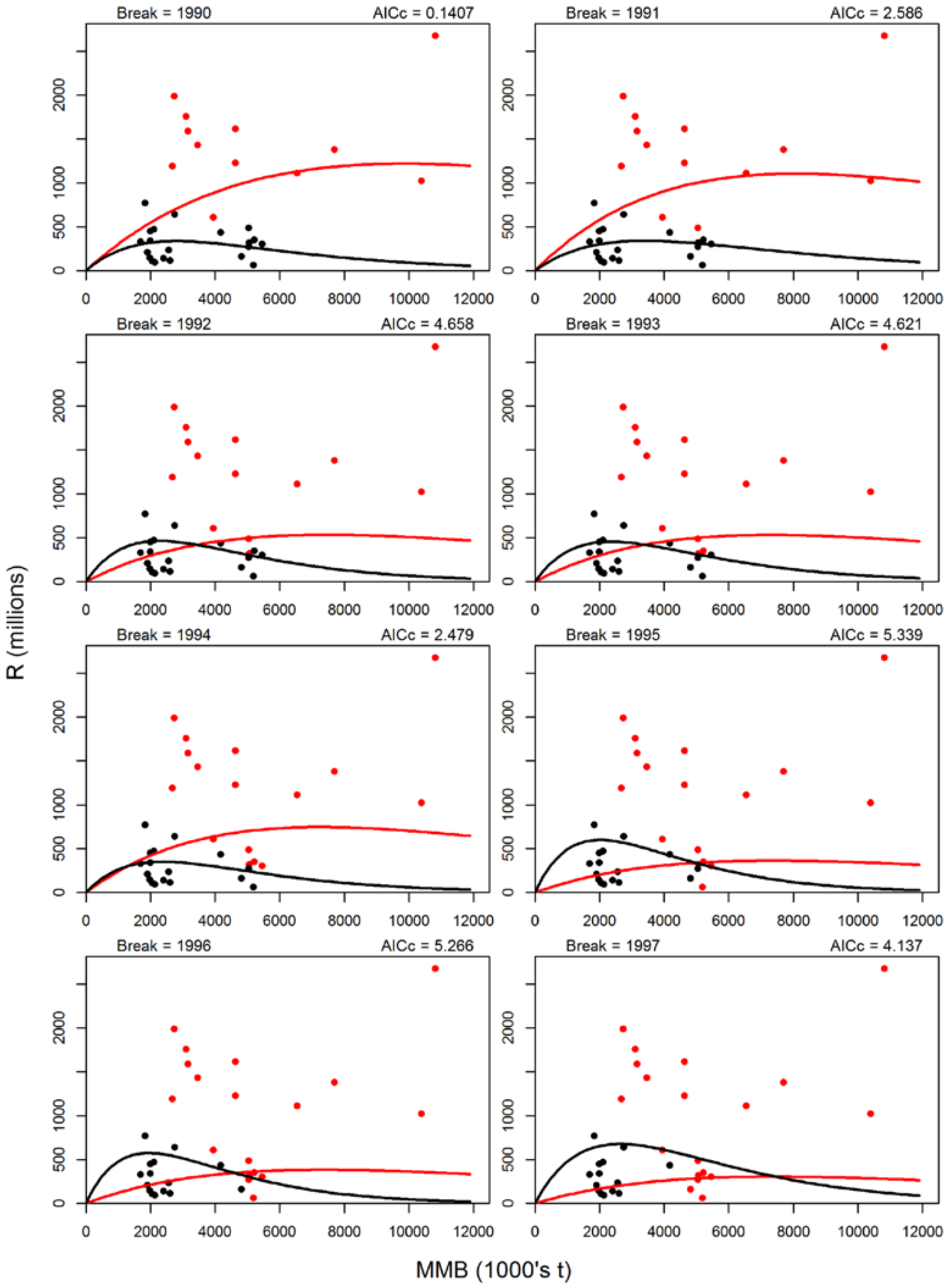


Figure D3. Fits on the arithmetic scale for Ricker models with no breakpoint (upper left graph) and with 1-breakpoint for break years 1978-2005. For 1-breakpoint models, the pre-break data (circles) and model fit (line) are shown in red, whereas the post-break data and fit are shown in black.



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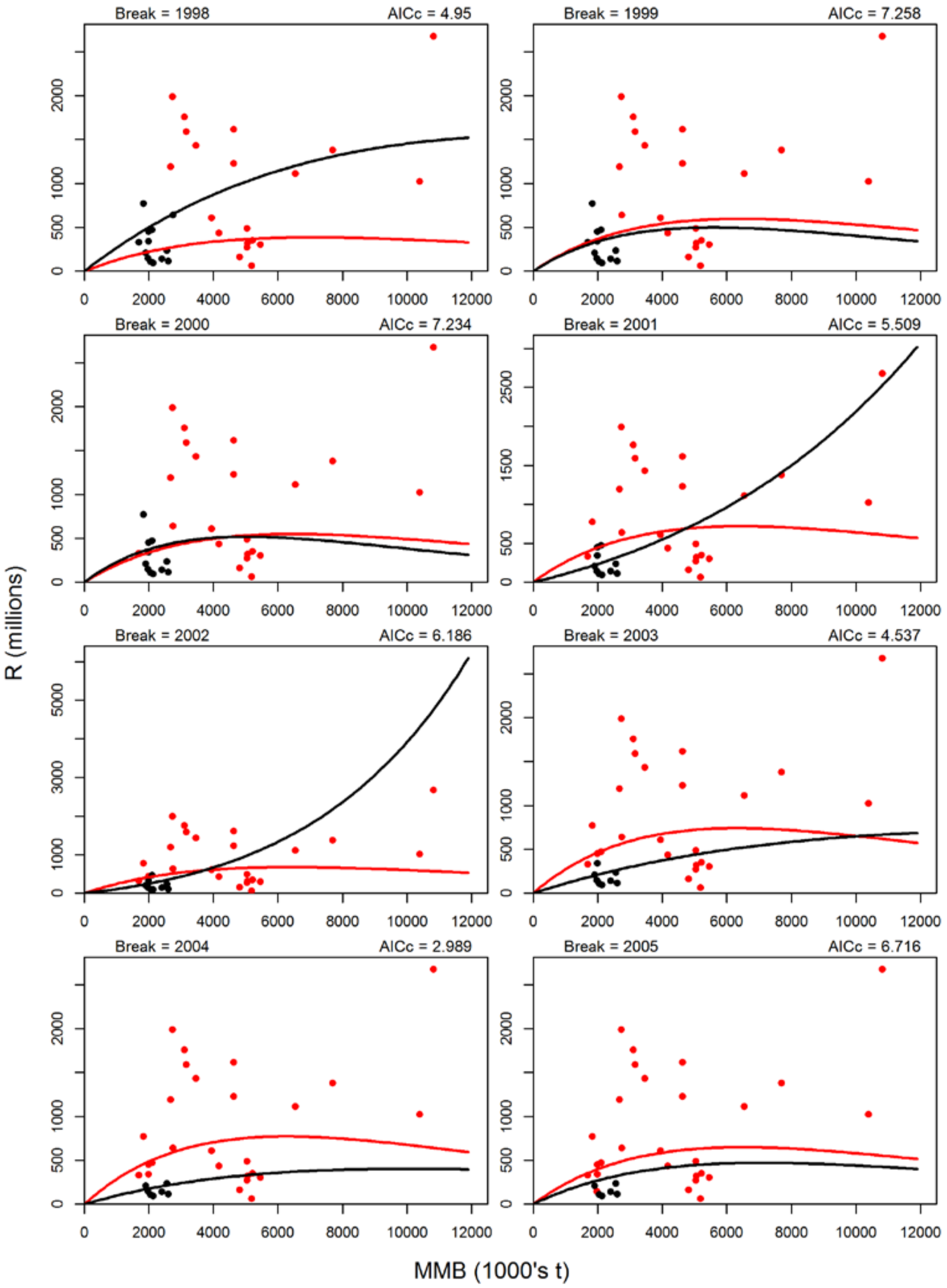

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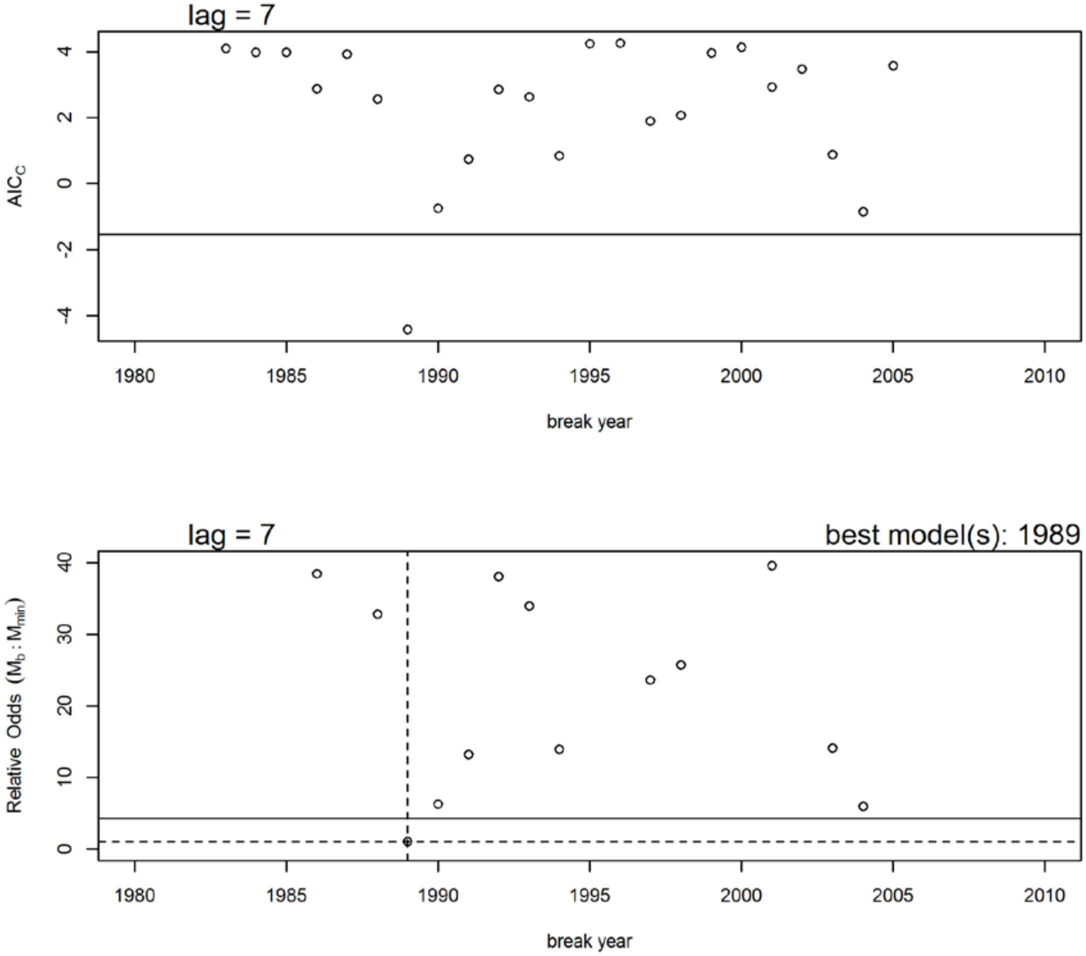


Figure D4. Results from the B-H stock-recruit breakpoint analysis. Upper graph: AICc vs. year of breakpoint for the 1-breakpoint models (circles) and AICc for the model with no breakpoint (horizontal line). Lower graph: probabilistic odds for all 1-breakpoint models (circles) and the no breakpoint model (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.

