

# Saint Matthew Island Blue King Crab Stock Assessment 2016

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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 tonnes (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 tonnes (0.461 million pounds), less than half the 529.3 tonnes (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 tonnes (0.655 million pounds), but the fishery performance was relatively poor with a retained catch of 140 tonnes (0.309 million pounds).
3. **Stock biomass:** Following a period of low numbers after the stock was declared overfished in 1999, trawl-survey indices of SMBKC stock abundance and biomass generally increased in subsequent years, with survey estimated mature male biomass reaching 9516 tonnes (20.98 million pounds; CV = 0.55) in 2011, the second highest in the 37-year time series used in this assessment. Survey mature male biomass then declined to 5652 tonnes (12.46 million pounds; CV = 0.33) in 2012 and to 2202 tonnes (4.459 million pounds; CV = 0.22) in 2013 before going back up to 5472 tonnes (12.06 million pounds; CV = 0.44) in 2014 and 5134 tonnes (11.32 million pounds; CV = 0.76).
4. **Recruitment:** Because little information about the abundance of small crab is available for this stock, recruitment has been assessed in terms of the number of male crab within the 90-104 mm CL size class in each year. The 2013 trawl-survey area-swept estimate of 0.335 million male SMBKC in this size class marked a three-year decline and was the lowest since 2005. That decline did not continue as the 2014 survey estimate is 0.723 million. The survey recruitment is 0.992 million in 2015, but the majority of this survey estimate is from one tow with a great deal of uncertainty.
5. **Management performance:** In recent assessments, estimated total male catch has been determined as the sum of fishery-reported retained catch, estimated male discard mortality in the directed fishery, and estimated male bycatch mortality in the groundfish fisheries, as these have been the only sources of non-negligible fishing mortality to consider.

The stock was above the minimum stock-size threshold (MSST) in 2014/15 and is hence not overfished. Overfishing did not occur in 2014/15.

6. **Basis for the OFL:** Estimated mature-male biomass (MMB) on 15 February is used as the measure of biomass for this Tier 4 stock, with males measuring 105 mm CL or more considered mature. The  $B_{MSY}$  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.

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<sup>1</sup>1983/84 refers to a fishing year that extends from 1 July 1983 to 30 June 1984.

## 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

All of the time series used in this assessment have been updated to include the most recent fishery and survey results. This assessment makes use of an updated full trawl-survey time series supplied by R. Foy in August 2015, updated groundfish bycatch estimates based on 1999-2014 NMFS AKRO data also supplied by R. Foy, and the ADF&G pot survey data in 2015.

### Changes in Assessment Methodology

This assessment is done using Gmacs. The model is based upon the 3-stage length-based assessment model first presented in May 2011 by Bill Gaeuman and accepted by the CPT in May 2012. There are several differences between the Gmacs assessment and the previous model. One of the major differences being that natural and fishing mortality are continuous within any number of discrete seasons. Season length in Gmacs is controlled simply by changing the proportion of natural mortality that is applied during each season. For example, in this assessment four seasons are defined and the proportion of natural mortality that is applied each season is 0, 0.44, 0.185, and 0.375 in the final season. In Gmacs the proportion of natural mortality that is applied each season is fixed (i.e. it can not change from year to year). The previous model allowed the proportion of natural mortality to change seasonally each year (i.e. during the second season natural mortality ranged from 0.05 to 0.18 before the year 2000 and was constant at 0.44 after 2000).

In Gmacs the size transition matrix is a combination of the growth matrix and the molting probability. The growth matrix is derived from empirical molt increment data and the molting probability for each size class in the model is derived from an inverse logistic curve. Put simply, Gmacs does not allow the user to specify the size transition matrix directly, thus getting our size transition matrix to match that used in the previous model exactly was not possible. However, it is close:

$$\begin{bmatrix} 0.2056 & 0.6799 & 0.1144 \\ 0 & 0.3963 & 0.6037 \\ 0 & 0 & 1 \end{bmatrix} \quad (1)$$

Also see Figure 26. Further details of the Gmacs model and configuration used are provided in Appendix A (SMBKC Model Description).

### Changes in Assessment Results

Changes in assessment results depend on model scenario. The Gmacs base model scenario attempts to match the 2015 assessment by specifying the same (or similar) dynamics and parameter values. However, a different Gmacs scenario (Gmacs selex) provides a much better match to the 2015 model assessment.

## B. Responses to SSC and CPT Comments

### CPT and SSC Comments on Assessments in General

Spring 2016 CPT

Comment: *comments*

Response:

## CPT and SSC Comments Specific to SMBKC Stock Assessment

Spring 2016 CPT

Comment: *comments*

Response:

## 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<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 (cf. 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 77.0 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

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



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).

CL. Spermatophore diameter also increased with increasing CL with an asymptote at  $\sim 100$  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 (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 tonnes (1.202 million pounds) in 1977, and harvests peaked in 1983 when 164 vessels landed 4288 tonnes (9.454 million pounds) (Fitch et al. 2012; Table 1XX). 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 4990 tonnes (11.0 million pounds) as defined by the Fishery Management Plan 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 (Table XX2a). 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 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 tonnes (1.167 million pounds), closing again by regulation on 1 February 2010. Seven participating vessels landed a catch of 209 tonnes (460859 pounds) with a reported effort of 10697 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, prompting ADF&G to close the fishery again for the 2013/14 season. Due to abundance an above thresholds, the fishery was reopened for the 2014/15 season with a low TAC of 297 tonnes (0.655 million pounds) and in 2015/16 the TAC was further reduced to 186 tonnes (0.411 million pounds).

Though historical observer data are limited due to very limited sampling, 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 3XX), with total male discard mortality in the 2012/13 directed fishery estimated at about 12% (88 tonnes or 0.193 million pounds) of the reported retained catch weight, assuming 20% handling mortality. On the other hand, these same data suggest a significant 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, and observers recorded no bycatch of blue king crab in sampled pot lifts during 2013/14. 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 5XX).

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

## D. Data

### Summary of New Information

Data used in this assessment have been updated to include the most recently available fishery and survey numbers. In addition, this assessment makes use of an updated trawl-survey time series provided by R. Foy in August 2015, as well as updated 1993-2014 groundfish bycatch estimates based on AKRO data also supplied by R. Foy. The data extent and availability used in each of the Gmacs models is shown in Figure 3).

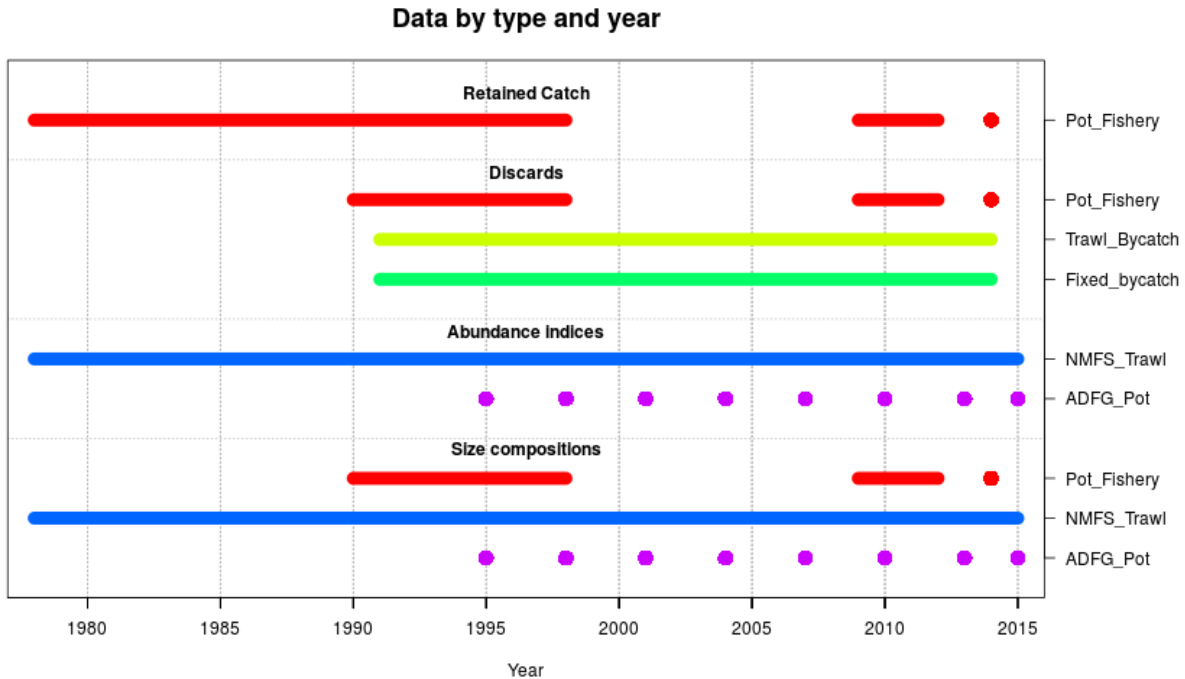


Figure 3: Data extent for the SMBKC assessment.

### 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; Table 1XX); results from the annual NMFS eastern Bering Sea trawl survey (1978-2015; Table 2XX); results from the triennial ADF&G SMBKC pot survey (every third year during 1995-2013) and 2015 pot survey (Table 1); size-frequency information from ADF&G crab-observer pot-lift sampling (1990/91-1998/99, 2009/10-2012/13, and 2014/15; Table XX3); and NMFS groundfish-observer bycatch biomass estimates (1992/93-2014/15; Table XX5). 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 where the other is not represented (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). Note that for this assessment the newly available NMFS groundfish observer data reported by ADF&G statistical area was not used.



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



Table 1: 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 six triennial ADF&G SMBKC pot surveys. Source: D. Pengilly and R. Gish, 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

## Other Data Sources

As with the most recent model configuration developed for this assessment, this version makes use of a growth transition matrix based on Otto and Cummiskey (1990). Other relevant data sources, including assumed population and fishery parameters, are presented in Appendix A, which provides a detailed description of the Gmacs model configuration used for this assessment.

## Excluded Data Sources

Groundfish bycatch size-frequency data are available for selected years. These data were used in model-based assessments prior to 2011. However, they have since been excluded because these data tend to be severely limited: for example, 2012/13 data include a total of just 4 90-mm+ CL male blue king crab from reporting areas 521 and 524.

## 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 (2010 SAFE; 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 of 90 mm or above 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 at least 105 mm CL are considered mature, whereas 120 mm CL is considered a proxy for the legal size of 5.5 in carapace width, including spines. Additional motivation for these stage definitions comes from an estimated average growth increment of about 14 mm per molt for SMBKC (Otto and Cummiskey 1990).

Concerns about the pre-2011 assessment model led to the CPT and SSC recommendations that included development of an alternative model with provisional assessment based on survey biomass or some other index of abundance. An alternative 3-stage model was proposed to the CPT in May 2011 but was requested to proceed with a survey-based approach for the Fall 2011 assessment. In May 2012 the CPT approved a slightly revised and better documented version of the alternative model for assessment.

The 2015 SMBKC stock assessment model, first used in Fall 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 at least 90 mm in CL, but it 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.

## Assessment Methodology

The 2016 SMBKC assessment model makes use of the modeling framework Gmacs. The aim when developing this model was to provide a fit to the data that best matched the 2015 SMBKC stock assessment model. A detailed description of the Gmacs model and its implementation is presented in Appendix A.

