Saint Matthew Island Blue King Crab Stock Assessment 2018

Jie Zheng[1] and James Ianelli[2]
[1]Alaska Department of Fish and Game, jie.zheng@alaska.gov
[2]NOAA, jim.ianelli@noaa.gov

September 2018

Executive Summary

1. **Stock**: Blue king crab, *Paralithodes platypus*, Saint Matthew Island (SMBKC), Alaska.
2. **Catches**: Peak historical harvest was 4288 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 1975-2018 NMFS trawl survey mean biomass is 5,664 t with the 8th lowest value occurring in 2018 (the third lowest since 2000) with a biomass of $\geq$ 90 mm carapace length (CL) and larger male crab of just at 1,730 t (~31% of the long term mean; 3.814 million lbs with a CV of 28%). The most recent 3-year average of the NMFS survey is 41% of the mean value, suggesting a general decline in biomass compared to the survey estimates in 2010 and 2011 that were over 6 times the current average. The assessment model estimates dampen the interannual variability observed in the survey biomass and suggest that the stock (in survey biomass units) is presently at about 27% of the long term model-predicted survey biomass average. The trend from these values suggests a slight decline.
4. **Recruitment**: Recruitment is based on estimated number of male crab within the 90-104 mm CL size class in each year. The 2018 trawl-survey area-swept estimate of 0.154 million male SMBKC in this size class is the third lowest in the 41 years since 1978 and follows the lowest (as observed in 2017). The recent six-year (2013 - 2018) average recruitment that is only 45% of this 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 (the total (all sizes) in the pot-survey index was also the lowest and was 12% of the mean).
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 stock was above the minimum stock-size threshold (MSST) in 2016/17 and is hence not overfished. Overfishing did not occur in this year as the directed fishery was closed (Tables 1 and 2). Nonetheless, the low survey values and paucity of crabs in the region, as indicated by the surveys, remains a concern.
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 or more considered mature. The

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

Table 1: Status and catch specifications (1000 t) for the reference model. Notes: A - calculated from the assessment reviewed by the Crab Plan Team in September 2013, B - calculated from the assessment reviewed by the Crab Plan Team in September 2014, C - calculated from the assessment reviewed by the Crab Plan Team in September 2015, D - calculated from the assessment reviewed by the Crab Plan Team in September 2016, E - calculated from the assessment reviewed by the Crab Plan Team in September 2017.

Year	MSST	Biomass (MMB_{mating})	TAC	Retained catch	Total male catch	OFL	ABC
2013/14	1.50^{A}	3.01^{A}	0.00	0.00	0.00	0.56	0.45
2014/15	1.86^{B}	2.48^{B}	0.30	0.14	0.15	0.43	0.34
2015/16	1.84^{C}	2.11^{C}	0.19	0.05	0.05	0.28	0.22
2016/17	1.93^{D}	2.12^{D}	0.00	0.00	0.05	0.28	0.22
2017/18	1.93^{E}	2.13^{E}	0.00	0.00	0.05	0.28	0.22
2018/19		2.09^{E}				0	0

Table 2: Status and catch specifications (million pounds) for the reference model.

Year	MSST	Biomass (MMB_{mating})	TAC	Retained catch	Total male catch	OFL	ABC
2013/14	3.4^{A}	6.64^{A}	0.000	0.000	0.0006	1.24	0.99
2014/15	4.1^{B}	5.47^{B}	0.655	0.309	0.329	0.94	0.75
2015/16	4.1^{C}	4.65^{C}	0.419	0.110	0.110	0.62	0.49
2016/17	4.3^{D}	4.68^{D}	0.410	0.000	0.000	0.62	0.49
2017/18	4.3^{E}	4.69^{E}	0.41	0.000	0.000	0.62	0.49
2018/19		4.61^{E}				0	0

B_{MSY} proxy is obtained by averaging estimated MMB over a specific reference time period, and current CPT/SSC guidance recommends using the full assessment time frame as the default reference period (Table 3).

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
2013/14	4b	3.06	3.01	0.98	0.18	1	1978-2013	0.18
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	0.09	1	1978-2016	0.18
2018/19	4b	3.86	2.09	0.54	0.09	1	1978-2017	0.18
2019/20	4b	3.86	2.09	0.54	0.09	1	1978-2017	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 makes use of two new survey data points including the 2018 NMFS trawl-survey estimate of abudance, and the 2018 ADF&G pot survey CPUE. Both of these surveys have associated size compositon data. The assessment also uses updated 2010-2017 groundfish and fixed gear bycatch estimates based on NMFS Alaska Regional Office (AKRO) data. The directed fishery has been closed since 2016/17 so fishery data in recent years is unavailable.

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 Bill Gaeuman and accepted by the CPT in May 2012. A difference from the original approach and that used here is that natural and fishing mortality 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 spawning biomass as estimated relative to the spawning biomass that would have occurred had there been no historical fishing mortality. Details of this implementation are 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 2017. The addition of new data introduced this year area are presented sequentially. Two alternative models are presented for sensitivity. One involves a re-analysis of the NMFS trawl survey data using a spatio-temporal Delta-GLMM approach (VAST model, Thorson and Barnett 2017) and the other configuration (named "Fit survey") simply adds emphasis on the design-based survey data (assumes a lower input variance). The VAST model suggests a modest increase from the 2017 survey estimate. However, the model tends to moderate the noise in the survey observations and declines

B. Responses to SSC and CPT Comments

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.

2. *add ability to estimate bycatch fishing mortality rates when observer data are missing but effort data is available*

   This was completed.

3. *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 to include an alternative time series estimated from the NMFS trawl survey using the VAST spatiotemporal Delta GLMM model and continued with the iterative re-weighting for composition data.

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 division, has detected regional population differences between blue king crab collected from St. Matthew Island and the Pribilof Islands[2]. 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.

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. They 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 4288 t (9.454 million pounds) (Fitch et al. 2012; Table 7).

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

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 (460,859 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 during 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. 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 makes use of two new survey data points including the 2018 NMFS trawl-survey estimate of abudance, and the 2018 ADF&G pot survey CPUE. Both of these surveys have associated size compositon data. The assessment also uses updated 1993-2016 groundfish and fixed gear bycatch estimates based on AKRO data. The fishery was closed in 2016/17 so no directed fishery catch data were available. The data used in each of the new models is shown in Figure 3.

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

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 (1978-2018; 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 NMFS groundfish-observer bycatch biomass estimates (1992/93-2016/17; 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 NMFS Bering Sea reporting areas 521 and 524 (Figure 6).

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.

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 (Zheng et al. 1997). 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 5.5in 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 just three stages (male size classes) determined 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

Five models were presented in the previous assessment. This year, four models are presented with the reference model being the same configuration as last year, three sensitivities are considered, one with a different treatment of NMFS bottom trawl survey (BTS) data using a geo-spatial model (VAST; Thorson and Barnett 2017), another which weights the survey data more heavily, and a third which weights the size composition data according to Francis' (2011) approach. In addition to these sensitivities, we also evaluated the impact of adding new data to the reference model. In summary, the following lists the models presented and the naming convention used:

1. **2017 Model**: the 2017 recommended model without any new data
2. **BTS**: adds in the 2018 bottom trawl survey (BTS) data
3. **BTS and pot**: as with previous but including the 2018 ADFG pot survey data (Model 16.0 or "reference case")
4. **VAST**: applies a geo-spatial delta-GLMM model (Thorson and Barnett 2017) to the BTS data which provides a different BTS index. See appendix B for details and diagnostics. This is a preliminary examination as more work is needed to ensure options for the BTS CPUE data were specified appropriately.
5. **Fit survey**: an exploratory scenario that's the same as the reference model except the NMFS trawl survey is up-weighted by $\lambda^{\mathrm{NMFS}} = 2$ and the ADF&G pot survey is up-weighted by $\lambda^{\mathrm{ADFG}} = 2$.

Note that SSC convention would label these (item 3 above) as model 16.0 (the model used last year). Since so few models are presented here, for simplicity model 16.0 is labeled "reference" and for the others, the naming convention above was used to make it easier to remember the main characteristic of the model configuration.

Results

a. Sensitivity to new data

Results for scenarios are provided with comparisons to the 2016 model and sensitivity new data are shown in Figures 7 and 8 with recruitment and spawning biomass shown in Figures 9 and 10, respectively. The fits to survey CPUEs and spawning biomass show that the addition of new data results in more of a decline than in the 2016 assessment, especially with the addition of the pot survey. The model with all new data is henceforth referred to as the "reference model."

b. Alternative NMFS bottom-trawl survey index

Results comparing model fits between the "VAST" spatio-temporal index and the reference case show different time-series of data and a different model fit (Figure 11). The effect on spawning biomass suggests estimates were consistently higher since 1990 compared to the reference model (Figure 12).

c. 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 mean absolute residual (MAR) are presented in Table 16. The SDNR for the trawl survey is acceptable at 1.45 in the reference model, and improves to 1.36 in the **Francis weight** model (since size composition data are re-weighted). The SDNRs for the pot surveys show much the same pattern between each of the scenarios, but are much higher values (ranging from 3.72 to 5.45). These values are very high, and whilst they can be improved by down-weighting the pot survey, we chose to retain the values as the pot survey considered important to include (down-weighting the data further would effectively exclude the signal from this series). The MAR for the trawl and pot surveys shows the same pattern among each of the scenarios as the SDNR. The SDNR (and MAR) values for the trawl survey and pot survey size compositions were excellent, ranging from 0.49 to 0.78. The SDNRs for the directed pot fishery and other size compositions were all accepatable.

d. Parameter estimates

Model parameter estimates for each of the Gmacs scenarios are summarized in Tables 12, 13, and 15. 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” scenario 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 runs, presumably because higher estimates of recruits in some years are required to match the observed biomass trends.

c. Graphs of estimates.

Selectivity estimates show some variability between models (Figure 13). Estimated recruitment is variable over time for all models and in recent years is well below average (Figure 14). Estimated mature male biomass on 15 February also fluctuates considerably (Figure 15). Estimated natural mortality each year (M_t) is presented in Figure 16.

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 is slightly above the 2017 value for the key sensitivities (Figures **??**). All of the models fit the pot survey CPUE poorly (Figure 17. For both surveys the standardized residuals tend to have similar patterns with some improvement (generally) for the VAST model (Figures 18 and 19).

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 20, 21, and 22) for all scenarios. Representative residual plots of the composition data fits are generally poor (Figures 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).

The contrast between the reference model and the “Francis weighted” model show minor differences (Figures **??** and 17). Unsurprisingly, the **fit surveys** model configuration fits the the NMFS survey biomass and ADF&G pot survey CPUE data better but still has a similar residual pattern (note that that this scenario was only included for exploratory purposes and forcing these weights resulted in worse SDNR and MAR values for the two abundance indices).

e. Retrospective and historic analyses.

The ability to conduct retrospective analyses with this software remains under development.

f. Uncertainty and sensitivity analyses.

Estimated standard deviations of parameters and selected management measures for the four models are summarized in Tables 12, 13, and 14 (and compiled together in Table 15. Probabilities for mature male biomass and OFL in 2017 are presented in Section F.

g. Comparison of alternative model scenarios.

The estimates of mature male biomass (Figure 15), for the **fit surveys** sensitivity stands out as being quite different from the other models due to a low value for pot survey catchability being estimated (which tends to scale the population). This scenario results in a lower MMB from the mid-1980s through to the late-1990s, and is again lower in the most recent 5 years. This scenario upweights both the trawl survey and the pot survey abundance indices (it upweights the pot survey more than the trawl survey) and represents a model run that places greater trust in the abundance indices, particularly the pot survey, than other data sources.

In summary, the use of the reference model for management purposes is preferred since it provides the best fit to the data and is consistent with previous model specifications. Research on alternative model specifications (e.g., natural mortality variability) was limited this year. The model using the "VAST" time series may take better account of spatial processes but requires more research to ensure it has been appropriately applied and the assumptions are reasonable. Consequently, the reference model appears reasonable and appropriate for ACL and OFL determinations for this stock in 2017. Nonetheless, the **Fit surveys** model, while difficult to statistically justify, portends a more dire stock status (see below) and should highlight the caution needed in managing this resource.

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 (2013 SAFE), 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

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

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

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- 2017, 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 2018 for all scenarios are summarized in Table 4. ABC is 80% of the OFL.

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

Component	Reference	VAST	Fit surveys	Francis weights	NA
MMB_{2018}	2141.716	2089.749	1249.315	2282.678	4084.014
B_{MSY}	3888.059	3863.373	3759.320	4334.962	9930.858
F_{OFL}	0.078	0.077	0.039	0.074	0.053
OFL_{2018}	0.000	0.000	0.000	0.000	0.000
ABC_{2018}	0.000	0.000	0.000	0.000	0.000

G. Rebuilding Analysis

This stock is not currently subject to a rebuilding plan.

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 Future Outlook

The outlook for recruitment looks relatively pessimistic. The dynamic-B_0 analysis, which removes historical fishing and projects the population based on estimated recruitments, indicates that the effect of fishing has reduced the stock to about 181%. The other aspects of depletion (ignoring stock-recruit relationship) may reflect variable survival rates due to environmental conditions and range shifts.

J. Acknowledgements

We thank the Crab Plan Team, Doug Pengilly for reviewing the earlier draft of this manuscript. Some materials in the report are from the SAFE report prepared by Bill Gaeuman in 2014. We thank Andre Punt for his input into the Gmacs model and for finding the error in the old SMBKC model code.

K. References

Alaska Department of Fish and Game (ADF&G). 2013. Crab observer training and deployment manual. Alaska Department of Fish and Game Shellfish Observer Program, Dutch Harbor. Unpublished.

Collie, J.S., A.K. Delong, and G.H. Kruse. 2005. Three-stage catch-survey analysis applied to blue king crabs. Pages 683-714 [In] Fisheries assessment and management in data-limited situations. University of Alaska Fairbanks, Alaska Sea Grant Report 05-02, Fairbanks.

Daly, B., R. Foy, and C. Armistead. 2014. The 2013 eastern Bering Sea continental shelf bottom trawl survey: results for commercial crab species. NOAA Technical Memorandum, NMFS-AFSC.

Donaldson, W.E., and S.C. Byersdorfer. 2005. Biological field techniques for lithodid crabs. University of Alaska Fairbanks, Alaska Sea Grant Report 05-03, Fairbanks.