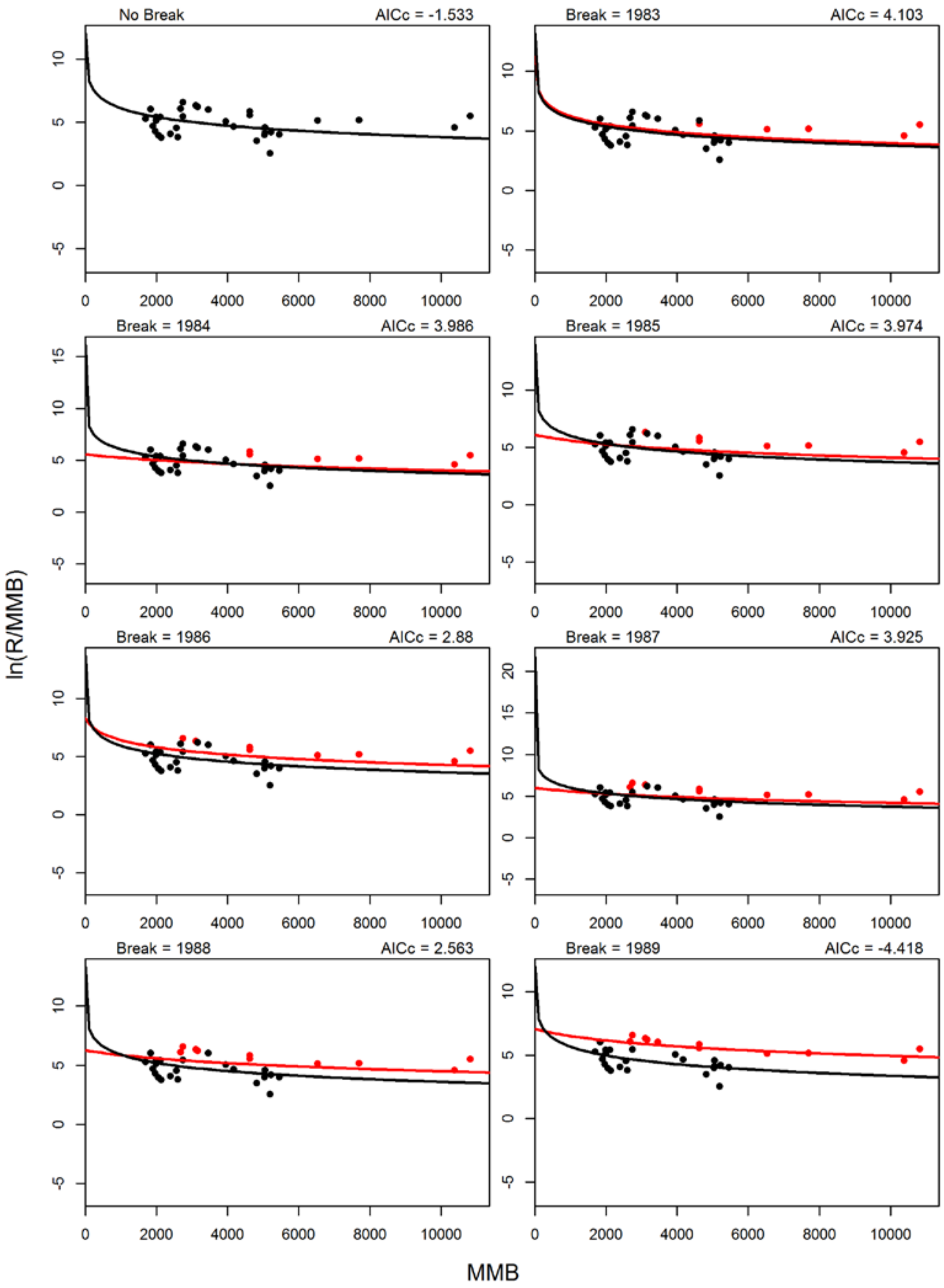
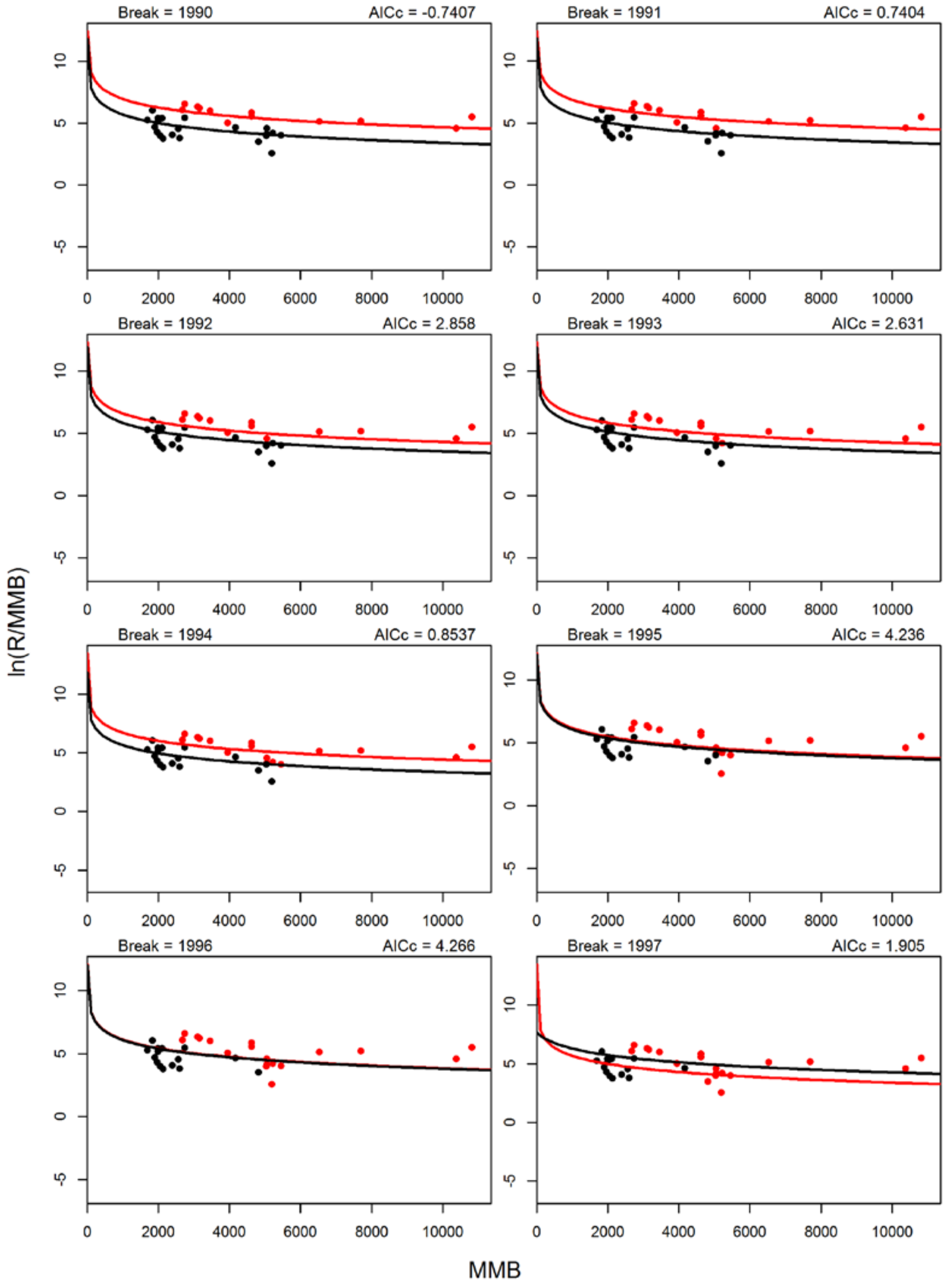


Figure D5. Fits for B-H models with no breakpoint (upper left graph) and with 1-breakpoint for break years 1978-2005. For 1-breakpoint models, the pre-break data (circles) and model fit (line) are shown in red, whereas the post-break data and fit are shown in black.



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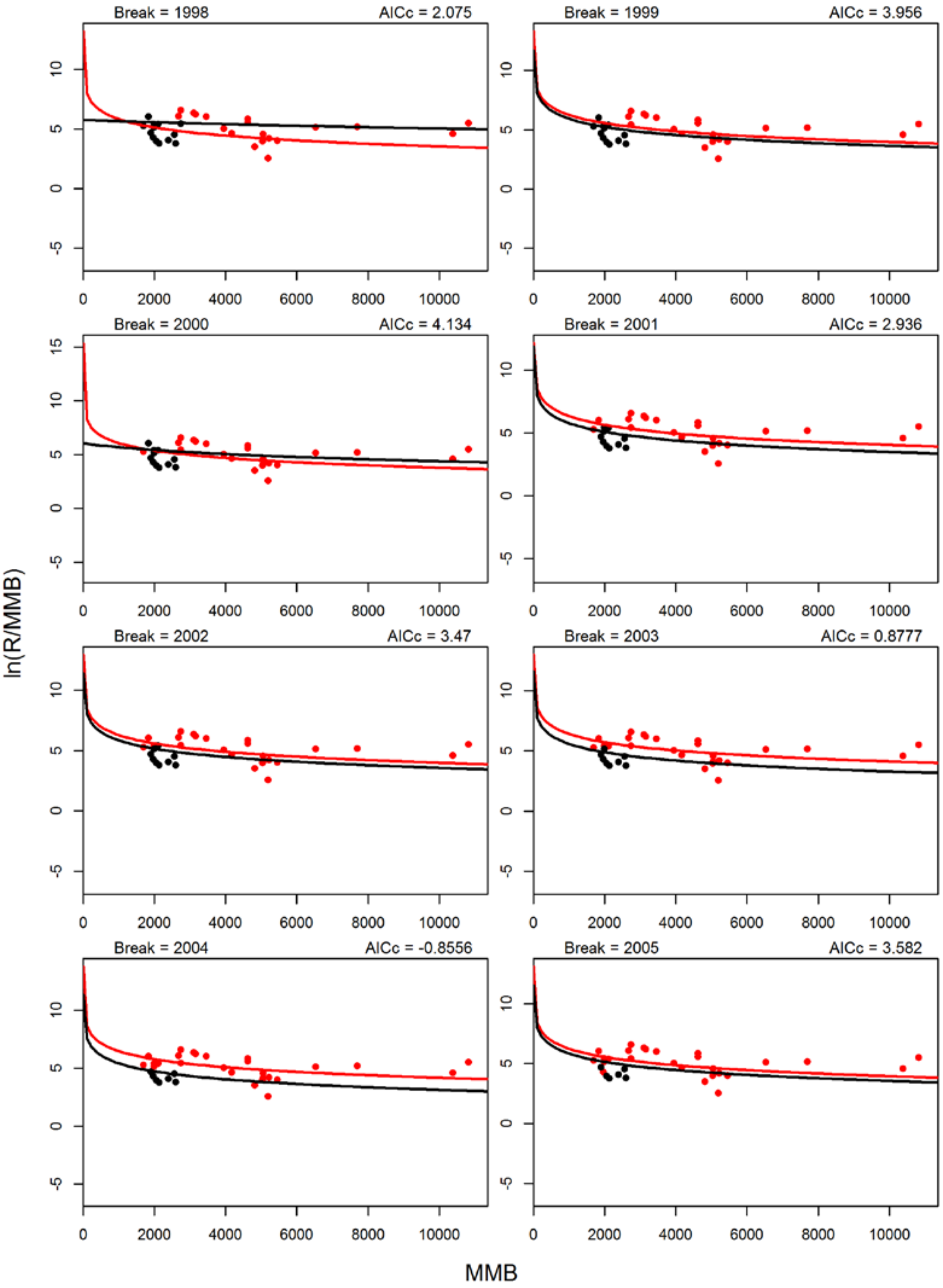

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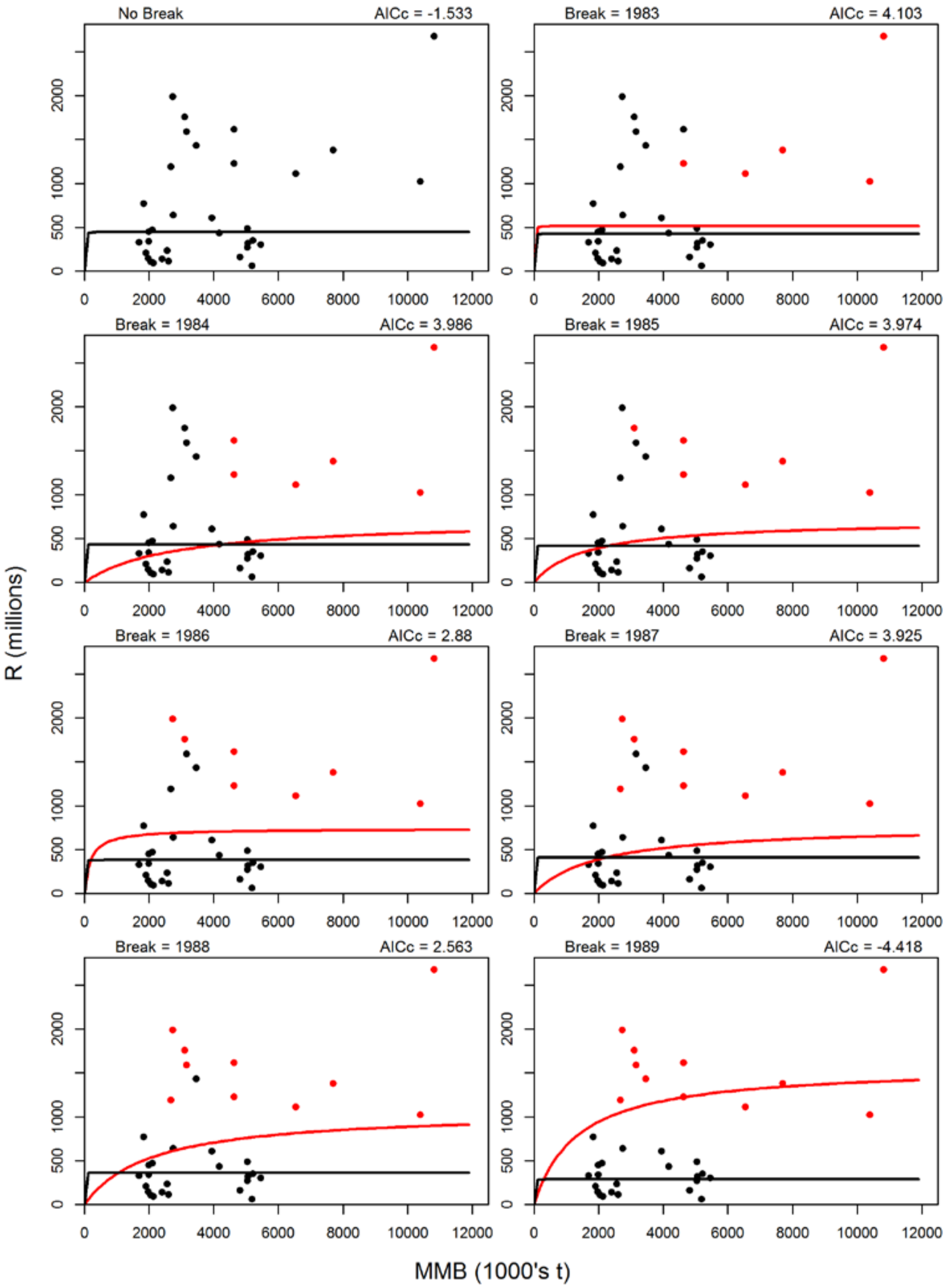
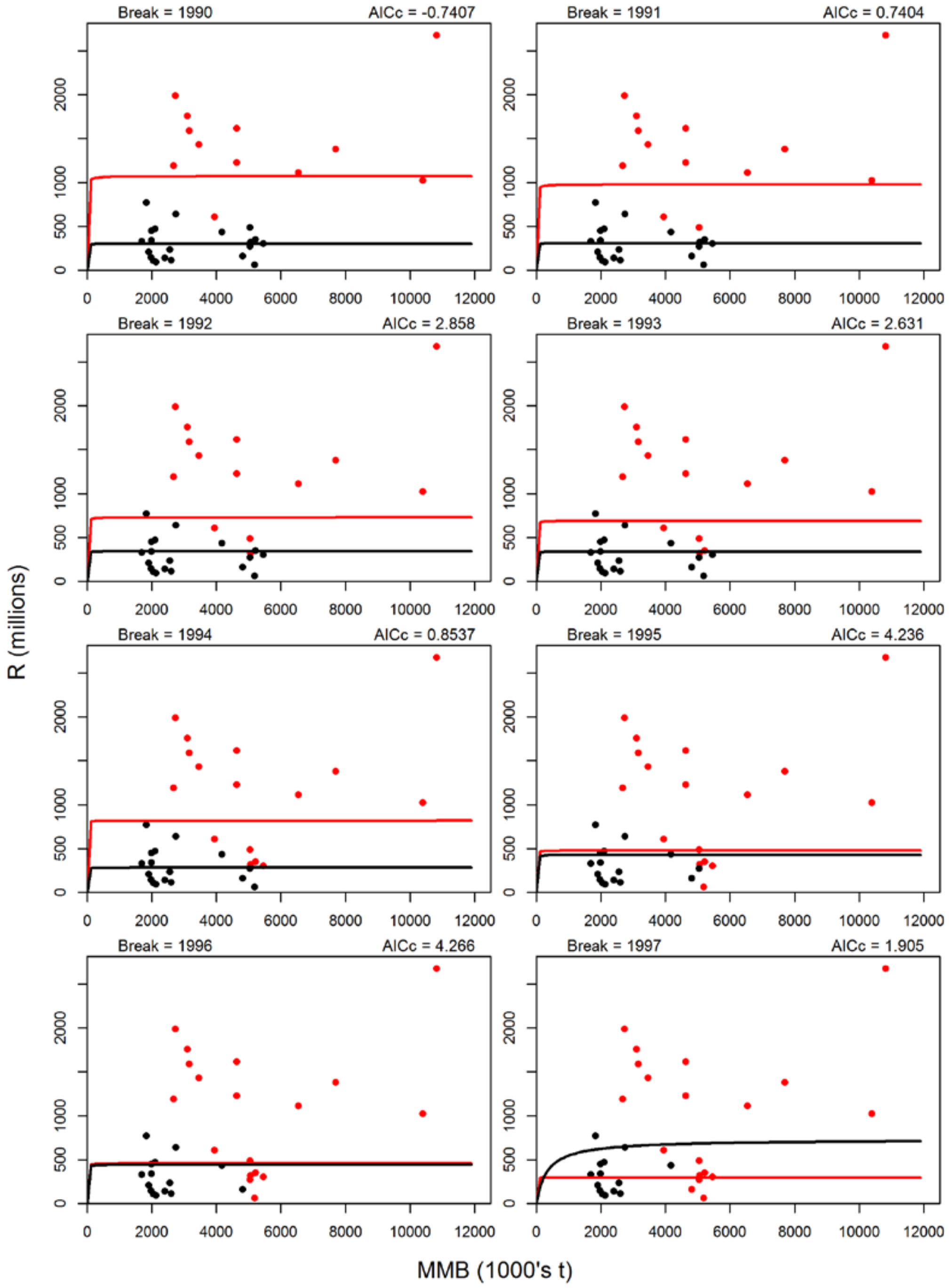


Figure D6. Fits on the arithmetic scale for B-H models with no breakpoint (upper left graph) and with 1-breakpoint for break years 1978-2005. For 1-breakpoint models, the pre-break data (circles) and model fit (line) are shown in red, whereas the post-break data and fit are shown in black.