## Model Selection and Evaluation

Four different Gmacs model scenarios were considered. In this document results from these models and the 2015 model are compared.

1. **2015 Model:** model output from 2015 provided by Jie.
2. **Gmacs base:** tries to match as closely as possible the 2015 Model.
3. **Gmacs selex:** directed pot, NMFS trawl survey and ADF&G pot survey selectivities are estimated for stage-1 and stage-2 crab.
4. **Gmacs CV:** additional CV is estimated for the ADF&G pot survey as well as estimating the directed pot, NMFS trawl survey and ADF&G pot survey selectivities for stage-1 and stage-2 crab.
5. **Gmacs M:** natural mortality ( $M$ ) is fixed at  $0.18 \text{ yr}^{-1}$  during all years as well as estimating the directed pot, NMFS trawl survey and ADF&G pot survey selectivities for stage-1 and stage-2 crab.

## Results

Preliminary results for the Gmacs configuration are provided here with comparisons to the 2015 model.

- a. Effective sample sizes.

Observed and estimated effective sample sizes are compared in Table XX.

- b. Tables of estimates.

Model parameter estimates are summarized in Tables 2, 3, 4, and 5. Negative log likelihood values and management measures for the four Gmacs scenarios are compared in Table 6. Estimated abundances by stage and mature male biomasses for three of the scenarios are listed in Tables 7, 8, and 9.

The scenarios that estimated selectivities fit the data better. Scenarios with additional CV for the pot survey CPUE fit the trawl survey data better and result in higher abundance and biomass estimates in most recent years. Estimated directed pot and trawl survey selectivities  $> 1.0$  for stage-2 crab are also troublesome.

- c. Graphs of estimates.

Estimated (and fixed) selectivities are compared in Figure 7 and molting probabilities are shown in Figure 8. The various model fits to total male ( $> 89$  mm CL) trawl survey biomass are compared in Figure 9, and the fits to pot survey CPUE are compared in Figure 10. Standardized residuals of total male trawl survey biomass and pot survey CPUE are plotted in Figure 12. Fits to stage compositions for trawl survey, pot survey, and commercial observer data are shown in Figures 13, 14, and 15 for the all scenarios. Bubble plots of stage composition residuals for trawl survey, pot survey, and commercial observer data are shown in Figures 16, 17, and 18 for the Gmacs base model. Fits to retained catch biomass and bycatch death biomass are shown for all Gmacs scenarios in Figure 19. Estimated recruitment and mature male biomass are compared in Figures 20 and 21, respectively.

d. Graphic evaluation of the fit to the data.

Model estimated relative survey biomasses are different in each of the scenarios. The Gmacs base model has a comparatively low biomass in the early years compared with the other scenarios, including the 2015 model (Figure 9). The Gmacs CV scenario that includes additional CV for the pot survey CPUE results in much higher biomass estimates in recent years (Figure 9). Estimated pot survey CPUEs are also dependent on scenarios, and the difference among scenarios are very similar to the relative survey biomasses (Figure 10).

Estimated recruitment to the model is variable over time (Figure 20). Estimated recruitment during recent years is generally low in all scenarios. Estimated mature male biomasses on 15 February also fluctuates strongly over time; the high biomass estimates in recent years for the Gmacs CV scenario is quite different to the other scenarios (Figure 21).

e. Retrospective and historic analyses. Gmacs retrospective analyses under development.

f. Uncertainty and sensitivity analyses.

Estimated standard deviations of parameters for the four Gmacs scenarios are summarized in Tables 2, 3, 4, and 5. Probabilities for mature male biomass and OFL in 2015 are illustrated in section “F. Calculation of the OFL”.

g. Comparison of alternative model scenarios.

Discussion to come

## 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

$$F_{OFL} = \begin{cases} F_{MSY}, & \text{when } B/B_{MSY} > 1 \\ F_{MSY} \frac{(B/B_{MSY} - \alpha)}{(1 - \alpha)}, & \text{when } \beta < B/B_{MSY} \leq 1 \end{cases} \quad (2)$$

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

where  $B$  is quantified as mature-male biomass (MMB) at mating with time of mating assigned a nominal date of 15 February. Note that as  $B$  itself is a function of the fishing mortality  $F_{OFL}$ , in case b) numerical approximation of  $F_{OFL}$  is required. As implemented for this assessment, all calculations proceed according to the model equations given in Appendix A. In particular, the OFL catch is computed using equations A3,

A4, and A5, with  $F_{OFL}$  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 1978-2015, to define a  $B_{MSY}$  proxy in terms of average estimated MMB and to put  $\gamma = 1.0$  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, and MMB in 2015 for 18 scenarios are summarized in Table 10XX. ABC is 80% of the OFL.

OFL, ABC, retained catch and bycatches for 2015 are summarized for scenarios 10 and 10-4 below:

## G. Rebuilding Analysis

This stock is not currently subject to a rebuilding plan.

## H. Data Gaps and Research Priorities

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

With the decline of estimated population biomass during recent years, outlook for this stock is not promising. If the decline continues, the stock will fall to depleted status soon.

## 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.

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Table 2: Model parameter estimates and standard deviations (SD) for the **Gmacs base** model.

Parameter	Estimate	SD
Natural mortality ( $M$ ) deviation in 1998/99	1.8054000	0.1074600
$\log(R_0)$	13.5960000	0.0519520
$\log(\bar{R})$	13.6910000	0.1229600
$\log(N_1)$	14.6210000	0.1684500
$\log(N_2)$	14.1760000	0.1899200
$\log(N_3)$	13.8250000	0.2055600
ADF&G pot survey catchability ( $q$ )	0.0000043	0.0000003
$\bar{F}_{\text{pot}}$	-1.3747000	0.0536940
$\bar{F}_{\text{trawl bycatch}}$	-11.6890000	0.0833040
$\bar{F}_{\text{fixed bycatch}}$	-9.5781000	0.0835810

Table 3: Model parameter estimates and standard deviations (SD) for the **Gmacs selex** model that estimates stage-1 and stage-2 selectivity.

Parameter	Estimate	SD
Natural mortality ( $M$ ) deviation in 1998/99	1.5947000	0.1354000
$\log(R_0)$	13.5320000	0.0538760
$\log(\bar{R})$	13.6250000	0.1238100
$\log(N_1)$	14.7360000	0.1699300
$\log(N_2)$	14.3040000	0.2017300
$\log(N_3)$	14.2290000	0.2084800
ADF&G pot survey catchability ( $q$ )	0.0000040	0.0000003
$\log(\bar{F}_{\text{pot}})$	-1.4963000	0.0563790
$\log(\bar{F}_{\text{trawl bycatch}})$	-11.6930000	0.0828660
$\log(\bar{F}_{\text{fixed bycatch}})$	-9.5847000	0.0830210
Stage-1 directed pot selectivity 1978-2008	-0.7176300	0.1759200
Stage-2 directed pot selectivity 1978-2008	-0.3821800	0.1269500
Stage-1 directed pot selectivity 2009-2015	-0.7424500	0.1879900
Stage-2 directed pot selectivity 2009-2015	0.1526600	0.0955460
Stage-1 NMFS trawl selectivity	-0.1540100	0.0714200
Stage-2 NMFS trawl selectivity	0.1827200	0.0587180
Stage-1 ADF&G pot selectivity	-0.8813900	0.1383800
Stage-2 ADF&G pot selectivity	-0.0695420	0.0819370

Table 4: Model parameter estimates and standard deviations (SD) for the **Gmacs CV** model that estimates stage-1 and stage-2 selectivity.

Parameter	Estimate	SD
Natural mortality ( $M$ ) deviation in 1998/99	1.8464000	0.1718500
$\log(R_0)$	13.6500000	0.0598450
$\log(\bar{R})$	13.7430000	0.1265400
$\log(N_1)$	14.7180000	0.1695900
$\log(N_2)$	14.2700000	0.2007900
$\log(N_3)$	14.1570000	0.2092000
ADF&G pot survey catchability ( $q$ )	0.0000034	0.0000004
$\log\text{AddCV}$	-1.7807000	0.1827300
$\log(\bar{F}_{\text{pot}})$	-1.5200000	0.0562760
$\log(\bar{F}_{\text{trawl bycatch}})$	-11.7250000	0.0845790
$\log(\bar{F}_{\text{fixed bycatch}})$	-9.6169000	0.0846910
Stage-1 directed pot selectivity 1978-2008	-0.7201700	0.1759500
Stage-2 directed pot selectivity 1978-2008	-0.3855500	0.1274000
Stage-1 directed pot selectivity 2009-2015	-0.9639300	0.1902100
Stage-2 directed pot selectivity 2009-2015	0.0341370	0.0955080
Stage-1 NMFS trawl selectivity	-0.2131800	0.0681820
Stage-2 NMFS trawl selectivity	0.1420300	0.0566140
Stage-1 ADF&G pot selectivity	-1.0710000	0.1344600
Stage-2 ADF&G pot selectivity	-0.1620700	0.0813780

Table 5: Model parameter estimates and standard deviations (SD) for the **Gmacs M** model that estimates stage-1 and stage-2 selectivity.

Parameter	Estimate	SD
$\log(R_0)$	13.3650000	0.0523920
$\log(\bar{R})$	13.4580000	0.1231200
$\log(N_1)$	14.7670000	0.1699600
$\log(N_2)$	14.3540000	0.2027600
$\log(N_3)$	14.3890000	0.2024100
ADF&G pot survey catchability ( $q$ )	0.0000047	0.0000003
$\log(\bar{F}_{\text{pot}})$	-1.4553000	0.0574300
$\log(\bar{F}_{\text{trawl bycatch}})$	-11.6130000	0.0811320
$\log(\bar{F}_{\text{fixed bycatch}})$	-9.5048000	0.0812590
Stage-1 directed pot selectivity 1978-2008	-0.5798400	0.1835900
Stage-2 directed pot selectivity 1978-2008	-0.3456700	0.1280600
Stage-1 directed pot selectivity 2009-2015	-0.7206600	0.1889300
Stage-2 directed pot selectivity 2009-2015	0.1360500	0.0951510
Stage-1 NMFS trawl selectivity	-0.0350400	0.0702790
Stage-2 NMFS trawl selectivity	0.2851200	0.0629400
Stage-1 ADF&G pot selectivity	-0.8312000	0.1428100
Stage-2 ADF&G pot selectivity	0.0187320	0.0817210



Table 6: Comparisons of negative log-likelihood values and management measures for the four Gmacs model scenarios. Biomass and OFL are in tonnes.

Component	Gmacs base	Gmacs selex	Gmacs CV	Gmacs M
Pot Retained Catch	-66.34	-66.87	-67.07	-66.63
Pot Discarded Catch	8.86	3.89	4.13	4.15
Trawl bycatch Discarded Catch	-6.61	-6.61	-6.61	-6.61
Fixed bycatch Discarded Catch	-6.55	-6.59	-6.60	-6.60
NMFS Trawl Survey	24.60	26.48	24.82	34.06
ADF&G Pot Survey CPUE	68.94	57.18	9.36	60.89
Directed Pot LF	-11.41	-11.86	-12.01	-11.60
NMFS Trawl LF	19.74	12.70	0.73	14.03
ADF&G Pot LF	-1.30	-4.98	-7.80	-3.89
Recruitment deviations	38.02	38.64	36.17	42.13
F penalty	9.53	9.53	9.53	9.52
M penalty	6.48	6.47	6.48	0.00
Prior	16.43	21.97	34.22	21.97
Total	100.39	79.94	25.35	91.44
Total estimated parameters	276.00	284.00	285.00	282.00
MMB2015	3294.92	2612.73	4088.82	2122.75
Foff	0.37	0.36	0.37	0.32

Table 7: Population abundances (N) by crab stage in numbers of crab and mature male biomass (MMB) at survey in tonnes on 15 February for the **2015 model**. All abundances are at time of survey (season 3).