Fitch, H., M. Deiman, J. Shaishnikoff, and K. Herring. 2012. Annual management report for the commercial and subsistence shellfish fisheries of the Bering Sea, 2010/11. Pages 75-1776 [In] Fitch, H., M. Schwenzfeier, B. Baechler, T. Hartill, M. Salmon, M. Deiman, E.

Evans, E. Henry, L. Wald, J. Shaishnikoff, K. Herring, and J. Wilson. 2012. Annual management report for the commercial and subsistence shellfish fisheries of the Aleutian Islands, Bering Sea and the Westward Region<U+FFFD><U+FFFD><U+FFFD>s Shellfish Observer Program, 2010/11. Alaska Department of Fish and Game, Fishery Management Report No. 12-22, Anchorage.

Fournier, D.A., H.J. Skaug, J. Ancheta, J. Ianelli, A. Magnusson, M.N. Maunder, A. Nielsen, and J. Sibert. 2012. AD Model Builder: using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. Optim. Methods Softw. 27:233-249.

Francis, R.I.C.C. 2011. Data weighting in statistical fisheries stock assessment models. Can. J. Fish. Aquat. Sci. 68: 1124-1138.

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

Gish, R.K., V.A. Vanek, and D. Pengilly. 2012. Results of the 2010 triennial St. Matthew Island blue king crab pot survey and 2010/11 tagging study. Alaska Department of Fish and Game, Fishery Management Report No. 12-24, Anchorage.

Jensen, G.C. and D.A. Armstrong. 1989. Biennial reproductive cycle of blue king crab, Paralithodes platypus, at the Pribilof Islands, Alaska and comparison to a congener, P. camtschatica. Can. J. Fish. Aquat. Sci. 46: 932-940.

Moore, H., L.C. Byrne, and D. Connolly. 2000. Alaska Department of Fish and Game summary of the 1998 mandatory shellfish observer program database. Alaska Dept. Fish and Game, Commercial Fisheries Division, Reg. Inf. Rep. 4J00-21, Kodiak.

North Pacific Fishery Management Council (NPFMC). 1998. Fishery Management Plan for Bering Sea/Aleutian Islands king and Tanner crabs. North Pacific Fishery Management Council, Anchorage.

North Pacific Fishery Management Council (NPFMC). 1999. Environmental assessment/regulatory impact review/initial regulatory flexibility analysis for Amendment 11 to the Fishery Management Plan for Bering Sea/Aleutian Islands king and Tanner crabs. North Pacific Fishery Management Council, Anchorage.

North Pacific Fishery Management Council (NPFMC). 2000. Environmental assessment/regulatory impact review/initial regulatory flexibility analysis for proposed Amendment 15 to the Fishery Management Plan for king and Tanner crab fisheries in the Bering Sea/Aleutian Islands and regulatory amendment to the Fishery Management Plan for the groundfish fishery of the Bering Sea and Aleutian Islands area: A rebuilding plan for the St. Matthew blue king crab stock. North Pacific Fishery Management Council, Anchorage. Draft report.

North Pacific Fishery Management Council (NPFMC). 2007. Public Review Draft: Environmental assessment for proposed Amendment 24 to the Fishery Management Plan for Bering Sea and Aleutian Islands king and Tanner crabs to revise overfishing definitions. 14 November 2007. North Pacific Fishery Management Council, Anchorage.

Otto, R.S. 1990. An overview of eastern Bering Sea king and Tanner crab fisheries. Pages 9-26 [In] Proceedings of the international symposium on king and Tanner crabs. University of Alaska Fairbanks, Alaska Sea Grant Program Report 90-4, Fairbanks.

Otto, R.S., and P.A. Cummiskey. 1990. Growth of adult male blue king crab (Paralithodes platypus). Pages 245-258 [In] Proceedings of the international symposium on king and Tanner crabs. University of Alaska Fairbanks, Alaska Sea Grant Report 90-4, Fairbanks.

Paul, J.M., A. J. Paul, R.S. Otto, and R.A. MacIntosh. 1991. Spermatophore presence in relation to carapace length for eastern Bering Sea blue king crab (Paralithodes platypus, Brandt, 1850) and red king crab (P. Camtschaticus, Tilesius, 1815). J. Shellfish Res. 10: 157-163.

Pengilly, D. and D. Schmidt. 1995. Harvest Strategy for Kodiak and Bristol Bay Red king Crab and St. Matthew Island and Pribilof Blue King Crab. Alaska Department of Fish and Game, Commercial Fisheries Management and Development Division, Special Publication Number 7, Juneau.

Somerton, D.A., and R.A. MacIntosh. 1983. The size at sexual maturity of blue king crab, Paralithodes platypus, in Alaska. Fishery Bulletin 81: 621-828.

Thorson, J.T., Ianelli, J.N., Larsen, E., Ries, L., Scheuerell, M.D., Szuwalski, C., and Zipkin, E. 2016. Joint dynamic species distribution models: a tool for community ordination and spatiotemporal monitoring. Glob. Ecol. Biogeogr. 25(9): 1144<U+FFFD><U+FFFD><U+FFFD>1158. doi:10.1111/geb.12464. url: http://onlinelibrary.wiley.com/doi/10.1111/geb.12464/abstract.

Thorson, J.T., Scheuerell, M.D., Shelton, A.O., See, K.E., Skaug, H.J., and Kristensen, K. 2015. Spatial factor analysis: a new tool for estimating joint species distributions and correlations in species range. Methods Ecol. Evol. 6(6): 627<U+FFFD><U+FFFD><U+FFFD>637. doi:10.1111/2041-210X.12359. url: http://onlinelibrary.wiley.com/doi/10.1111/2041-210X.12359/abstract

Thorson, J. T., and L. A. K. Barnett. 2017. Comparing estimates of abundance trends and distribution shifts using single- and multispecies models of fishes and biogenic habitat. ICES Journal of Marine Science 75:1311-1321.

Webber, D., J. Zheng, and J. Ianelli, 2016. Stock assessment of Saint Matthews Island Blue King Crab. North Pacific Fishery Managment Council. Anchorage AK.

Zheng, J. 2005. A review of natural mortality estimation for crab stocks: data-limited for every stock? Pages 595-612 [In] Fisheries Assessment and Management in Data-Limited Situations. University of Alaska Fairbanks, Alaska Sea Grant Program Report 05-02, Fairbanks.

Zheng, J., and G.H. Kruse. 2002. Assessment and management of crab stocks under uncertainty of massive die-offs and rapid changes in survey catchability. Pages 367-384 [In] A.J. Paul,E.G. Dawe, R. Elner, G.S. Jamieson, G.H. Kruse, R.S. Otto, B. Sainte-Marie, T.C. Shirley, and D. Woodby (eds.). Crabs in Cold Water Regions: Biology, Management, and Economics. University of Alaska Fairbanks, Alaska Sea Grant Report 02-01, Fairbanks.

Zheng, J., M.C. Murphy, and G.H. Kruse. 1997. Application of catch-survey analysis to blue king crab stocks near Pribilof and St. Matthew Islands. Alaska Fish. Res. Bull. 4:62-74.

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			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

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				

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

	Abundance					Biomass		
	Stage-1	Stage-2	Stage-3			Total		Number
Year	(90-104 mm)	(105-119 mm)	(120+ mm)	Total	CV	(90+ mm CL)	CV	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

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		50	100
2018		62	286		50	100

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

Parameter	Estimate	SD
Natural mortality deviation in 1998/99 (δ^M_{1998})	1.628	0.127
$\log(\bar{R})$	13.894	0.056
$\log(n^0_1)$	14.924	0.172
$\log(n^0_2)$	14.574	0.200
$\log(n^0_3)$	14.377	0.206
q_{pot}	3.569	0.245
$\log(\bar{F}^{\text{df}})$	-1.852	0.052
$\log(\bar{F}^{\text{tb}})$	-9.268	0.078
$\log(\bar{F}^{\text{fb}})$	-8.181	0.078
log Stage-1 directed pot selectivity 1978-2008	-0.636	0.174
log Stage-2 directed pot selectivity 1978-2008	-0.304	0.126
log Stage-1 directed pot selectivity 2009-2017	-0.283	0.150
log Stage-2 directed pot selectivity 2009-2017	-0.000	0.000
log Stage-1 NMFS trawl selectivity	-0.217	0.064
log Stage-2 NMFS trawl selectivity	-0.000	0.000
log Stage-1 ADF&G pot selectivity	-0.665	0.115
log Stage-2 ADF&G pot selectivity	-0.000	0.000
F_{OFL}	0.039	0.006
OFL	0.000	0.000

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

Parameter	Estimate	SD
Natural mortality deviation in 1998/99 (δ^M_{1998})	1.741	0.103
$\log(\bar{R})$	14.127	0.048
$\log(n^0_1)$	14.944	0.167
$\log(n^0_2)$	14.576	0.192
$\log(n^0_3)$	14.400	0.191
q_{pot}	2.501	0.134
$\log(\bar{F}^{\text{df}})$	-2.021	0.040
$\log(\bar{F}^{\text{tb}})$	-9.604	0.068
$\log(\bar{F}^{\text{fb}})$	-8.519	0.068
log Stage-1 directed pot selectivity 1978-2008	-0.728	0.170
log Stage-2 directed pot selectivity 1978-2008	-0.350	0.123
log Stage-1 directed pot selectivity 2009-2017	-0.085	0.149
log Stage-2 directed pot selectivity 2009-2017	-0.000	0.000
log Stage-1 NMFS trawl selectivity	-0.246	0.063
log Stage-2 NMFS trawl selectivity	-0.000	0.000
log Stage-1 ADF&G pot selectivity	-0.584	0.116
log Stage-2 ADF&G pot selectivity	-0.000	0.000
F_{OFL}	0.074	0.006
OFL	0.000	0.000

Table 14: Model parameter estimates, selected derived quantities, and their standard deviations (SD) for the "Fit survey" model.

Parameter	Estimate	SD
Natural mortality deviation in 1998/99 (δ^M_{1998})	2.242	0.085
$\log(\bar{R})$	14.363	0.063
$\log(n^0_1)$	15.499	0.413
$\log(n^0_2)$	15.332	0.434
$\log(n^0_3)$	15.166	0.402
q_{pot}	0.918	0.037
$\log(\bar{F}^{\mathrm{df}})$	-2.895	0.036
$\log(\bar{F}^{\mathrm{tb}})$	-10.404	0.065
$\log(\bar{F}^{\mathrm{fb}})$	-9.319	0.065
log Stage-1 directed pot selectivity 1978-2008	-0.372	0.135
log Stage-2 directed pot selectivity 1978-2008	-0.114	0.116
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	-0.000	0.000
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}	0.053	0.003
OFL	0.000	0.000

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

Parameter	Ref	VAST	FitSurvey
F_{OFL}	0.039	0.074	0.053
$\log(\bar{F}^{\mathrm{df}})$	-1.852	-2.021	-2.895
$\log(\bar{F}^{\mathrm{fb}})$	-8.181	-8.519	-9.319
$\log(\bar{F}^{\mathrm{tb}})$	-9.268	-9.604	-10.404
$\log(\bar{R})$	13.894	14.127	14.363
$\log(n^0_1)$	14.924	14.944	15.499
$\log(n^0_2)$	14.574	14.576	15.332
$\log(n^0_3)$	14.377	14.400	15.166
q_{pot}	0.004	0.003	0.001
Natural mortality deviation in 1998/99 (δ^M_{1998})	1.628	1.741	2.242
OFL	0.000	0.000	0.000
log Stage-1 ADF&G pot selectivity	-0.665	-0.584	-0.000
log Stage-1 NMFS trawl selectivity	-0.217	-0.246	-0.000
log Stage-1 directed pot selectivity 1978-2008	-0.636	-0.728	-0.372
log Stage-1 directed pot selectivity 2009-2017	-0.283	-0.085	-0.000
log Stage-2 ADF&G pot selectivity	-0.000	-0.000	-0.000
log Stage-2 NMFS trawl selectivity	-0.000	-0.000	-0.000
log Stage-2 directed pot selectivity 1978-2008	-0.304	-0.350	-0.114
log Stage-2 directed pot selectivity 2009-2017	-0.000	-0.000	-0.000

Table 16: Comparisons of data weights, Francis LF weights (i.e. the new weights that should be applied to the LFs), SDNR values, and MAR values for the four model scenarios.

Component	Reference	VAST	Fit survey	Francis	NA
NMFS trawl survey weight	1.00	1.00	1.00	1.00	2.00
ADF&G pot survey weight	1.00	1.00	1.00	1.00	2.00
Directed pot LF weight	1.00	1.00	1.00	1.00	1.95
NMFS trawl survey LF weight	1.00	1.00	1.00	1.00	0.22
ADF&G pot survey LF weight	1.00	1.00	1.00	1.00	0.10
Fancis weight for directed pot LF	0.00	0.00	0.00	0.00	0.00
Francis weight for NMFS trawl survey LF	0.00	0.00	0.00	0.00	0.00
Francis weight for ADF&G pot survey LF	0.00	0.00	0.00	0.00	0.00
SDNR NMFS trawl survey	1.45	1.46	1.66	1.98	2.40
SDNR ADF&G pot survey	3.77	3.75	4.42	4.82	6.80
SDNR directed pot LF	0.71	0.71	0.76	0.88	1.63
SDNR NMFS trawl survey LF	1.24	1.23	1.32	1.42	1.31
SDNR ADF&G pot survey LF	0.89	0.88	0.97	1.11	1.36
MAR NMFS trawl survey	1.18	1.16	1.24	1.07	1.65
MAR ADF&G pot survey	2.96	2.94	2.62	2.95	3.40
MAR directed pot LF	0.60	0.60	0.60	0.61	0.91
MAR NMFS trawl survey LF	0.53	0.53	0.55	0.69	0.86
MAR ADF&G pot survey LF	0.69	0.68	0.71	0.86	1.04

Table 17: Comparisons of negative log-likelihood values for the four model scenarios. It is important to note that some of these models cannot be compared since the input sample size (or variances) are modified by re-weighting (e.g., **Francis** model).