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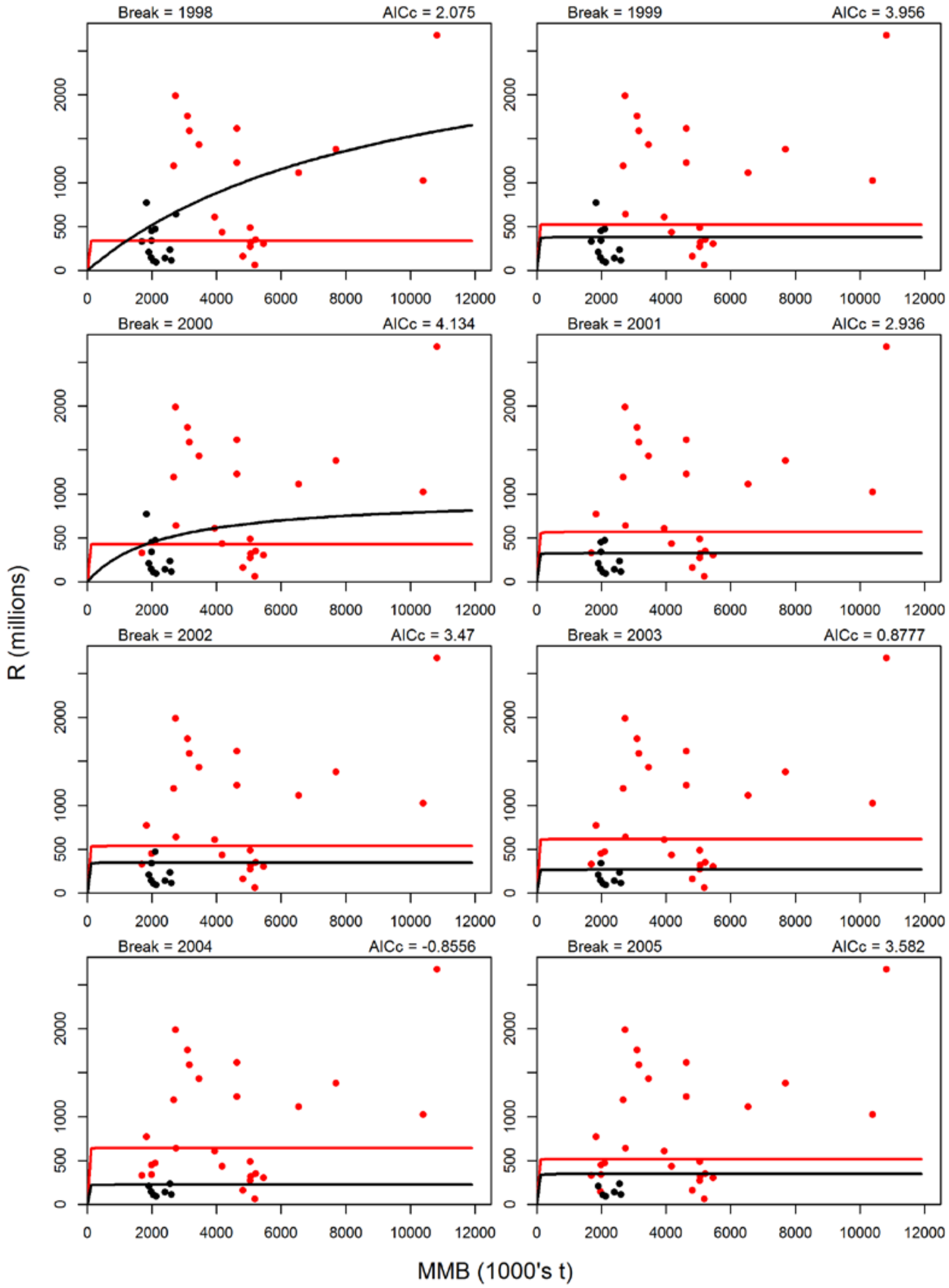

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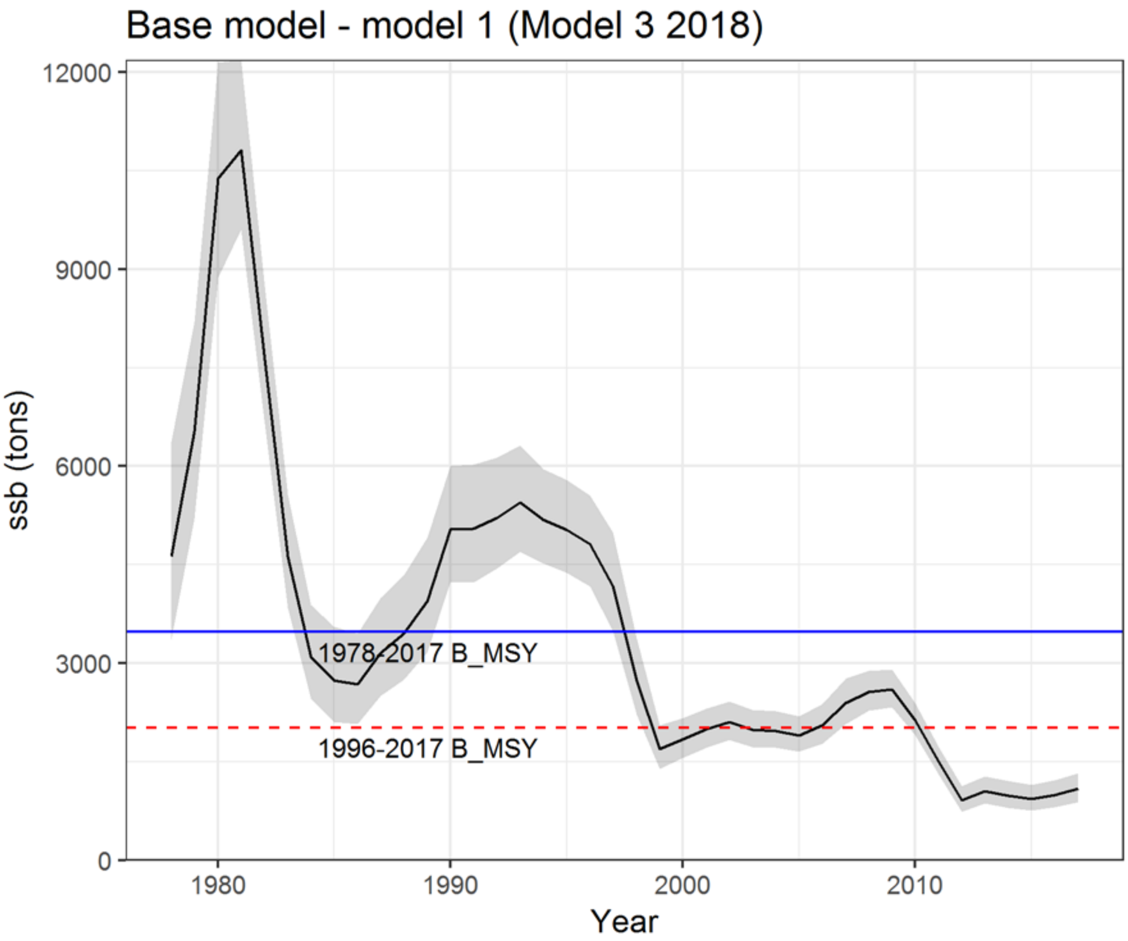


Figure D7. Computed B_{MSY} proxy (average mature male biomass) for the corresponding year ranges based on the 2018 assessment model with GMACS code updates.

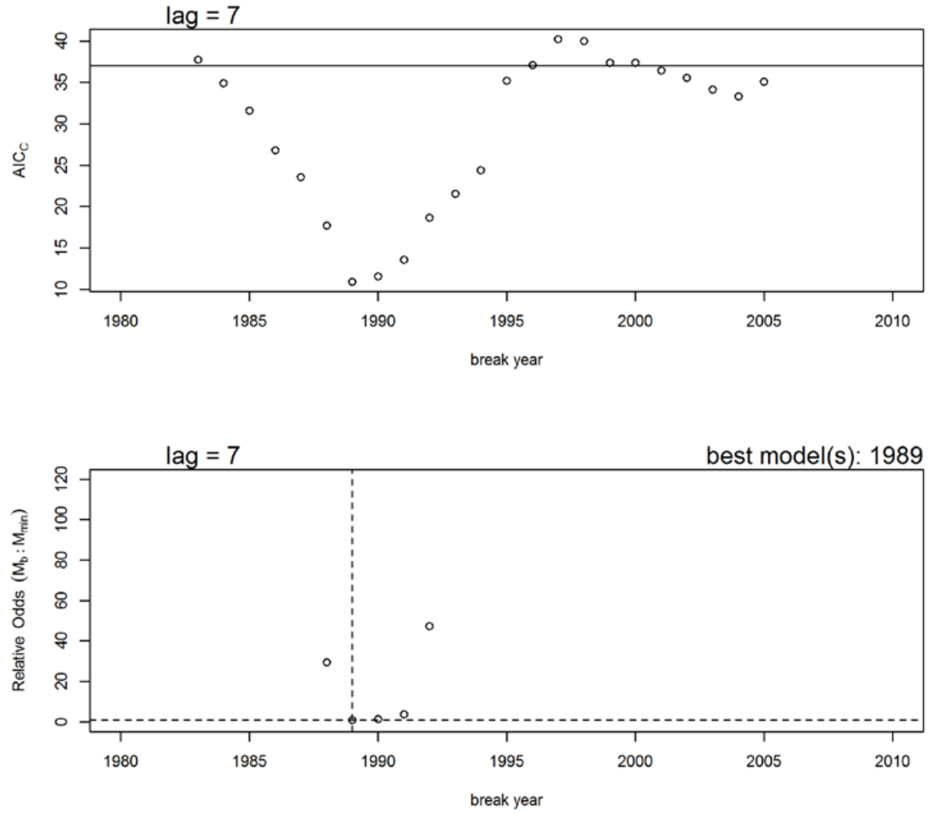


Figure D8. Results from the sensitivity analysis for Ricker stock-recruit breakpoint analysis. Upper graph: AICc vs. year of breakpoint for the 1-breakpoint models (circles) and AICc for the model with no breakpoint (horizontal line). Lower graph: probabilistic odds for all 1-breakpoint models (circles) 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.