Year	$N_1$	$N_2$	$N_3$	MMB
1978	3782350	2419470	1678340	4562
1979	4841660	2943230	2203410	6295
1980	4218520	3805080	3265810	9501
1981	1755600	3733730	4603820	9721
1982	1876200	2216680	4779900	7070
1983	1012660	1760260	3409680	4368
1984	866184	1107100	2020700	3067
1985	1278900	837916	1498640	2826
1986	1895780	998129	1282260	2845
1987	1865030	1417950	1371850	3415
1988	1653320	1538130	1646100	3835
1989	2648820	1454690	1888610	4405
1990	1719180	2008780	2082160	4853
1991	2467290	1643490	2389520	4531
1992	2717060	1930930	2162950	4689
1993	2969560	2176260	2269050	5095
1994	1744630	2393860	2398840	5034
1995	1847540	1751950	2431880	4911
1996	2150610	1618910	2310670	4502
1997	1306420	1746730	2143670	3901
1998	852401	1283640	1799810	1923
1999	456270	415120	691298	1623
2000	479496	405329	785188	1775
2001	479076	415779	858978	1913
2002	215485	418944	925671	2031
2003	453805	265868	982790	1970
2004	293347	353951	953565	2012
2005	656367	289723	973699	1980
2006	970389	480511	958382	2150
2007	716526	727161	1040240	2492
2008	1251670	646712	1205010	2748
2009	1129620	946953	1329280	3024
2010	1057710	967554	1482740	2821
2011	896425	919677	1431650	2454
2012	581850	802819	1230770	2106
2013	681566	586163	1061620	2440
2014	619320	594288	1180390	2482
2015	496048	557095	1218120	2680

Table 8: Population abundances (N) by crab stage in numbers of crab, mature male biomass (MMB) at survey in tonnes on 15 February for the **Gmacs base** model. All abundances are at time of survey (season 3).

Year	$N_1$	$N_2$	$N_3$	MMB
1978	3255149	1745630	1402666	2540
1979	2644323	2426526	2316986	4286
1980	1126235	2304998	3382846	6688
1981	992395	1402492	3189705	6585
1982	738746	1027667	1793731	3630
1983	686101	759715	1919257	3950
1984	904924	641076	1323143	2687
1985	1195419	726109	1136628	2244
1986	1247549	919252	1239376	2404
1987	1177020	1012785	1420834	2781
1988	2478039	1003699	1567211	3108
1989	1624299	1739571	1837592	3420
1990	1753294	1498261	2229010	4431
1991	1844115	1490948	2156035	4249
1992	2110962	1540151	2254818	4441
1993	1667104	1708314	2314273	4514
1994	1774896	1512107	2237756	4441
1995	1643871	1508342	2226850	4396
1996	1051184	1432808	2207393	4381
1997	726449	1071149	1855845	3751
1998	411807	307249	602573	2050
1999	447247	335454	697335	1406
2000	380578	365047	794366	1606
2001	185139	336910	883787	1811
2002	315210	216591	925447	1940
2003	260489	250556	911773	1884
2004	453670	230839	912654	1897
2005	792862	334026	921958	1878
2006	462221	560227	1013160	2003
2007	983955	441893	1157051	2379
2008	984234	704348	1281965	2539
2009	953135	791217	1427153	2849
2010	922034	802140	1416114	2832
2011	605101	789025	1286841	2561
2012	755064	604702	1194961	2430
2013	718195	628941	1375098	2784
2014	571248	616058	1474058	3003
2015	798892	528358	1596489	3295

Table 9: Population abundances (N) by crab stage in numbers of crab, mature male biomass (MMB) at survey in tonnes on 15 February for **Gmacs selex** model. All abundances are at time of survey (season 3).

Year	$N_1$	$N_2$	$N_3$	MMB
1978	3465373	1964705	1947297	3648
1979	2536619	2618435	2902462	5494
1980	1051793	2307355	3958354	7940
1981	940958	1361011	3665119	7617
1982	697350	984761	2166901	4438
1983	660298	722005	2205414	4570
1984	906428	613951	1542269	3161
1985	1250828	717992	1306748	2607
1986	1246128	948035	1382828	2699
1987	1173316	1021507	1555205	3069
1988	2713984	1004487	1683754	3358
1989	1713304	1873833	1958062	3630
1990	1749939	1593249	2406435	4792
1991	1897122	1520517	2353506	4671
1992	2123490	1580072	2440744	4828
1993	1513175	1728658	2492652	4892
1994	1708295	1431431	2385679	4788
1995	1523346	1443828	2305282	4577
1996	846351	1343005	2231059	4456
1997	608756	925099	1815520	3706
1998	375028	321482	695554	2117
1999	410848	319294	778655	1587
2000	382349	339026	850663	1734
2001	199403	329307	917857	1883
2002	333229	222176	951435	1992
2003	252872	262636	938020	1937
2004	504902	230513	939940	1957
2005	766339	363012	949483	1926
2006	591479	554782	1048223	2084
2007	997149	513201	1196986	2438
2008	879583	735450	1352537	2687
2009	843386	742152	1492631	3010
2010	712037	723663	1438516	2902
2011	460293	643783	1250433	2526
2012	533679	474383	1080360	2214
2013	464877	460078	1192498	2439
2014	413692	416296	1212432	2496
2015	725639	372754	1262169	2613



Figure 5: Catches of 181 male blue king crab measuring at least 90 mm CL from the 2014 NMFS trawl-survey at the 56 stations used to assess the SMBKC stock. Note that the area north of St. Matthew Island, which includes the large catch of 67 crab at station R-24, is not represented 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.

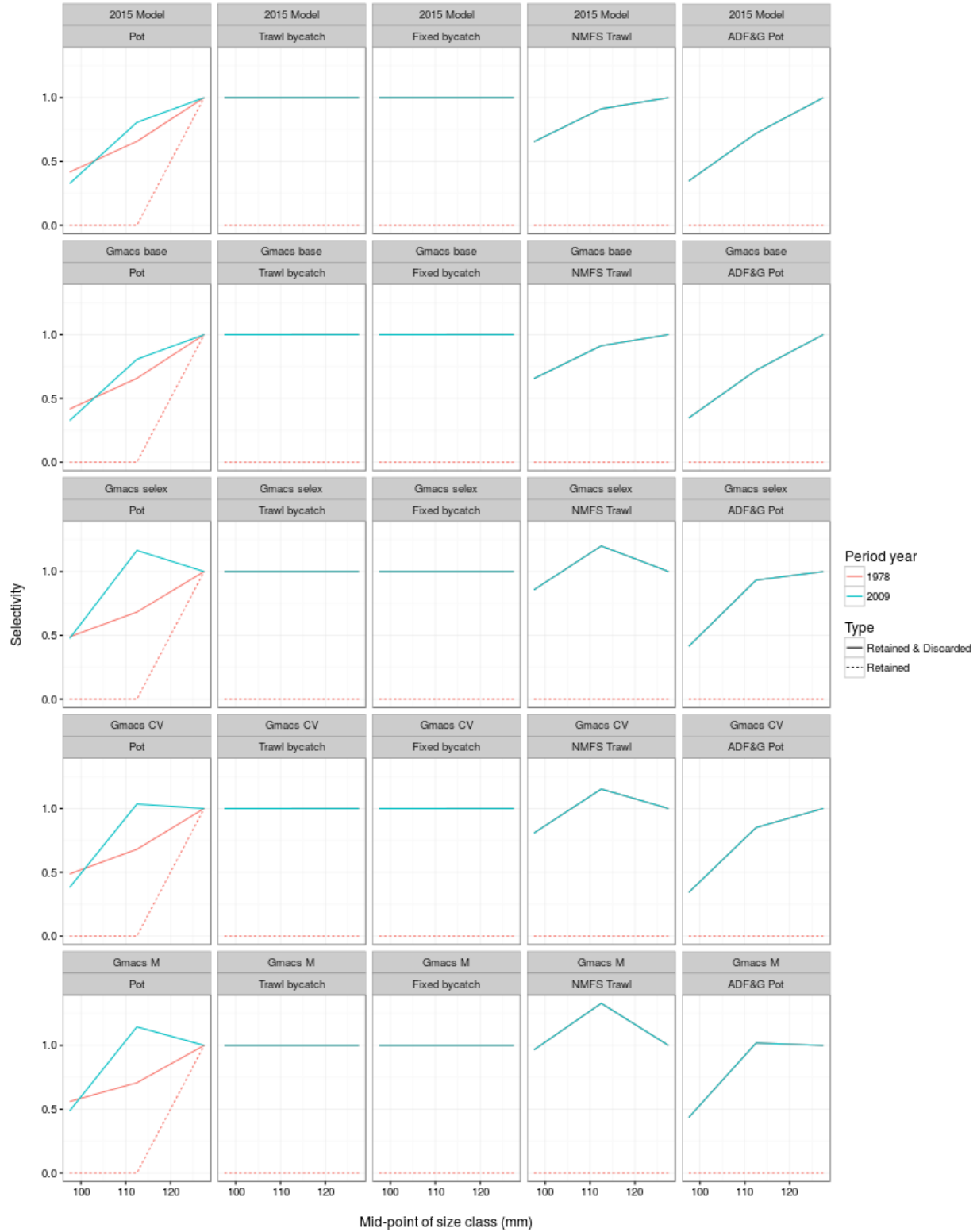


Figure 7: Estimated (and fixed to match the 2015 model selectivities in the Gmacs base scenario) stage-1 and stage-2 selectivities for each of the different model scenarios (the stage-3 selectivities are all fixed at 1). Estimated selectivities are shown for the directed pot fishery, the trawl bycatch 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 2009-2015.