Component	Ref	VAST	FitSurvey	Francis	NA
Pot Retained Catch	-71.54	-71.52	-70.90	-70.33	-68.90
Pot Discarded Catch	8.71	8.63	9.58	14.86	65.13
Trawl bycatch Discarded Catch	-7.16	-7.43	-7.43	-7.43	-7.43
Fixed bycatch Discarded Catch	-7.13	-7.41	-7.39	-7.42	-7.42
NMFS Trawl Survey	-3.89	-3.95	12.65	9.31	47.61
ADF&G Pot Survey CPUE	56.94	56.02	88.60	112.37	231.05
Directed Pot LF	-11.17	-11.15	-9.87	-5.87	29.74
NMFS Trawl LF	18.75	17.86	25.86	39.90	107.77
ADF&G Pot LF	-5.47	-5.61	-3.89	0.49	33.54
Recruitment deviations	53.72	54.03	57.33	54.55	69.20
F penalty	14.49	14.49	14.49	14.49	14.49
M penalty	6.47	6.47	6.47	6.47	6.49
Prior	12.66	12.66	12.66	12.66	13.61
Total	65.39	63.10	128.15	174.06	534.87
Total estimated parameters	139.00	141.00	141.00	141.00	141.00

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 **2016 model**.

Year	n_1	n_2	n_3	MMB
1978	3024666	2068576	1713619	4812
1979	4242186	2402462	2397110	6687
1980	3599593	3204521	3574696	10411
1981	1353493	3105050	4917923	10787
1982	1476139	1796399	4926372	7774
1983	777972	1432839	3536665	4867
1984	666841	915951	2125534	3434
1985	938437	681847	1593775	3154
1986	1407597	758643	1396375	3082
1987	1353975	1050525	1497974	3593
1988	1238076	1116681	1718315	3888
1989	2805889	1072770	1880176	4396
1990	1756923	1948631	2170700	5455
1991	1822678	1642784	2634119	5473
1992	1950634	1578274	2587859	5617
1993	2193543	1629627	2681897	5834
1994	1539215	1784821	2736464	5565
1995	1778114	1464820	2633188	5477
1996	1608434	1494547	2546266	5283
1997	903444	1408043	2476531	4693
1998	663921	978997	2072077	3282
1999	398649	328936	803832	1873
2000	441508	335125	874958	2013
2001	409457	361580	941758	2168
2002	145914	352113	1007753	2281
2003	334551	199362	1032913	2155
2004	227560	255850	994709	2148
2005	513233	213897	981453	2076
2006	764071	362188	976420	2232
2007	515032	553247	1070115	2593
2008	942251	469811	1207057	2784
2009	753585	689955	1333843	2881
2010	726500	655586	1441629	2571
2011	600084	628647	1338753	2149
2012	340146	548653	1104279	1764
2013	440819	374605	895883	2001
2014	361877	374243	979041	1990
2015	346131	329310	980571	1987
2016	416427	305470	996381	2105
2017	243561	337319	1025157	2192
2018	653212	249989	1049658	2142

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
1978	3030796	2135863	1752594	4963
1979	4247810	2428215	2464175	6828
1980	3594861	3216240	3644236	10556
1981	1323670	3106242	4981464	10907
1982	1479572	1779858	4977213	7853
1983	785671	1429315	3571248	4934
1984	665382	919158	2153614	3491
1985	922941	682080	1618842	3207
1986	1431374	749921	1416022	3110
1987	1351394	1061141	1512273	3632
1988	1230543	1118729	1735381	3921
1989	2841297	1069170	1894767	4420
1990	1761240	1967548	2184472	5501
1991	1824710	1651497	2655631	5524
1992	1955041	1582314	2610579	5665
1993	2211548	1633470	2703431	5881
1994	1564451	1796319	2758259	5619
1995	1658174	1482956	2659868	5550
1996	1617846	1432438	2566368	5252
1997	903275	1392833	2463106	4650
1998	603860	973865	2053754	3260
1999	387847	318433	809168	1871
2000	431495	325518	873086	1999
2001	393788	352714	934391	2144
2002	139008	340282	995631	2244
2003	328890	191525	1016162	2115
2004	192422	250041	976224	2107
2005	480592	192021	959724	2010
2006	717427	336412	944118	2142
2007	409298	518235	1025675	2469
2008	796028	398593	1141664	2581
2009	616585	583384	1229316	2583
2010	544411	542553	1287266	2190
2011	418954	487895	1133807	1647
2012	219467	399293	842037	1162
2013	266576	256703	588679	1326
2014	209279	236325	646507	1259
2015	190947	197045	618631	1226
2016	215223	173625	612716	1279
2017	132202	179583	619466	1296
2018	132361	134239	619285	1249

Table 20: 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 model that uses the VAST BTS index.

Year	n_1	n_2	n_3	MMB
1978	3089623	2139308	1793930	5046
1979	4190990	2462770	2505993	6938
1980	3476396	3195408	3691157	10621
1981	1365290	3032067	4998828	10855
1982	1500563	1778950	4959112	7811
1983	733757	1440941	3555254	4904
1984	618380	893528	2136851	3426
1985	846366	646906	1585842	3097
1986	1199777	694789	1362664	2946
1987	1331598	911364	1417784	3283
1988	1247272	1057911	1579094	3567
1989	3040671	1058541	1735309	4097
1990	1896925	2077260	2065041	5409
1991	1981784	1764869	2624353	5593
1992	2189134	1709016	2657026	5896
1993	2538882	1808330	2828620	6323
1994	1866393	2040088	2982268	6313
1995	1947502	1735130	2998821	6494
1996	2159153	1680233	3003897	6369
1997	1313733	1782282	3004970	6189
1998	832399	1335891	2741380	4668
1999	512023	392506	1056651	2417
2000	568732	420561	1129022	2585
2001	519008	462116	1209211	2781
2002	178090	447610	1292316	2920
2003	442825	249248	1321830	2751
2004	247674	333852	1271539	2753
2005	760799	251145	1253935	2627
2006	1067807	515109	1246466	2909
2007	607128	776332	1401831	3464
2008	1165152	596243	1605465	3671
2009	843025	858429	1751670	3793
2010	722983	762220	1884162	3417
2011	608710	662101	1760393	2885
2012	371778	564748	1469158	2378
2013	422580	397998	1205729	2579
2014	351765	371703	1248068	2458
2015	317808	322786	1202812	2360
2016	364454	287301	1176149	2407
2017	223878	301976	1161668	2395
2018	213385	226843	1142651	2283

Table 21: 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 **fit surveys** model.

Year	n_1	n_2	n_3	MMB
1978	5385868	4554302	3860757	11766
1979	6531404	4566273	5669629	14649
1980	3612021	5220878	7618053	20407
1981	1406958	3779553	9313164	19745
1982	1266548	2050062	8942236	15735
1983	745777	1397817	6990560	11797
1984	586531	886162	4969874	8695
1985	663630	626414	3941999	7935
1986	830810	584239	3302488	6487
1987	1775067	665240	2946785	5895
1988	3733852	1228338	2774212	5940
1989	7914396	2527202	3056606	8341
1990	2201432	5331304	4374662	13319
1991	3074011	3014924	6222881	13858
1992	3487281	2743297	6394423	14090
1993	4824091	2888134	6594260	14906
1994	3564848	3695433	6888170	15475
1995	2739370	3247694	7254220	16493
1996	4367448	2630698	7393759	15839
1997	3934711	3351104	7359157	16794
1998	2857331	3343748	7413862	12631
1999	854087	600424	1657853	3776
2000	1587996	683657	1768730	4077
2001	3371232	1128060	1973648	4962
2002	634607	2287764	2539308	7328
2003	188693	1117583	3334952	7494
2004	105430	477017	3366576	6831
2005	822159	217773	3062446	5970
2006	1909399	538974	2746081	5739
2007	3944388	1262325	2746875	6535
2008	1217442	2647893	3295379	9145
2009	1354062	1567376	4202653	8838
2010	1612522	1287300	4337120	8050
2011	841330	1341193	4158057	7651
2012	521479	921683	3834658	6706
2013	557660	601206	3372724	6664
2014	595638	515702	3173470	5981
2015	452557	508965	2906288	5472
2016	192334	425468	2705557	5284
2017	75239	250024	2492335	4712
2018	52299	125414	2213658	4084

Figures

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

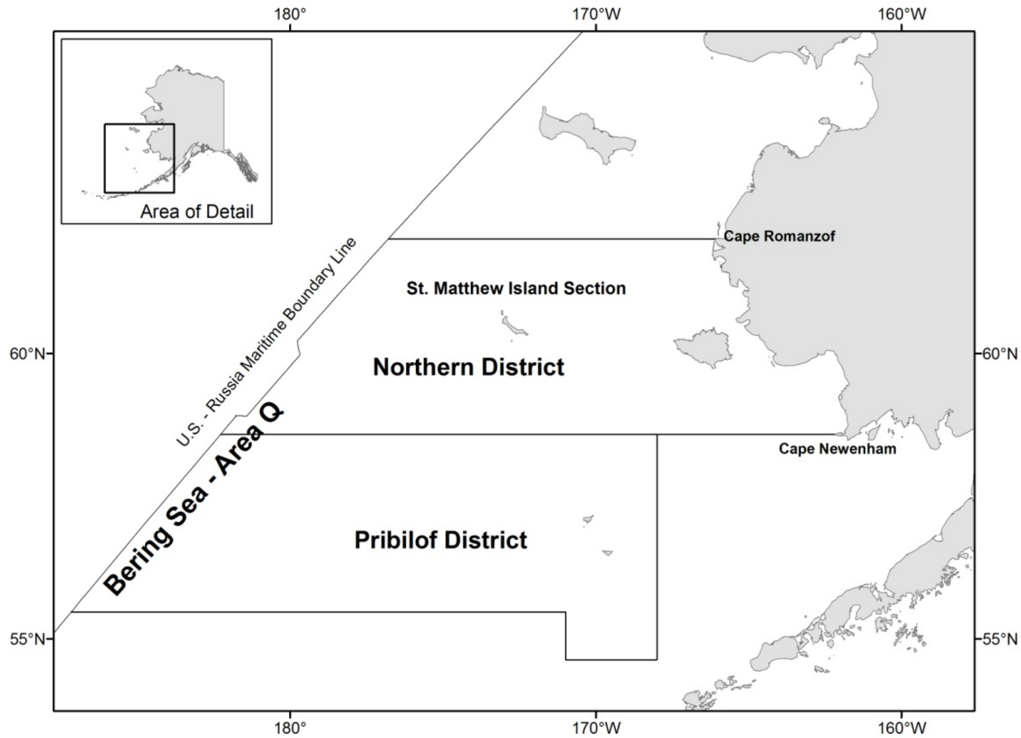

Figure 2: King crab Registration Area Q (Bering Sea).

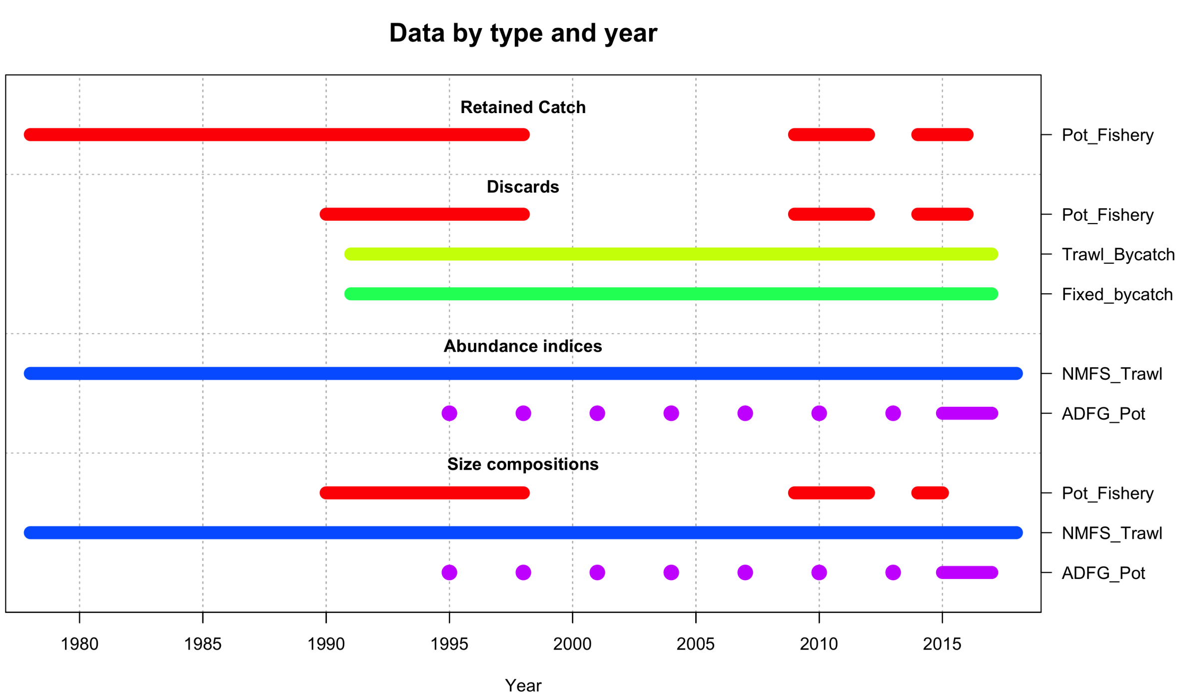

Figure 3: Data extent for the SMBKC assessment (with the 2017 Pot survey included).