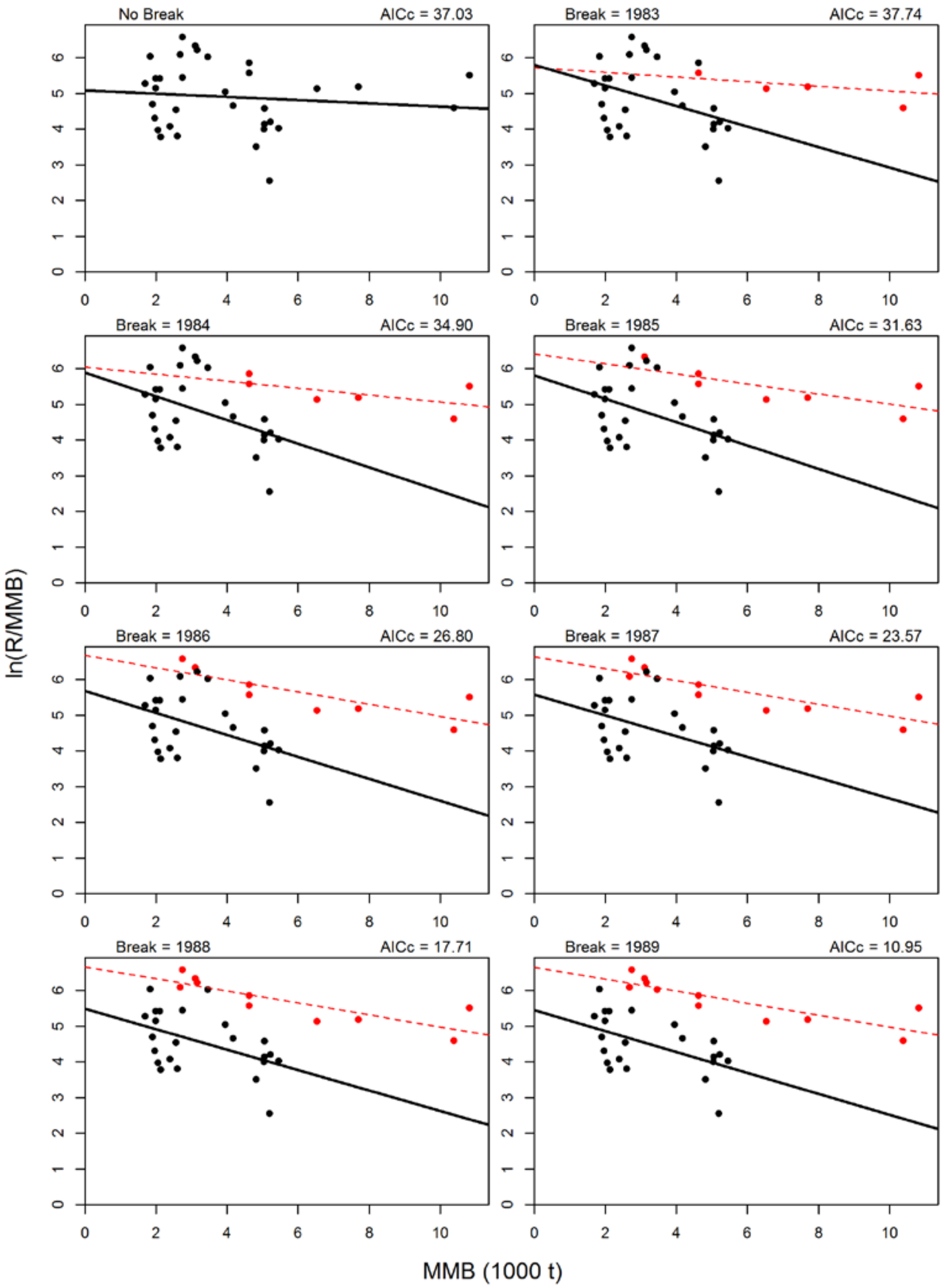
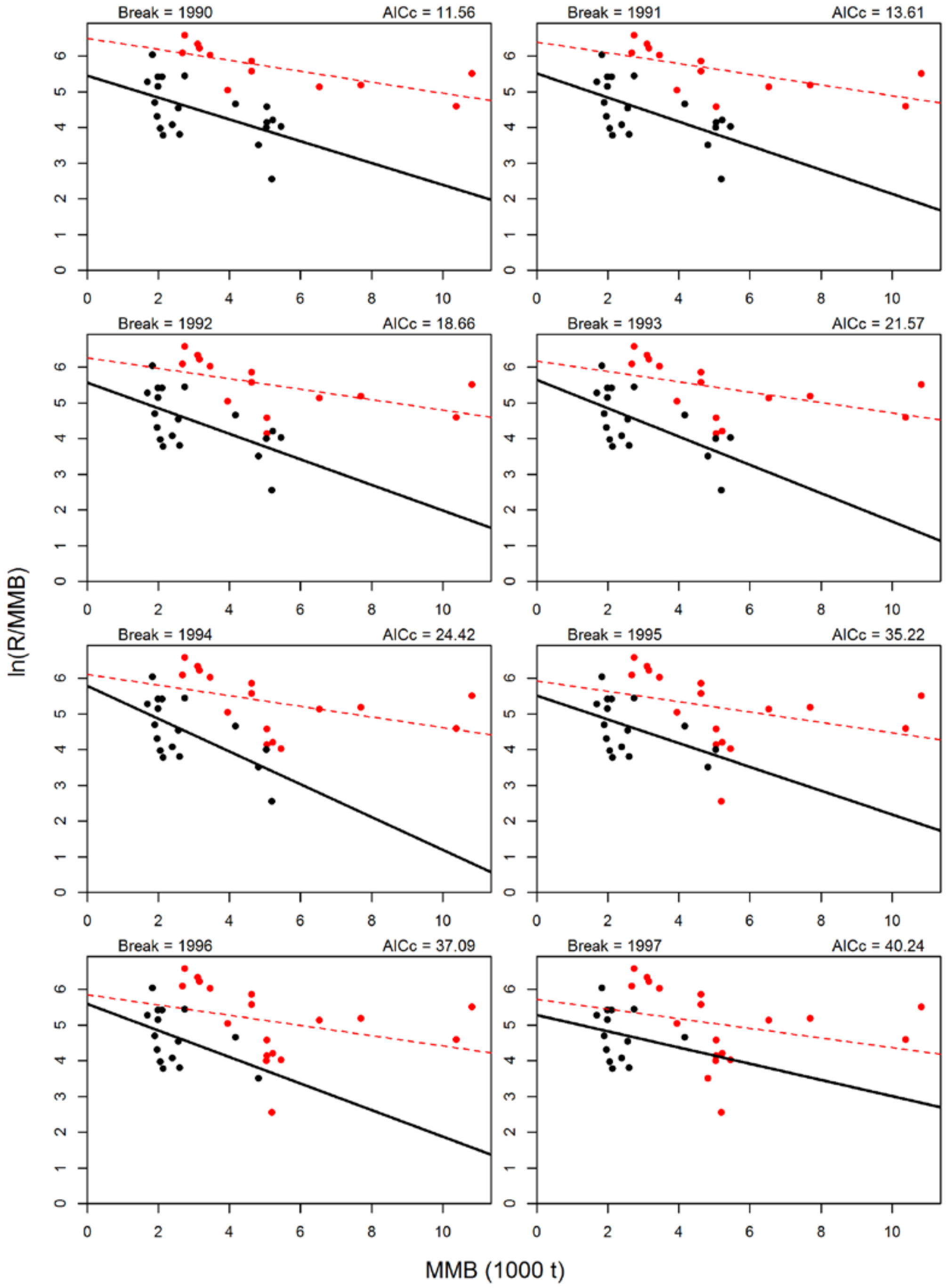


Figure D9. Fits for the sensitivity analysis using the Ricker models with no breakpoint (upper left graph) and with 1-breakpoint for break years 1978-2005. For 1-breakpoint models, the pre-break data (circles) and model fit (line) are shown in red, whereas the post-break data and fit are shown in black.



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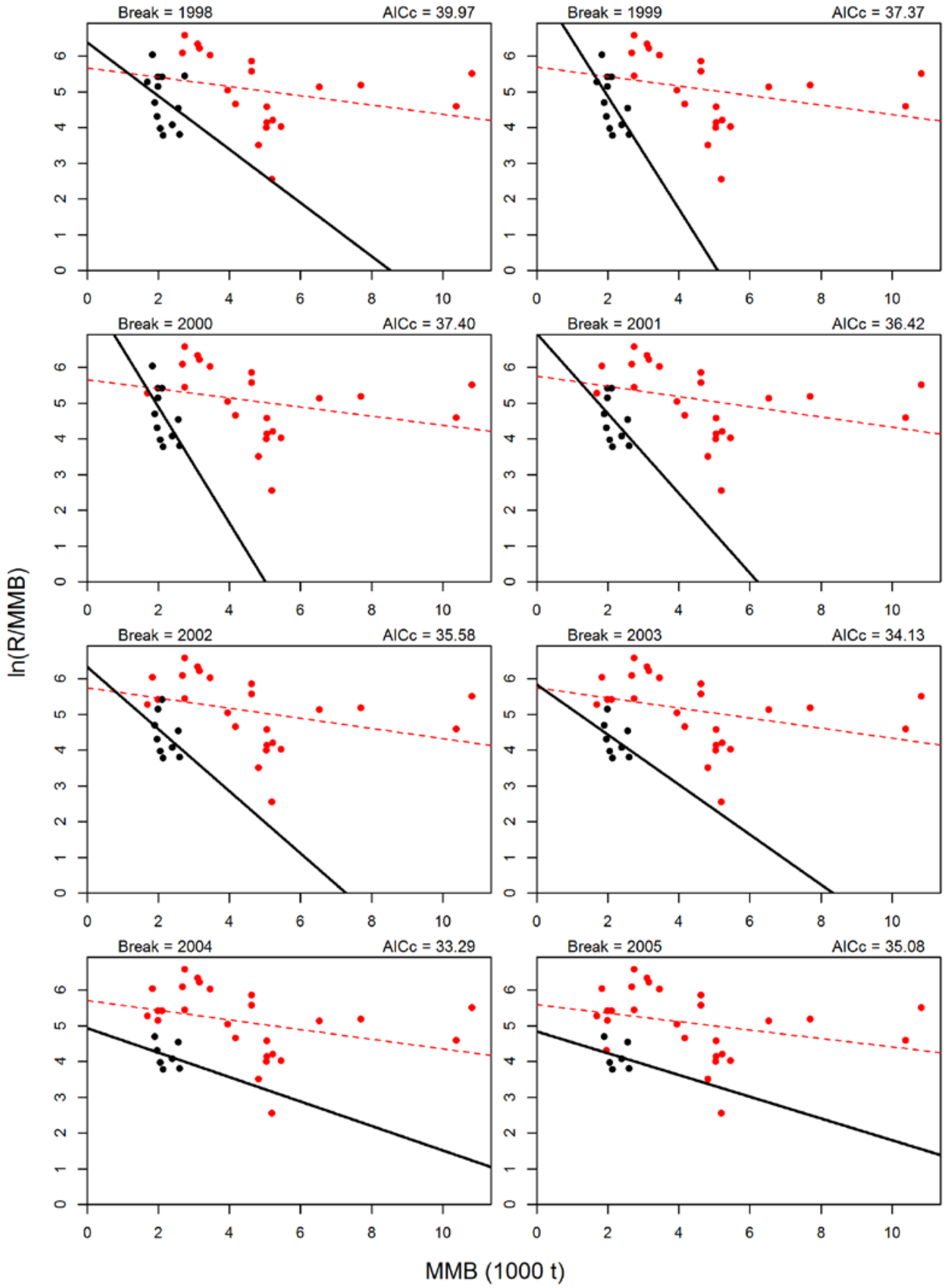

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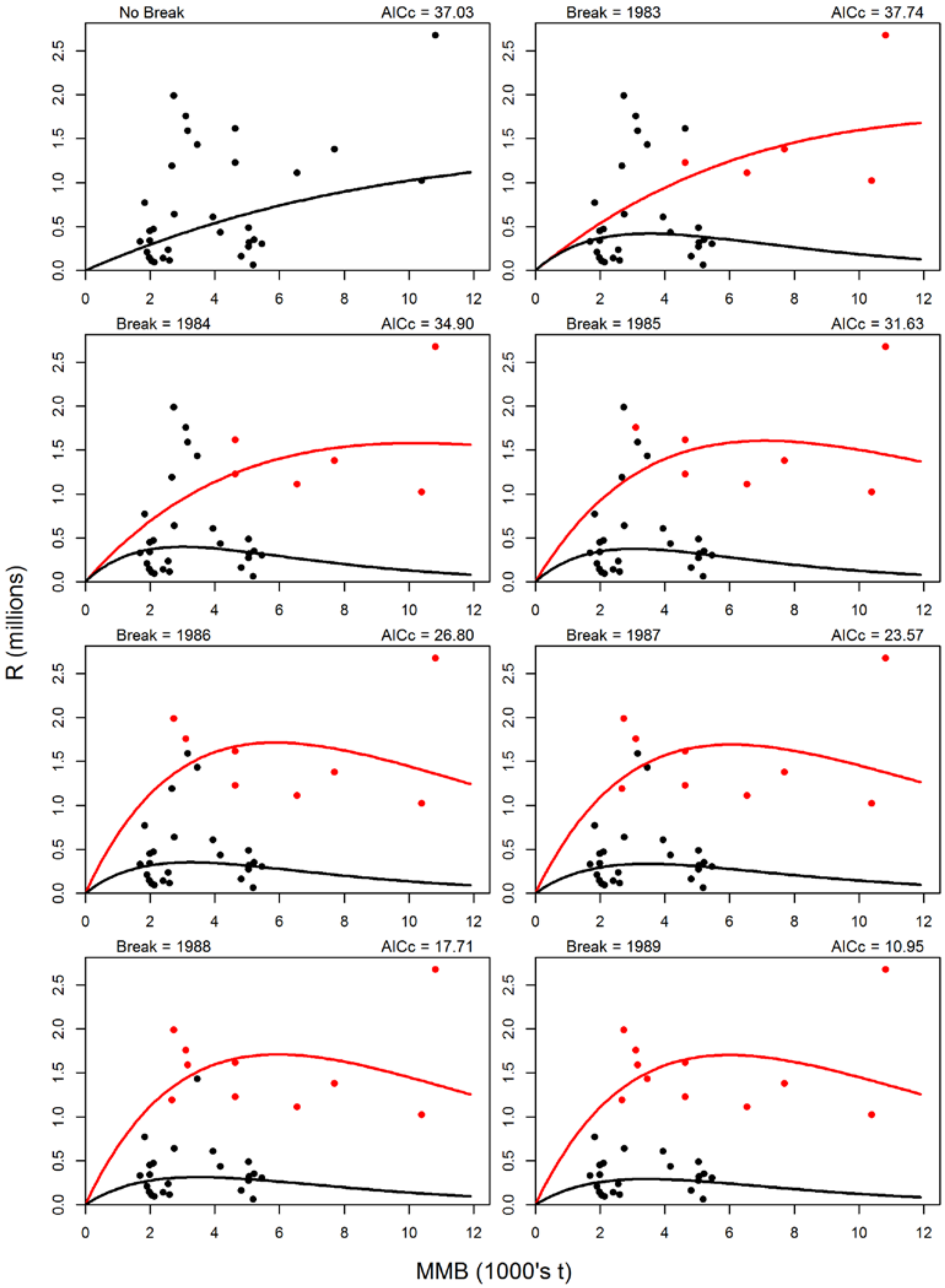
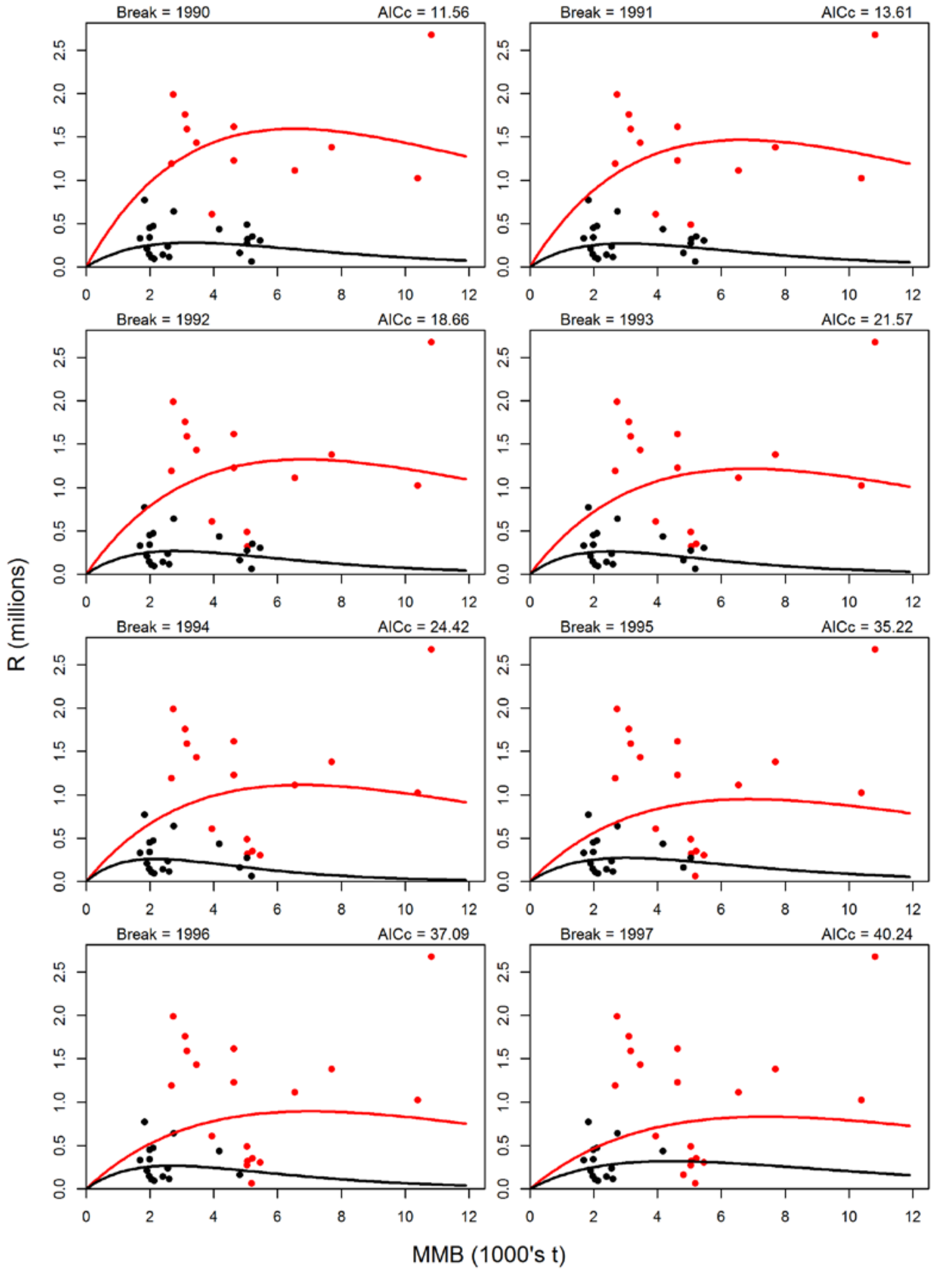


Figure D10. Fits on the arithmetic scale for the sensitivity analysis using the Ricker models with no breakpoint (upper left graph) and with 1-breakpoint for break years 1978-2005. For 1-breakpoint models, the pre-break data (circles) and model fit (line) are shown in red, whereas the post-break data and fit are shown in black.