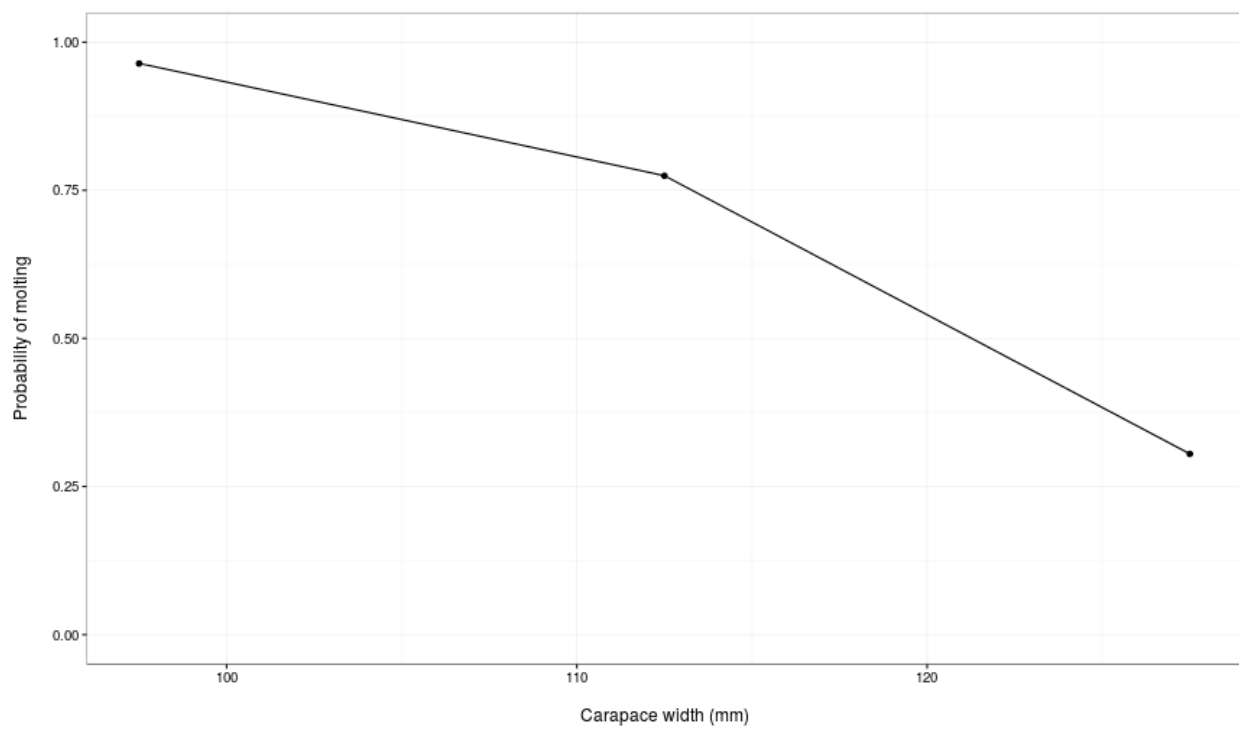


Figure 8: Molting probabilities by stage used in all of the Gmacs model scenarios.



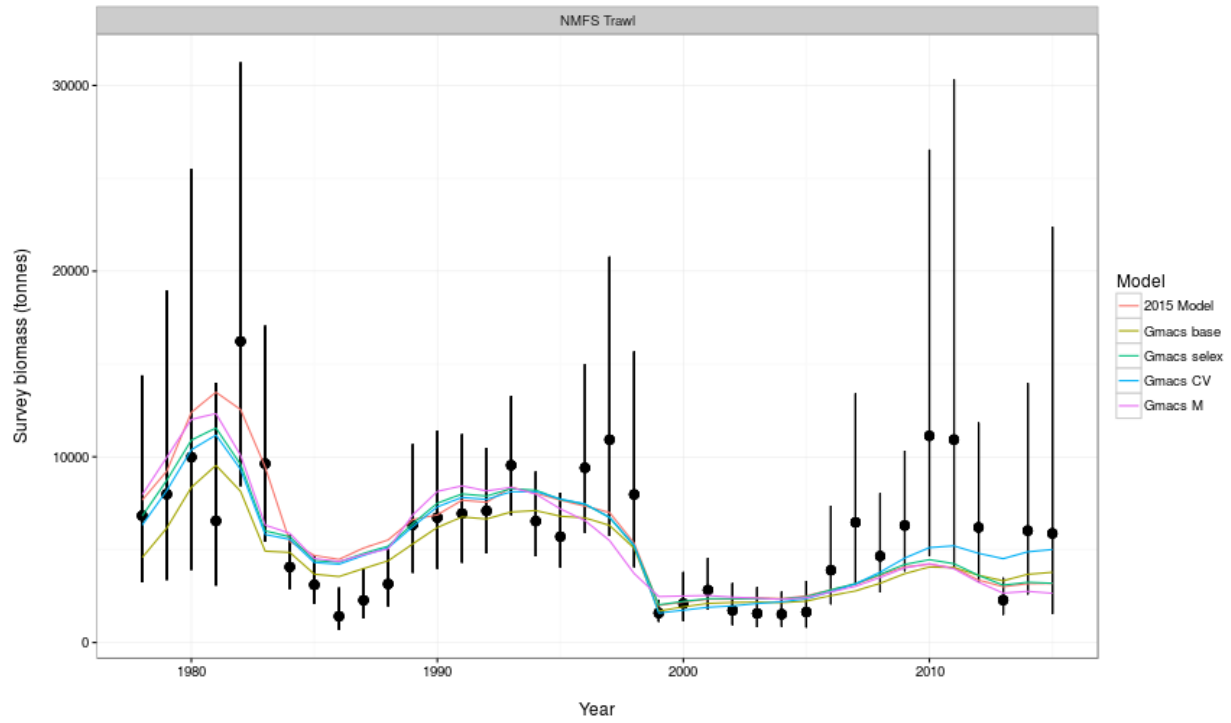


Figure 9: Comparisons of area-swept estimates of total male survey biomass (tonnes) and model predictions for the 2015 and each of the Gmacs model scenarios. The error bars are plus and minus 2 standard deviations.

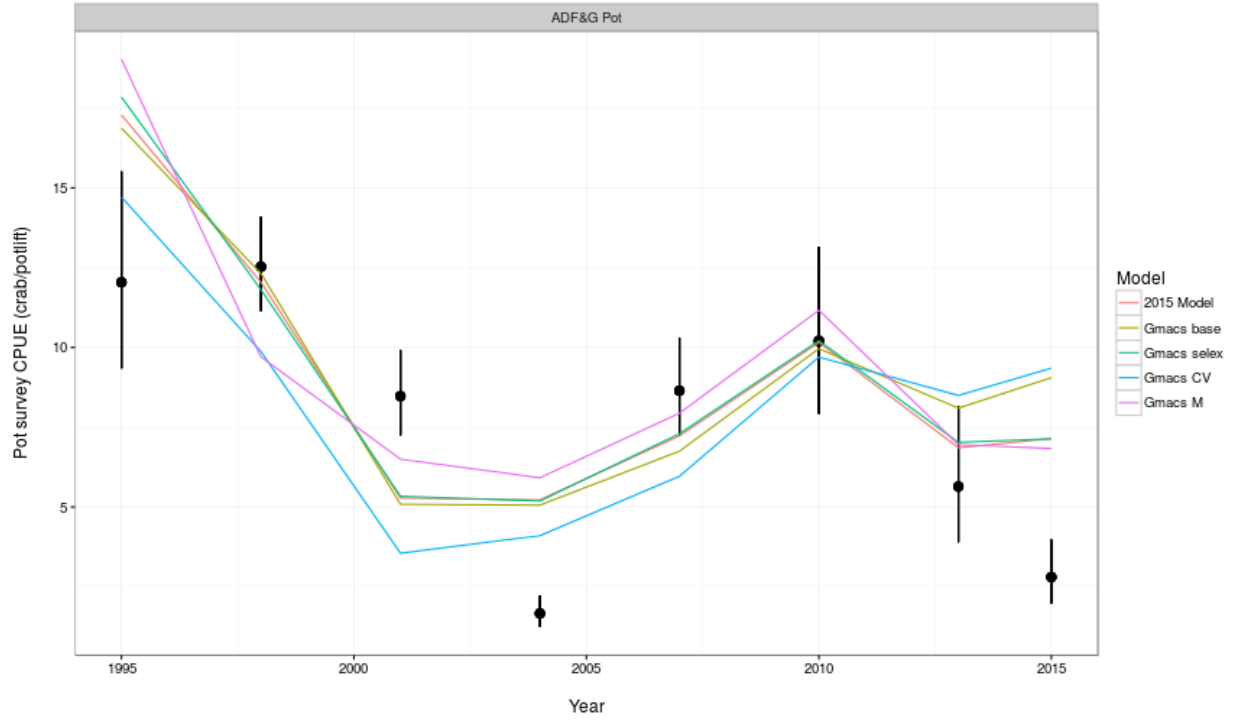


Figure 10: Comparisons of total male pot survey CPUEs and model predictions for 2016 model estimates without additional CV for the pot survey CPUE. The error bars are plus and minus 2 standard deviations.

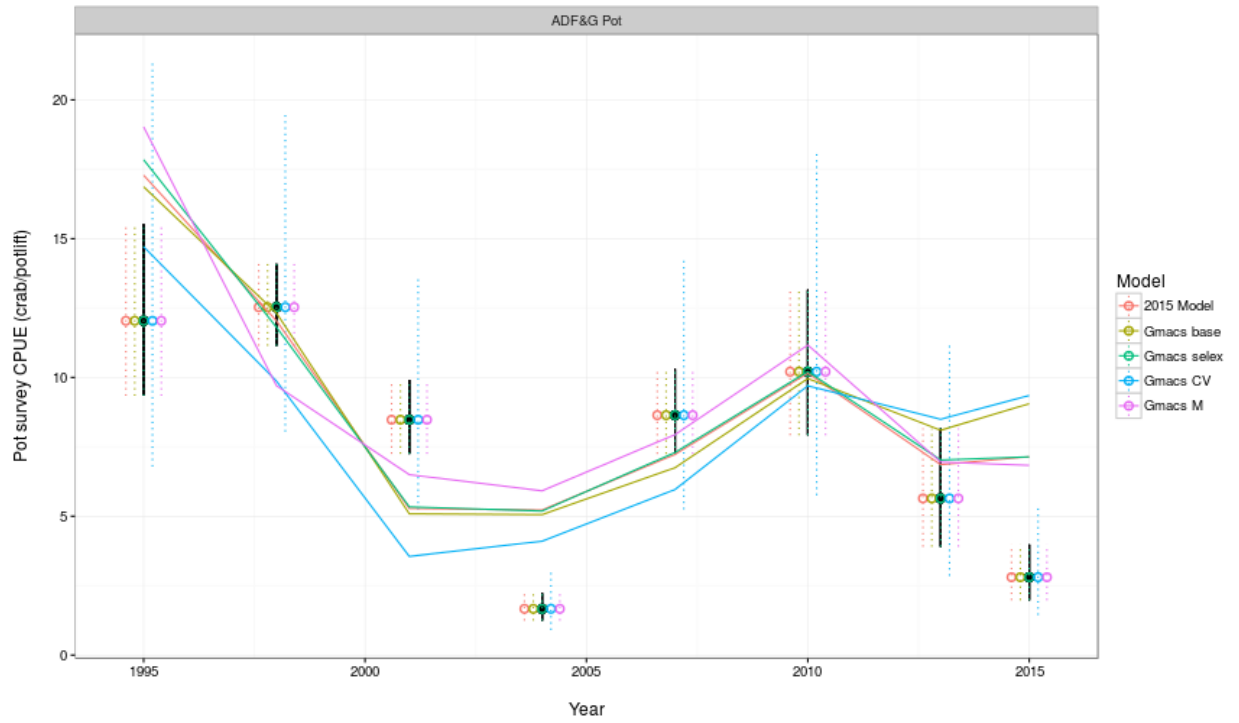


Figure 11: Comparisons of total male pot survey CPUEs and model predictions for 2016 model estimates without additional CV for the pot survey CPUE. The error bars are plus and minus 2 standard deviations.