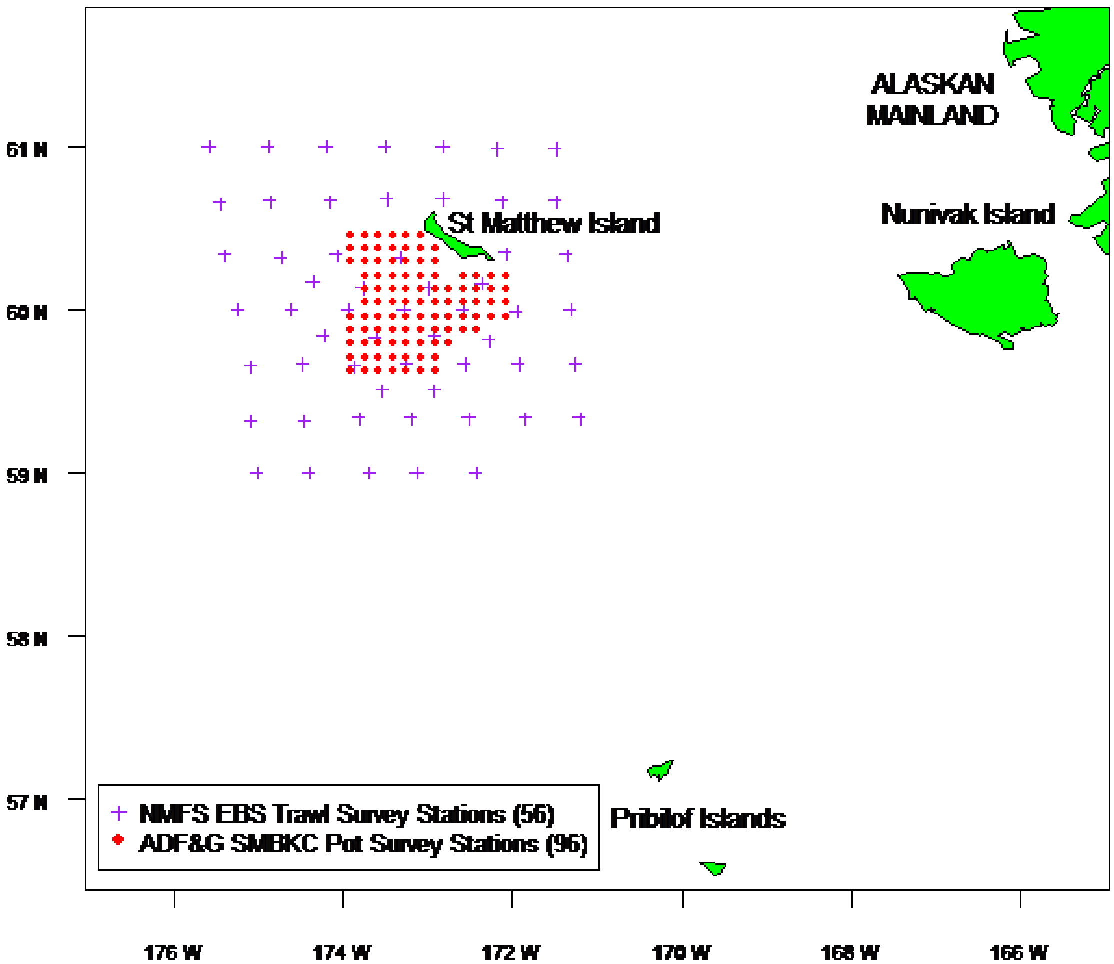

Figure 4: Trawl and pot-survey stations used in the SMBKC stock assessment.

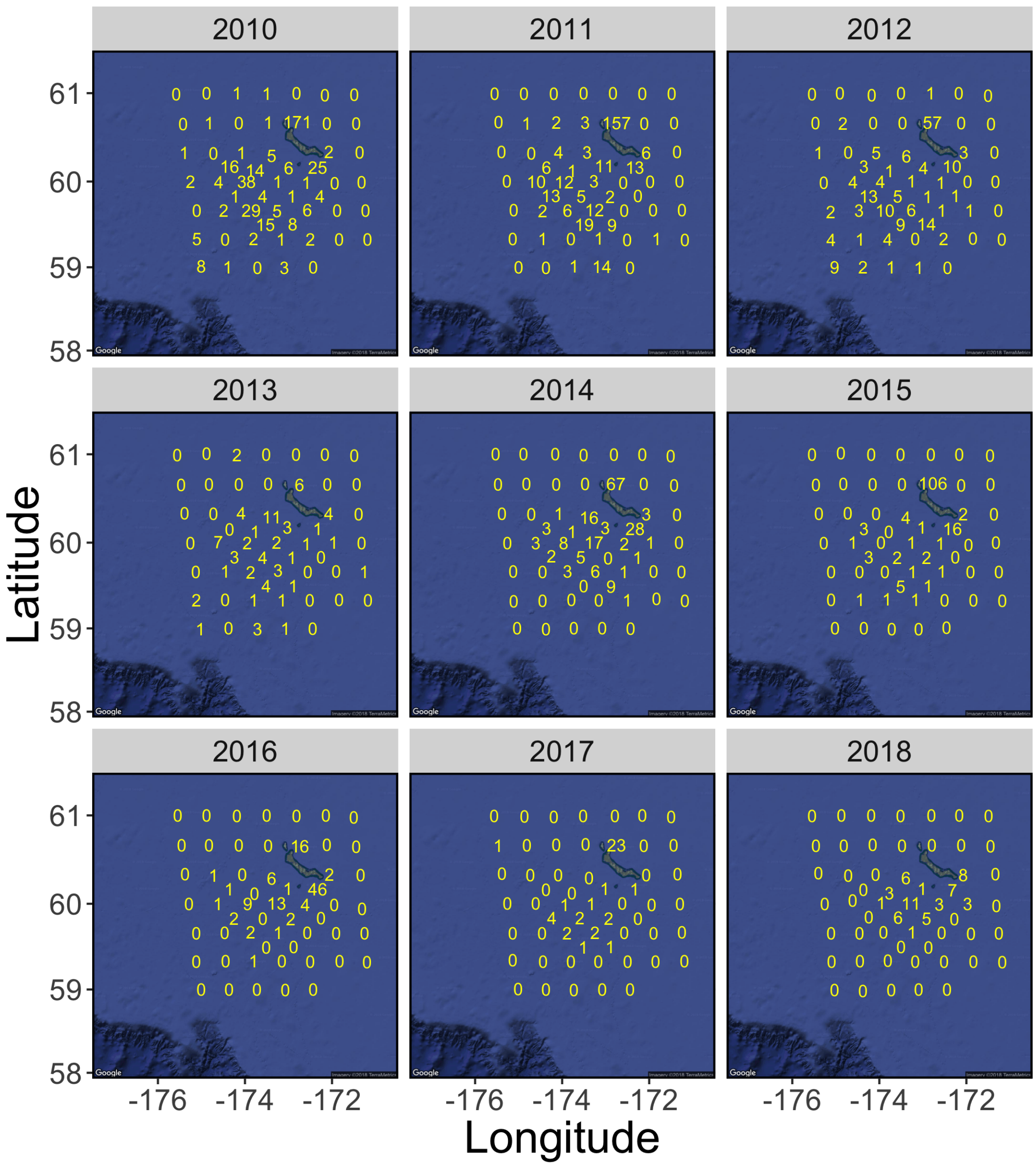

Figure 5: Catches (in numbers) of male blue king crab measuring 90 mm CL from the 2012-2017 NMFS trawl-survey at the 56 stations used to assess the SMBKC stock. Note that the area north of St. Matthew Island, which often shows large catches of crab at station R-24 is not covered in the ADF&G pot-survey data used in the assessment.

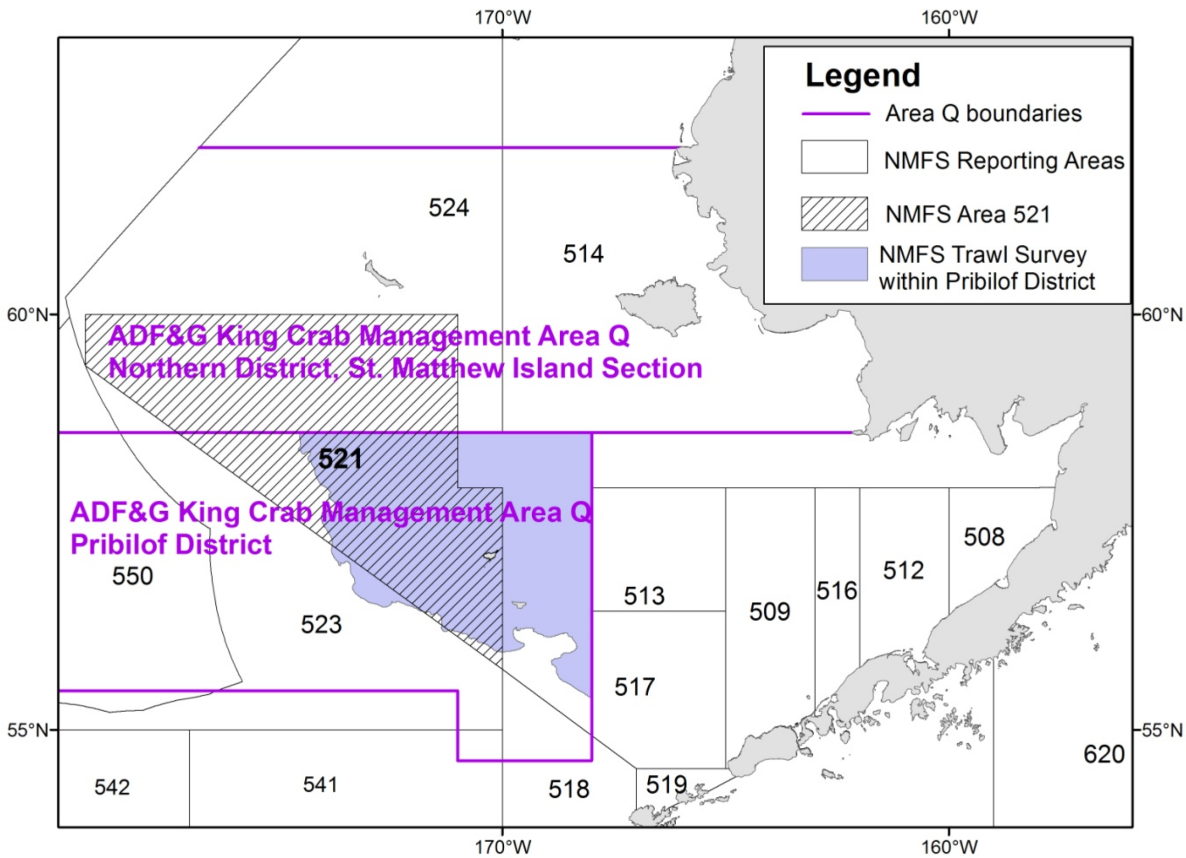

Figure 6: NFMS Bering Sea reporting areas. Estimates of SMBKC bycatch in the groundfish fisheries are based on NMFS observer data from reporting areas 524 and 521.

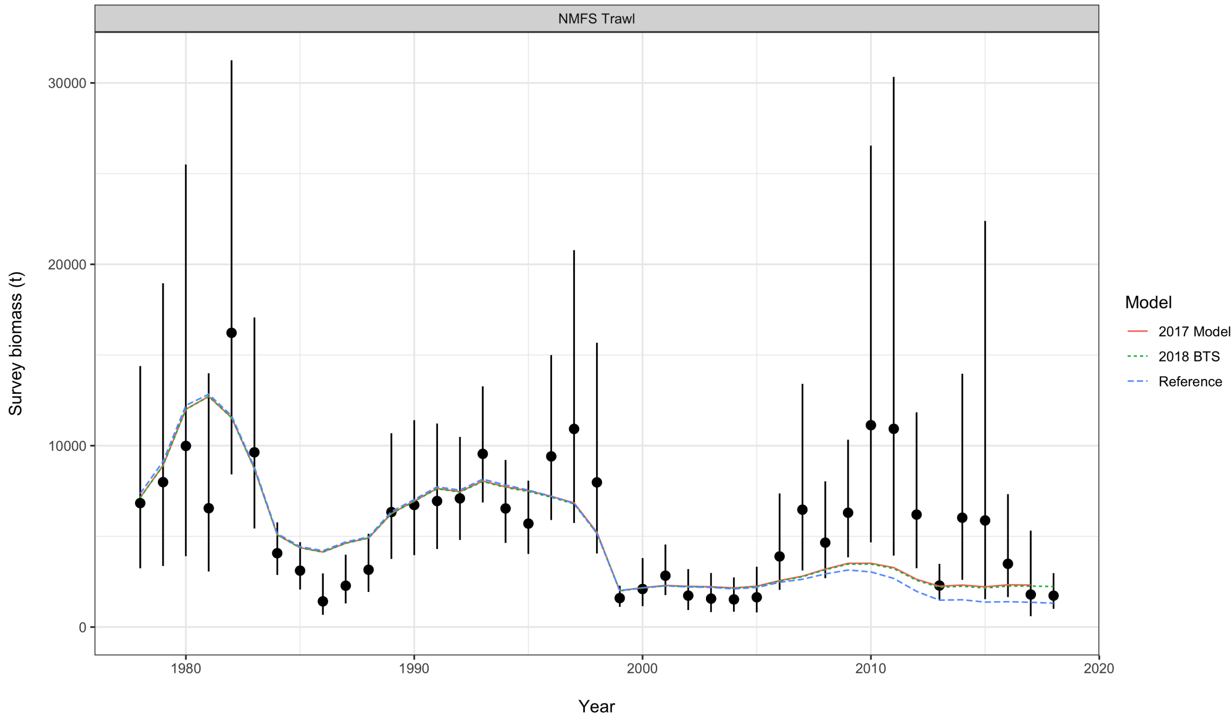

Figure 7: Fits to NMFS area-swept trawl estimates of total (>90mm) male survey biomass with the addition of new data. Error bars are plus and minus 2 standard deviations.

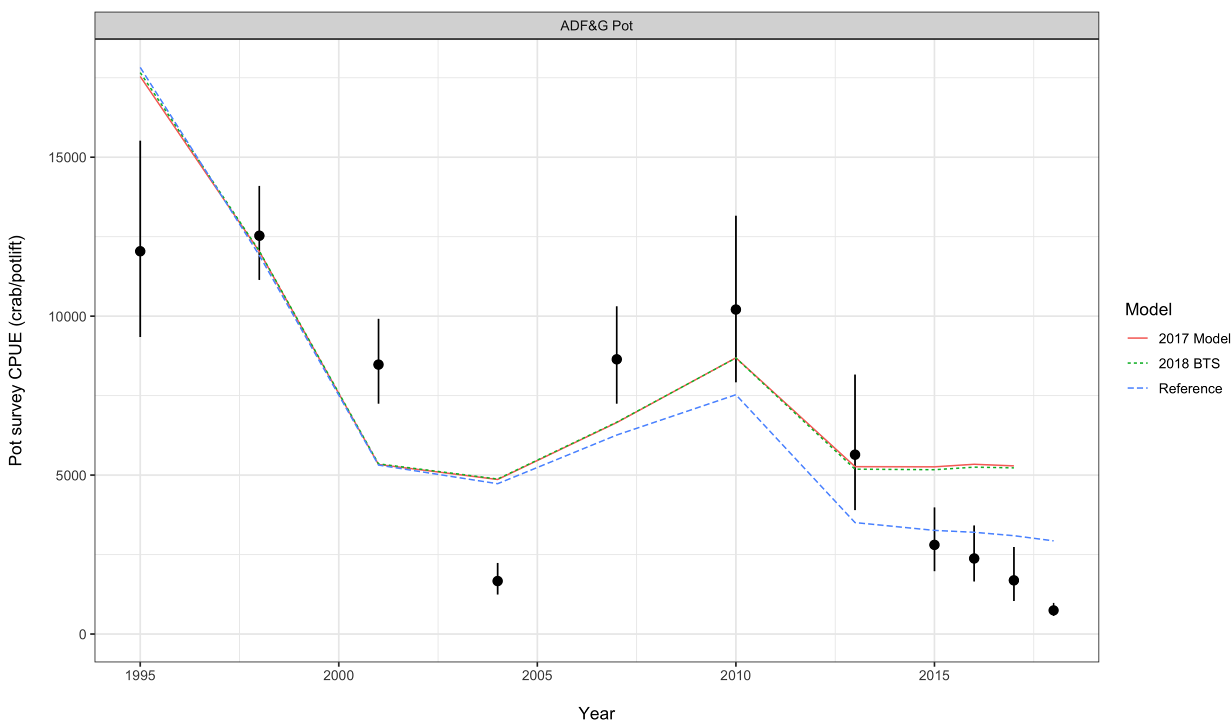

Figure 8: Comparisons of fits to CPUE from the ADF&G pot surveys with the addition of new data. Error bars are plus and minus 2 standard deviations.

