

# Saint Matthew Island Blue King Crab Stock Assessment 2018

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## 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<sup>1</sup>. 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 45% 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 index... [placeholder].
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  $B_{MSY}$  proxy is obtained by averaging estimated MMB over a specific reference time period, and current

<sup>1</sup>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 <sup>A</sup>	3.01 <sup>A</sup>	0.00	0.00	0.00	0.56	0.45
2014/15	1.86 <sup>B</sup>	2.48 <sup>B</sup>	0.30	0.14	0.15	0.43	0.34
2015/16	1.84 <sup>C</sup>	2.11 <sup>C</sup>	0.19	0.05	0.05	0.28	0.22
2016/17	1.93 <sup>D</sup>	2.12 <sup>D</sup>	0.00	0.00	0.05	0.28	0.22
2017/18	1.93 <sup>E</sup>	2.12 <sup>E</sup>	0.00	0.00	0.05	0.28	0.22
2018/19		2.05 <sup>E</sup>			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 <sup>A</sup>	6.64 <sup>A</sup>	0.000	0.000	0.0006	1.24	0.99
2014/15	4.1 <sup>B</sup>	5.47 <sup>B</sup>	0.655	0.309	0.329	0.94	0.75
2015/16	4.1 <sup>C</sup>	4.65 <sup>C</sup>	0.419	0.110	0.110	0.62	0.49
2016/17	4.3 <sup>D</sup>	4.68 <sup>D</sup>	0.410	0.000	0.000	0.62	0.49
2017/18	4.3 <sup>E</sup>	4.68 <sup>E</sup>	0.41	0.000	0.000	0.62	0.49
2018/19		4.51 <sup>E</sup>			0	0	

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 ( $MMB_{mating}$ )	$B/B_{MSY}$	$F_{OFL}$	$\gamma$	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	2.05	0.53	0.09	1	1978-2017	0.18
2019/20	4b	3.86	2.05	0.53	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 abundance, and the 2018 ADF&G pot survey CPUE. Both of these surveys have associated size composition 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 Alaskans 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 CPT had the following requests:*

1. *specify priors (e.g., gamma) using mean and variance/standard deviation for all parameters to ease specifying priors*

This was completed.

2. *include an option to calculate dynamic  $B_{MSY}$*

This was completed.

3. *add the ability to <U+FFFD><U+FFFD><U+FFFD>jitter<U+FFFD><U+FFFD><U+FFFD> initial parameter values*

The framework for conducting this research has been added but has yet to be fully tested.

4. *add the ability to conduct retrospective analyses*

Incomplete.

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

This was completed.

6. 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 introduced an alternative time-series estimated from the NMFS trawl survey using the VAST spatio-temporal 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 ( $58^{\circ}\text{N}$ ) and south of Cape Romanzof ( $61^{\circ}\text{N}$ ).

### 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<sup>2</sup>. 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 camtschaticus*, 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. Spermatophore diameter also increased with increasing CL with an asymptote at ~ 100 mm CL. They noted, however, that although spermatophore 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

<sup>2</sup>NOAA grant Bering Sea Crab Research II, NA16FN2621, 1997.

(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).

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<sup>3</sup>. 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).

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<sup>3</sup>D. Pengilly, ADF&G, pers. comm.

## 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 abundance, and the 2018 ADF&G pot survey CPUE. Both of these surveys have associated size composition 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.

### 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  $\lambda^{\text{NMFS}} = 1.5$  and the ADF&G pot survey is up-weighted by  $\lambda^{\text{ADFG}} = 2$ .
6. **Francis weights:** is similar to the reference model except that it also uses the Francis iterative re-weighting method (Francis 2011), to re-weight the size-composition data relative to the abundance indices. The trawl survey and pot survey weights were unchanged. In this scenario the multinomial distribution was used instead as the theory underpinning the Francis weighting method is based on this distribution.

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 17. 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 acceptable.

### d. Parameter estimates

Model parameter estimates for each of the Gmacs scenarios are summarized in Tables 12, 13, 15, and 16. These parameter estimates are compared in Table 16. Negative log-likelihood values and management measures for each of the model configurations are compared in Tables 4 through 18.

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 16).

### 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 17). All of the models fit the pot survey

CPUE poorly (Figure 18. For both surveys the standardized residuals tend to have similar patterns with some improvement (generally) for the VAST model (Figures 19 and 20).

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 21, 22, and 23) for all scenarios. Representative residual plots of the composition data fits are generally poor (Figures 24 and 25). 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 26 ).

The contrast between the reference model and the “Francis weighted” model show minor differences (Figures 17 and 18). Unsurprisingly, the **fit surveys** model configuration fits the NMFS survey biomass and ADF&G pot survey CPUE data better but still has a similar residual pattern (note 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, 14, and 15 (and compiled together in Table 16. 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  $\alpha$  and  $\beta$ ,  $F_{OFL}$  is determined by the control rule

$$F_{OFL} = \begin{cases} F_{MSY}, & \text{when } B/B_{MSY} > 1 \\ F_{MSY} \frac{(B/B_{MSY}-\alpha)}{(1-\alpha)}, & \text{when } \beta < B/B_{MSY} \leq 1 \\ F_{OFL} < F_{MSY} \text{ with directed fishery } F = 0 \text{ when } B/B_{MSY} \leq \beta \end{cases} \quad (1)$$

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  $M = 0.18 \text{ yr}^{-1}$  in setting the  $F_{MSY}$  proxy value  $\gamma M$ . The parameters  $\alpha$  and  $\beta$  are assigned their default values  $\alpha = 0.10$  and  $\beta = 0.25$ . The  $F_{OFL}$ , OFL, ABC, and MMB in 2017 for all scenarios are summarized in Table 4. ABC is 80% of the OFL.

```
## Error in names(df) <- c("Component", "Reference", "VAST", "Fit surveys", : 'names' attribute [5] must
```

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

rownames.df.	v	v.1	v.2
$MMB_{2018}$	2079.874	2046.818	2939.645
$B_{MSY}$	3886.804	3862.834	4334.390
$F_{OFL}$	0.075	0.075	0.101
$OFL_{2018}$	0.000	0.000	0.000
$ABC_{2018}$	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 68%. The other aspects of depletion (ignoring stock-recruit relationship) may reflect variable survival rates due to environmental conditions and range shifts.

## J. Acknowledgements

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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			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: 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 omitted.

Year	Dates	GHL/TAC	Harvest					
			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				

```
## Error in data.frame(Model, Parameter, Estimate): arguments imply differing number of rows: 57, 76
## Error: `var` must evaluate to a single number or a column name, not a character vector
## Error in names(df) <- c("Component", "Reference", "VAST", "Fit survey", : 'names' attribute [5] must
## Error in names(df) <- c("Component", "Ref", "VAST", "FitSurvey", "Francis"): 'names' attribute [5] m
```

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.

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

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	Stage-2	Stage-3	Total CPUE	CV	Number of crabs
	(90-104 mm)	(105-119 mm)	(120+ mm)			
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

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.

Year	Number measured			Input sample sizes		
	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

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 ( $\delta_{1998}^M$ )	1.652	0.127
$\log(\bar{R})$	14.064	0.060
$\log(n_1^0)$	14.922	0.171
$\log(n_2^0)$	14.551	0.201
$\log(n_3^0)$	14.360	0.206
$q_{pot}$	3.644	0.280
$\log(\bar{F}^{df})$	-1.923	0.053
$\log(\bar{F}^{tb})$	-9.019	0.082
$\log(\bar{F}^{fb})$	-8.217	0.082
log Stage-1 directed pot selectivity 1978-2008	-0.654	0.174
log Stage-2 directed pot selectivity 1978-2008	-0.315	0.126
log Stage-1 directed pot selectivity 2009-2017	-0.463	0.154
log Stage-2 directed pot selectivity 2009-2017	-0.000	0.000
log Stage-1 NMFS trawl selectivity	-0.243	0.066
log Stage-2 NMFS trawl selectivity	-0.000	0.000
log Stage-1 ADF&G pot selectivity	-0.852	0.127
log Stage-2 ADF&G pot selectivity	-0.026	0.078
$F_{OFL}$	0.079	0.010
OFL	123.610	28.638

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 ( $\delta_{1998}^M$ )	1.711	0.106
$\log(\bar{R})$	14.193	0.049
$\log(n_1^0)$	14.942	0.167
$\log(n_2^0)$	14.578	0.192
$\log(n_3^0)$	14.401	0.191
$q_{pot}$	2.876	0.157
$\log(\bar{F}^{df})$	-2.037	0.039
$\log(\bar{F}^{tb})$	-9.625	0.068
$\log(\bar{F}^{fb})$	-8.540	0.068
log Stage-1 directed pot selectivity 1978-2008	-0.718	0.171
log Stage-2 directed pot selectivity 1978-2008	-0.344	0.123
log Stage-1 directed pot selectivity 2009-2017	-0.305	0.146
log Stage-2 directed pot selectivity 2009-2017	-0.000	0.000
log Stage-1 NMFS trawl selectivity	-0.241	0.061
log Stage-2 NMFS trawl selectivity	-0.000	0.000
log Stage-1 ADF&G pot selectivity	-0.810	0.127
log Stage-2 ADF&G pot selectivity	-0.000	0.000
$F_{OFL}$	0.101	0.008
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 ( $\delta_{1998}^M$ )	2.160	0.107
$\log(\bar{R})$	14.583	0.065
$\log(n_1^0)$	15.456	0.417
$\log(n_2^0)$	15.288	0.438
$\log(n_3^0)$	15.120	0.418
$q_{pot}$	1.010	0.052
$\log(\bar{F}^{df})$	-2.901	0.045
$\log(\bar{F}^{tb})$	-10.043	0.071
$\log(\bar{F}^{fb})$	-9.243	0.071
log Stage-1 directed pot selectivity 1978-2008	-0.343	0.141
log Stage-2 directed pot selectivity 1978-2008	-0.082	0.119
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
$F_{OFL}$	0.083	0.006
OFL	367.950	44.694

Table 15: Model parameter estimates, selected derived quantities, and their standard deviations (SD) for the "Francis weights" model.

Parameter	Estimate	SD
Natural mortality deviation in 1998/99 ( $\delta_{1998}^M$ )	1.634	0.136
$\log(\bar{R})$	14.033	0.064
$\log(n_1^0)$	14.885	0.285
$\log(n_2^0)$	14.561	0.318
$\log(n_3^0)$	14.361	0.317
$q_{pot}$	3.526	0.248
$\log(\bar{F}^{df})$	-1.884	0.060
$\log(\bar{F}^{tb})$	-9.044	0.081
$\log(\bar{F}^{fb})$	-8.243	0.081
log Stage-1 directed pot selectivity 1978-2008	-0.514	0.157
log Stage-2 directed pot selectivity 1978-2008	-0.319	0.128
log Stage-1 directed pot selectivity 2009-2017	-0.420	0.141
log Stage-2 directed pot selectivity 2009-2017	-0.000	0.000
log Stage-1 NMFS trawl selectivity	-0.181	0.083
log Stage-2 NMFS trawl selectivity	-0.000	0.000
log Stage-1 ADF&G pot selectivity	-0.799	0.092
log Stage-2 ADF&G pot selectivity	-0.000	0.000
$F_{OFL}$	0.076	0.010
OFL	117.650	26.963

Table 16: Comparisons of parameter estimates for the four model scenarios.

Parameter	Estimate	SD
Natural mortality deviation in 1998/99 ( $\delta_{1998}^M$ )	1.634	0.136
$\log(\bar{R})$	14.033	0.064
$\log(n_1^0)$	14.885	0.285
$\log(n_2^0)$	14.561	0.318
$\log(n_3^0)$	14.361	0.317
$q_{pot}$	3.526	0.248
$\log(\bar{F}^{df})$	-1.884	0.060
$\log(\bar{F}^{tb})$	-9.044	0.081
$\log(\bar{F}^{fb})$	-8.243	0.081
log Stage-1 directed pot selectivity 1978-2008	-0.514	0.157
log Stage-2 directed pot selectivity 1978-2008	-0.319	0.128
log Stage-1 directed pot selectivity 2009-2017	-0.420	0.141
log Stage-2 directed pot selectivity 2009-2017	-0.000	0.000
log Stage-1 NMFS trawl selectivity	-0.181	0.083
log Stage-2 NMFS trawl selectivity	-0.000	0.000
log Stage-1 ADF&G pot selectivity	-0.799	0.092
log Stage-2 ADF&G pot selectivity	-0.000	0.000
$F_{OFL}$	0.076	0.010
OFL	117.650	26.963

Table 17: 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.

rownames.df.	v	v.1	v.2
NMFS trawl survey weight	1.00	1.00	1.00
ADF&G pot survey weight	1.00	1.00	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
Francis weight for directed pot LF	0.00	0.00	0.00
Francis weight for NMFS trawl survey LF	0.00	0.00	0.00
Francis weight for ADF&G pot survey LF	0.00	0.00	0.00
SDNR NMFS trawl survey	1.45	1.45	1.88
SDNR ADF&G pot survey	3.78	3.76	3.88
SDNR directed pot LF	0.71	0.71	0.79
SDNR NMFS trawl survey LF	1.23	1.22	1.28
SDNR ADF&G pot survey LF	0.80	0.80	0.84
MAR NMFS trawl survey	1.18	1.18	1.15
MAR ADF&G pot survey	2.96	2.94	2.56
MAR directed pot LF	0.59	0.59	0.64
MAR NMFS trawl survey LF	0.52	0.55	0.64
MAR ADF&G pot survey LF	0.49	0.49	0.60

Table 18: 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).