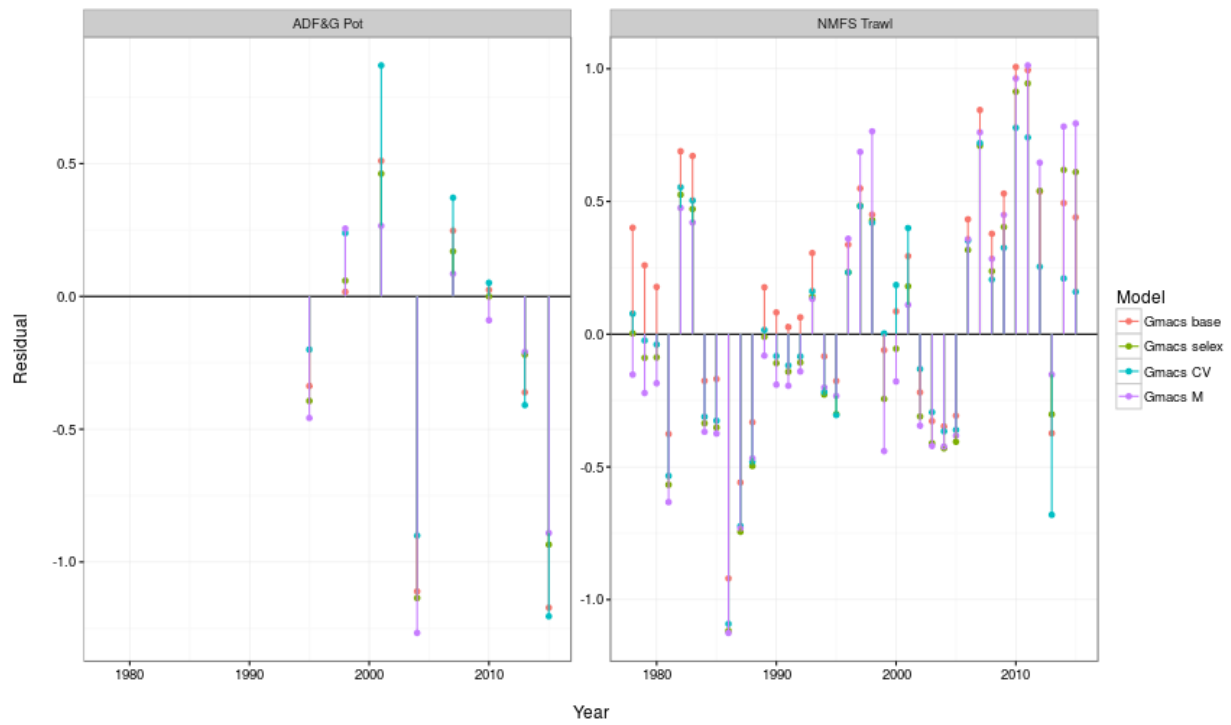


Figure 12: Standardized residuals for area-swept estimates of total male survey biomass and total male pot survey CPUEs for each of the Gmacs model scenarios.

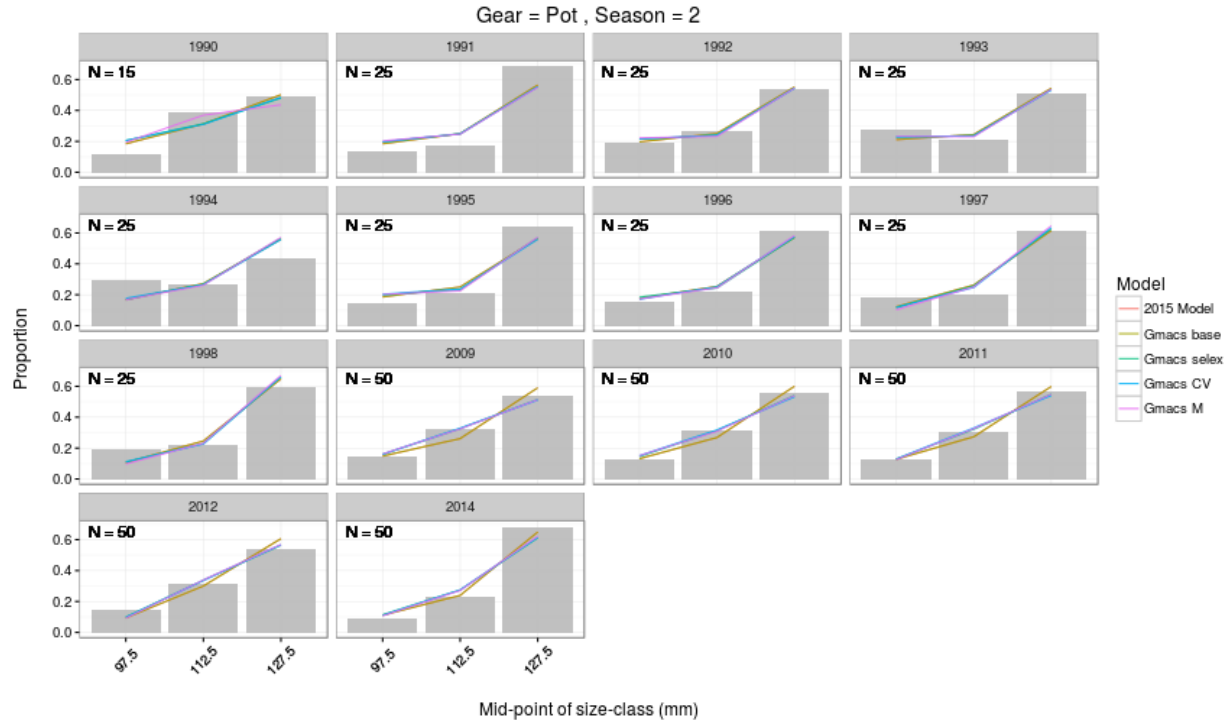


Figure 13: Observed and model estimated size-frequencies of SMBKC by year retained in the directed pot fishery for the 2015 model and each of the Gmacs model scenarios.

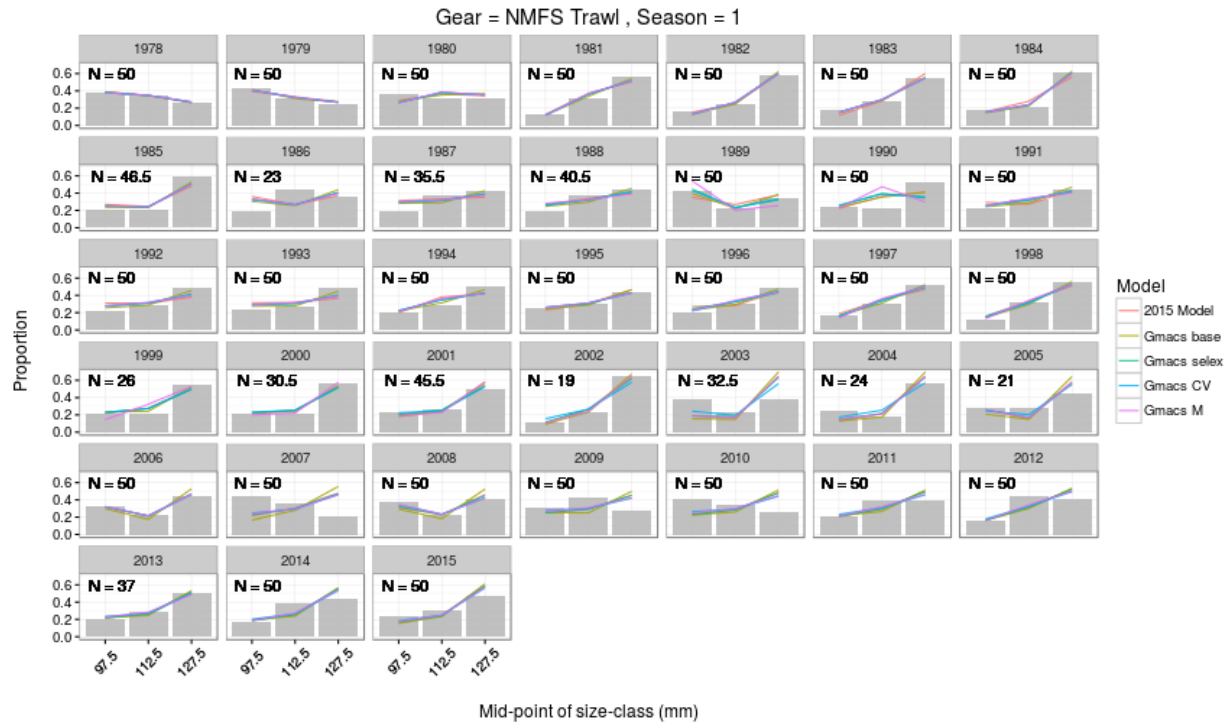


Figure 14: Observed and model estimated size-frequencies of discarded male SMBKC by year in the NMFS trawl survey for the 2015 model and each of the Gmacs model scenarios.

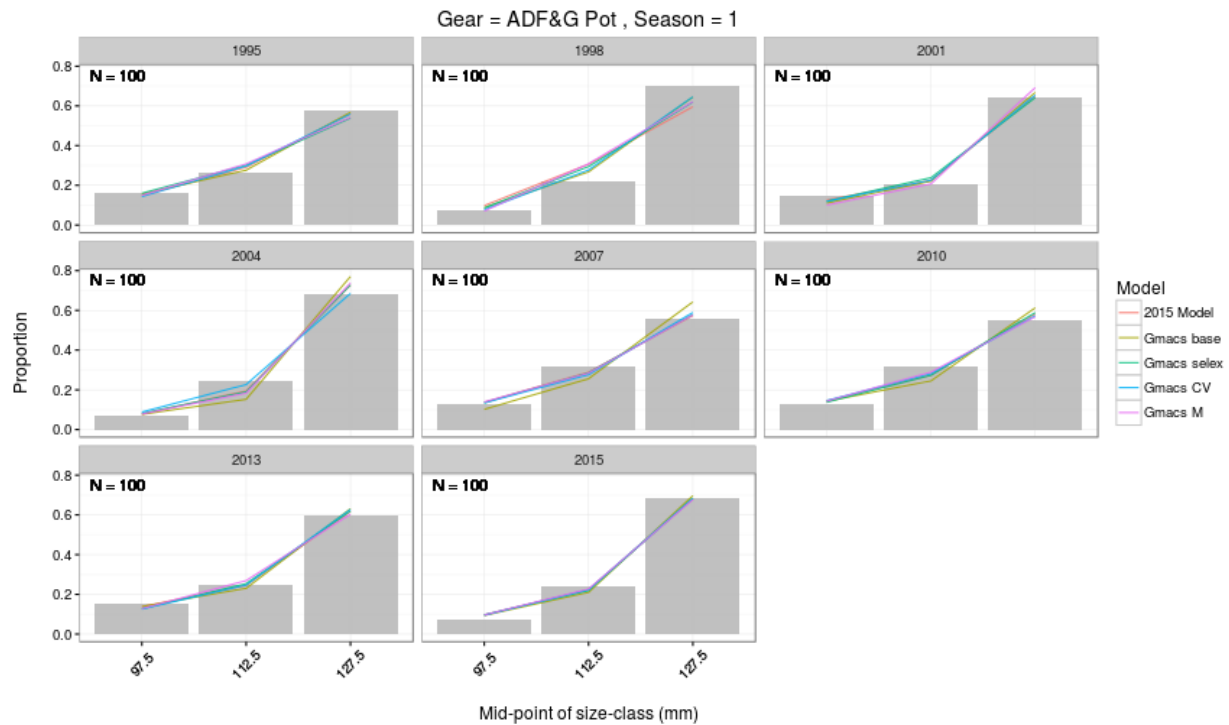


Figure 15: Observed and model estimated size-frequencies of discarded SMBKC by year in the ADF&G pot survey for the 2015 model and each of the Gmacs model scenarios.