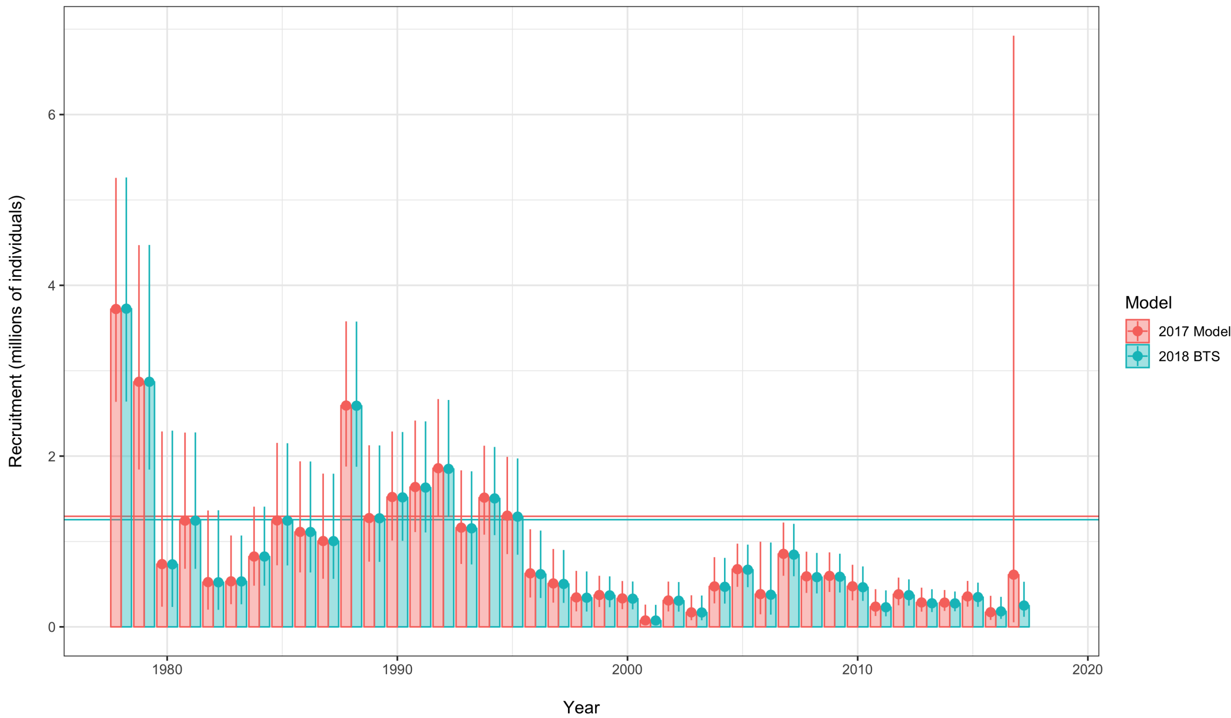

Figure 9: Sensitivity of new data in 2017 on estimated recruitment ; 1978-2017.

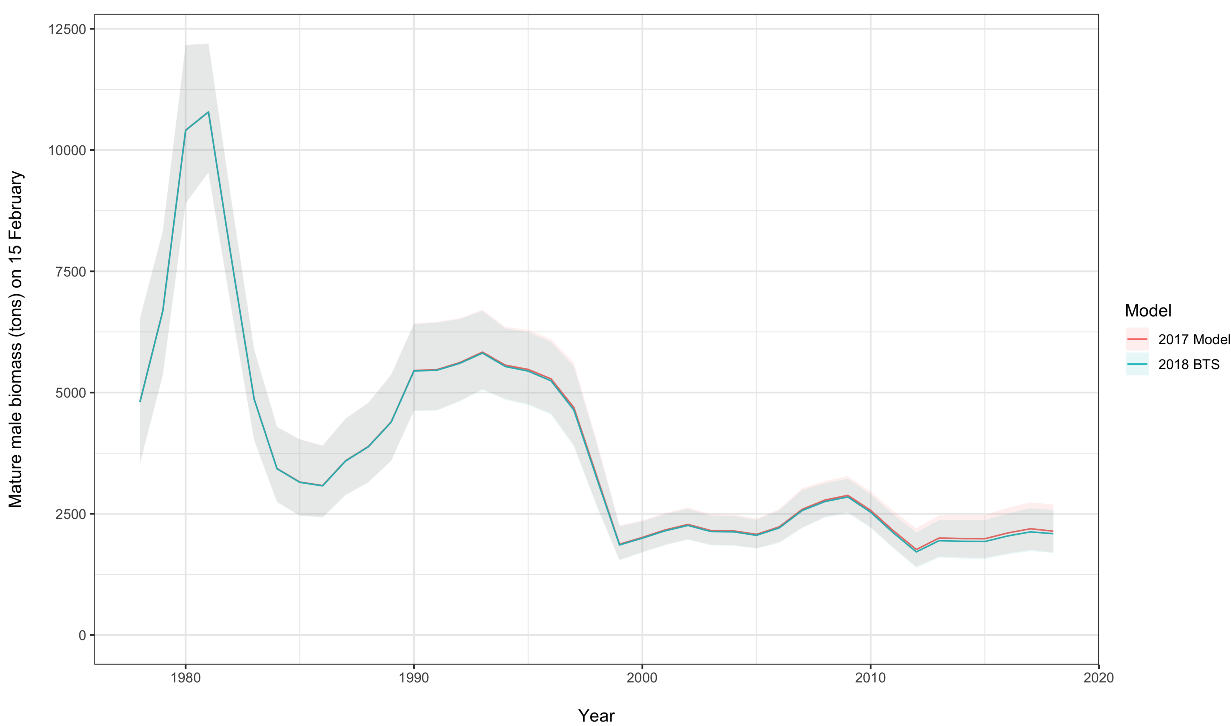

Figure 10: Sensitivity of new data in 2017 on estimated mature male biomass (MMB); 1978-2017.

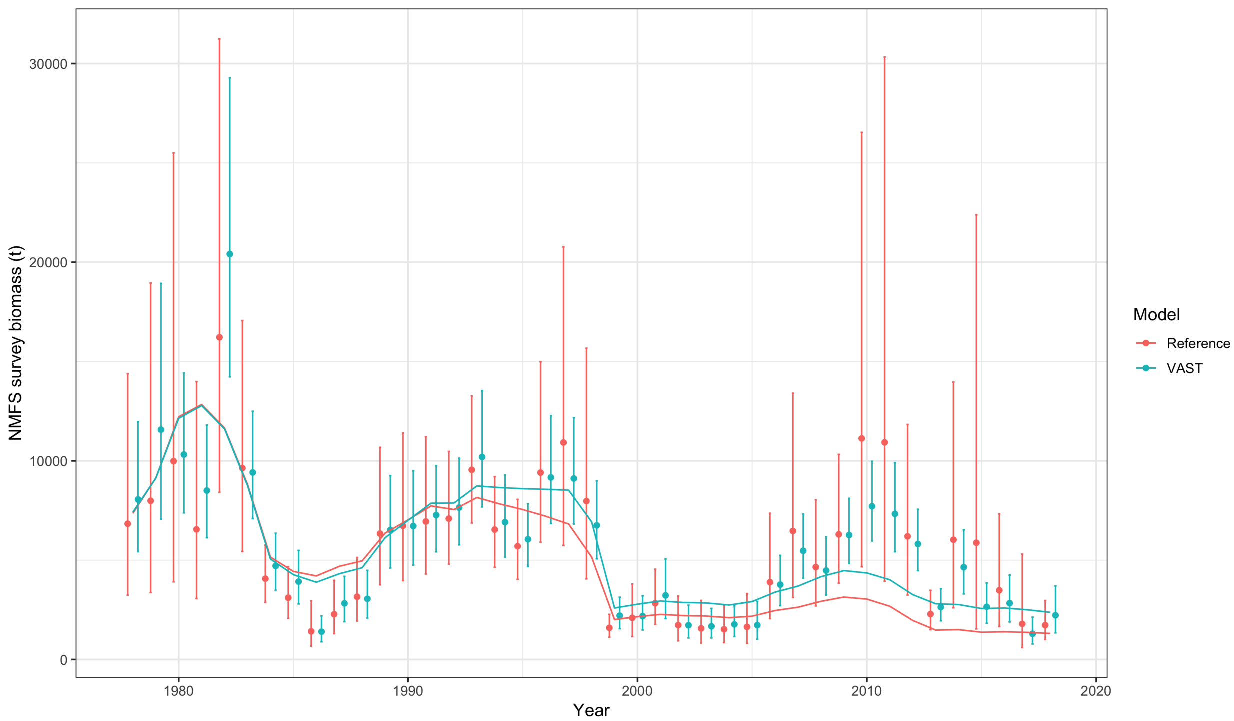

Figure 11: Comparisons of fits to area-swept estimates of total (>90mm) male survey biomass (t) for the standard design-based estimate and for estimates derived from the VAST spatio-temporal model of Thorson and Barnett (2017). Error bars are plus and minus 2 standard deviations.

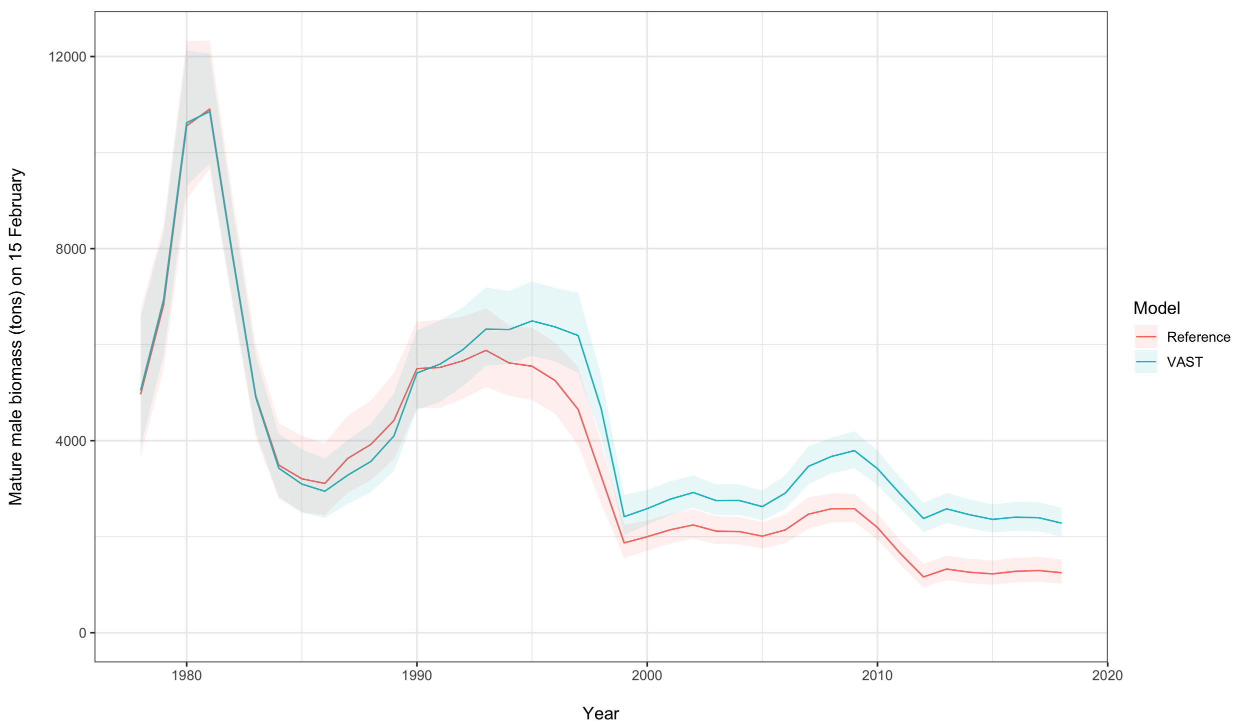

Figure 12: Sensitivity of new data in 2017 on estimated mature male biomass (MMB); 1978-2017 comparing the reference model with that fitted to the VAST BTS estimates.