rownames.df	v	v.1	v.2
Pot Retained Catch	-71.53	-71.51	-71.08
Pot Discarded Catch	8.98	8.86	12.65
Trawl bycatch Discarded Catch	-7.16	-7.43	-7.43
Fixed bycatch Discarded Catch	-7.13	-7.41	-7.42
NMFS Trawl Survey	-3.93	-4.13	1.79
ADF&G Pot Survey CPUE	57.07	56.32	62.59
Directed Pot LF	-11.31	-11.29	-8.84
NMFS Trawl LF	18.24	17.60	27.26
ADF&G Pot LF	-7.40	-7.31	-6.47
Recruitment deviations	54.06	54.22	52.89
F penalty	14.49	14.49	14.49
M penalty	6.47	6.47	6.47
Prior	12.66	12.66	12.66
Total	63.51	61.54	89.56
Total estimated parameters	139.00	141.00	141.00

Table 19: Population abundances ( $n$ ) 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	3024922	2086739	1724023	4852
1979	4240047	2408619	2414981	6724
1980	3596322	3205345	3592523	10446
1981	1349015	3103465	4932916	10813
1982	1475777	1793332	4937671	7792
1983	781015	1431619	3544542	4882
1984	666737	917276	2131828	3448
1985	933666	682227	1599713	3167
1986	1410067	756060	1401084	3088
1987	1349408	1051072	1500842	3599
1988	1231930	1114268	1720553	3889
1989	2800176	1068481	1880245	4391
1990	1751533	1943967	2168051	5444
1991	1814447	1638179	2629042	5458
1992	1939804	1572075	2580521	5597
1993	2184234	1621425	2671608	5805
1994	1553368	1776819	2722835	5530
1995	1770996	1470209	2619079	5455
1996	1600406	1492288	2536540	5262
1997	912971	1402736	2466491	4667
1998	660072	982651	2061864	3267
1999	394429	327570	798264	1861
2000	442238	332276	869215	1999
2001	405730	361051	935594	2156
2002	144739	349822	1001981	2267
2003	341000	197936	1026825	2142
2004	227176	259039	989522	2142
2005	505714	214734	978691	2071
2006	763530	358195	973816	2222
2007	521969	551618	1065875	2583
2008	935989	473155	1203366	2781
2009	760272	687507	1331847	2875
2010	729825	658569	1439361	2570
2011	600891	631519	1338696	2152
2012	345260	550062	1105739	1768
2013	442425	377974	898268	2009
2014	367919	376270	982886	1999
2015	352929	333411	985384	1999
2016	379413	310687	1003124	2122
2017	186467	318040	1029874	2180
2018	634481	211182	1038420	2080

Table 20: Population abundances ( $n$ ) 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	3024941	2086744	1724025	4852
1979	4239965	2408632	2414987	6724
1980	3596344	3205302	3592526	10446
1981	1349025	3103464	4932899	10813
1982	1475780	1793338	4937657	7792
1983	781016	1431623	3544534	4882
1984	666738	917278	2131823	3448
1985	933667	682228	1599710	3167
1986	1410067	756061	1401082	3088
1987	1349409	1051073	1500841	3599
1988	1231932	1114269	1720553	3889
1989	2800176	1068482	1880245	4391
1990	1751534	1943967	2168052	5444
1991	1814448	1638180	2629043	5458
1992	1939805	1572076	2580522	5597
1993	2184235	1621426	2671609	5805
1994	1553370	1776820	2722837	5530
1995	1770998	1470210	2619081	5455
1996	1600408	1492289	2536543	5262
1997	912973	1402738	2466495	4667
1998	660074	982653	2061868	3267
1999	394430	327571	798265	1861
2000	442239	332277	869216	1999
2001	405731	361052	935595	2156
2002	144740	349823	1001982	2267
2003	341000	197937	1026826	2142
2004	227177	259039	989524	2142
2005	505715	214734	978693	2071
2006	763531	358196	973818	2222
2007	521970	551619	1065877	2583
2008	935990	473156	1203369	2781
2009	760273	687508	1331849	2875
2010	729826	658570	1439363	2570
2011	600893	631520	1338699	2152
2012	345261	550063	1105742	1768
2013	442426	377975	898271	2009
2014	367920	376271	982889	1999
2015	352930	333413	985388	1999
2016	379414	310688	1003127	2122
2017	186468	318041	1029878	2180

Table 21: Population abundances ( $n$ ) 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 Francis weights model.

Year	$n_1$	$n_2$	$n_3$	MMB
1978	2914158	2107534	1724626	4878
1979	4110549	2352595	2415404	6660
1980	3272000	3113252	3552247	10263
1981	1255767	2888789	4821836	10358
1982	1252747	1669317	4727728	7247
1983	752019	1263907	3284909	4156
1984	589896	845294	1824879	2791
1985	797309	614749	1298973	2469
1986	1195843	656276	1102745	2411
1987	1416960	896378	1180842	2818
1988	1481565	1101427	1381697	3256
1989	3404588	1206002	1614487	4029
1990	1438930	2332738	2073038	5713
1991	1815552	1589318	2715817	5567
1992	2022514	1556550	2627746	5667
1993	2472885	1663260	2710930	5929
1994	1478514	1954580	2804465	5885
1995	1775538	1486535	2770349	5768
1996	1693651	1500281	2671388	5530
1997	769965	1458341	2592267	4987
1998	664628	919851	2182322	3417
1999	413378	324515	845070	1945
2000	389302	342029	908581	2084
2001	464065	334225	968329	2187
2002	151330	374068	1021377	2331
2003	403096	209704	1055881	2209
2004	204945	298185	1025667	2254
2005	428497	215067	1026496	2161
2006	847860	314466	1006528	2234
2007	564417	585018	1079224	2646
2008	889231	508147	1235657	2881
2009	860820	672564	1371981	2929
2010	707726	710694	1475014	2687
2011	538185	636243	1393311	2249
2012	344859	516030	1147911	1801
2013	471797	366494	915902	2028
2014	369039	389149	994635	2033
2015	286665	338310	1001843	2033
2016	297822	274688	1012976	2101
2017	175628	259829	1012138	2085

Table 22: Population abundances ( $n$ ) 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	3086180	2144492	1796061	5056
1979	4184994	2462530	2510058	6945
1980	3474109	3191923	3693858	10623
1981	1370283	3029615	4999108	10853
1982	1499107	1780973	4958594	7813
1983	737431	1440783	3555714	4905
1984	619887	895561	2137521	3430
1985	845851	648434	1587568	3102
1986	1199316	695002	1364827	2951
1987	1328705	911172	1419653	3286
1988	1241661	1056205	1580281	3568
1989	3000724	1054790	1734903	4092
1990	1864456	2053331	2058992	5370
1991	1936773	1738508	2604122	5525
1992	2113240	1674731	2622482	5792
1993	2405884	1753884	2775161	6157
1994	1721126	1946538	2897294	6048
1995	2008251	1621665	2866461	6108
1996	1954427	1677170	2842064	6055
1997	1151829	1664994	2848612	5738
1998	820528	1205119	2535480	4228
1999	474540	382263	983702	2269
2000	525310	395882	1059342	2427
2001	486869	429286	1134414	2604
2002	170462	418491	1210213	2734
2003	414502	235277	1237840	2578
2004	278490	313143	1191632	2581
2005	718214	261787	1179695	2500
2006	1004954	494446	1185751	2772
2007	740604	733801	1334688	3292
2008	1227507	657322	1541106	3620
2009	949225	914018	1734685	3823
2010	906181	840880	1908263	3544
2011	759229	792082	1838908	3163
2012	456990	693244	1617581	2770
2013	562703	488921	1405282	3033
2014	487769	481377	1473992	2972
2015	462143	436327	1460013	2922
2016	506682	406853	1462081	3045
2017	274824	422315	1474381	3082
2018	407282	295610	1469410	2940

Table 23: Population abundances ( $n$ ) 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	5159537	4361084	3687283	11213
1979	6210267	4373769	5405672	13986
1980	3673747	4974775	7269812	19463
1981	1540288	3733146	8904090	18930
1982	1435675	2110417	8589692	15134
1983	924987	1513838	6744725	11444
1984	759383	1026332	4845730	8627
1985	888512	770974	3926869	8069
1986	1169500	759806	3384557	6842
1987	2073978	915706	3136254	6538
1988	3432758	1480998	3087326	6799
1989	7016427	2439826	3416727	8943
1990	2176388	4792406	4545548	13018
1991	3012152	2822327	6091388	13390
1992	3410492	2644416	6181631	13578
1993	4658345	2811786	6359402	14361
1994	3595317	3576027	6638067	14873
1995	2415186	3225465	6988280	15949
1996	3767773	2439220	7129303	15116
1997	3507563	2947152	6984231	15576
1998	2577269	2967449	6856068	11783
1999	935872	614530	1723836	3915
2000	1680050	734770	1838776	4266
2001	2898966	1197252	2066729	5214
2002	560274	2042480	2606795	7177
2003	183891	994184	3260530	7216
2004	104651	433447	3241730	6549
2005	981856	202910	2936121	5717
2006	1923313	624740	2648339	5653
2007	3575445	1298593	2709815	6506
2008	1607754	2450926	3247373	8834
2009	1497545	1723791	4100573	8829
2010	1772043	1420514	4344790	8209
2011	1093878	1475839	4248690	7957
2012	687238	1109613	4006465	7204
2013	763979	757501	3630856	7292
2014	799080	684574	3487434	6713
2015	589916	680368	3273389	6284
2016	429463	560172	3111618	6152
2017	190561	429189	2921581	5674

## Figures



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

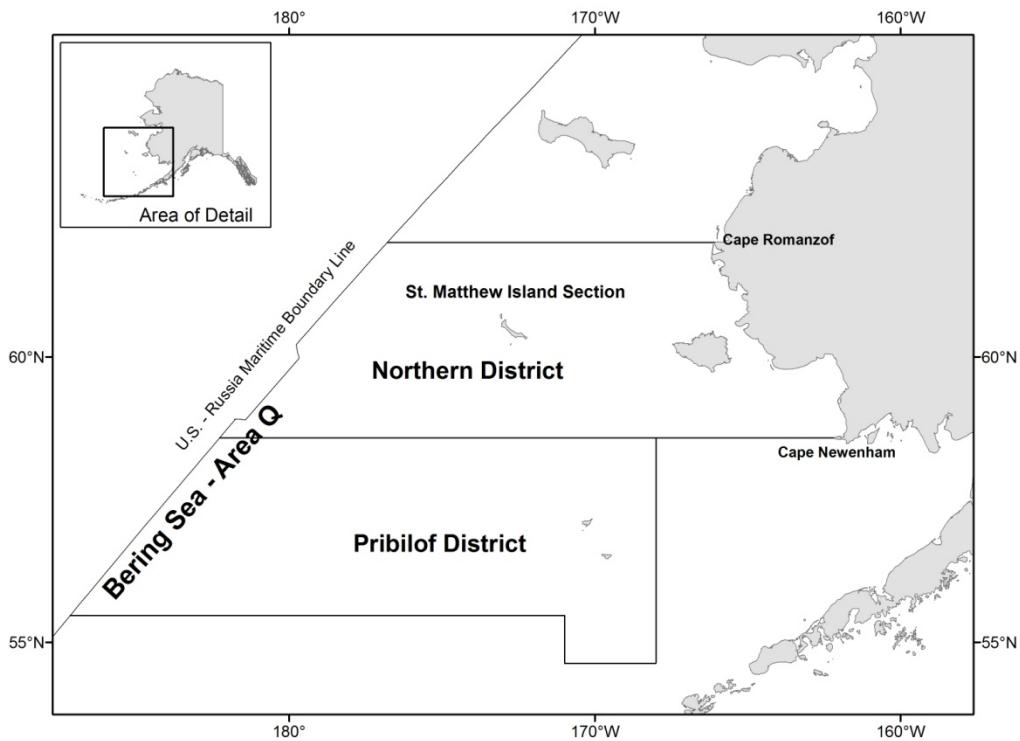


Figure 2: King crab Registration Area Q (Bering Sea).

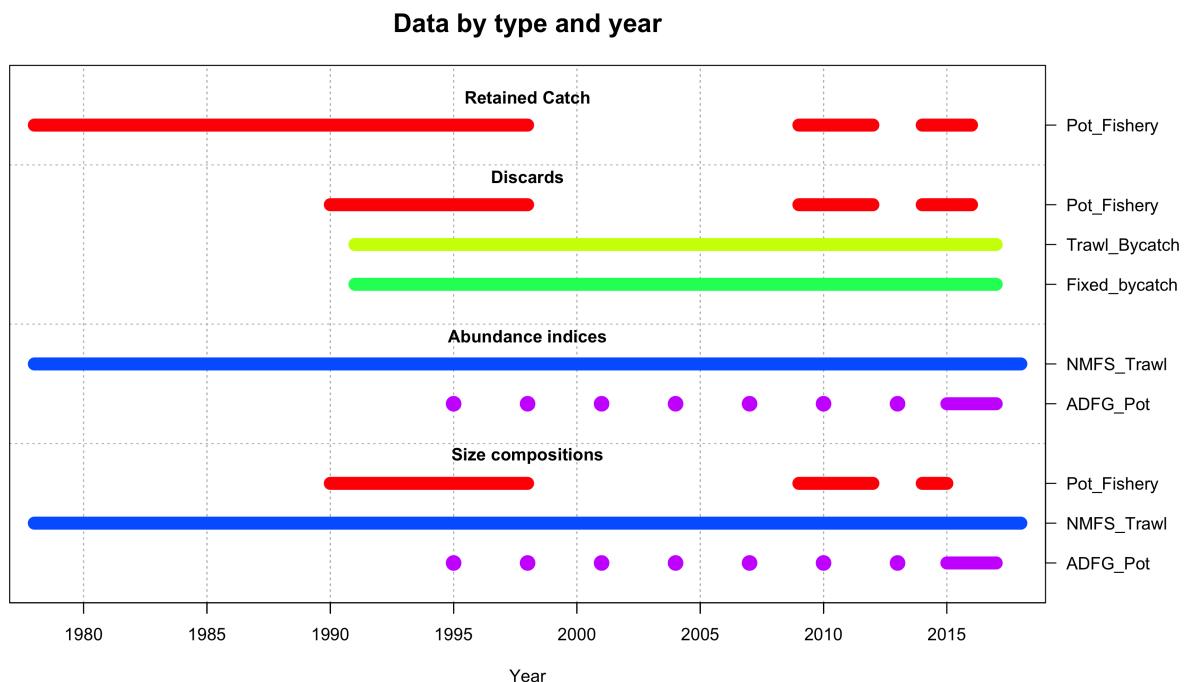


Figure 3: Data extent for the SMBKC assessment (with the 2017 Pot survey included).