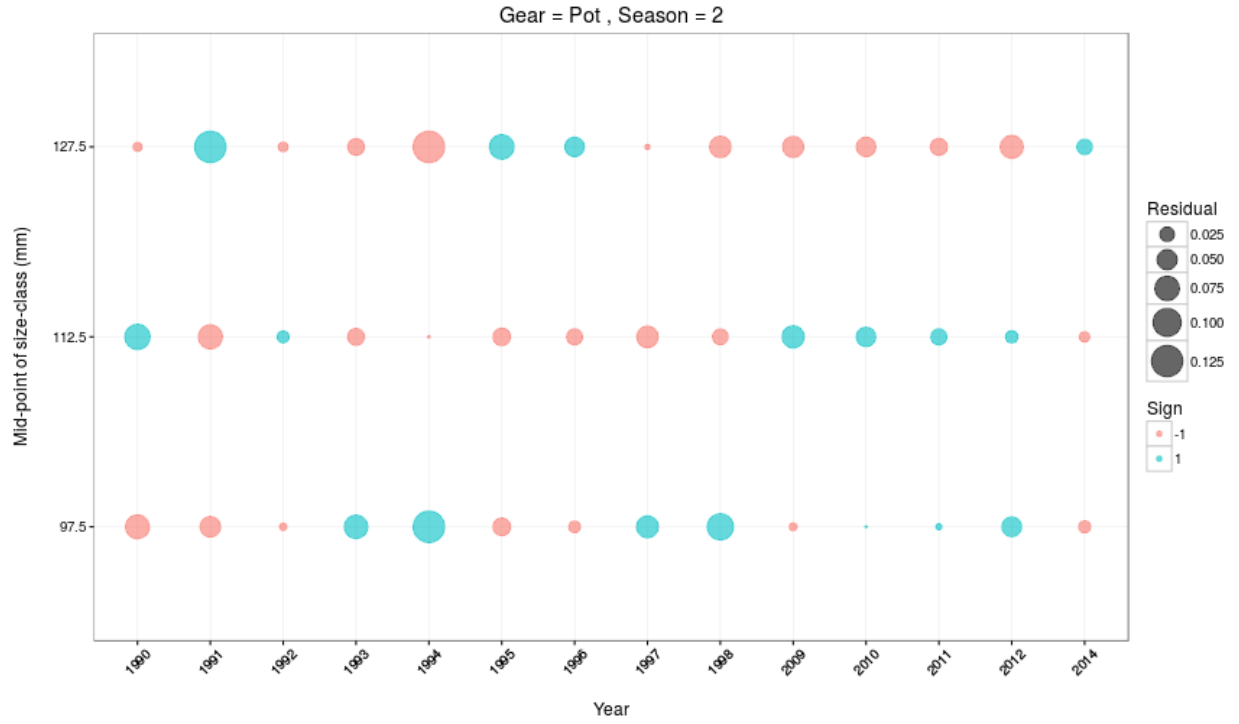


Figure 16: Bubble plots of residuals by stage and year for the directed pot fishery size composition data for St. Mathew Island blue king crab (SMBKC) in the **Gmacs base** model.

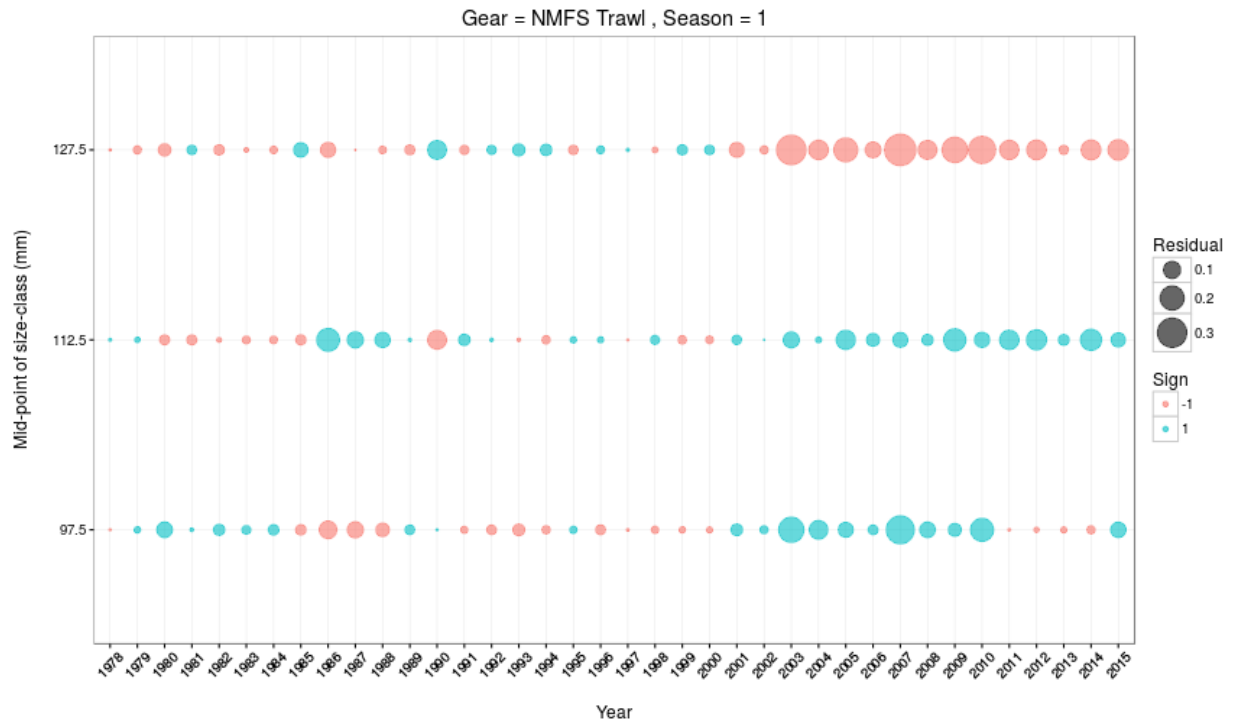


Figure 17: Bubble plots of residuals by stage and year for the NMFS trawl survey size composition data for St. Mathew Island blue king crab (SMBKC) in the **Gmacs base** model.

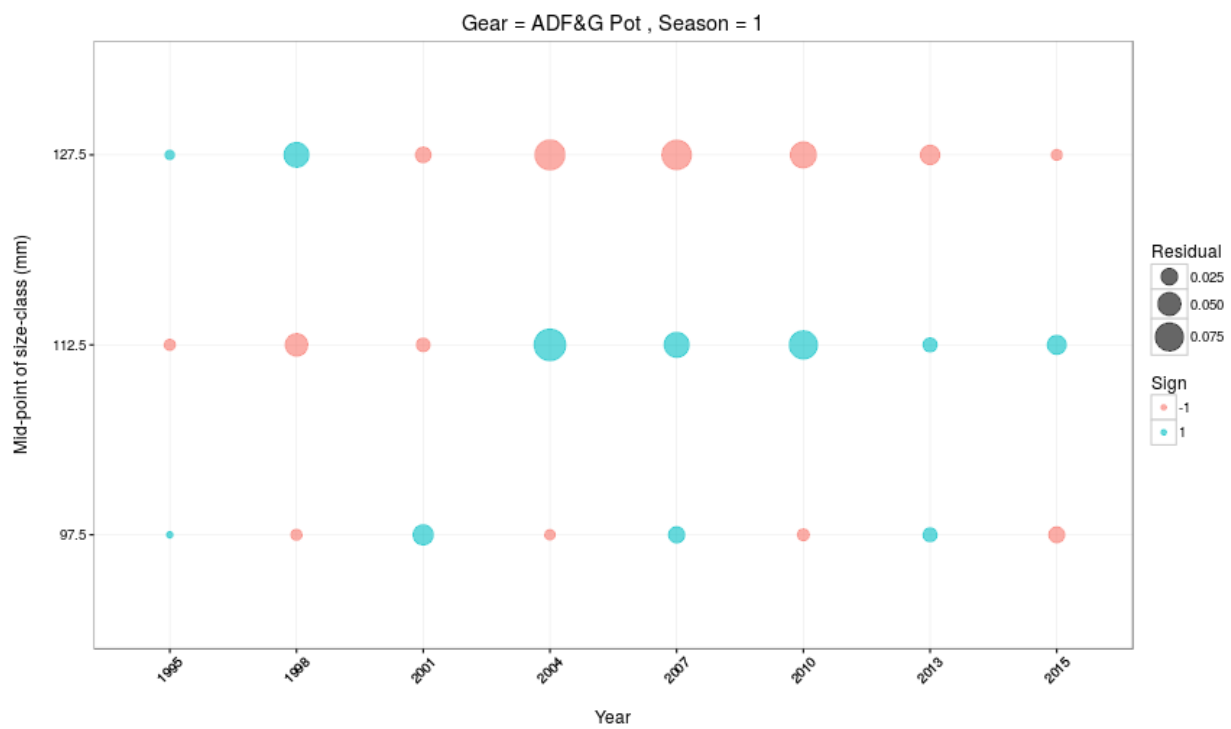


Figure 18: Bubble plots of residuals by stage and year for the ADF&G pot survey size composition data for St. Mathew Island blue king crab (SMBKC) in the **Gmacs base** model.