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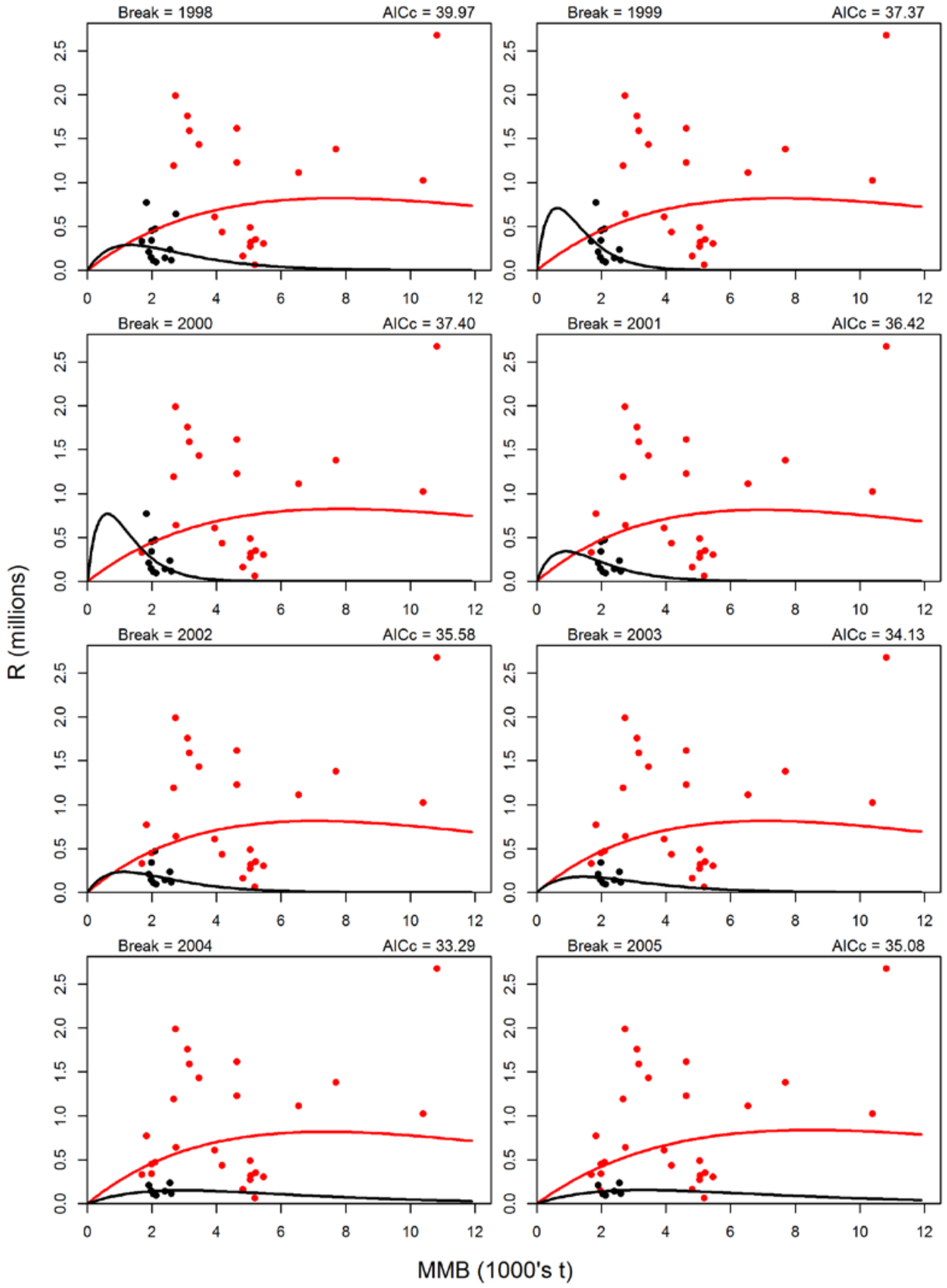

Figure D10. Continued.

Ecosystem and Socioeconomic Profile of the Saint Matthew Blue King Crab stock in the Bering Sea

Erin Fedewa, Brian Garber-Yonts, Kalei Shotwell and Katie Palof

September 2019

Executive Summary

National initiative and NPFMC recommendations suggest a high priority for conducting an ecosystem and socioeconomic profile (ESP) for the Saint Matthew blue king crab (SMBKC) stock. Scores for stock assessment prioritization, habitat prioritization, climate vulnerability assessment, and data classification analysis were moderate to high. The SMBKC ESP follows the new standardized framework for evaluating ecosystem and socioeconomic considerations for SMBKC and may be considered a proving ground for potential operational use in the main stock assessment.

We use information from a variety of data streams available for the SMBKC stock in the Bering Sea and present results of applying the ESP process through a metric and subsequent indicator assessment. Analysis of the ecosystem and socioeconomic metrics for SMBKC by life history stage along with information from the literature identified a suite of indicators for testing and continued monitoring within the ESP. Results of the metric and indicator assessment are summarized below as ecosystem and socioeconomic considerations that can be used for evaluating concerns in the main stock assessment.

Ecosystem Considerations

- Despite repeated fishery closures, SMBKC mature male biomass and recruitment estimates remain below-average following a 1989 regime shift in the Bering Sea, suggesting that environmental factors may be impeding recruitment success and stock recovery.
- Highly specific thermal optimums and habitat requirements of SMBKC likely limit mobility in response to warmer than average bottom temperatures and shifting predator distributions in the Bering Sea.
- Large catches of Pacific cod in the St. Matthew Island management boundary in 2016 preceded declines in BKC recruitment and the overfished declaration in 2018.
- Trend modeling for ecosystem indicators revealed poor conditions for SMBKC in recent years, attributed to above average bottom temperatures, a reduction in the cold pool extent, and an increase in mean benthic predator biomass in the St. Matthew Island management boundary.

Socioeconomic Considerations

- Vessel engagement in the SMBKC fishery as measured by annual counts of active vessels during years that the fishery has opened, has declined relative to the pre-rationalization period reflecting consolidation of the crab fleet following rationalization.
- In the most recent open seasons, the active fleet has been reduced to 3-4 vessels, with TAC utilization also declining to 26% during the 2015/16 season.
- Ex-vessel revenue share and the Local Quotient for Saint Paul both reached high values during 2010, concurrent with a peak in ex-vessel price; large declines in both metrics over the subsequent open seasons, despite relatively high ex-vessel prices during the next four open SMBKC seasons indicate that both vessels and processors active during those years have shifted into other fisheries.

Introduction

Ecosystem-based science is becoming a component of effective marine conservation and resource management; however, the gap remains between conducting ecosystem research and integrating with the stock assessment. A consistent approach has been lacking for deciding when and how to incorporate ecosystem and socioeconomic information into a stock assessment and how to test the reliability of this information for identifying future change. A new standardized framework termed the ecosystem and socioeconomic profile (ESP) has recently been developed to serve as a proving ground for testing ecosystem and socioeconomic linkages within the stock assessment process (Shotwell et al., *In Review*). The ESP uses data collected from a large variety of national initiatives, literature, process studies, and laboratory analyses in a four-step process to generate a set of standardized products that culminate in a focused, succinct, and meaningful communication of potential drivers on a given stock. The ESP process and products are supported in several strategic documents (Sigler et al., 2017; Dorn et al., 2018; Lynch et al., 2018) and recommended by the North Pacific Fishery Management Council's (NPFMC) groundfish and crab Plan Teams and the Scientific and Statistical Committee (SSC).

This ESP for Bering Sea Saint Matthew blue king crab (hereafter referred to as SMBKC) follows a template for ESPs (Shotwell et al., *In Review*) and replaces the previous ecosystem considerations chapter in the 2011 Bering Sea and Aleutian Islands Crab SAFE document and the stock-specific report cards produced in recent years. The four-step ESP process begins with an evaluation of the stock assessment classification results (Lynch et al., 2018) to assess the priority for conducting an ESP and the target ecosystem linkage level. Once it is established to conduct an ESP, the second step is a metric assessment. Metrics are quantitative stock-specific measures that identify vulnerability or resilience of the stock with respect to biological or socioeconomic processes. Where possible, evaluating these metrics by life history stage can highlight potential bottlenecks and lead to a mechanistic understanding of ecosystem or socioeconomic pressures on the stock. The third step is an indicator assessment where a time-series suite is created that represent the critical processes identified by the metric assessment. These indicators must be useful for stock assessment in that they are regularly updated, reliable, consistent, and long-term. The indicator suite is then monitored in a series of statistical tests that gradually increase in complexity depending on the data availability of the stock. The final step of the ESP is to report potential ecosystem and socioeconomic recommendations, data gaps, caveats, and future research priorities.

Justification

The national initiative prioritization scores for SMBKC are overall moderate to high primarily because the distribution of this stock depends greatly on habitat, there was increasing model development for this stock, and there is potential vulnerability to impacts of future ocean acidification. Also in 2018 the stock was declared overfished, warranting the Crab Plan Team to request an evaluation of ecosystem factors to inform the stock rebuilding plan. Current data availability as well as target data availability for five attributes of stock assessment model input data (i.e. catch, size composition, abundance, life history and ecosystem linkage) were classified for the SMBKC stock in order to identify data gaps and assess the priority for conducting an ESP. SMBKC is currently managed as a Tier 4 crab stock and as such, the new data classification scores characterize the stock as data-limited with insufficient life history, natural mortality and recruitment data. Both current and target data availability attribute levels for the SMBKC stock size composition attribute were classified as a 3, which adequately supports a size-structured stock assessment. However, catch, abundance, life history and ecosystem linkage attributes were highlighted as having gaps between current and target data availability. Research priorities for data classification include improvements in survey extent/design to better understand the spatial extent of the stock, increases in stock specific growth and other life history information, and understanding mechanisms for detecting productivity regimes in the population. These initiative scores and data classification levels suggest a high priority for conducting an ESP for SMBKC.

Data

Initially, information on SMBKC was gathered through a variety of national initiatives that were conducted by AFSC personnel. These include (but are not limited to) stock assessment prioritization, habitat assessment prioritization, climate vulnerability analysis, and stock assessment categorization. A form was submitted to stock assessment authors to gather results from all the initiatives in one location. The form data serves as the initial starting point for developing the ESP metrics for groundfish and crab stocks in the BSAI and GOA fishery management plans (FMP).

Data used to generate metrics and indicators for the SMBKC ESP were collected from surveys, regional reports, laboratory studies and the literature (Table 1). Information for the first year of life was collected primarily from laboratory studies completed at the Kodiak Fisheries Research Center (Long and Daly, 2017), Hatfield Marine Science Center (Stoner et al., 2013) and the Alutiiq Pride Shellfish Hatchery (Herter et al., 2011). Data for late-juvenile through adult BKC stages were derived from the annual NOAA eastern Bering Sea bottom trawl survey and the triannual Alaska Department of Fish and Game St. Matthew Pot Survey. The NOAA bottom trawl survey has been collected annually since 1975 and uses a standardized 376 station grid from Bristol Bay to northwest of St. Matthew Island. Data collected on the survey provides fishery-independent estimates of groundfish and crab abundances and biological data (Zacher et al., 2019). Due to the rocky substrate preferences of BKC, much of the habitat utilized by the SMBKC stock is untrawlable and biomass estimates are underrepresented using NOAA standardized survey gear. As a result, Alaska Department of Fish and Game has conducted the St. Matthew Pot Survey triannually since 1995. In addition to reporting spatial trends in CPUE, the pot survey provides biological data from areas not surveyed by the NOAA trawl survey and is better suited to sample nearshore areas where mature female BKC are concentrated (Watson, 2004; Pengilly and Vanek, 2014).

Information on BKC habitat use was derived from essential fish habitat (EFH) model output and maps (Laman et al., 2017) as well as a recent data rescue effort to recover historic cruise data across all life history stages of the Pribilof Islands BKC stock (Armstrong et al., 2015). Data from the NOAA Resource Ecology and Ecosystem Modeling (REEM) food habits database were used to determine species compositions of benthic predators on commercial crab species. The Food Habits database consists of diet data collected from major groundfish species during the annual NOAA eastern Bering Sea bottom trawl survey.

Data used to generate socioeconomic metrics and indicators are derived from fishery-dependent sources, including commercial landings data for SMBKC collected in ADFG fish tickets (sourced from AKFIN), and effort statistics reported in the most recent ADFG Annual Management Report for BSAI shellfish fisheries estimated from ADF&G Crab Observer program data (Leon et al. 2017).

Metrics Assessment

National Metrics

The national initiative form data were summarized into a metric panel (Figure 1) that acts as a first pass ecosystem and socioeconomic synthesis. Metrics range from estimated values to qualitative scores of population dynamics, life history, or economic data for a given stock (see Shotwell et al., *In Review* for more details). To simplify interpretation, the metrics are rescaled by using a percentile rank for SMBKC relative to all other stocks in the groundfish and crab FMP's. Additionally, some metrics are reversed so that all metrics can be compared on a low to high scale between all stocks in the FMP. These adjustments allow for initial identification of vulnerable (percentile rank value is high) and resilient (percentile rank value is low) traits for SMBKC. Data quality estimates are also provided from the lead stock assessment author (0 or green shaded means no data to support answer, 4 or purple shaded means complete data), and if there are no data available for a particular metric then an "NA" will appear in the panel. The metric panel gives context for how SMBKC relate to other groundfish and crab stocks and highlights the potential vulnerabilities and data gaps for the stock. The 80th and 90th percentile rank areas are provided to highlight metrics that cross into these zones indicating a high level of vulnerability for SMBKC (Figure 1, yellow and red shaded area).