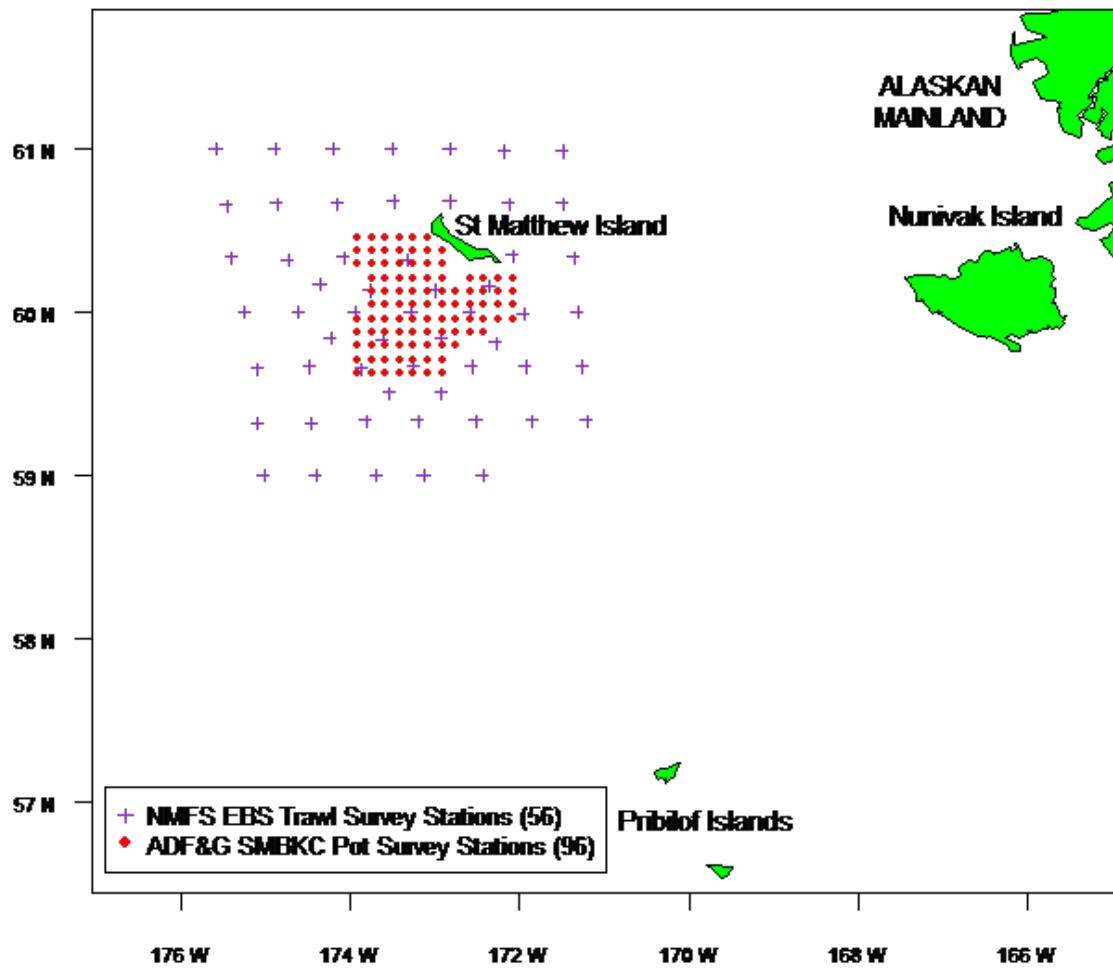


Figure 4: Trawl and pot-survey stations used in the SMBKC stock assessment.

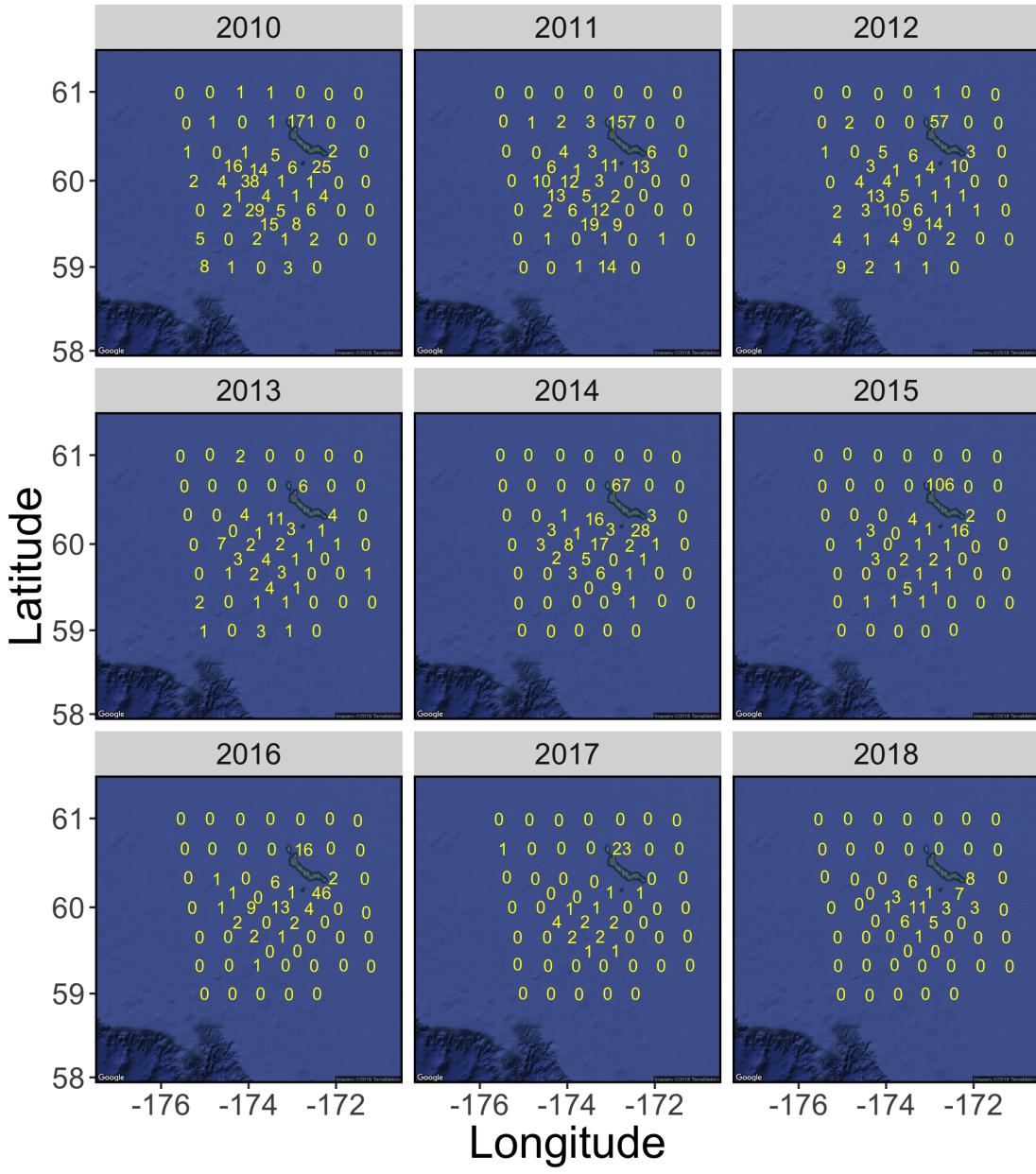


Figure 5: Catches (in numbers) of male blue king crab measuring 90 mm CL from the 2012-2017 NMFS trawl-survey at the 56 stations used to assess the SMBKC stock. Note that the area north of St. Matthew Island, which often shows large catches of crab at station R-24 is not covered in the ADF&G pot-survey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

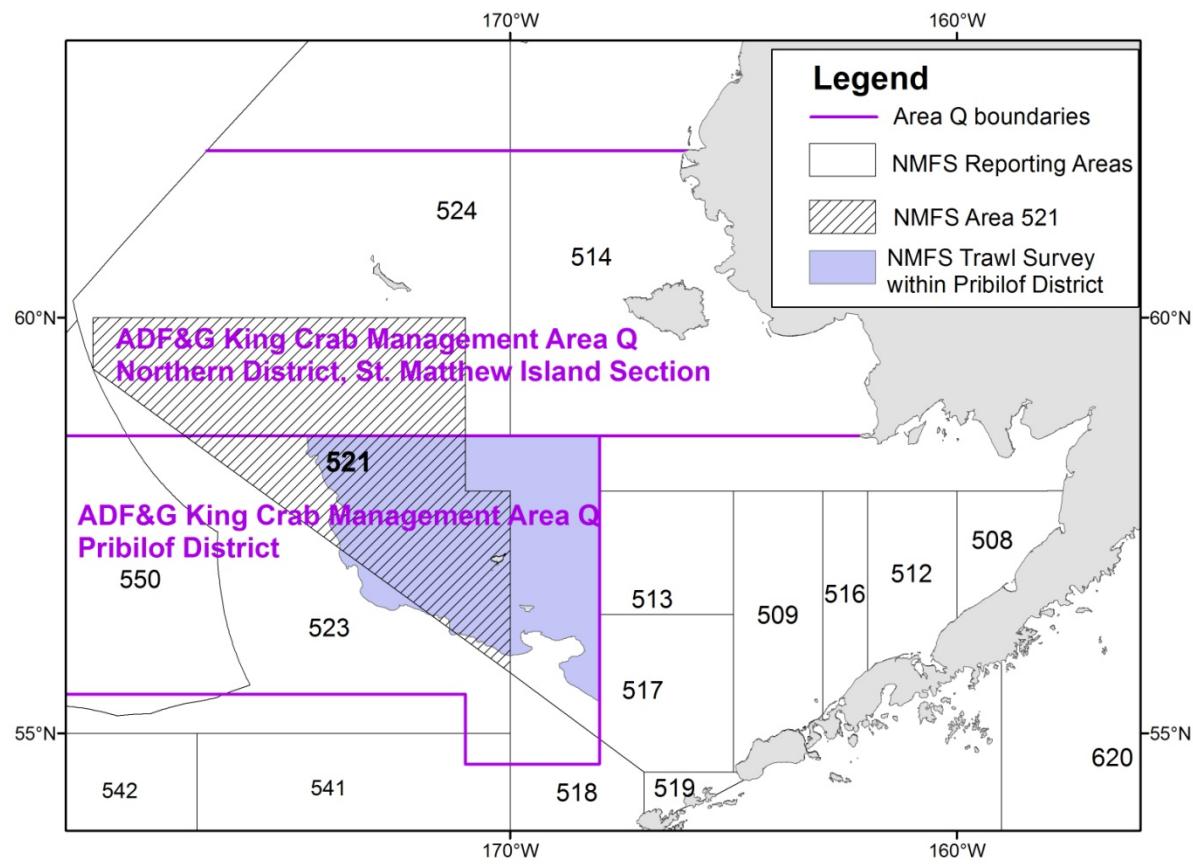


Figure 6: NFMS Bering Sea reporting areas. Estimates of SMBKC bycatch in the groundfish fisheries are based on NMFS observer data from reporting areas 524 and 521.