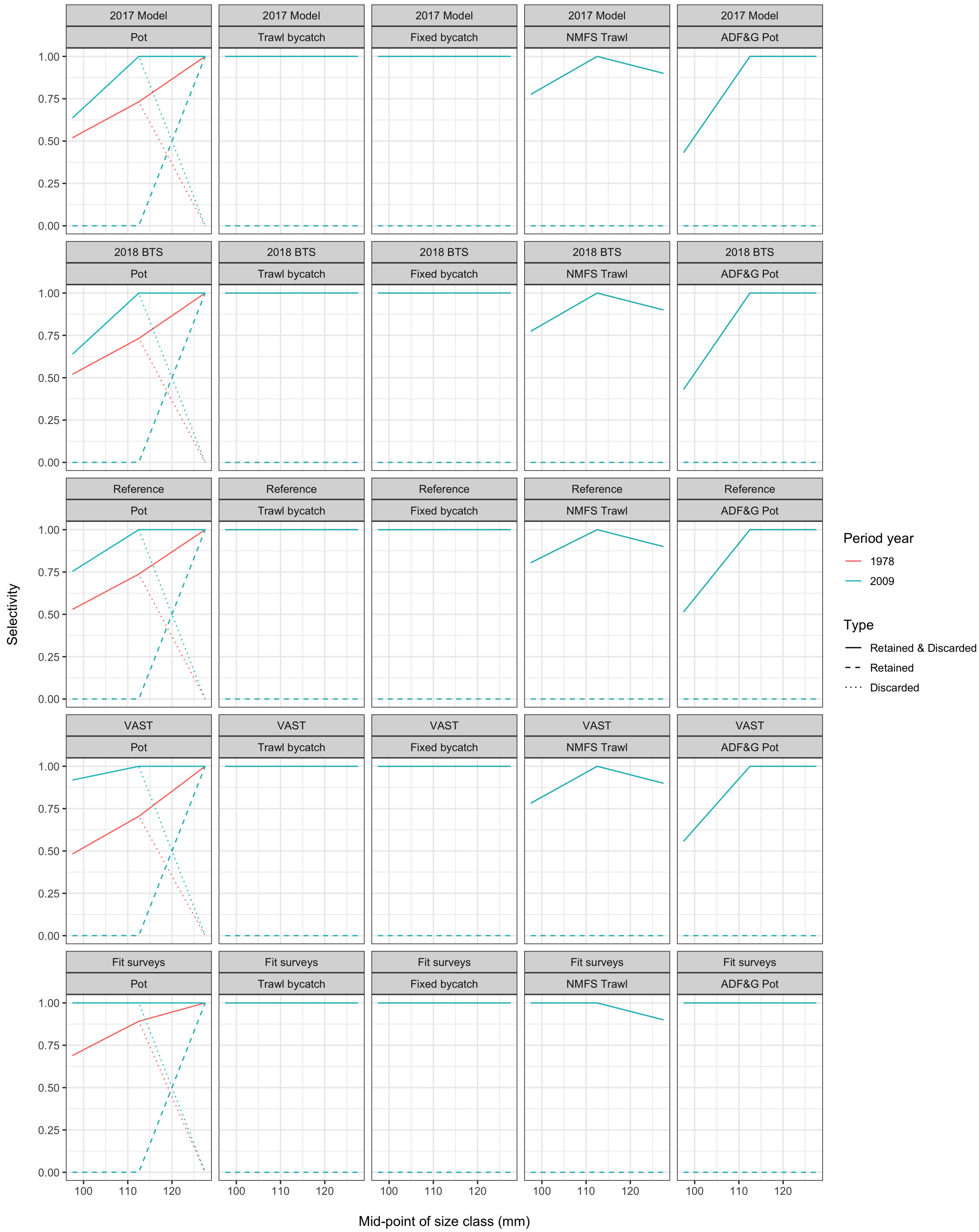

Figure 13: Comparisons of the estimated stage-1 and stage-2 selectivities for the different model scenarios (the stage-3 selectivities are all fixed at 1). Estimated selectivities are shown for the directed pot fishery, the trawl bycatch fishery, the fixed bycatch fishery, the NMFS trawl survey, and the ADF&G pot survey. Two selectivity periods are estimated in the directed pot fishery, from 1978-2008 and 2009-2017.

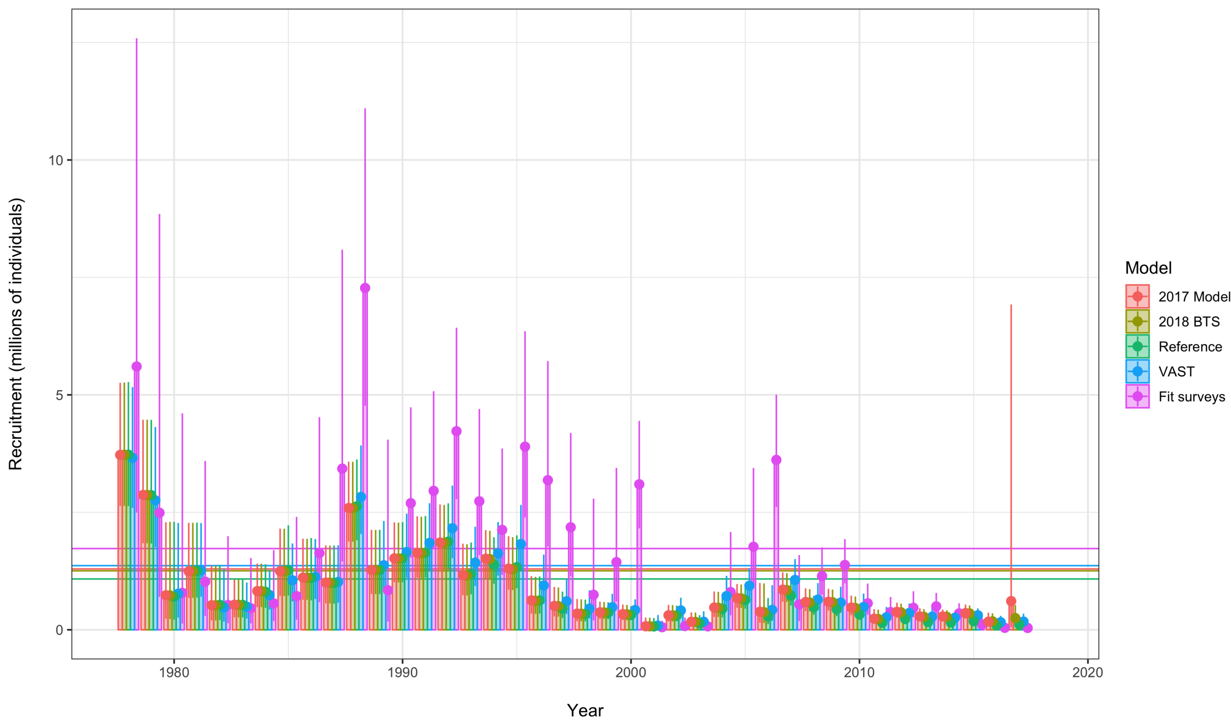

Figure 14: Estimated recruitment 1979-2017 comparing model alternatives. The solid horizontal lines in the background represent the estimate of the average recruitment parameter ($\bar{R}$) in each model scenario.

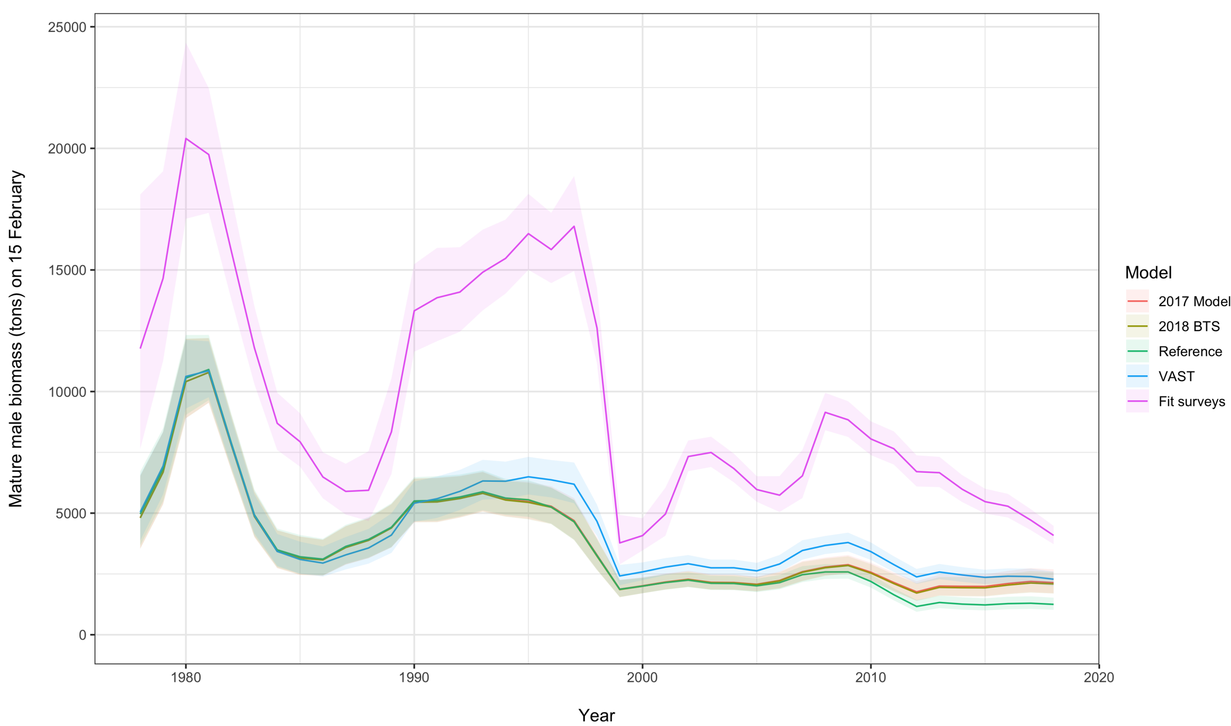

Figure 15: Comparisons of estimated mature male biomass (MMB) time series on 15 February during 1978-2017 for each of the model scenarios.

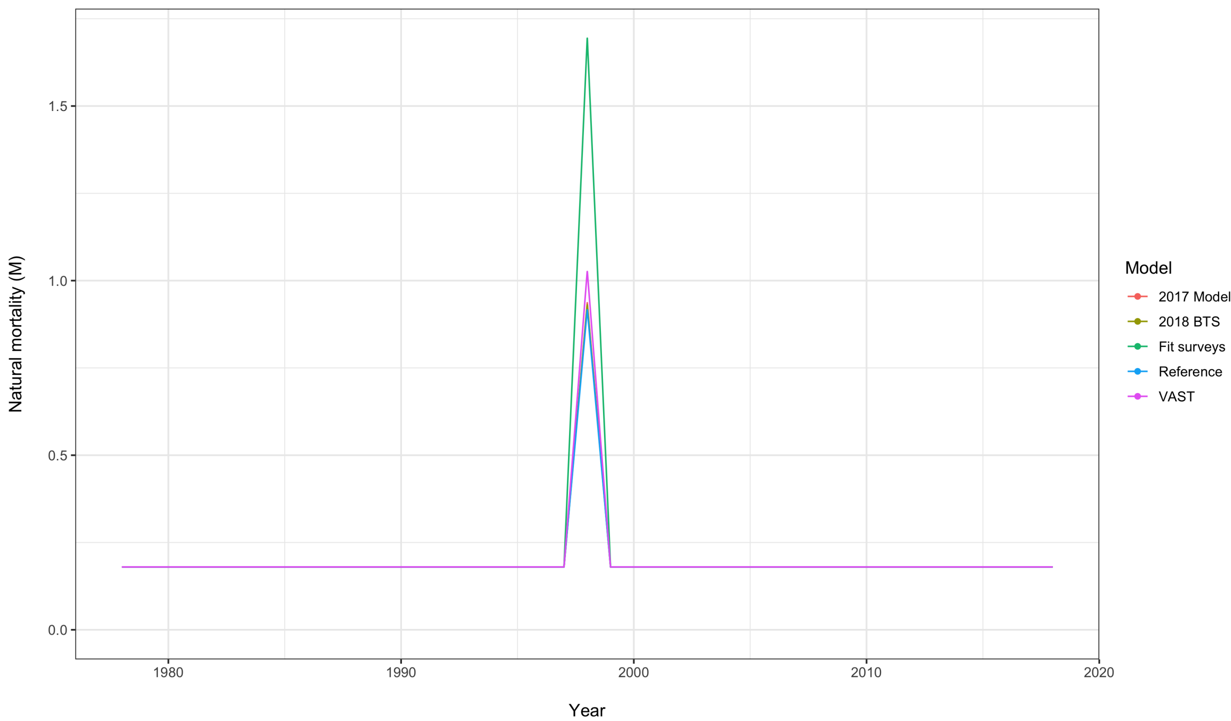

Figure 16: Time-varying natural mortality (M_t). Estimated pulse period occurs in 1998/99 (i.e. M_{1998}).

```
## Error in data.frame(Model = names(M)[i], as.data.frame(A$dSurveyData)): arguments imply differing nu
```

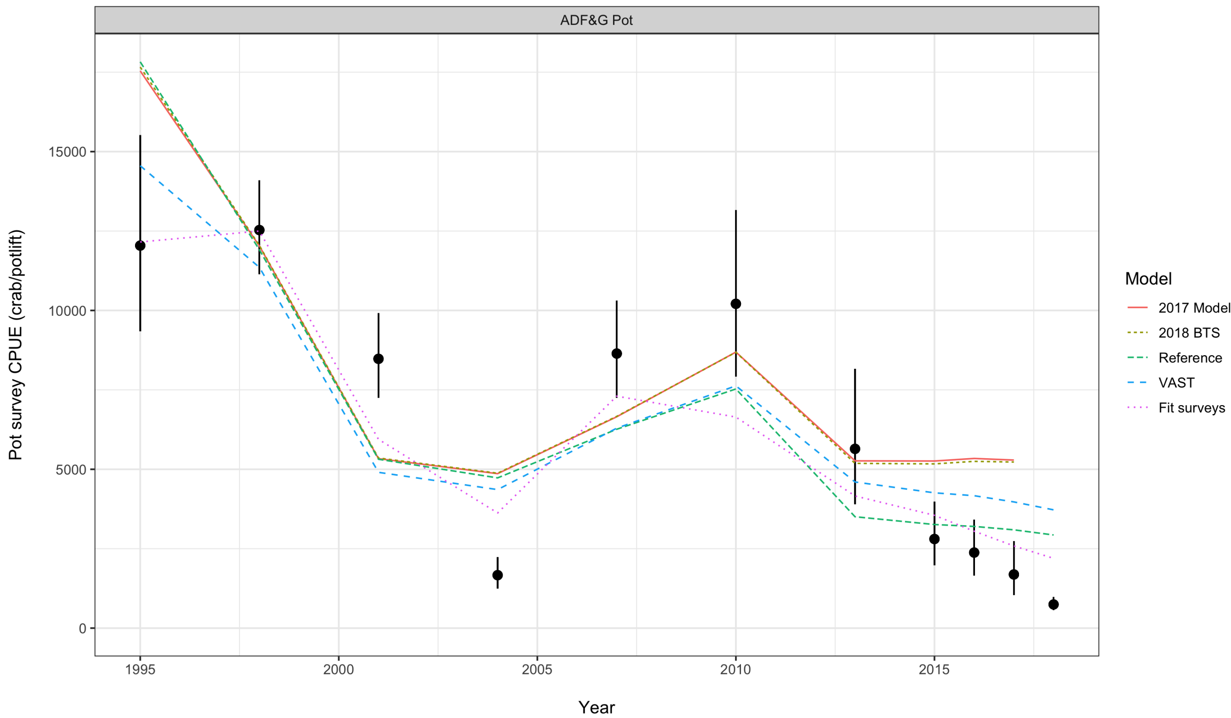

Figure 17: Comparisons of total (90+ mm CL) male pot survey CPUEs and model predictions for the model scenarios. The error bars are plus and minus 2 standard deviations.