For SMBKC ecosystem metrics, latitude range, depth range, adult mobility, ocean acidification sensitivity and predator stressors fell within the 90th percentile rank of vulnerability, suggesting that BKC are habitat specialists and highly sensitive to changes in resource availability and habitat requirements. Additionally, predation pressure is very high during early life history stages and BKC are particularly vulnerable to predators after molting. Recruitment variability, temperature range, fecundity, habitat specificity, habitat dependence index and habitat vulnerability index fell within the 80th percentile rank when compared to other stocks in the groundfish and crab FMP's. SMBKC were also relatively resilient for breeding strategy index, hatch size and ecosystem value top-down and bottom-up. These initial results suggest that stage-based information regarding the implications of high predation, climate change, and habitat quality would be both valuable for the stock and would assist with subsequent indicator development. For the three applicable socioeconomic metrics, values indicated medium to low vulnerability.

SMBKC had numerous data gaps for ecosystem metrics, including growth rate, length at 50% maturity, maximum length, spawning duration, dispersal ELH, prey specificity and mean trophic level. The data quality was rated as medium to complete for all metrics with data available except for natural mortality, recruitment variability and ecosystem value top-down. The numerous data gaps highlight the need for additional studies to contribute to a better understanding of BKC life history processes.

Ecosystem Processes

Data evaluated over ontogenetic shifts (e.g., egg, larvae, juvenile, adult) may be helpful for identifying specific bottlenecks in productivity and relevant indicators for monitoring. However, BKC early life history processes are not well understood and data has been provided primarily from laboratory studies (e.g. Stoner et al., 2013, Long and Daly, 2017). As a first attempt to synthesize distribution, habitat usage and phenology of BKC across all life stages, we created a baseline life history conceptual model which is detailed in Figure 2. In the conceptual model figure, abiotic and biotic processes were identified by each life stage from the lead author and relevant papers. The main categories of the primary ecosystem processes influencing BKC life stages were identified as water temperature, larval transport and retention, habitat suitability and impact of predation. Details on why these processes were highlighted in the conceptual model and the potential relationship between these processes and the different life stages are described below.

BKC larval development consists of four zoeal stages and one glaucothoe stage, after which larvae metamorphose and settle as stage C1 benthic juveniles (Persselin, 2006). Cultivation experiments reported a 91.7% survival rate of BKC larvae from hatching to C1 stage at 6°C with increased mortality at rearing temperatures greater than 9°C (Stevens et al., 2005; Stevens et al., 2008a). While BKC larvae exhibit an upper thermal tolerance in captivity, cooler water temperatures could, in turn, slow development rates and increase mortality due to both increased larval transport and larval stage duration (Loher, 2014). Dispersal pathways of SMBKC larvae are currently unknown but advection and dispersal rates may be a significant driver of recruitment dynamics, as observed in other EBS crab stocks (Rosenkranz et al., 1998; Richar et al., 2015; Daly et al., 2018). Transport to favorable settlement grounds in the nearshore waters of St. Matthew Island is most likely dependent on high localized retention rates of BKC larvae although studies are needed to identify relationships between oceanographic conditions, larval transport and recruitment success.

During the early juvenile stages, successful settlement requires shallow, nearshore waters (<50m) and hard substrate such as shell hash, gravel or rock due to the reliance of BKC on crypsis to evade predation (Armstrong et al., 1985; Daly and Long, 2014). Survival in juvenile BKC is linked to mollusk shell abundance, including mussels (*Modiolus modiolus*), scallops (*Chlamys* sp.), rock oysters (*Pododesmus macrochisma*), and hairy tritons (*Fusitriton oregonensis*) (Chilton et al., 2011; Palacios and Armstrong, 1985). Unlike RKC, juvenile BKC lack a heavy covering of carapace spines and do not form pods to offer protection from predation, emphasizing the role of habitat complexity in BKC survival (Stevens, 2014). In addition, juvenile BKC molt several times a year during early benthic instar stages and are especially vulnerable to predation while soft. Pacific cod have been shown to predate heavily on soft-shell female red king crab (Livingston, 1989) and are likely also a key predator on juvenile BKC. Early juvenile BKC appear to have a broad range of temperature tolerance, indicated by relatively high survival over the range of temperatures tested (1.5 to 12 °C) in a laboratory experiment (Stoner et al., 2013). This is likely advantageous during the juvenile stage when BKC utilize relatively shallow habitats more prone to temperature fluctuations.

Late juvenile and adult BKC are less reliant on habitat with complex substrate, however a suite of habitat variables can be used to predict SMBKC distribution and identify vulnerabilities associated with suitable habitat characteristics. EFH models suggest that the probability of mature BKC abundance is highest over coarser sediments and lower maximum tidal currents (Laman et al., 2017). Temperature and depth likely also represent vulnerabilities given that mature female BKC migrate to relatively shallow, nearshore waters south of St. Matthew Island during the spring and summer months when bottom temperatures reach their maximum (Pengilly and Vanek, 2014). BKC exhibit reduced growth rates at 12°C and above, with feeding ration increasing with temperature up to 6°C (Long and Daly, 2017). In addition to temperature effects on BKC physiology, laboratory studies have demonstrated temperature-mediated shifts in hatch timing and embryo development (Stevens et al., 2008b). The biannual molt and reproductive strategy characteristic of BKC in contrast to most other *Paralithodes* spp. suggests that energetic restrictions imposed by temperature or prey conditions may be a limitation in reproductive dynamics (Webb, 2014; Jensen et al., 1985). However, adult BKC are generalists and as such, it is hypothesized that benthic prey abundances may not play an important role in life history processes.

Socioeconomic Processes

As discussed in more historical detail in Leon et al. (2017), the commercial SMBKC fishery began in 1977, with 10 vessels harvesting 1.2 million pounds (including deadloss), increasing to 22 vessels in 1978, harvesting 2.0 million pounds, and declining over the next two years to 2 active vessels in 1980. Over the next three years, the fishery increased from 31 active vessels in 1981 harvesting 4.6 million pounds to 164 vessels landing 9.5 million pounds in 1983, the largest annual catch volume in the fishery to-date and the first year of management under a declared GHL, which began at 8 million pounds. In subsequent seasons through 1997, the GHL varied from 0.5 million to 5.0 million pounds, with an active fleet varying between 31 and 174 vessels and total landings varying between 1.0 million pounds in 1986 (exceeding the preseason declared GHL range of 0.2 – 0.5 million by 100%) to 4.6 million pounds in 1997. With the initial year of the CDQ program in 1998, the fishery opened with a GHL of 5.0 million pounds, with 1.0 million pounds allocated as CDQ quota in addition to 4.0 million pounds in the general allocation fishery; the latter was prosecuted by 131 active vessels harvesting 2.9 million pounds before the fishery was closed inseason, however, only one active vessel harvested CDQ and total 1998 catch cannot be reported due to confidentiality of the CDQ catch.

The stock declined following the 1998 season, being declared overfished by NMFS in 1999 based on the results of the summer trawl survey, and the fishery was closed from the 1999 to 2008/09 seasons, with a rebuilding plan being implemented beginning in 2000. The fishery reopened for the 2009/10 season under the CR program and TAC management (both of which began in 2005 for the 2005/06 crab season), with a combined TAC of 1.67 million pounds (90% issued as IFQ allocation and 10% as CDQ), and with 7 active vessels harvesting 0.46 million pounds (39% of the TAC). The fishery remained open over the next three seasons, increasing to 2.4 million pounds TAC in 2011/12, with 18 active vessels harvesting 1.9 million pounds (80% of the TAC), and 1.63 million pounds TAC in 2012/13, with 17 active vessels harvesting 1.62 million pounds, approaching full utilization of the TAC for the first time under the CR program. Due to low abundance in the 2013 survey, the fishery was closed for 2013/14, and opened for the next two seasons with substantially reduced TACs relative to previous open seasons, at 0.66 million pounds in 2014/15 and 0.41 million pounds in 2015/16, and the number of active vessels during the two most recent seasons reduced to 4 and 3 vessels, respectively, with a catch of 0.11 million pounds in 2015/16 and utilization of the available catch limit declining to 26%, the lowest level in the fishery to-date. The fishery has been closed during each of the last three crab seasons, beginning in 2016/17.

Over the 1977 to 1998 period, the SMBKC fishery was prosecuted during open seasons that varied in length and timing, with the earliest opening on June 7 in 1977, growing later over subsequent seasons to August 1 in 1982, September 1 in 1985, and September 16 in 1991, and September 15 from 1993 through 1998. Prior to 1982, SMBKC openings ranged from approximately 5 to 9 weeks, with the latest closing on September 3 after 19 days in both 1978 and 1980. Over subsequent years prior to 2005, openings in the fishery were limited to shorter spans of 1 to 11 days, with the latest closing in 1998 on September 26. With the implementation of the CR program, the regulatory season for SMBKC was shifted to October 15 through February 1, with active fishing typically during years when the fishery opened occurring within a period of 4-5 weeks beginning October 15, with final landings for the respective seasons occurring during early- to mid-November. Over the more recent history of the SMBKC fishery, active vessels have prosecuted the SMBKC fishery in the period preceding active fishing in the other rationalized crab fisheries (most commonly the Bristol Bay RKC and Bering Sea snow crab fisheries, with some vessels also fishing in the Bering Sea Tanner crab fisheries) and groundfish, with SMBKC contributing a component to associated vessels' fishing portfolio, and comprising a small to moderate proportion of total annual ex-vessel revenue for most vessels active in SMBKC during a given year.

Indicators Assessment

Indicator Suite

We first provide information on how we selected the indicators for this third step of the ESP process and then provide results on the indicators analysis.

Ecosystem Indicators

Very few studies have linked environmental or ecosystem conditions to recruitment of Bering Sea crab stocks, owing primarily to the highly variable nature of crab recruitment. Zheng and Kruse (2000) noted that strong year classes of red and blue king crab stocks in the early 1970's corresponded with low temperatures. However, recruitment trends are not consistently explained by temperatures or decadal-scale environmental variability (Zheng and Kruse, 2006). Furthermore, groundfish predation has been hypothesized as a mechanism driving recruitment variability. SMBKC recruitment was positively correlated with Pacific cod biomass, opposite of the hypothesized directionality of predation effects on recruitment (Zheng and Kruse, 2006). The lack of general or biologically meaningful relationships supporting recruitment hypotheses for SMBKC in these studies may be attributed to analyses using basin-scale indicators that are not relevant to the small spatial scale of the SMBKC management area.
When selecting a suite of indicators for the SMBKC ESP, efforts were instead focused on developing spatially explicit indicators bounded by the SMBKC management area. These indicators are described below.

Bottom temperature and cold pool indicators representing environmental conditions during the summer survey period are likely drivers of juvenile and adult BKC distribution, timing of the reproductive cycle and larval transport. BKC females move inshore in late spring to hatch eggs, molt and mate (Armstrong et al., 1981). These inshore movements may be triggered by warming bottom temperatures, suggesting that cold years in the Bering Sea have the potential to delay mating migrations, embryo development and hatching as demonstrated in laboratory studies (Stevens et al., 2008b). Temperature-mediated shifts in hatch timing could subsequently result in BKC larvae mismatches with prey resources, or increase the probability of advection away from favorable nursery grounds. Laboratory studies have also shown that temperature is a direct driver of growth, molt duration and feeding ration (Long et al., 2017: Stoner et al., 2013).

An indicator representing the cold pool extent (<2°C) is not only important in driving BKC distributions, but also in driving distributions of major predators of BKC. Pacific cod and several flatfish species typically avoid temperatures less than 1° C (Kotwicki and Lauth, 2013), suggesting that years with a large cold pool extent around St. Matthew Island may offer BKC a refuge from predation.

A SMBKC pre-recruit biomass index effectively tracks the number of males that will likely enter the fishery the following year. Small catches of these sub-legal BKC are often a reliable indicator of impending declines in mature male biomass and may be useful as an early indicator of stock recovery for the SMBKC rebuilding plan. Likewise, a male bycatch indicator tracks mortality in trawl and fixed gear fisheries and fluctuations in bycatch rates may necessitate different regulations on groundfish fisheries or area closures to limit BKC mortality due to bycatch.

Estimates of benthic predator biomass (i.e. Pacific cod, sablefish, Pacific halibut, skates, sculpin, octopus and assorted flatfish) and invertebrate biomass (i.e. brittle stars, sea stars, sea cucumber, bivalves, non-commercial crab species, shrimp and polychaetes) provide information on the relative fluctuations of these foraging guilds (BSAI ESR, 2018). Increases in benthic predator biomass may represent increased mortality events due to predation on BKC. Although no studies on BKC diet and foraging ecology exist to date, species included in the invert biomass indicator are important prey sources for other EBS commercial crab species, and therefore likely prey of BKC as well. Increases in invert biomass may suggest optimal foraging conditions for BKC. It is, however, important to note that bottom trawl survey methods result in very low catchability of polychaetes, which are recognized as an important prey source for EBS crab species. Furthermore, increases in highly mobile benthic foragers such as hermit crabs and sea stars may, instead, suggest increased competition for benthic resources. A better understanding of benthic production and foraging ecology in the Bering Sea, and specifically, the St. Matthew Island region, is necessary to refine foraging guild indicators and their impacts on SMBKC.

Socioeconomic Indicators

Indicators reported for applicable socioeconomic metrics are derived from fishery-dependent sources that represent full enumeration of commercial landings captured in ADFG fish tickets, and ADFG and NMFS observer program data that support reliable estimates of fishing effort in the SMBKC fishery and bycatch in groundfish fisheries, respectively. Due to the intermittent opening of the targeted SMBKC fishery over the last 20 years, however, substantial gaps in the time-series for most socioeconomic indicators indicate zero (0) values when no fishery occurred, and the small number of vessels or processors participating in the fishery during some recent openings prevents reporting the value of some indicators for those years to protect confidentiality of associated landings and/or catch and effort data. The socioeconomic indicators reported below were selected in part on the basis of maximal length of time-series available[1], however, discontinuities in some data series due to changes in data collection methods limit reporting of indicator values to 1991 and later. Also, because the most recent fishery-dependent data sources are typically available for the prior year or lagged by up to three years (as of the September-November assessment cycle for most Alaska-region FMP crab and groundfish stocks), socioeconomic indicators are limited to providing retrospective information. Although relative to other crab and groundfish stocks, SMBKC is not data-poor with regard to most socioeconomic dimensions relevant to the fishery, the time-series gaps in socioeconomic indicators reported below may limit the ability to identify trends or movements in the indicators contemporaneous with reported ecosystem indicators and other factors considered in the SMBKC assessment. Combined with other functional limitations, this may substantially diminish the utility of these or other potential socioeconomic indicators for many of the purposes envisioned for the ESP.

The socioeconomic indicators reported below can be grouped into two broad, interrelated categories: 1) those addressing dimensions of commercial value, constituent demand and community dependence, and 2) indicators related to the relative quantity and efficiency of fishing effort. The latter set of indicators are reported in the assessment and are included in Figure 4 to support visual comparison of the relative values and trends in the respective sets of indicators.