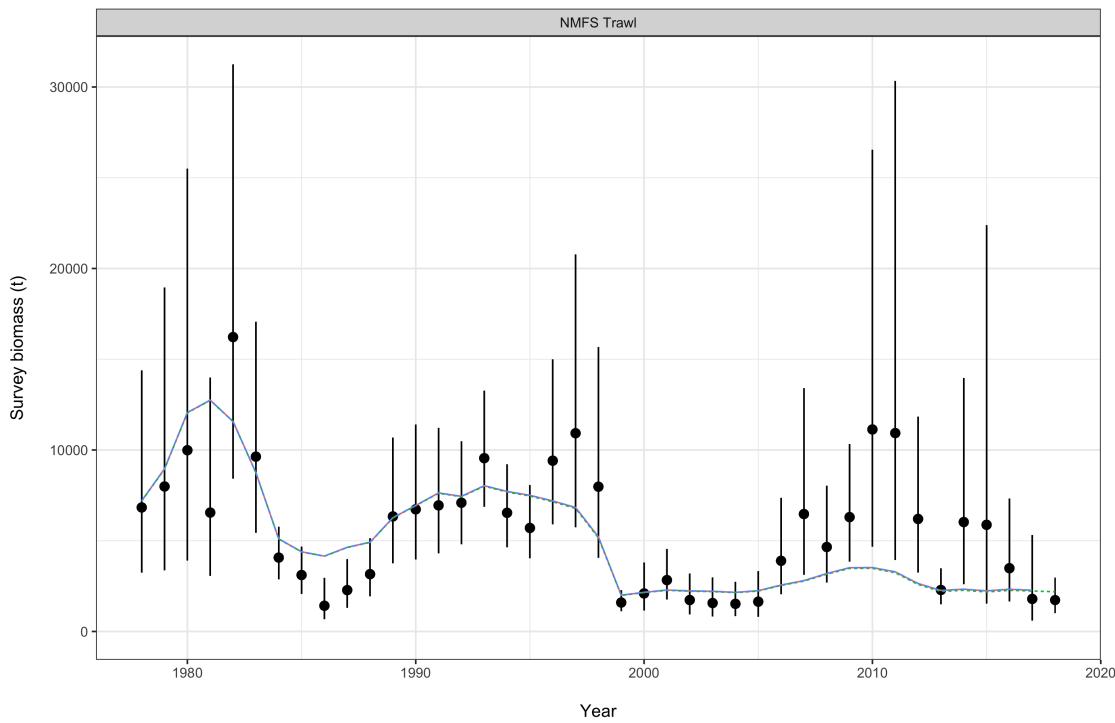


Figure 7: Fits to NMFS area-swept trawl estimates of total (>90mm) male survey biomass with the addition of new data. Error bars are plus and minus 2 standard deviations.

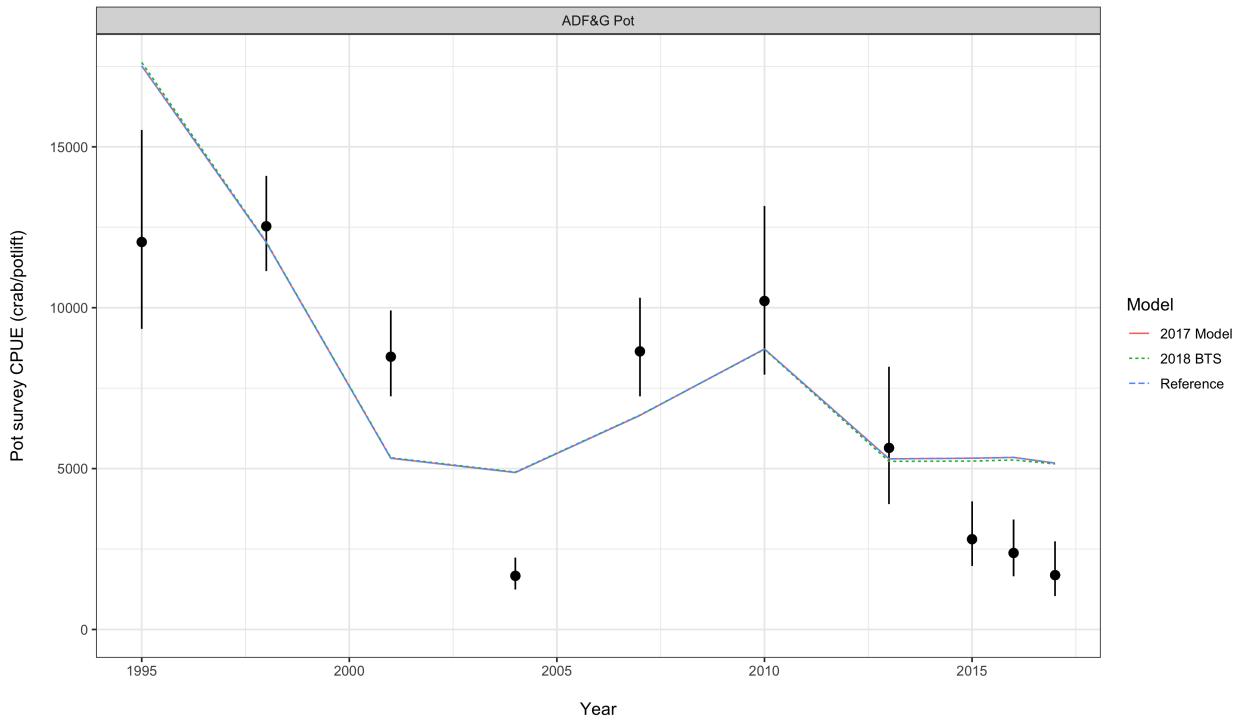


Figure 8: Comparisons of fits to CPUE from the ADF&G pot surveys with the addition of new data. Error bars are plus and minus 2 standard deviations.

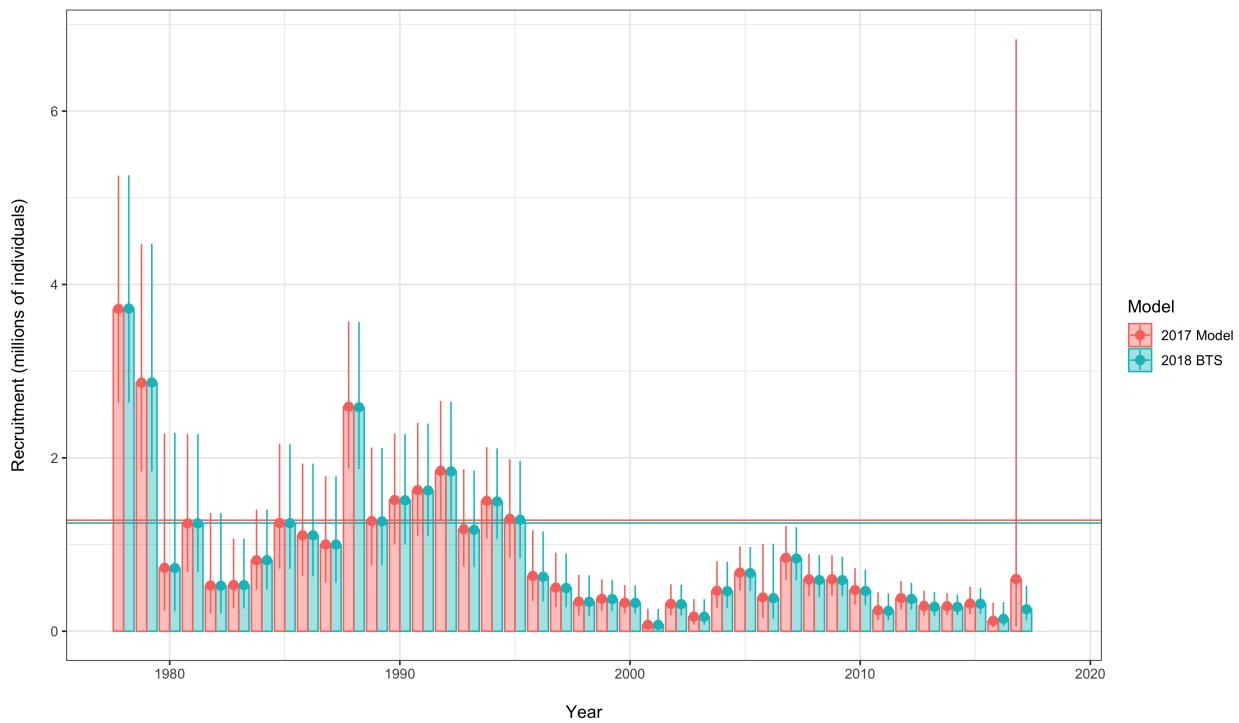


Figure 9: Sensitivity of new data in 2017 on estimated recruitment ; 1978-2017.

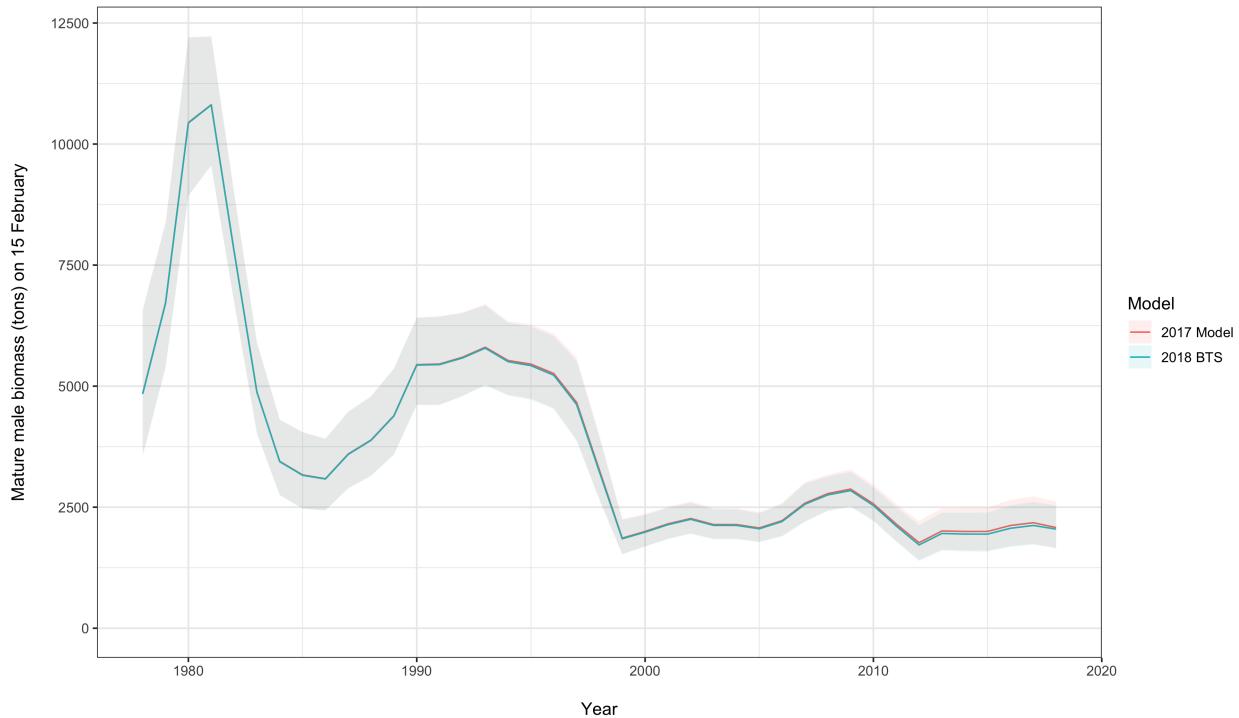


Figure 10: Sensitivity of new data in 2017 on estimated mature male biomass (MMB); 1978-2017.

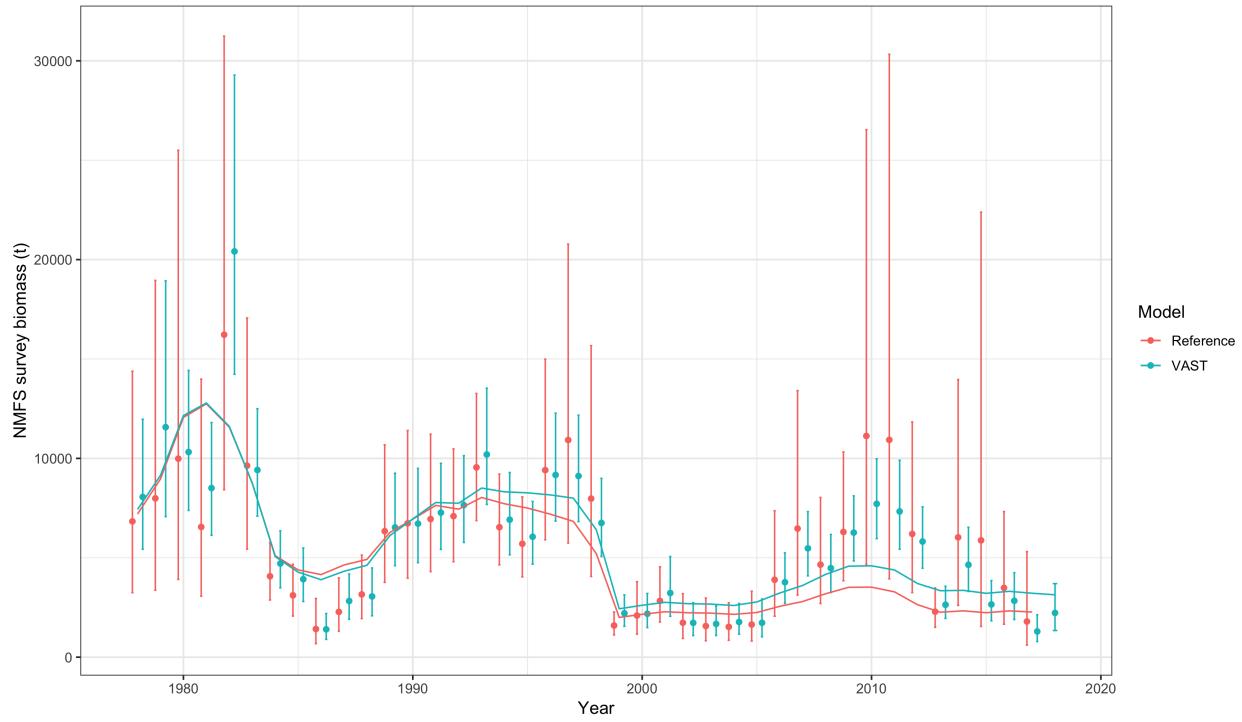


Figure 11: Comparisons of fits to area-swept estimates of total (>90mm) male survey biomass (t) for the standard design-based estimate and for estimates derived from the VAST spatio-temporal model of Thorson and Barnett (2017). Error bars are plus and minus 2 standard deviations.