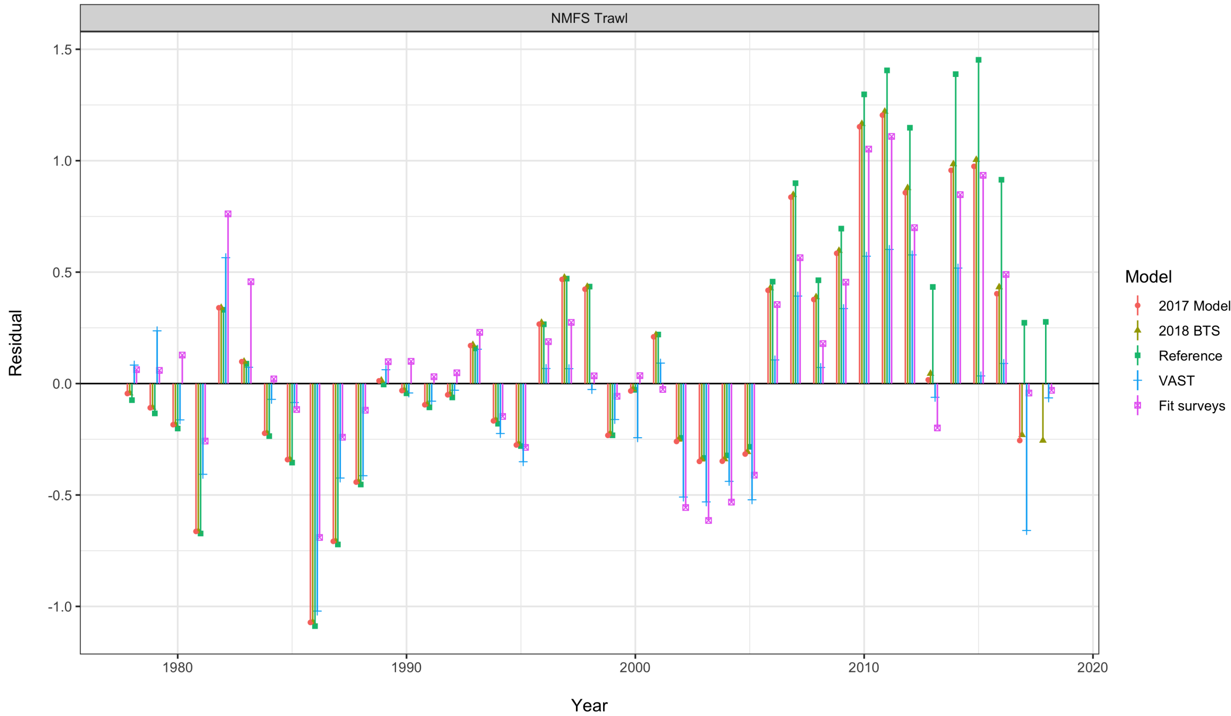

Figure 18: Standardized residuals for area-swept estimates of total male survey biomass for the model scenarios.

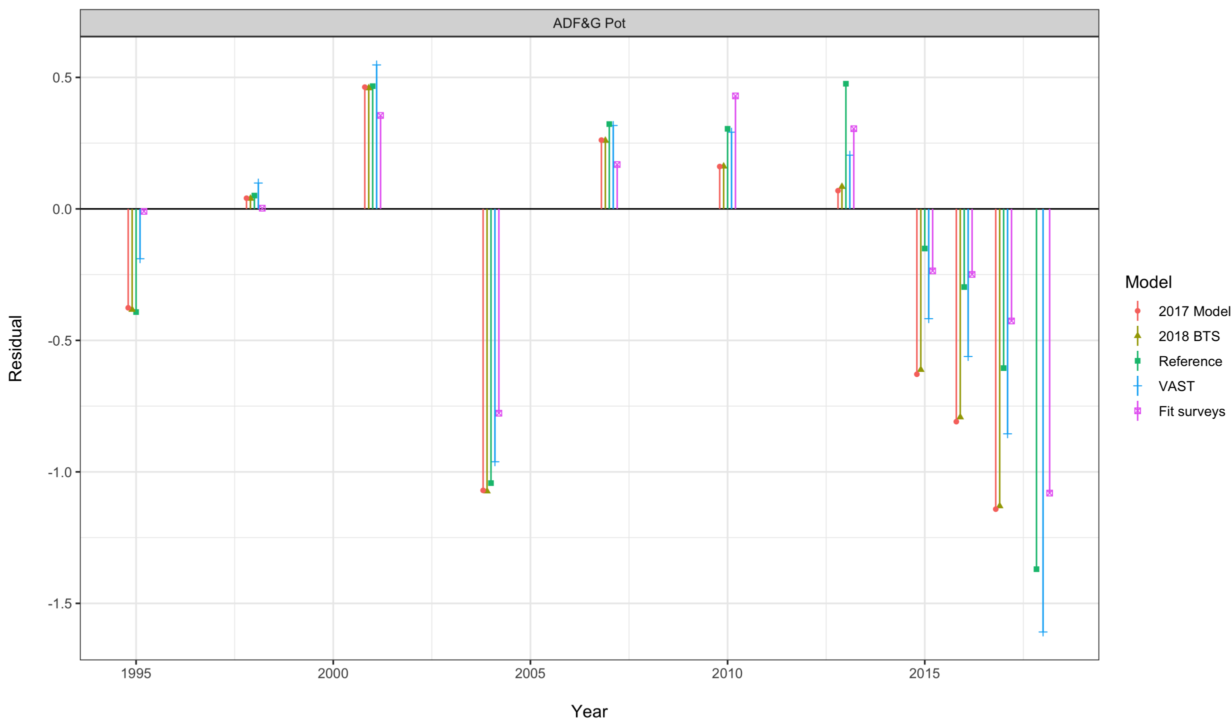

Figure 19: Standardized residuals for total male pot survey CPUEs for each of the Gmacs model scenarios.

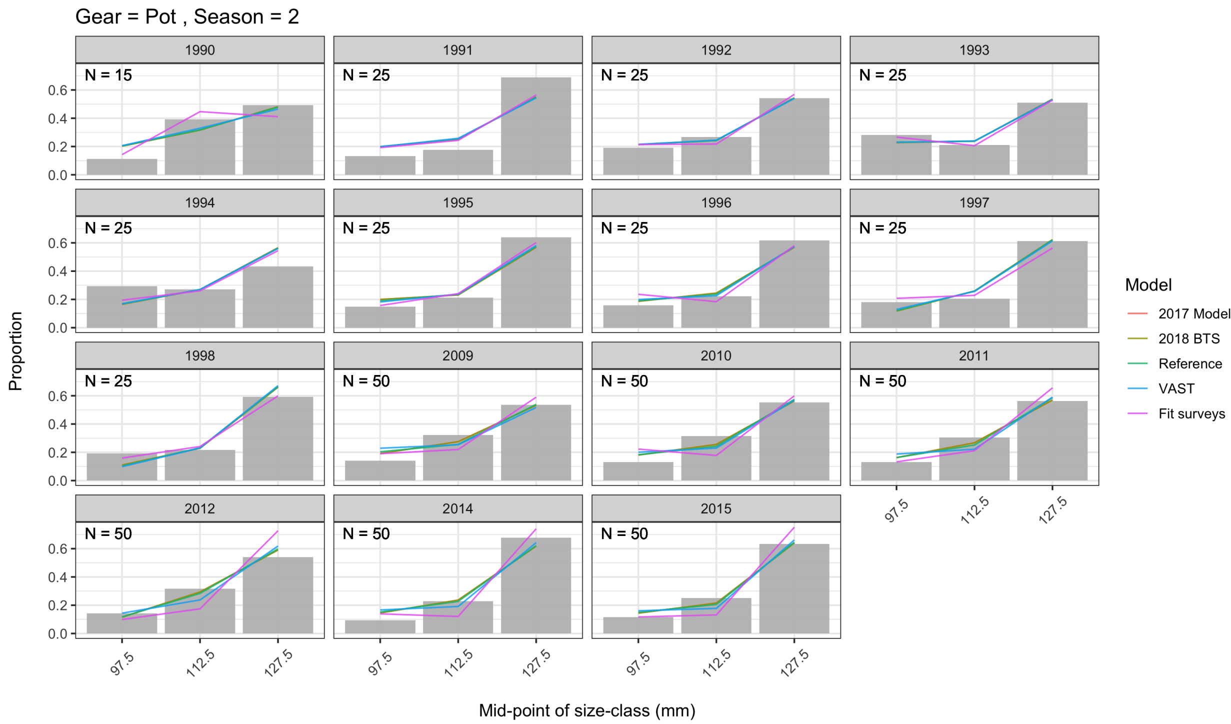

Figure 20: Observed and model estimated size-frequencies of SMBKC by year retained in the directed pot fishery for the model scenarios.

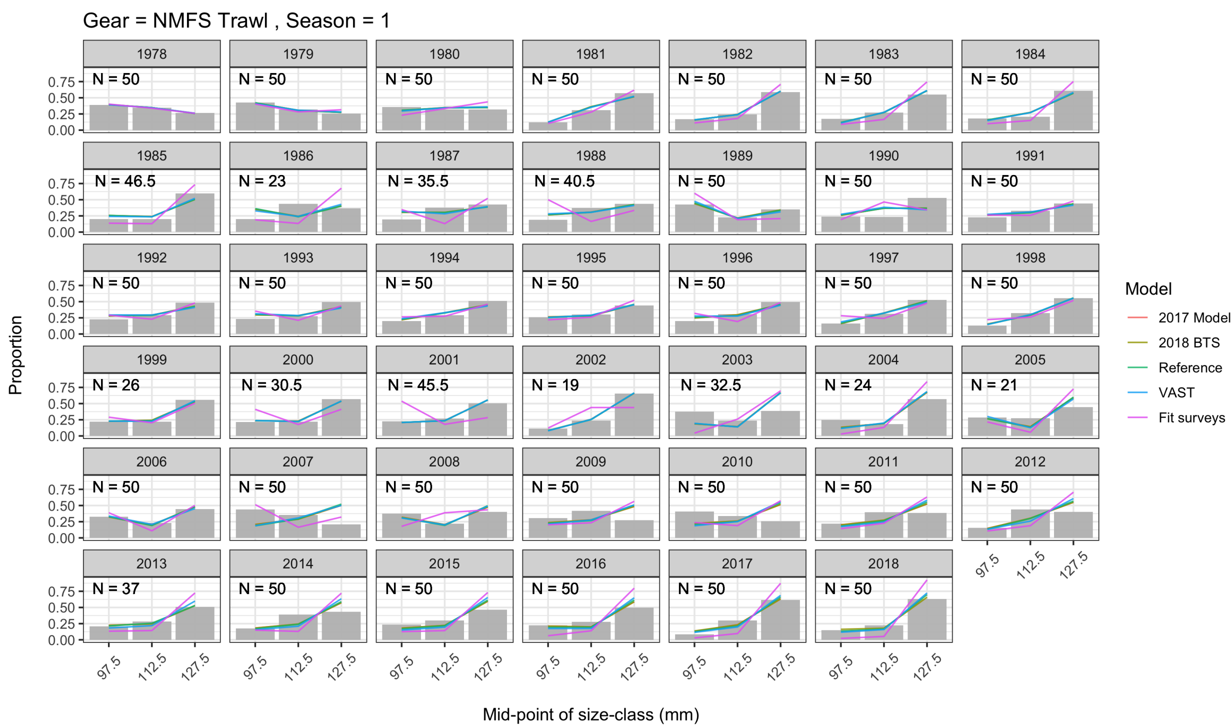

Figure 21: Observed and model estimated size-frequencies of discarded male SMBKC by year in the NMFS trawl survey for the model scenarios.

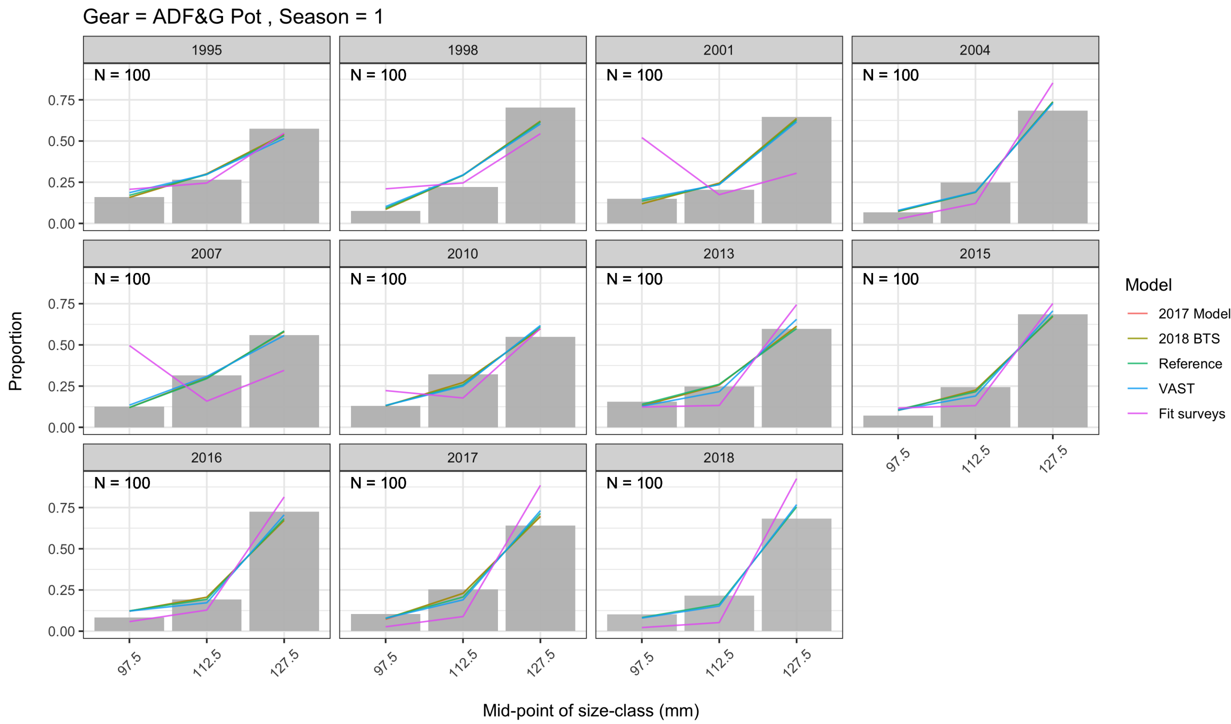

Figure 22: Observed and model estimated size-frequencies of discarded SMBKC by year in the ADF&G pot survey for the model scenarios.