Commercial value and constituent demand indicators

Ex-vessel price per pound, 1991-2015 ($2018)

Ex-vessel prices are revenue per pound of retained SMBKC catch, delivered live and sold to processors. Ex-vessel prices, combined with vessel operating costs and other factors, determine the economic return to vessels per unit of catch and, considering the availability and expected returns from alternative fishing targets, are a direct driver of the level and intensity of fishing effort.

SMB exvessel revenue share (% of total exvessel revenue)

This indicator represents the proportion of total annual ex-vessel revenue from all crab and groundfish landings for vessels active in the SMBKC fishery during a given calendar year that is produced from the SMBKC fishery. The reported values are calculated as the vessel-level mean SMBKC revenue share over the set of vessels active in the fishery for the year. Revenue share provides an indicator of the relative income dependence of participating vessels on the SMBKC fishery, where changes in the fishery that reduce the returns from fishing (e.g., reductions in TAC and/or ex-vessel price) are offset by income produced from alternative fishing targets.

Processors active in fishery

The number of processors (buyers) of SMBKC landings during the year; this provides an indicator of the density of the market for SMBKC landings.

Local Quotient of SMB landed catch in Saint Paul

St Paul represents the principal port of landing for the SMBKC fishery during the post-rationalization period, representing from 78% to 100% of all purchased landings in the fishery. The local quotient (LQ) represents the share of community landings attributed to SMBKC in relation to revenue from all other species landed in the community during years when the fishery was opened.

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[1] As one of the eight FMP crab stocks included in the Crab Rationalization Program, substantial additional data are available for the SMBKC fishery that are collected by NMFS in several mandatory reporting data collections that were initiated in 2005 to monitor the performance and effects of the management program, including the ownership of CR crab harvesting and processing quota share (QS) and the quantity and value of QS transfers between buyers and sellers, and vessel and plant operating cost, quota lease activity and value, and employment data reported by crab fishing and processing sector participants in the Crab Economic Data Report (EDR) program. Although these and other CR program-specific data collections provide substantial additional data to support a variety of socioeconomic indicators of potential utility for the purpose of the ESP (many of which are reported in BSAI Crab Economic Status Reports produced annually by AFSC (Garber-Yonts and Lee, 2019), the associated data series are only available beginning 2005 or more recent, and are largely subject to the same intermittency as other fishery-dependent data available for the SMBKC fishery.

TAC Utilization (%)

The percentage of the available catch allocation (GHL or TAC) that was harvested by participating vessels (including catch discarded as deadloss at the landing). Underutilization of the available TAC indicates a low value of expected returns from fishing SMBKC relative to alternative fishing targets, or idling the vessel.

Fishing effort

Vessels active in fishery

Total Potlifts

CPUE (no. of crabs per potlift - mean)

SMBKC male bycatch biomass (1000t)

Indicator Monitoring Analysis

The suite of indicators for SMBKC is monitored using a series of statistical tests that gradually increase in complexity depending on the stability of the indicator for monitoring the ecosystem or socioeconomic process and the data availability for the stock (Shotwell et al., *In Review*). At this time, we only report the results of the first stage indicator testing procedure for SMBKC. The first stage is a simple assessment of the trend and variance of the most recent year and a traffic-light evaluation of the most current year of data when available (Tables 2-3). The traffic-light ranking of the current year is based on the 20th and 80th percentiles of the time series and the color of blue, yellow, or red related to being below, within, or above the two percentiles (Caddy et al., 2015).

Ecosystem indicator trends suggest poor environmental conditions during the past 5 years for the SMBKC stock. Summer bottom water temperatures in the St. Matthew management area were at an all-time high in 2018 while the cold pool did not extend into the management area. Similar conditions were observed during 2019 summer survey operations. SMBKC pre-recruit biomass has also been on a steady decline since the mid-1990’s and the 2017 recruitment estimate is the third lowest in the 41 year time-series, following the lowest previously observed in 2016. Results of a recent breakpoint analysis suggest a SMBKC recruitment regime shift around 1996, corresponding with a 1989 brood year (Palof et al., 2019). Interestingly, there is empirical evidence for a 1989 regime shift in the North Pacific which was attributed to declines in Bering Sea groundfish recruitment and overall decreases in marine productivity (Hare and Mantua, 2000). Synchronous declines in time-lagged SMBKC recruitment suggest that ELH stages of BKC may have been negatively affected by these basin-scale ecological changes. Furthermore, warmer than average bottom temperatures in the St. Matthew Island management area in recent years correspond with low recruitment, suggesting that temperature may have an indirect effect on BKC early life history processes and survival to recruitment. In past years, trawl survey station R-24, on the northwest corner of St. Matthew Island, has been characterized by large catches of mature male BKC (Zacher et al., 2019). In 2018 and 2019, BKC catches were very low at R-24, corresponding with bottom temperatures nearing the upper limit of BKC thermal requirements. These observations may suggest that BKC habitat quality is decreasing as shallow, nearshore habitats warm to 6°C and above.

Benthic predator biomass was at an all-time high in 2016, attributed to high catches of Pacific cod surrounding St. Matthew Island. Likewise, in 2016 benthic invert biomass was up from previous years, characterized by high catches of several sea star species (*Ctenodiscus crispatus, Gorgonocephalus eucnemis and Leptasterias polaris*) as well as *Hyas coarctatus and Pagarus trigonocheirus*. 2016 biomass increases in highly mobile decapods and echinoderms may suggest increased competition for food resources available for juvenile and adult BKC. Both benthic predator and benthic invert biomasses have since declined, although remain above-average.

As a full suite of indicators is developed in the coming years, bayesian adaptive sampling (BAS) will be used for the second stage modeling application to quantify the association between hypothesized predictors and SMBKC along with the strength of support for each hypothesis.

Recommendations

In initial projections for the SMBKC rebuilding plan, recruitment appears to drive recovery time of the stock so we emphasize a concerted focus on developing a better understanding of early life history processes and the continued development of indicators relevant to larval and juvenile SMBKC. Developing an EFH habitat indicator for SMBKC should also be prioritized, as metric assessment results highlighted several vulnerabilities related to habitat. These updated indicators may then be used in second and third stage testing and modeling.

With these future priorities in mind, we provide the following set of considerations:

Ecosystem Considerations

- Despite repeated fishery closures, SMBKC mature male biomass and recruitment estimates remain below-average following a 1989 regime shift in the Bering Sea, suggesting that environmental factors may be impeding recruitment success and stock recovery.
- Highly specific thermal optimums and habitat requirements of SMBKC likely limit mobility in response to warmer than average bottom temperatures and shifting predator distributions in the Bering Sea.
- Large catches of Pacific cod in the St. Matthew Island management boundary in 2016 preceded declines in BKC mature male biomass, recruitment, and the overfished declaration in 2018.
- Trend modeling for SMBKC ecosystem indicators revealed poor conditions for SMBKC in recent years attributed to above average bottom temperatures, a reduction in the cold pool extent, and an increase in mean benthic predator biomass in the St. Matthew management boundary.

Socioeconomic Considerations

- Vessel engagement in the SMBKC fishery as measured by annual counts of active vessels during years that the fishery has opened, has declined relative to the pre-rationalization period reflecting consolidation of the crab fleet following rationalization.
- In the most recent open seasons, the active fleet has been reduced to 3-4 vessels, with TAC utilization also declining to 26% during the 2015/16 season.
- Ex-vessel revenue share and the Local Quotient for Saint Paul both reached high values during 2010, concurrent with a peak in ex-vessel price; large declines in both metrics over the subsequent open seasons, despite relatively high ex-vessel prices during the next four open SMBKC seasons indicate that both vessels and processors active during those years have shifted into other fisheries.

Data Gaps and Future Research Priorities

Additional data on BKC life history characteristics (i.e. growth-per-molt data and molting probabilities) as well as estimates for natural mortality would aide in a better understanding of stage-specific vulnerabilities. In addition, process-based studies are necessary in order to identify links between larval survival, recruitment and environmental factors. Examining larval drift patterns and spatial distributions of mature BKC around St. Matthew Island in relation to habitat characteristics will help to inform essential fish habitat models and the development of a larval retention indicator. Furthermore, additional groundfish stomach data outside of the summer survey time series would help to refine our understanding of predation pressure across life history stages of SMBKC. Likewise, spring bottom temperatures prior to the summer bottom trawl survey may help to understand SMBKC distribution in relation to survey catchability.

As noted above, in most socioeconomic dimensions, SMBKC fishery is relatively data rich in many respects. In the context of the ESP, however, the intermittent nature of the fishery and reliance on fishery-dependent socioeconomic data limits the available socioeconomic information to years when the fishery has opened. This complicates the depiction and/or interpretation of long-term averages for most socioeconomic indicators and suggests the need for development of indicators that are informative of social and economic factors relevant to the purposes of the ESP, but function on a continuous basis, including during years when the fishery is closed. Potential examples include estimation of current value of PSMFC QS assets, calculation of revenue share metrics for SMBKC processors and vessels identified with the SMBKC fishery on the basis of more continuous association than participation in the fishery during a particular year. Substantial improvements over the indicators reported above are feasible, however, are largely dependent on further development of clear objectives for the inclusion of social and economic indicators within the ESP framework.

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Table 1. List of data sources used in the SMBKC ESP evaluation. Please see the SMBKC SAFE document (Palof et al., 2019), the NOAA EBS Trawl Survey: Results for Commercial Crab Species Technical Memo (Zacher et al., 2019) and the SAFE Economic Status Report (Garber-Yonts and Lee, 2019) for more details

	Title	Description	Years	Extent
Ecosystem	RACE EBS Bottom Trawl Survey	Bottom trawl survey of groundfish and crab on standardized 376-station grid using an 83-112 Eastern otter trawl	1975-2019	EBS annual
	REEM Food Habits Database	Diet data collected from key groundfish species on the EBS bottom trawl survey	1987-2018	EBS annual
	ADF&G St. Matthew Island Pot Survey	Pot survey for blue king crab in the standard EBS bottom trawl survey area offshore and the nearshore area south and west of St. Matthew Island	1995-2018	St. Matthew Island Management Area, triannual
	Essential Fish Habitat Models	Habitat suitability MaxEnt models for describing essential fish habitat of groundfish and crab in Alaska, EFH 2017 Update	1970-2016	Alaska
	Historic Pribilof Island BKC Cruise Data	Data from zooplankton tows, beam trawl and rock dredge samples and side scan sonar to examine BKC processes across life history stages	1983-1984	Pribilof Islands, EBS
Socioeconomic	ADF&G fish ticket database	Volume, value, and port of landing for Alaska crab and groundfish commercial landings; data processed and provided by Alaska Fisheries Information Network	1992-2018	Alaska
	ADF&G Crab Observer program data	SMBKC catch and effort data (number of active vessels, total pots lifted, and CPUE), sourced from ADF&G Annual Fishery Management Report	1980-2017	Alaska

Table 2. First stage ecosystem indicator analysis for SMBKC including indicator title and short description. The recent five-year trend (up, down, or stable) and recent five-year mean (greater than (+), less than (-) or within 1 standard deviation (·) of long-term mean) are provided following the ESR methods. Fill is based on 2019 conditions for SMBKC relative to the 20th and 80th percentiles of the time series (yellow = average, blue = good, red = poor, no fill = no current year data). NA = data gap.

Title	Description	Trend	Mean
Summer Bottom Temperature	Average bottom temperature (°C) over all hauls within the SMBKC management boundary of the RACE Bering Sea shelf bottom trawl survey	**Up**	•
Proportion Cold Pool	Proportion of RACE Bering Sea shelf bottom trawl survey stations within the SMBKC management boundary less than 2°C	**Down**	**-**
SMBKC Pre-recruit Biomass	Model estimates for SMBKC recruitment. Includes male crab (105-119 mm CL) that will likely enter the fishery the following year.	**Stable**	•
Benthic Predator Biomass	Combined biomass (1,000t) of benthic predators within the SMBKC management boundary on the RACE Bering Sea shelf bottom trawl survey	**Stable**	+
Benthic Invert Biomass	Combined biomass (1,000t) of benthic invertebrates within the SMBKC management boundary on the RACE Bering Sea shelf bottom trawl survey	**Stable**	+

Table 3. First stage socioeconomic indicator analysis for SMBKC including indicator title and short description. The recent five-year trend (up, down, or stable) and recent five-year mean (greater than (+), less than (-) or within 1 standard deviation (·) of long-term mean) are provided following the ESR methods. Fill is based on most recent conditions for SMBKC relative to the 20th and 80th percentiles of the time series (yellow = average, blue = good, red = poor, no fill = no current year data). NA = data gap.

Title	Description	Trend	Mean
Vessels active in fishery	Annual count of crab vessels that delivered commercial landings of SMBKC to processors[2]	**Stable**	**–**
TAC Utilization	Percentage of the annual SMBKC TAC (GHL prior to 2005) that was harvested by active vessels, including deadloss discarded at landing.	**Down**	•
Total Potlifts	Fishing effort, as measured by estimated number of crab pots lifted by vessels during the SMBKC fishery	**Down**	•
CPUE	Fishing effort efficiency, as measured by estimated mean number of retained SMBKC per potlift	**Down**	•
Ex-vessel price per pound	Commercial value per unit (pound) of SMBKC landings (as adjusted by CFEC to account for post-season adjustments to ex-vessel settlements), measured as weighted average value over all ex-vessel sales reported.	**Down**	•
SMBKC ex-vessel revenue share	SMBKC ex-vessel revenue share as percentage of total calendar year ex-vessel revenue from all commercial landings in Alaska fisheries, mean value over all vessels active in SMBKC during the respective year.	**Down**	•
Processors active in fishery	Total number of crab processors that purchased landings of SMBKC from delivering vessels during the calendar year.	**Down**	•
Local Quotient of SMBKC landed catch in St. Paul	Ex-vessel value share of SMBKC landings to communities on St. Paul Island, as percentage of total value of commercial landings to St. Paul processors from all commercial Alaska fisheries, aggregate percentage over all landings during the respective year.	**Down**	•
SMBKC Male Bycatch in Groundfish Fishery	Incidental bycatch biomass estimates of male SMBKC (tons) in trawl and fixed gear fisheries	**Stable**	•

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[2] Includes crab catcher/processors that harvested and processed SMBKC catch on-board.