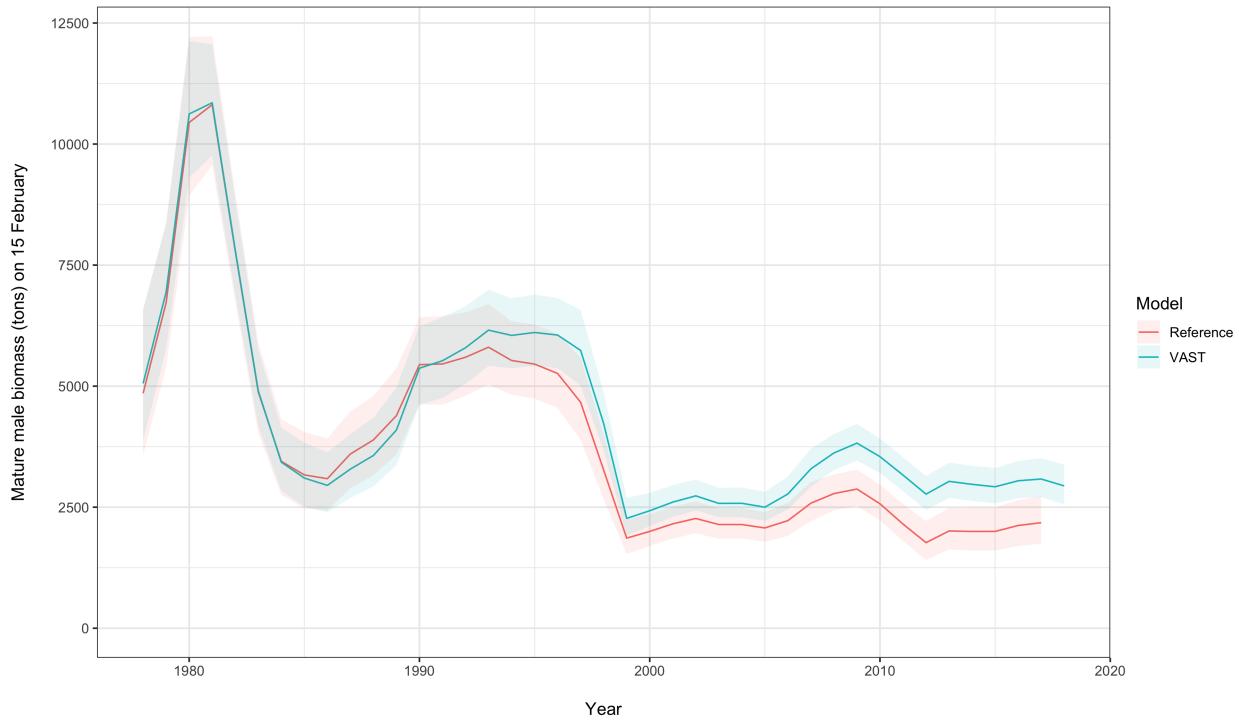


Figure 12: Sensitivity of new data in 2017 on estimated mature male biomass (MMB); 1978-2017 comparing the reference model with that fitted to the VAST BTS estimates.

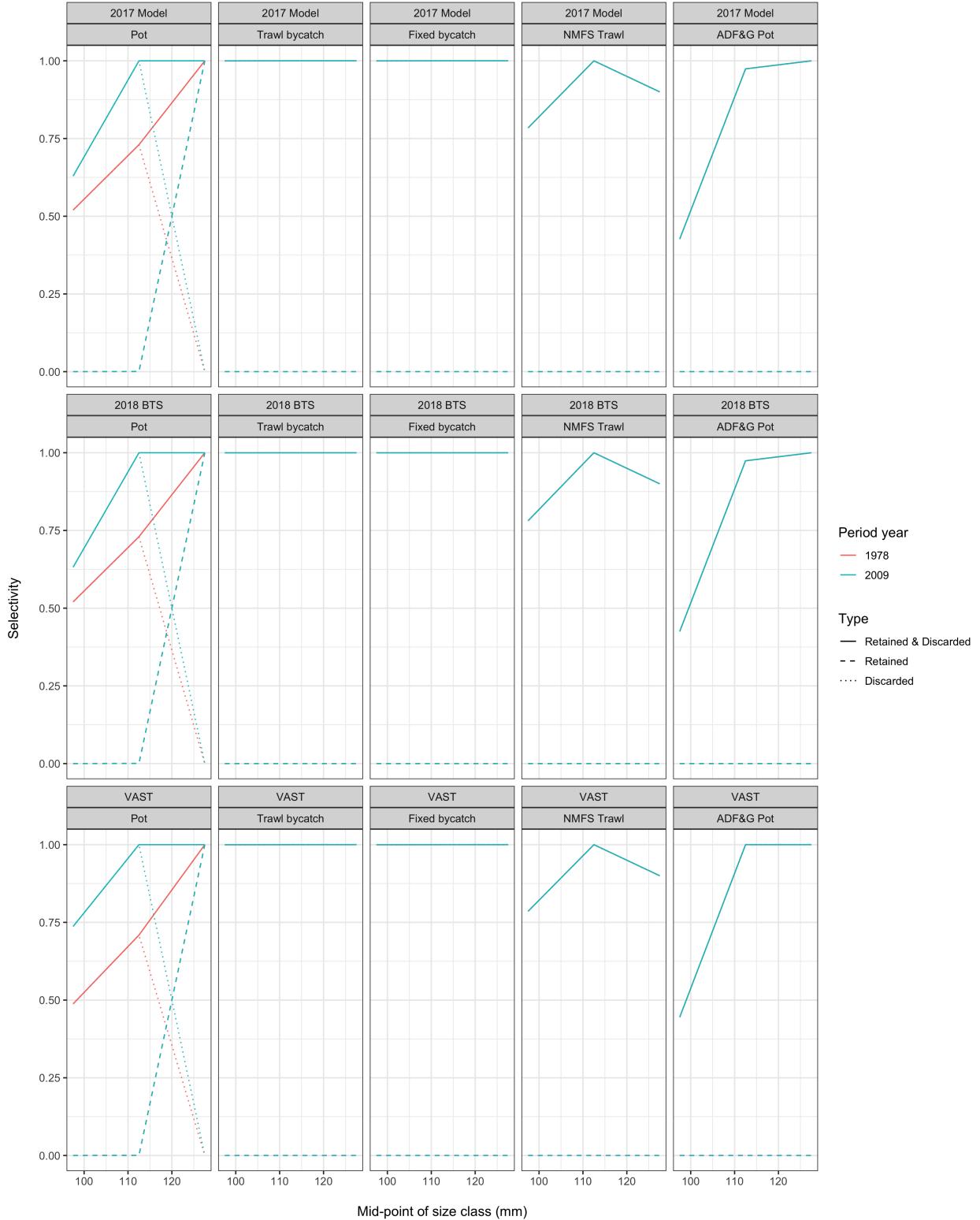


Figure 13: Comparisons of the estimated stage-1 and stage-2 selectivities for the different model scenarios (the stage-3 selectivities are all fixed at 1). Estimated selectivities are shown for the directed pot fishery, the trawl bycatch fishery, the fixed bycatch fishery, the NMFS trawl survey, and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

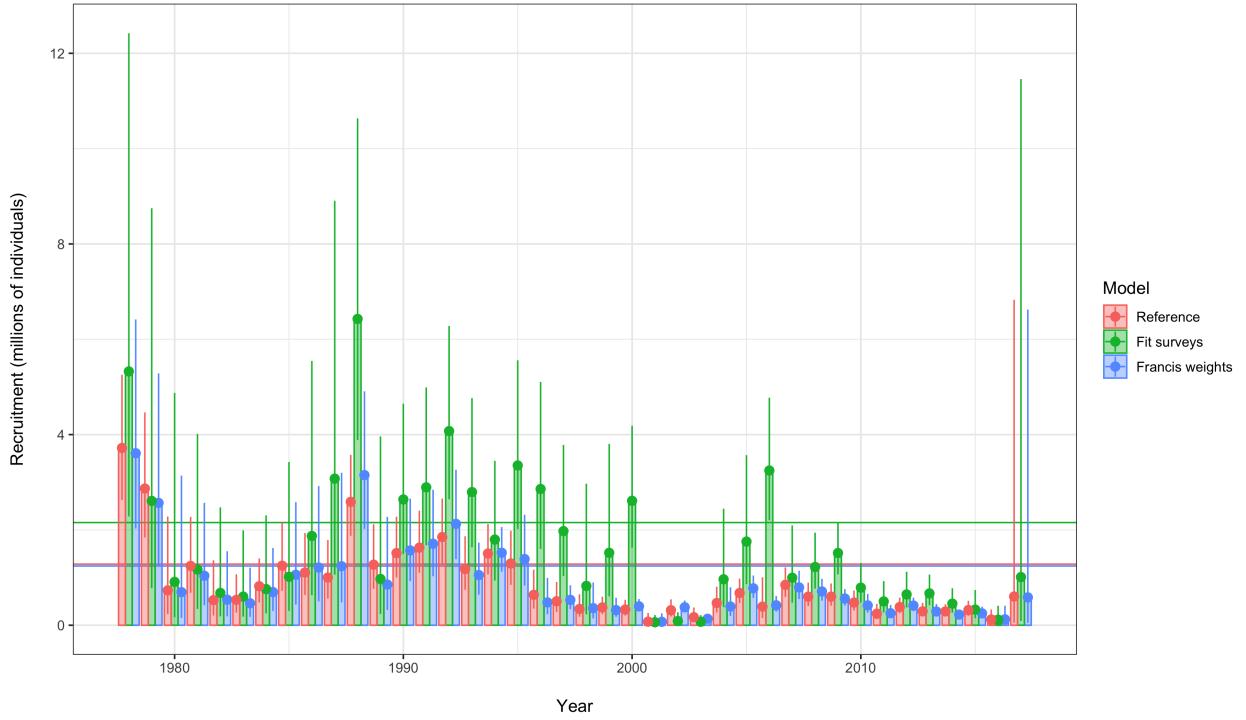


Figure 14: Estimated recruitment 1979-2017 comparing model alternatives. The solid horizontal lines in the background represent the estimate of the average recruitment parameter ( $\bar{R}$ ) in each model scenario.

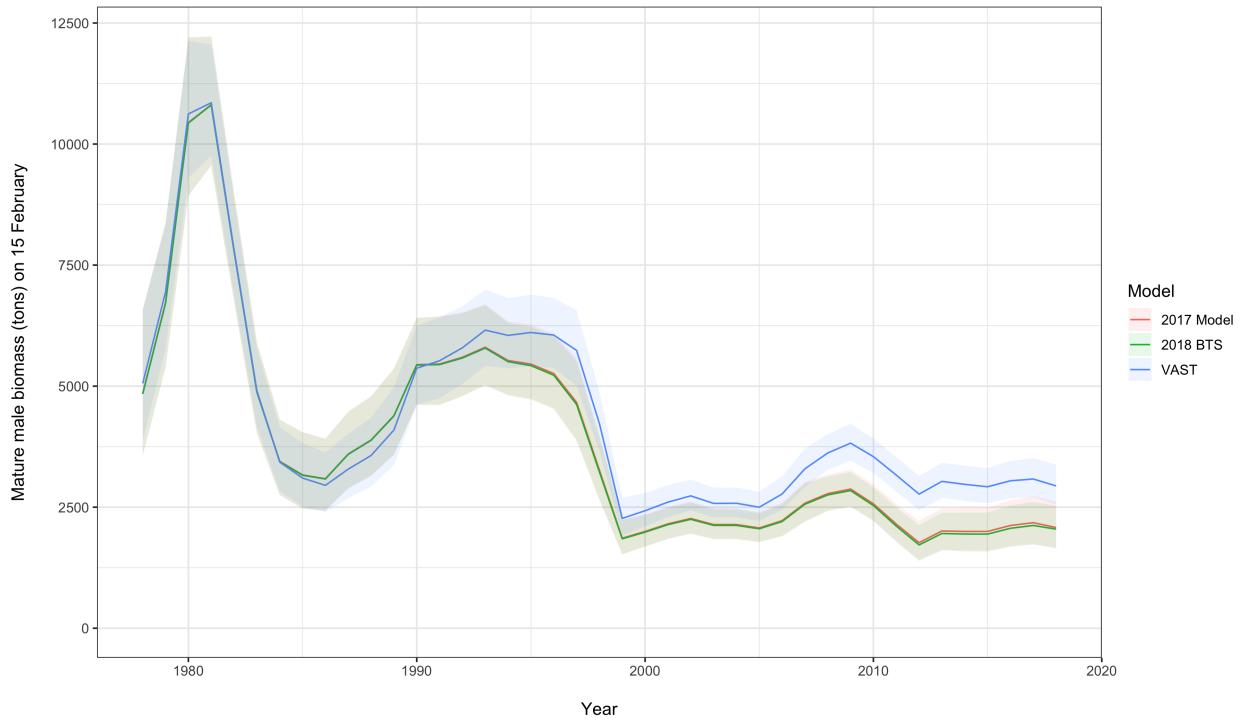


Figure 15: Comparisons of estimated mature male biomass (MMB) time series on 15 February during 1978-2017 for each of the model scenarios.