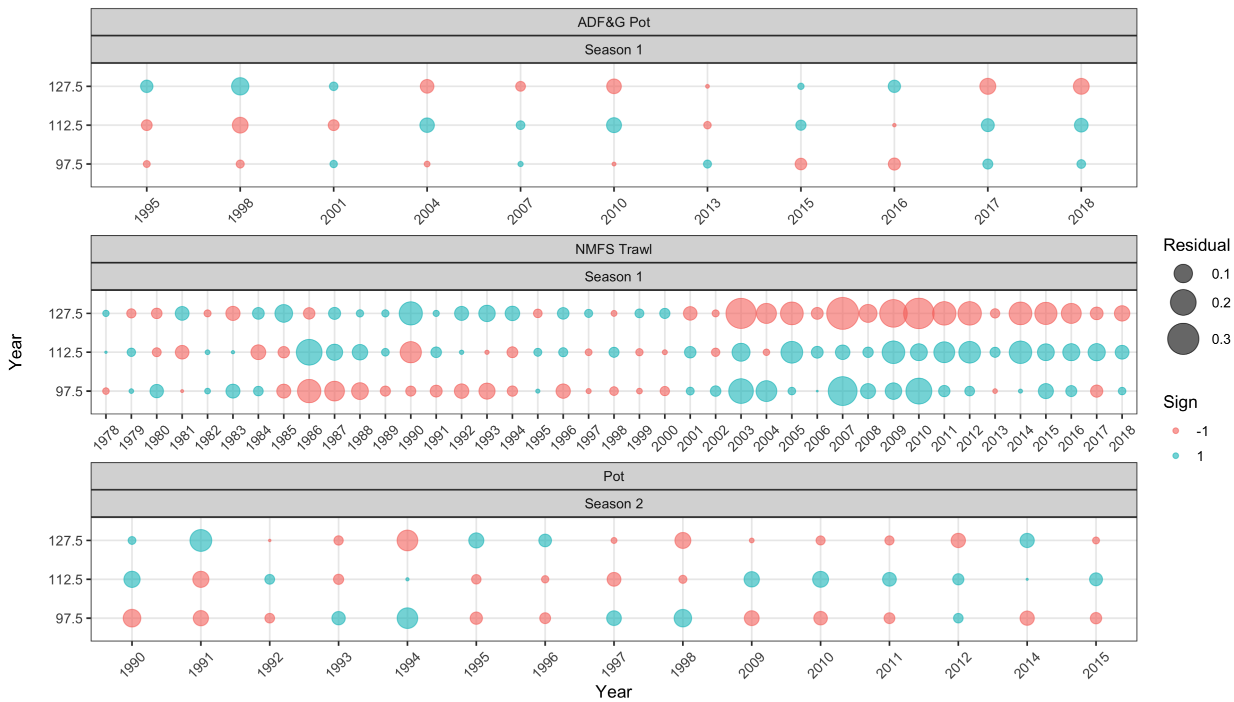

Figure 23: Bubble plots of residuals by stage and year for the directed pot fishery size composition data for SMBKC in the reference model.

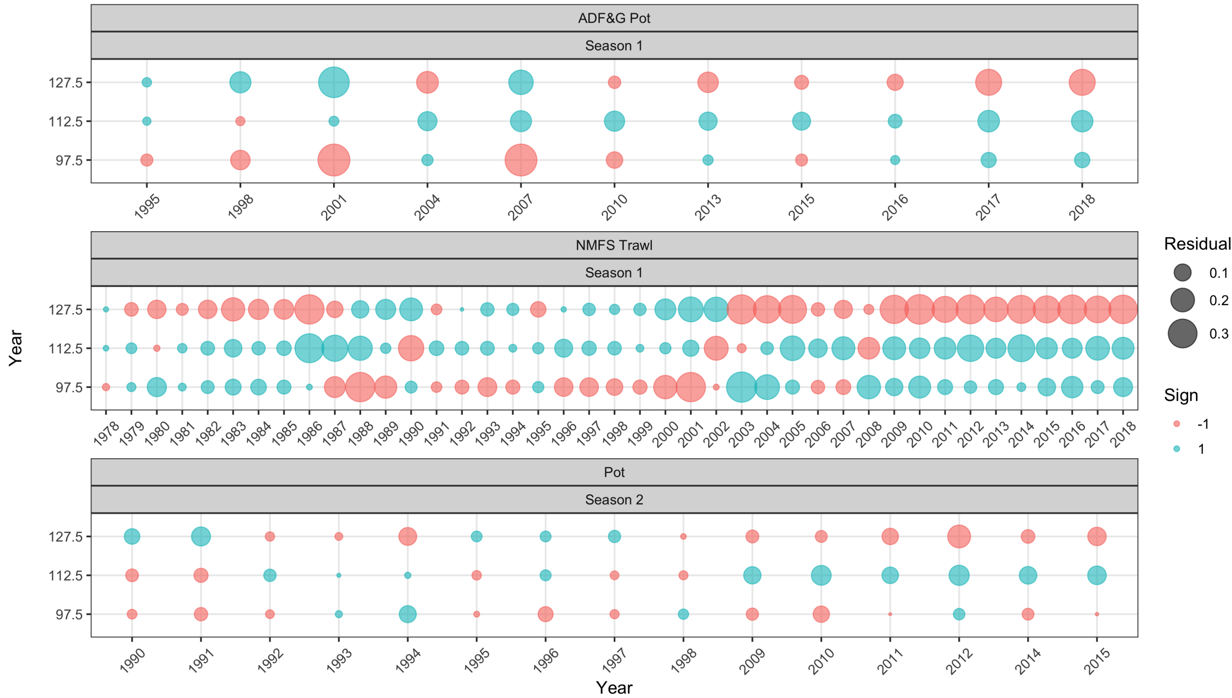

Figure 24: Bubble plots of residuals by stage and year for the ADF&G pot survey size composition data for SMBKC in the **fit surveys** model.

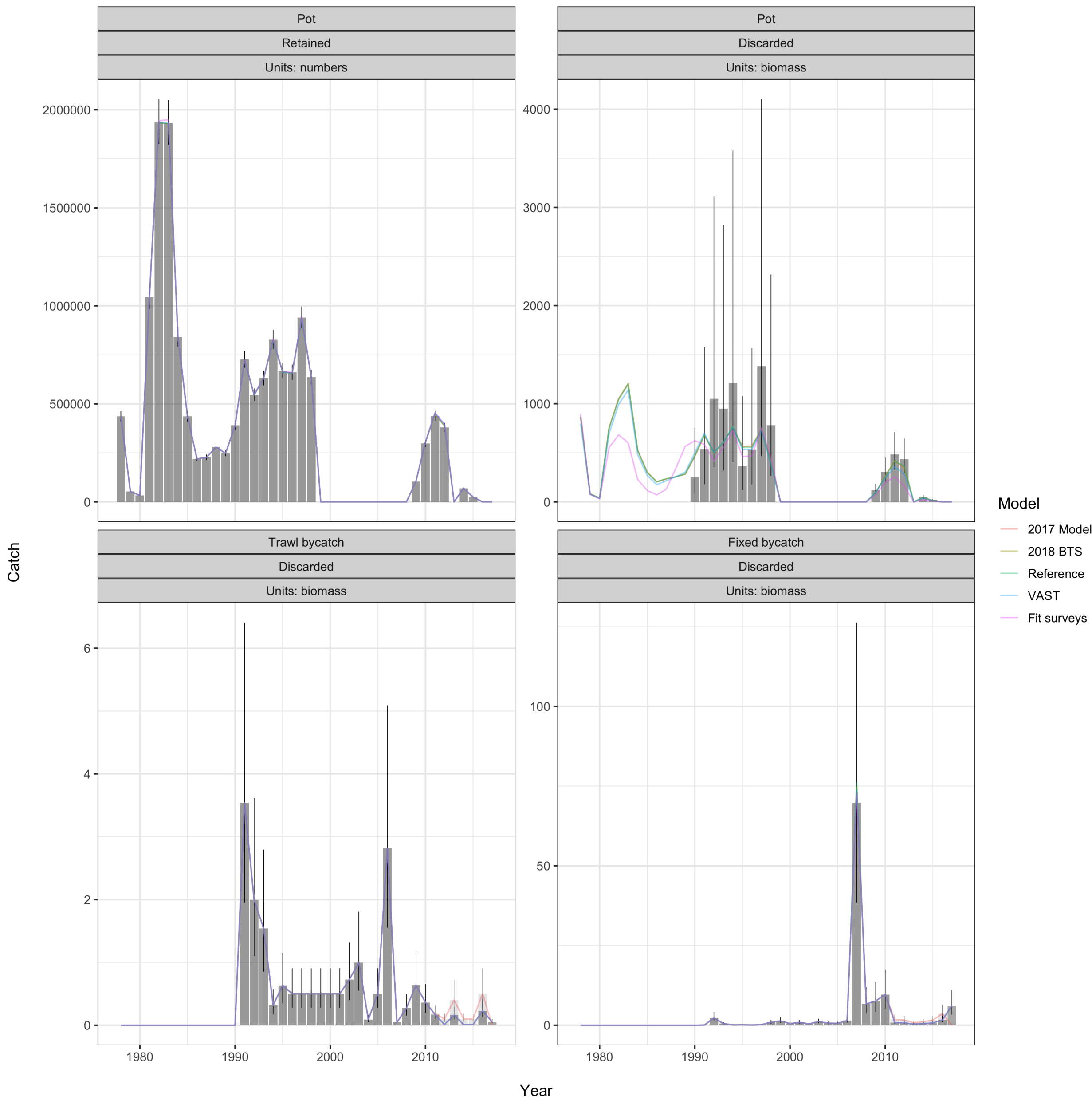

Figure 25: Comparison of observed and model predicted retained catch and bycatches in each of the Gmacs models. Note that difference in units between each of the panels, some panels are expressed in numbers of crab, some as biomass (tons).

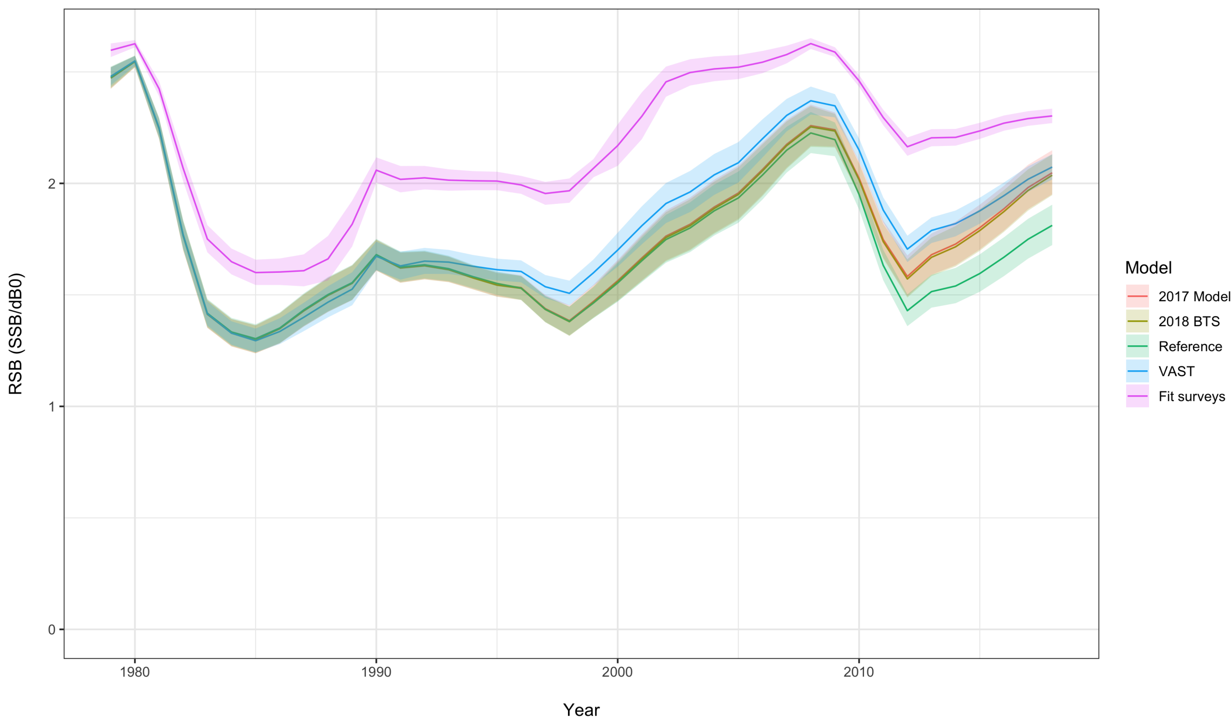

Figure 26: Comparisons of mature male biomass relative to the dynamic B_0 value, (15 February, 1978-2017) for each of the model scenarios.

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 5.5in carapace width (CW), whereas 105 mm CL is the management proxy for mature-male size (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 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 7)
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 22. 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

$$\boldsymbol{G} = \begin{bmatrix} 1-\pi_{12}-\pi_{13} & \pi_{12} & \pi_{13} \\ 0 & 1-\pi_{23} & \pi_{23} \\ 0 & 0 & 1 \end{bmatrix}, \tag{6}$$

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

$$\boldsymbol{S}_{t,y} = \begin{bmatrix} 1-e^{-Z_{1,t,y}} & 0 & 0 \\ 0 & 1-e^{-Z_{2,t,y}} & 0 \\ 0 & 0 & 1-e^{-Z_{3,t,y}} \end{bmatrix}. \tag{11}$$

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 23.

4. Model Parameters

Table 24 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 25 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 22: 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 23: 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)
Groundfish trawl bycatch biomass	1992/93 - 2016/17	NMFS groundfish observer program
Groundfish fixed-gear bycatch biomass	1992/93 - 2016/17	NMFS groundfish observer program
NMFS trawl-survey biomass index (area-swept estimate) and CV	1978-2017	NMFS EBS trawl survey
ADF&G pot-survey abundance index (CPUE) and CV	1995-2017	ADF&G SMBKC pot survey
NMFS trawl-survey stage proportions and total number of measured crab	1978-2017	NMFS EBS trawl survey
ADF&G pot-survey stage proportions and total number of measured crab	1995-2017	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)

Table 24: 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 Table 10	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 25: 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	4.0	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