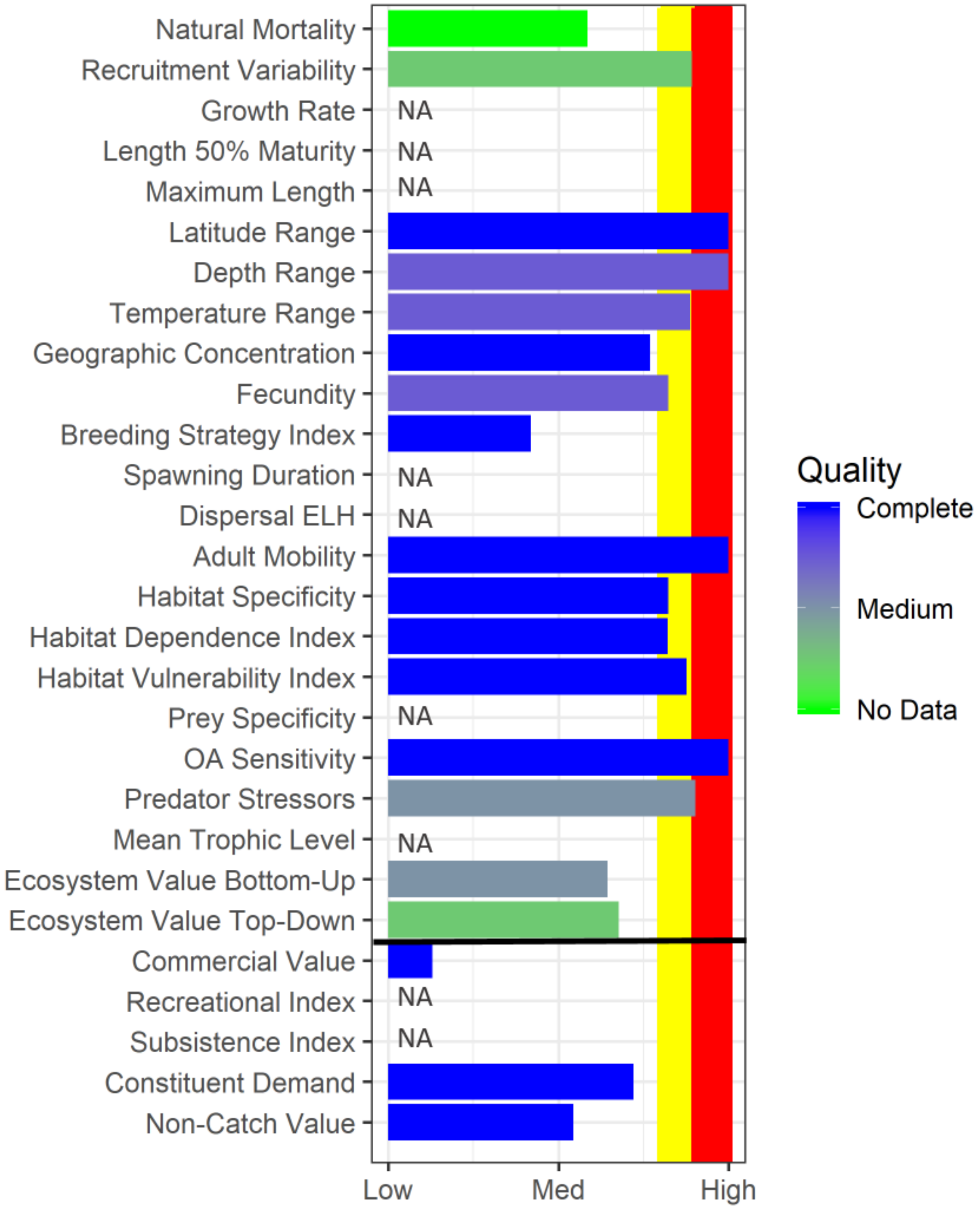

Figure 1. Baseline metrics for SMBKC graded as percentile rank over all groundfish and crab stocks in the FMP. Red bar indicates 90th percentile, yellow bar indicates 80th percentile. Higher rank values indicate a vulnerability and color of the horizontal bar describes data quality of the metric (see Shotwell et al., *In Review*, for more details on the metric definitions). Ecosystem indicators above and socioeconomic indicators below the horizontal black line.

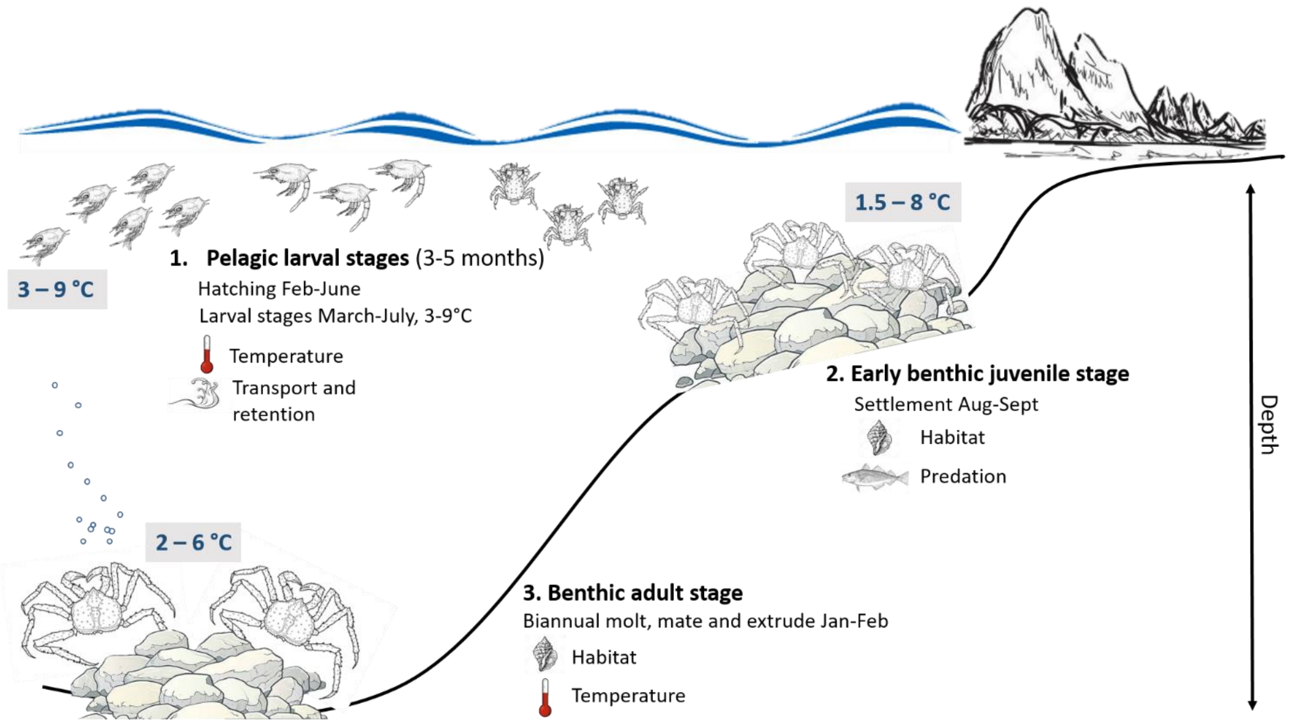

Figure 2. Conceptual diagram of phenological information by life history stage for SMBKC and processes likely affecting survival in each stage. Thermal requirements by life history stage were determined from BKC laboratory studies (Stoner et al., 2013, Stevens et al., 2008a, Stevens et al., 2008b).

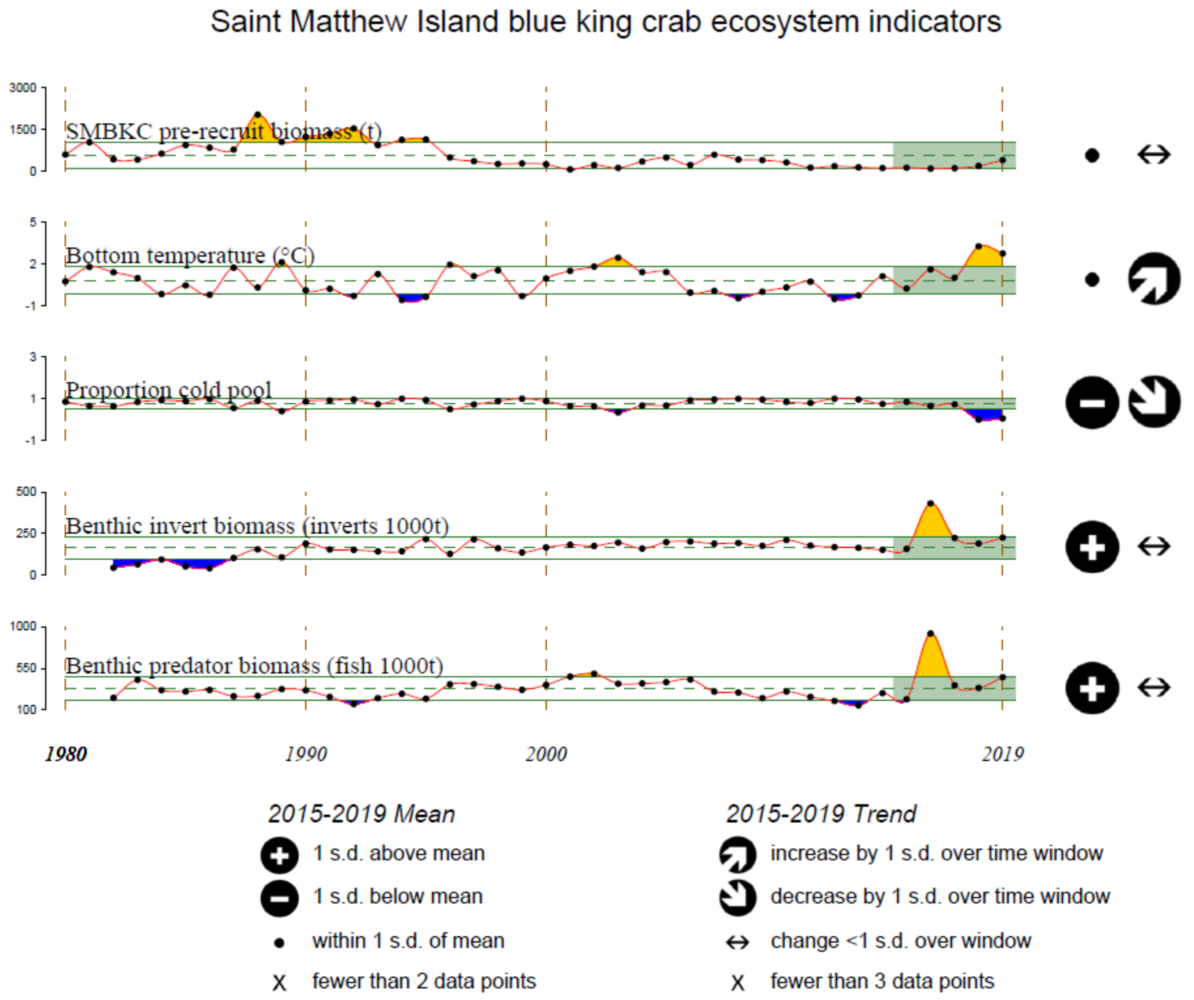

Figure 3. Selected ecosystem indicators for SMBKC with time series ranging from 1980 – 2019. Upper and lower solid green horizontal lines are 90th and 10th percentiles of time series. Dotted green horizontal line is mean of time series. Light green shaded area represents most recent five years for mean and trend analysis.

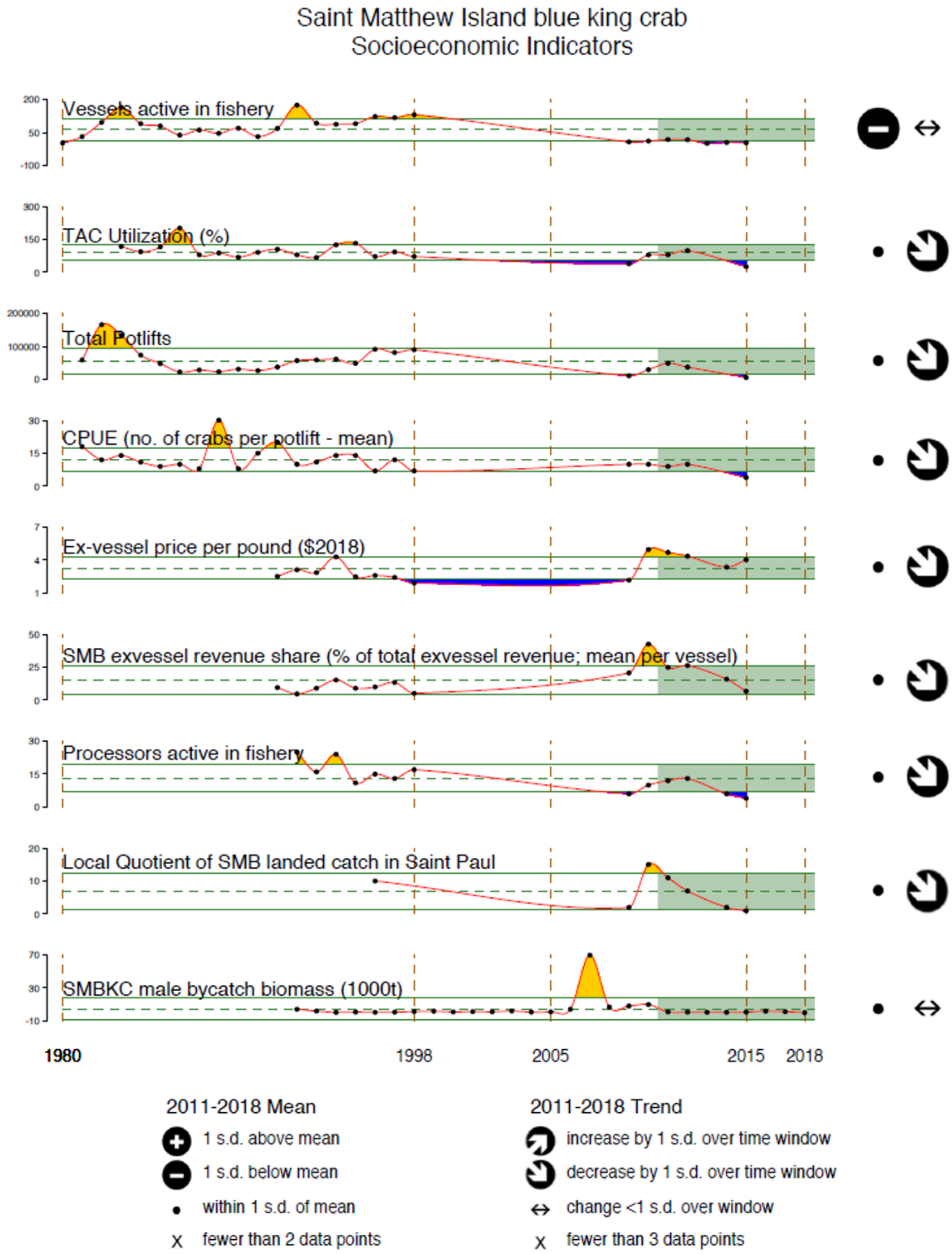

Figure 4. Selected socioeconomic indicators for SMBKC with time series ranging from 1980 – 2019. Upper and lower solid green horizontal lines are 90th and 10th percentiles of time series. Dotted green horizontal line is the mean of time series. For mean and trend analysis, the light green shaded area represents the most recent eight year period, which includes the most recent five year period (2011-2015) of open fisheries in more than two successive years.