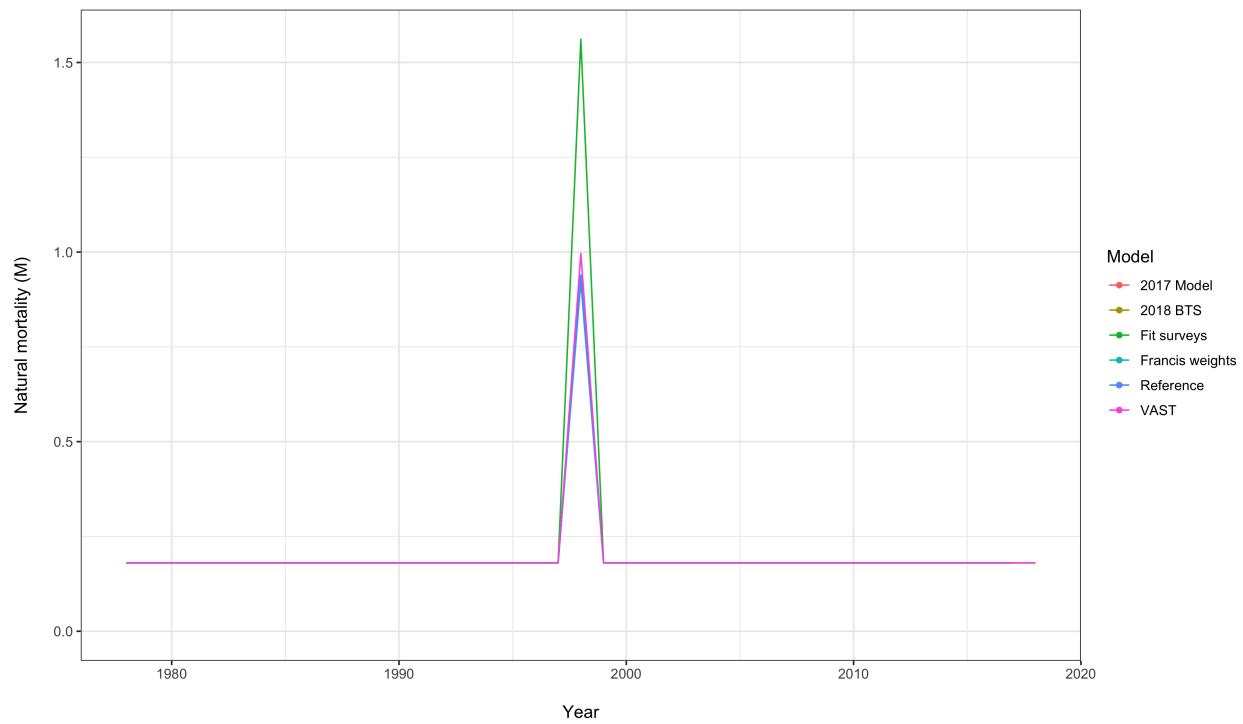


Figure 16: Time-varying natural mortality ( $M_t$ ). Estimated pulse period occurs in 1998/99 (i.e.  $M_{1998}$ ).

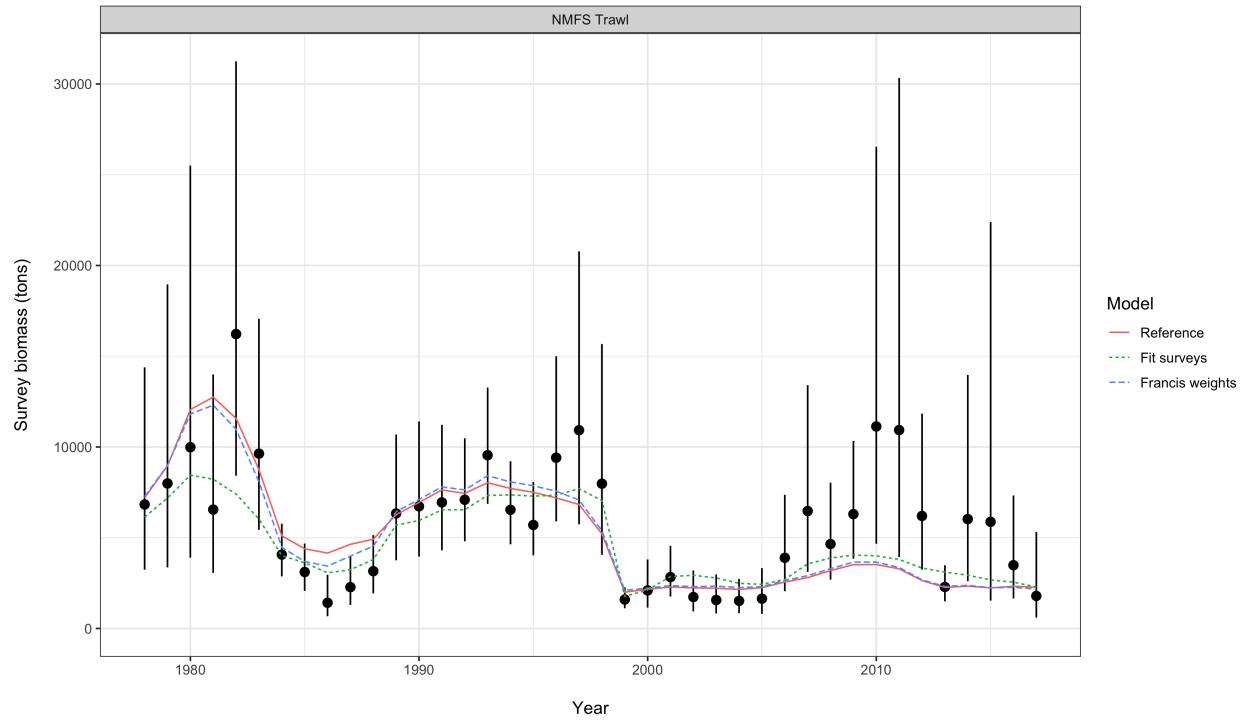


Figure 17: Comparisons of area-swept estimates of total (90+ mm CL) male survey biomass (tons) and model predictions for the model scenarios. The error bars are plus and minus 2 standard deviations.

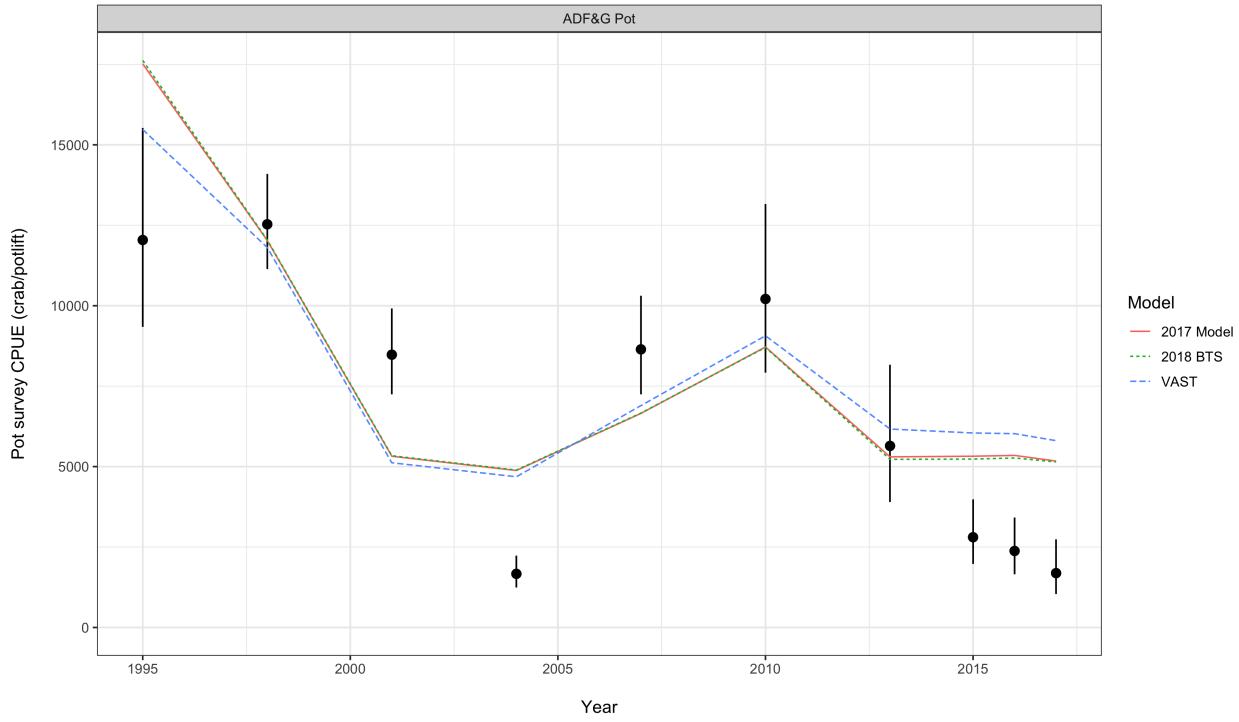


Figure 18: Comparisons of total (90+ mm CL) male pot survey CPUEs and model predictions for the model scenarios. The error bars are plus and minus 2 standard deviations.

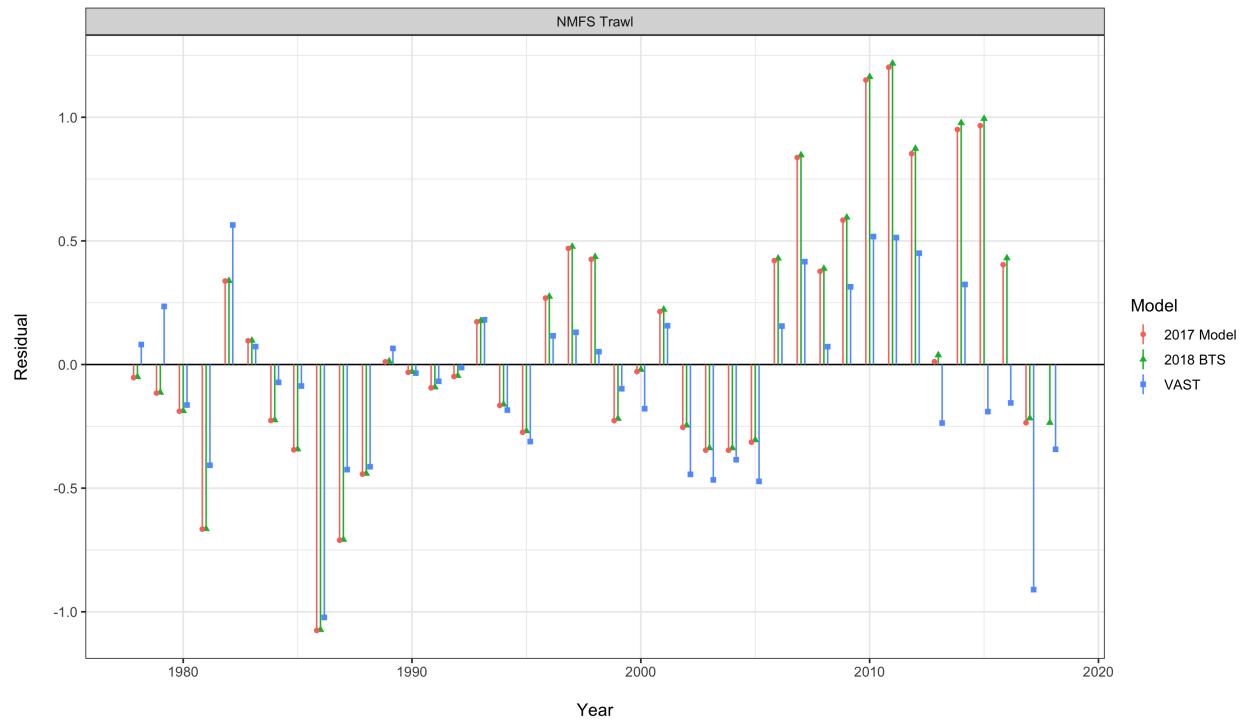


Figure 19: Standardized residuals for area-swept estimates of total male survey biomass for the model scenarios.

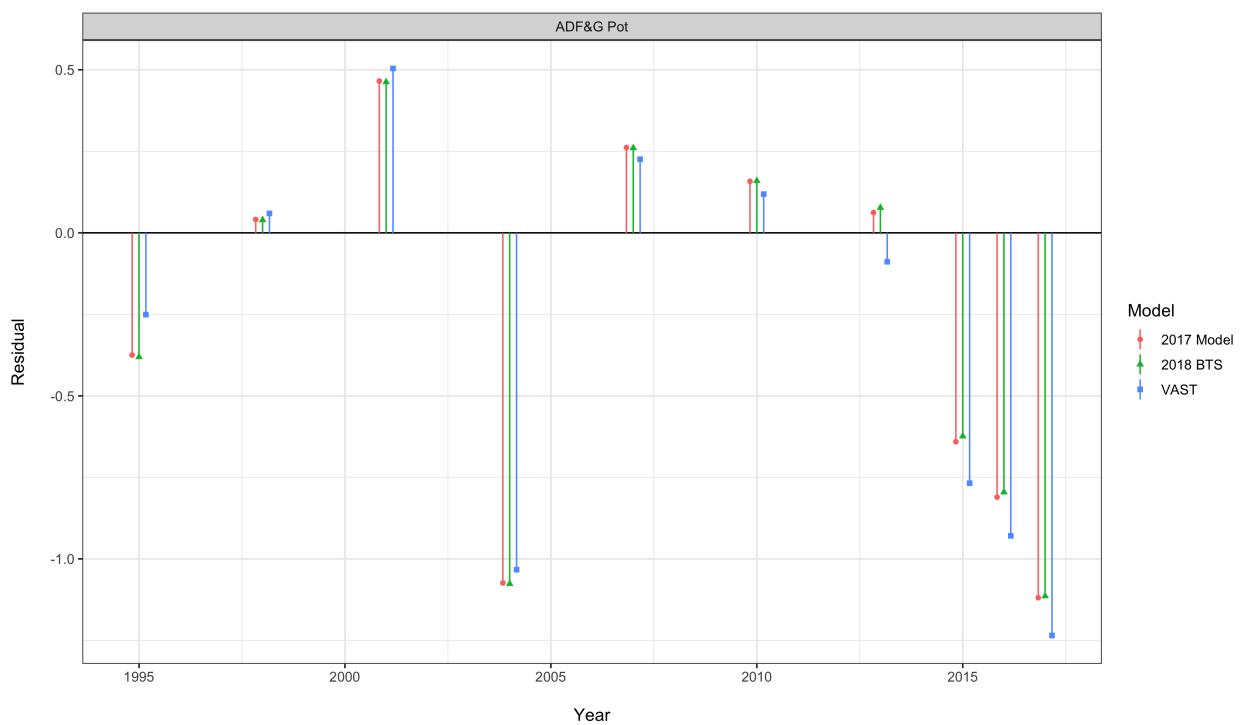


Figure 20: Standardized residuals for total male pot survey CPUEs for each of the Gmacs model scenarios.