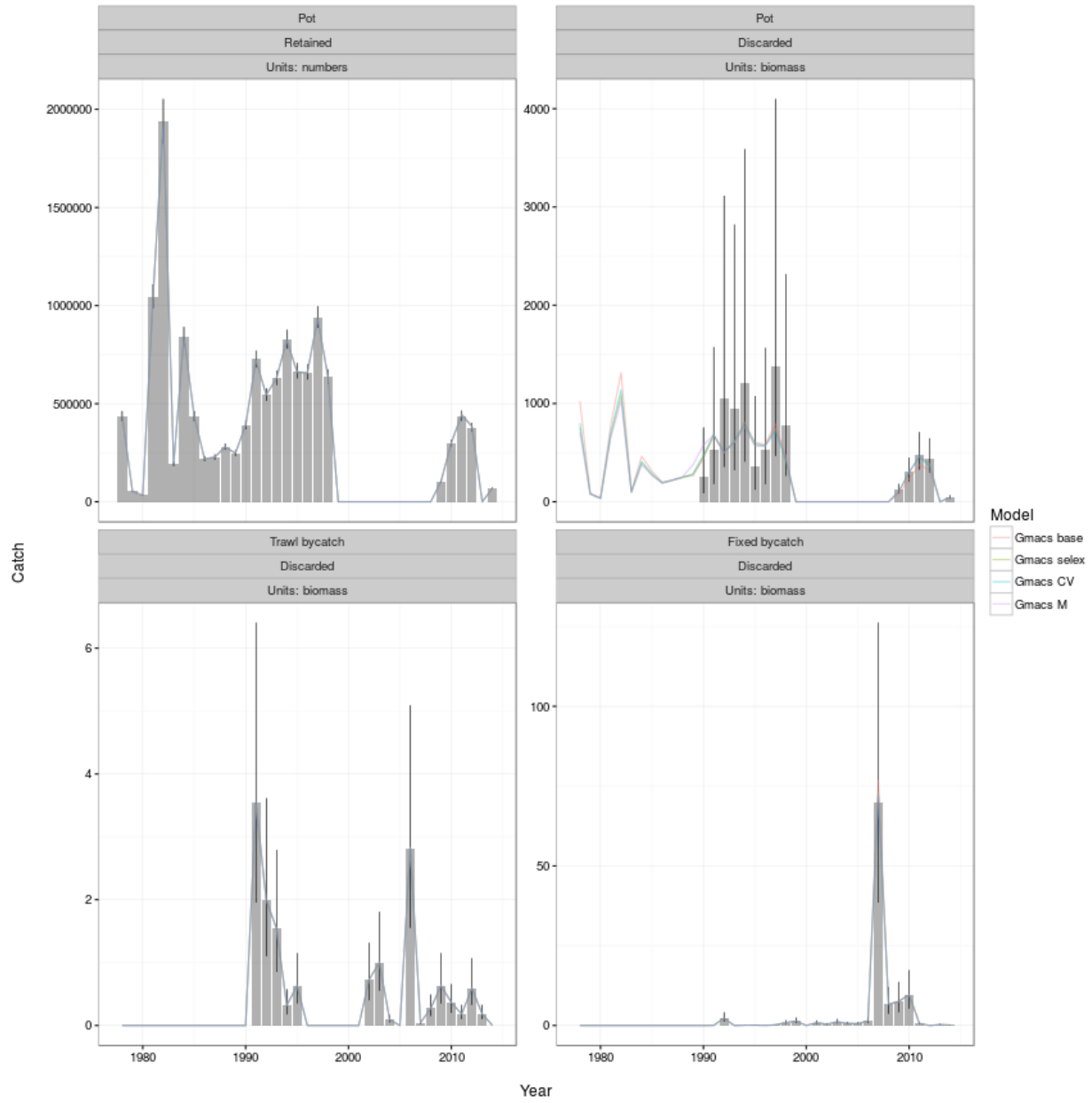


Figure 19: Comparison of observed and model predicted retained catch and bycatches in each of the Gmacs models. Note that difference in units between each of the panels.



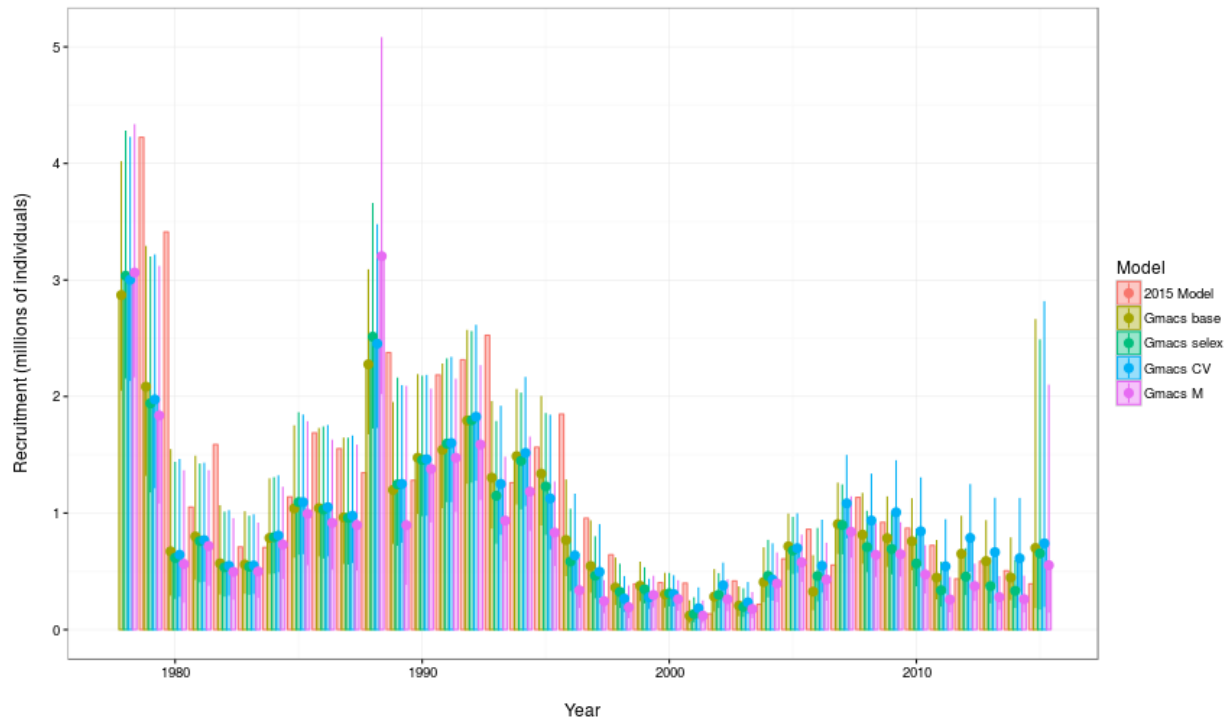


Figure 20: Estimated recruitment time series during 1979-2015 in each of the scenarios.

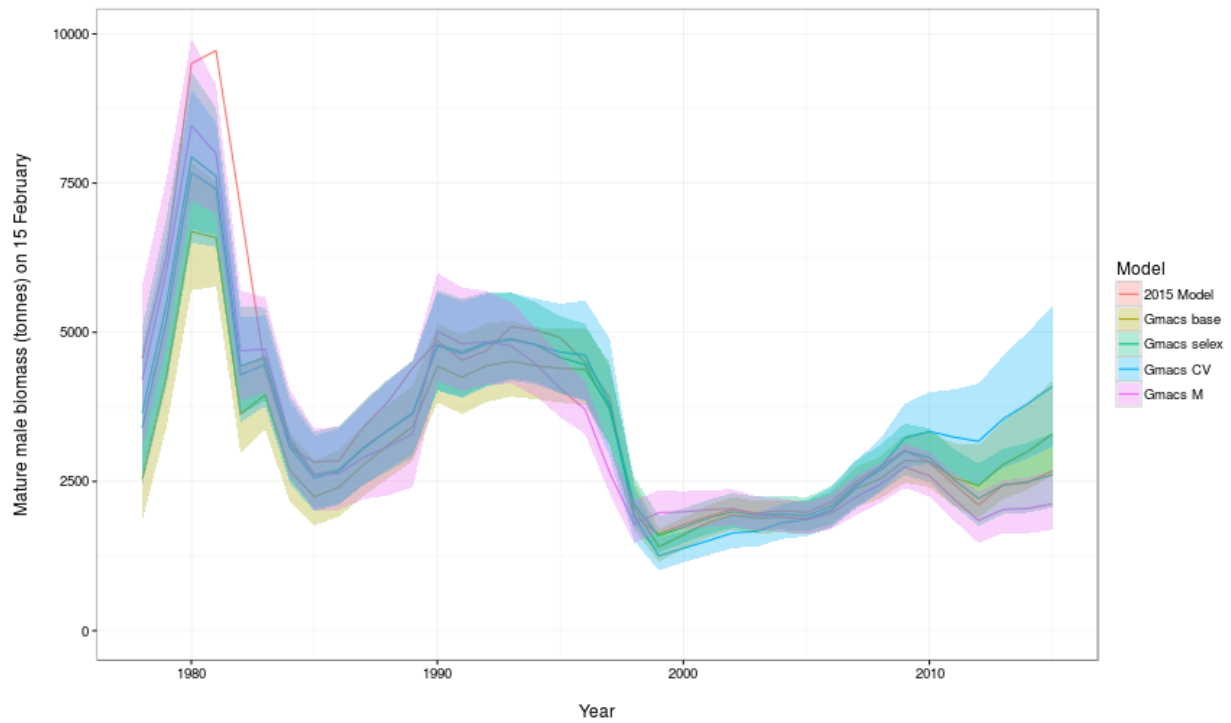


Figure 21: Estimated mature male biomass (MMB) time series on 15 February during 1978-2015 for each of the model scenarios.

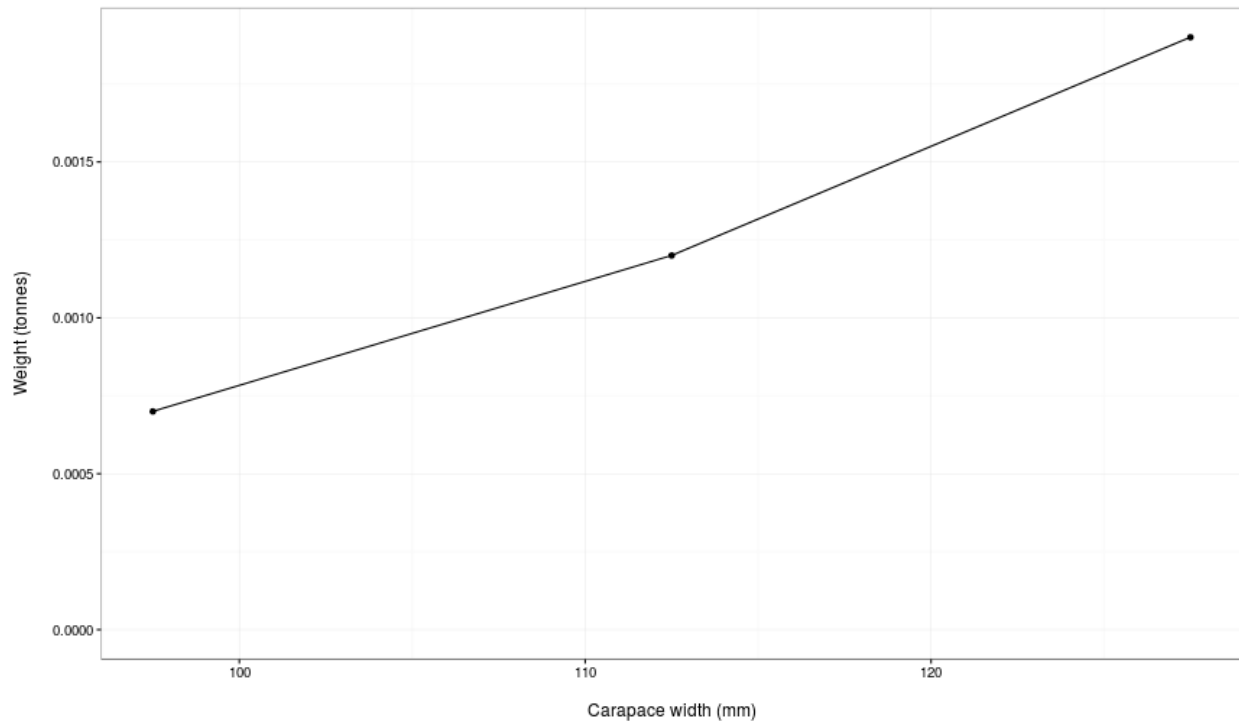


Figure 22: Relationship between carapace width (mm) and weight (kg) in all of the models (provided as a vector of weights at length to Gmacs).