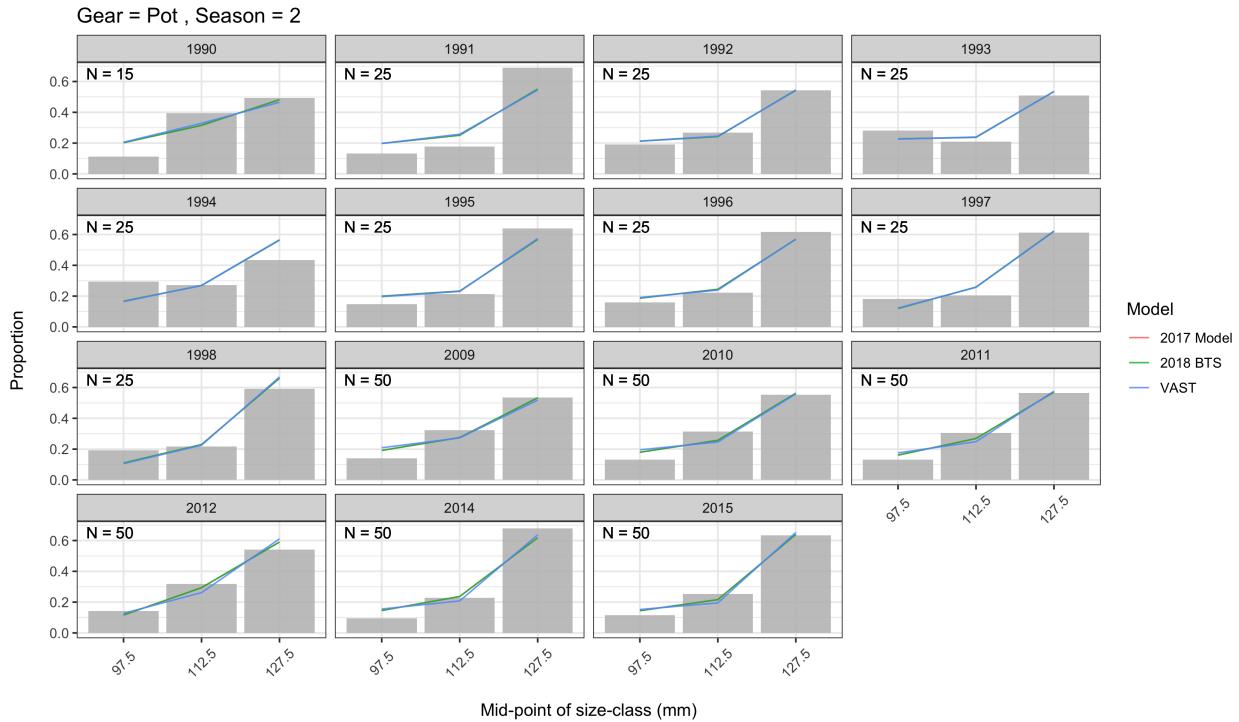


Figure 21: Observed and model estimated size-frequencies of SMBKC by year retained in the directed pot fishery for the model scenarios.

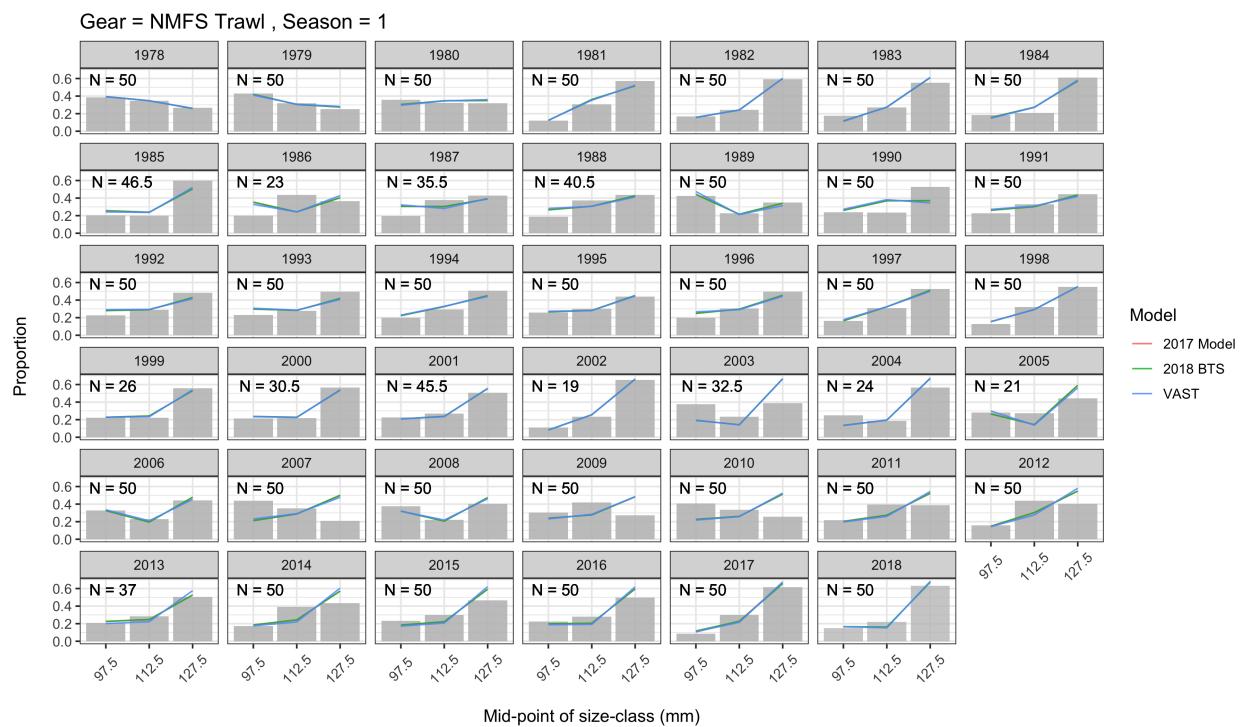


Figure 22: Observed and model estimated size-frequencies of discarded male SMBKC by year in the NMFS trawl survey for the model scenarios.

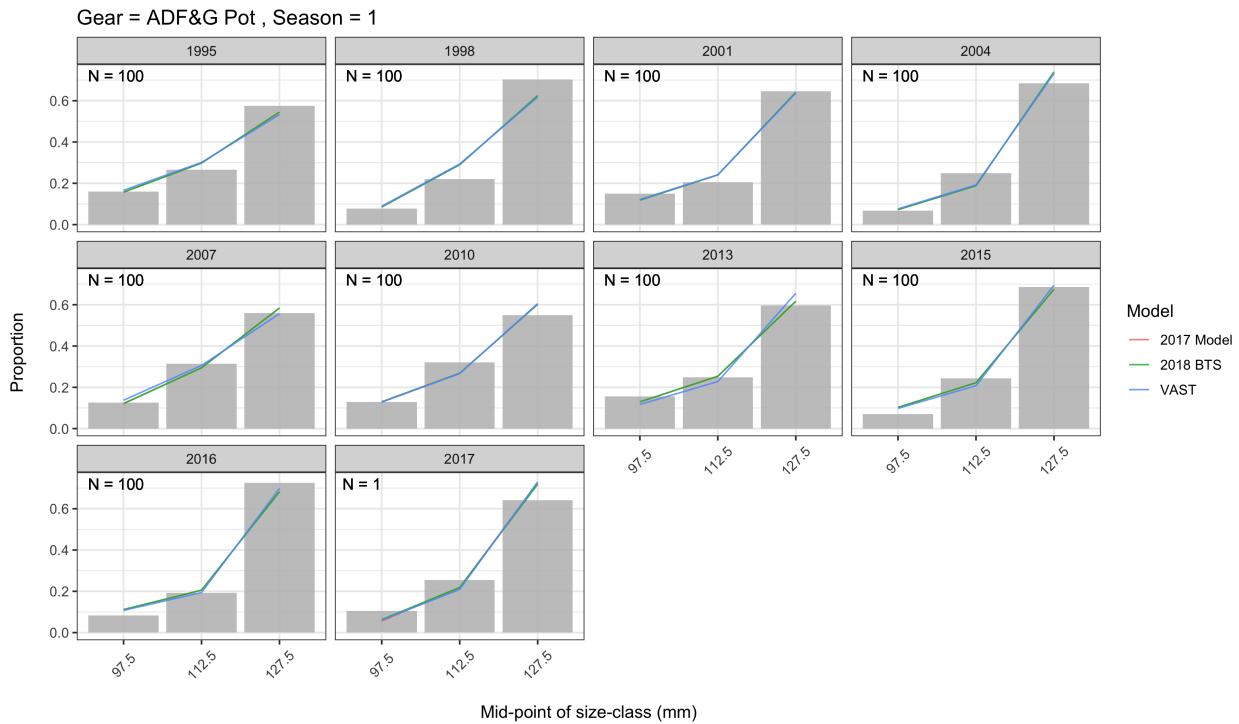


Figure 23: Observed and model estimated size-frequencies of discarded SMBKC by year in the ADF&G pot survey for the model scenarios.

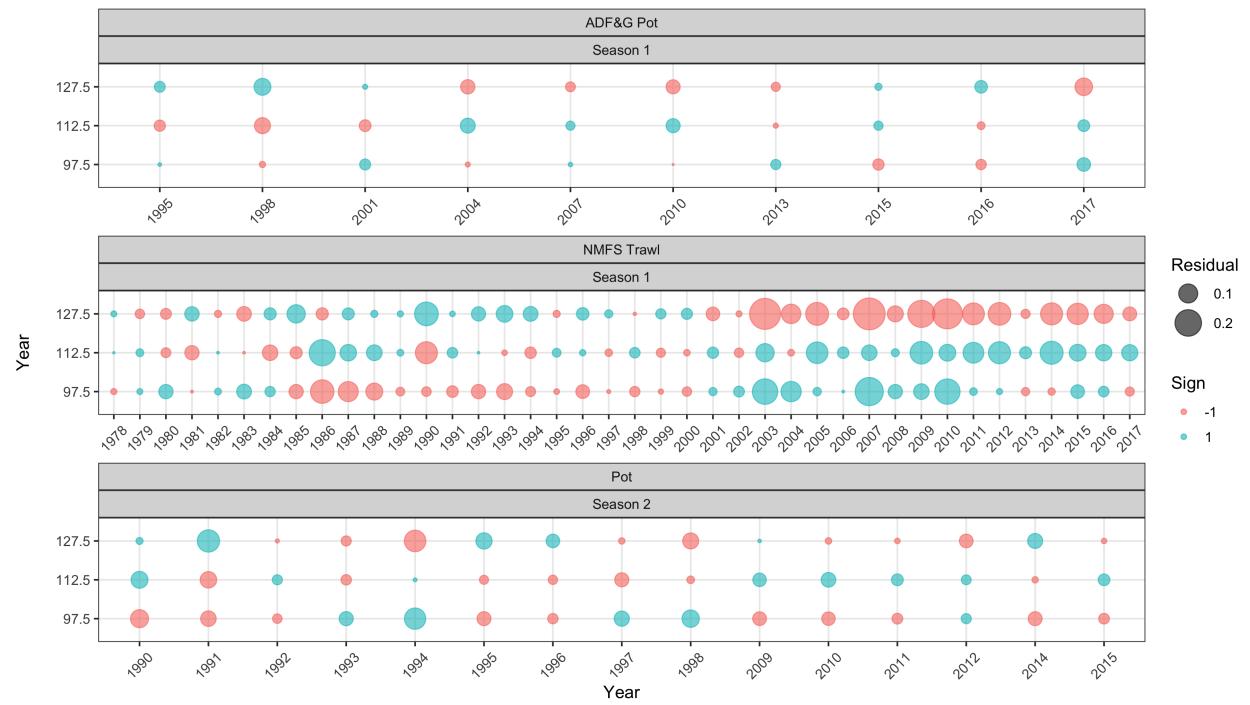


Figure 24: Bubble plots of residuals by stage and year for the directed pot fishery size composition data for SMBKC in the reference model.

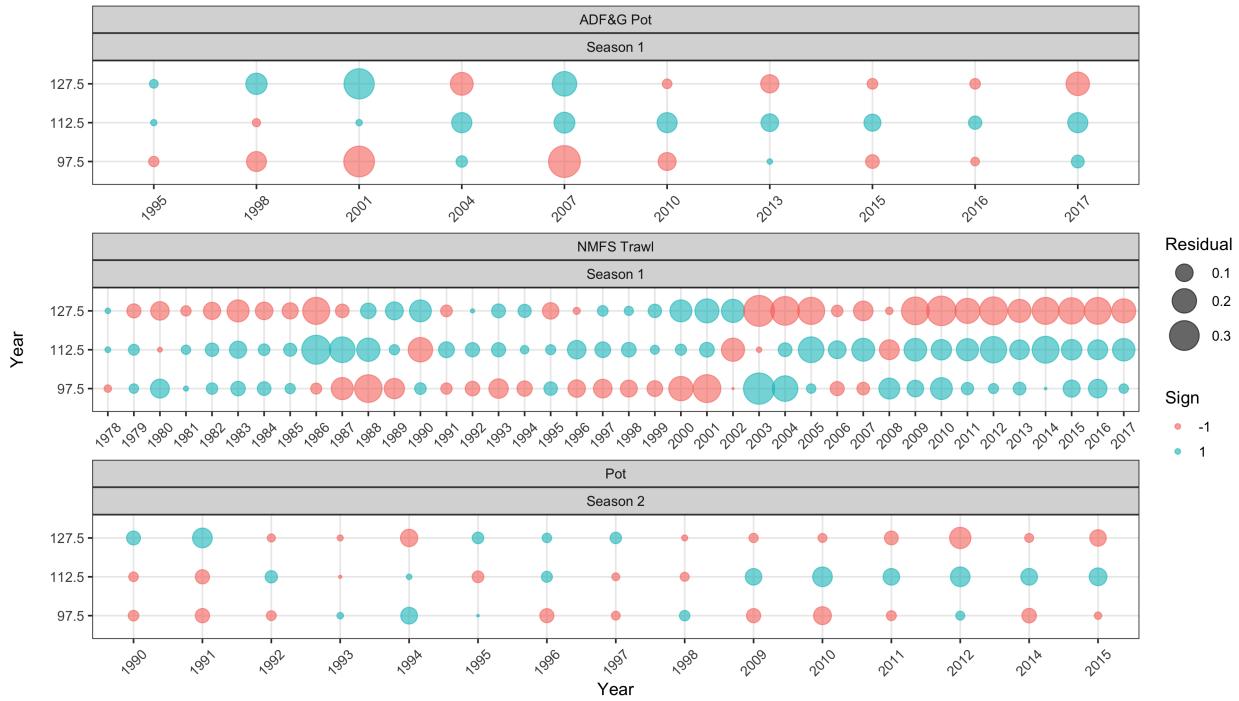


Figure 25: Bubble plots of residuals by stage and year for the ADF&G pot survey size composition data for SMBKC in the **fit surveys** model.

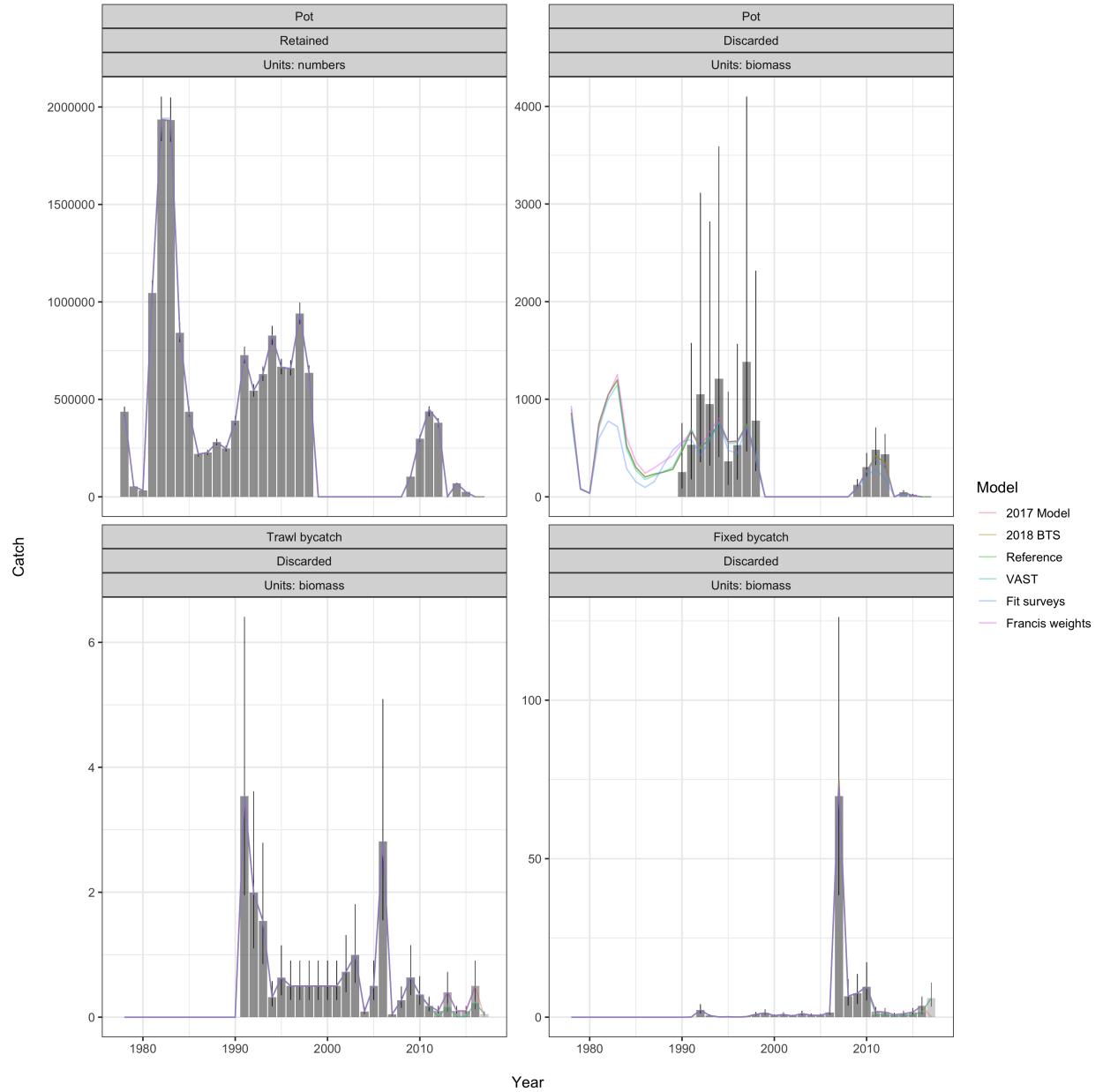


Figure 26: Comparison of observed and model predicted retained catch and bycatches in each of the Gmacs models. Note that difference in units between each of the panels, some panels are expressed in numbers of crab, some as biomass (tons).

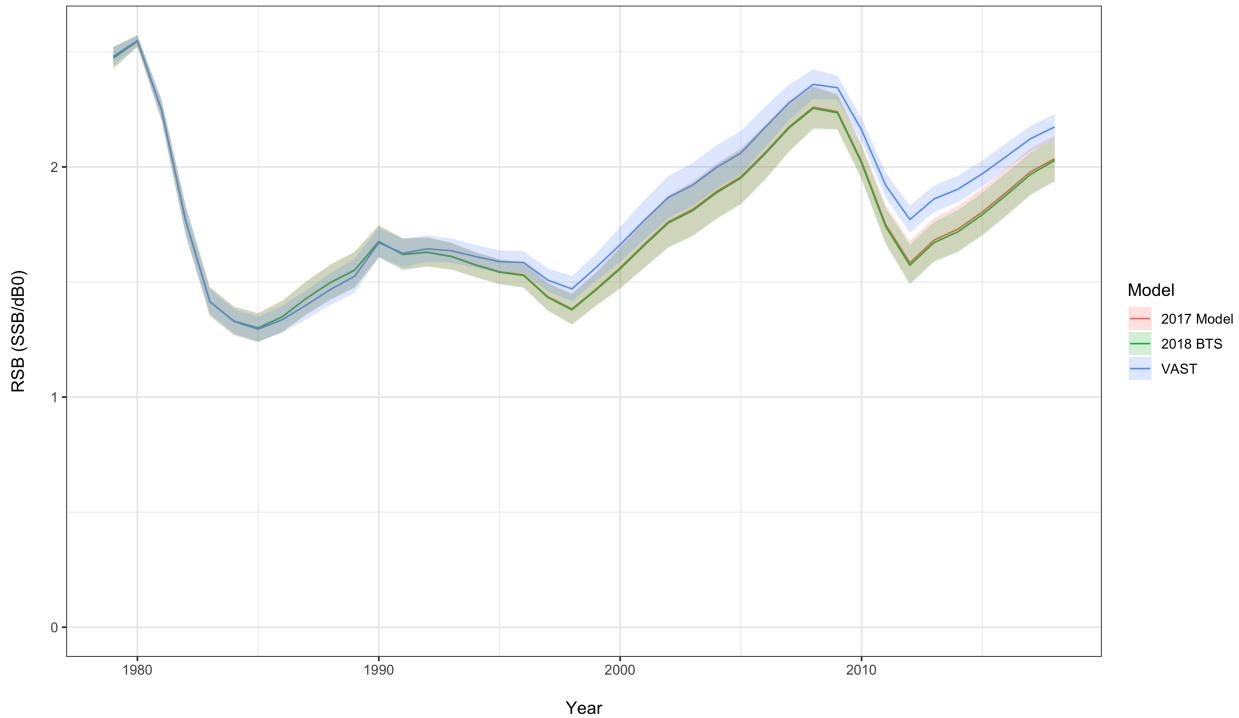


Figure 27: Comparisons of mature male biomass relative to the dynamic  $B_0$  value, (15 February, 1978-2017) for each of the model scenarios.

## 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 <U+FFF><U+FFF><U+FFF>recruit<U+FFF><U+FFF><U+FFF> 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 ( $\tau_t$ ), 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)
  - $\tau_2$  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 ( $\tau_t$ ) applied during each season in the model is provided in Table 24. 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,  $\tau_2$  varies and thus  $\tau_4$  varies also.

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

$$\mathbf{n}_{t,y} = n_{l,t,y} = [n_{1,t,y}, n_{2,t,y}, n_{3,t,y}]^\top. \quad (2)$$

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

$$\phi_l = [1, 0, 0]^\top, \quad (3)$$

and the recruitment is

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

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

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

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

$$\mathbf{G} = \begin{bmatrix} 1 - \pi_{12} - \pi_{13} & \pi_{12} & \pi_{13} \\ 0 & 1 - \pi_{23} & \pi_{23} \\ 0 & 0 & 1 \end{bmatrix}, \quad (6)$$

with  $\pi_{jk}$  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

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

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

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

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

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

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  $y$

$$Z_{t,y} = Z_{l,t,y} = M_{t,y} + F_{t,y}. \quad (10)$$

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

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

The basic population dynamics underlying Gmacs can thus be described as

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

### 3. Model Data

Data inputs used in model estimation are listed in Table 25.

### 4. Model Parameters

Table 26 lists fixed (externally determined) parameters used in model computations. In all scenarios, the stage-transition matrix is

$$\mathbf{G} = \begin{bmatrix} 0.2 & 0.7 & 0.1 \\ 0 & 0.4 & 0.6 \\ 0 & 0 & 1 \end{bmatrix} \quad (13)$$

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

Estimated parameters are listed in Table 27 and include an estimated natural mortality deviation parameter in 1998/99 ( $\delta_{1998}^M$ ) assuming an anomalous mortality event in that year, as hypothesized by Zheng and Kruse (2002), with natural mortality otherwise fixed at  $0.18 \text{ yr}^{-1}$ .

### 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 18). A lognormal distribution is assumed to characterize the catch data and is modelled as

$$\sigma_{t,y}^{\text{catch}} = \sqrt{\log \left( 1 + (CV_{t,y}^{\text{catch}})^2 \right)} \quad (14)$$

$$\delta_{t,y}^{\text{catch}} = \mathcal{N} \left( 0, (\sigma_{t,y}^{\text{catch}})^2 \right) \quad (15)$$

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

$$\sigma_{t,y}^I = \frac{1}{\lambda} \sqrt{\log \left( 1 + (CV_{t,y}^I)^2 \right)} \quad (16)$$

$$\delta_{t,y}^I = \log \left( I^{\text{obs}} / I^{\text{pred}} \right) / \sigma_{t,y}^I + 0.5\sigma_{t,y}^I \quad (17)$$

and the likelihood is

$$\sum \log (\delta_{t,y}^I) + \sum 0.5 (\sigma_{t,y}^I)^2 \quad (18)$$

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 reasonable 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 adequate. 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 abundance 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 24: Proportion of the natural mortality ( $\tau_t$ ) 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 25: 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 26: Fixed model parameters for all scenarios.

Parameter	Symbol	Value	Source/rationale
Trawl-survey catchability	$q$	1.0	Default
Natural mortality	$M$	$0.18 \text{ yr}^{-1}$	NPFMC (2007)
Size transition matrix	$\mathbf{G}$	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	$\sigma_R$	1.2	High value
Natural mortality SD	$\sigma_M$	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 27: 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 $\delta_{1998}^M$	-3	0.0	3	Normal(0, $\sigma_M^2$ )	4
Recruitment deviations $\delta_y^R$	-7	0.0	7	Normal(0, $\sigma_R^2$ )	3
Average directed fishery fishing mortality $\bar{F}^{\text{df}}$	-	0.2	-	-	1
Average trawl bycatch fishing mortality $\bar{F}^{\text{tb}}$	-	0.001	-	-	1
Average fixed gear bycatch fishing mortality $\bar{F}^{\text{fb}}$	-	0.001	-	-	1