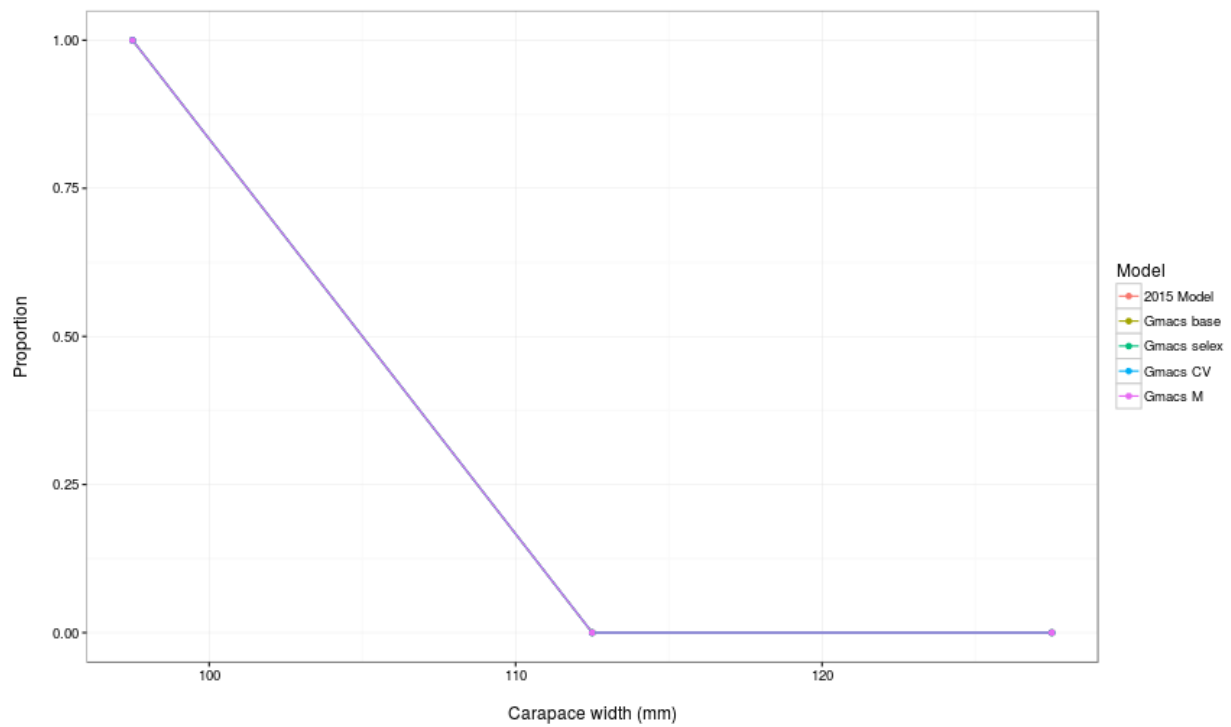


Figure 23: Distribution of carapace width (mm) at recruitment.

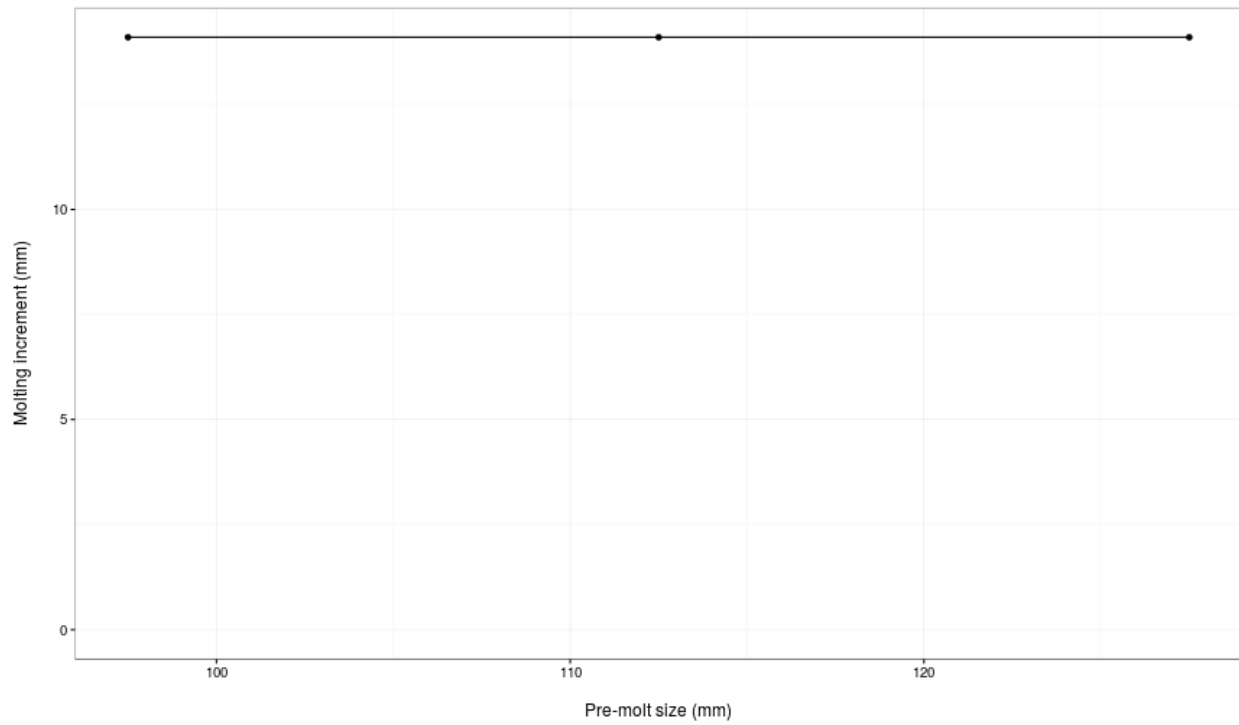


Figure 24: Growth increment (mm) each molt.

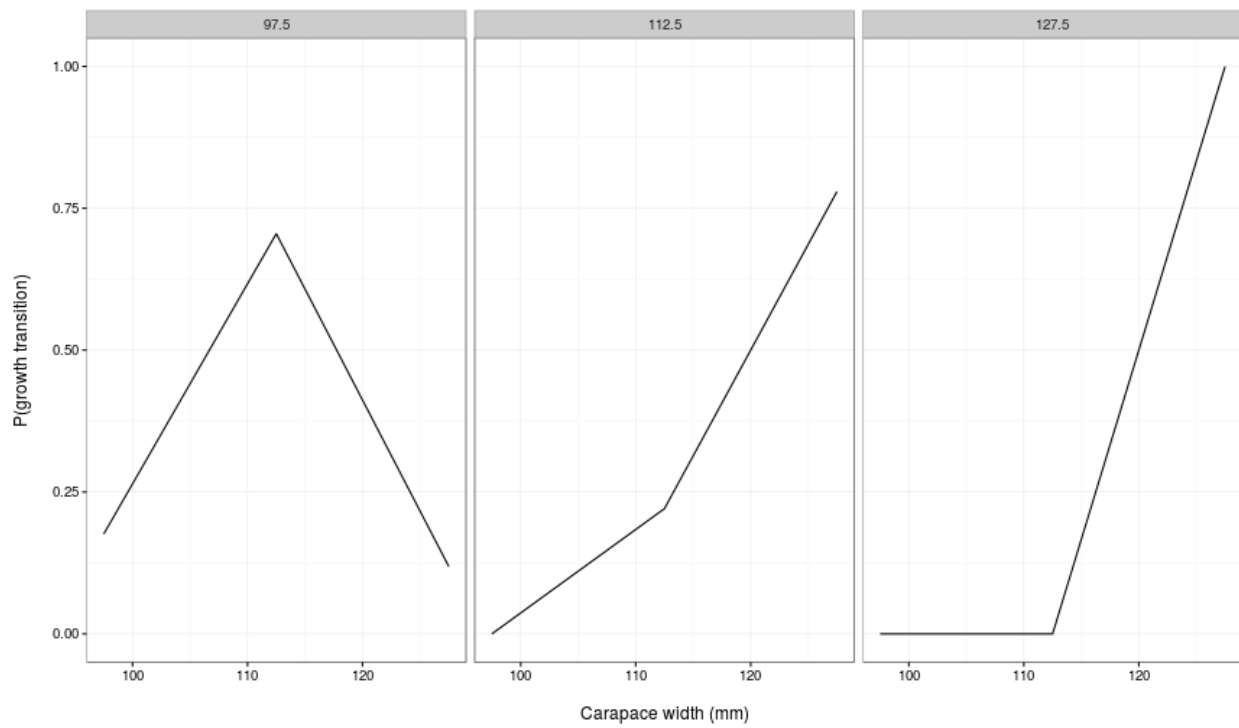


Figure 25: Probability of growth transition by stage. Each of the panels represent the stage before growth. The x-axes represent the stage after a growth (ignoring the probability of molting).

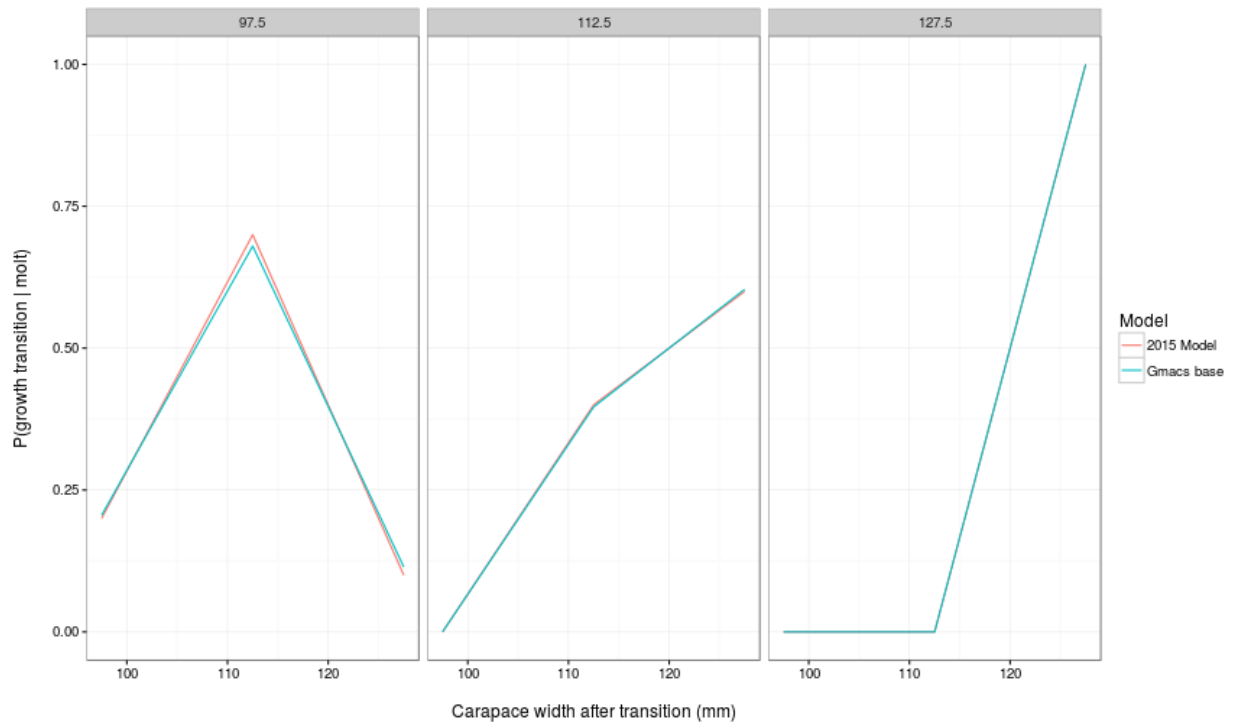


Figure 26: Probability of size transition by stage (i.e. the combination of the growth matrix and molting probabilities). Each of the panels represent the stage before a transition. The x-axes represent the stage after a transition.

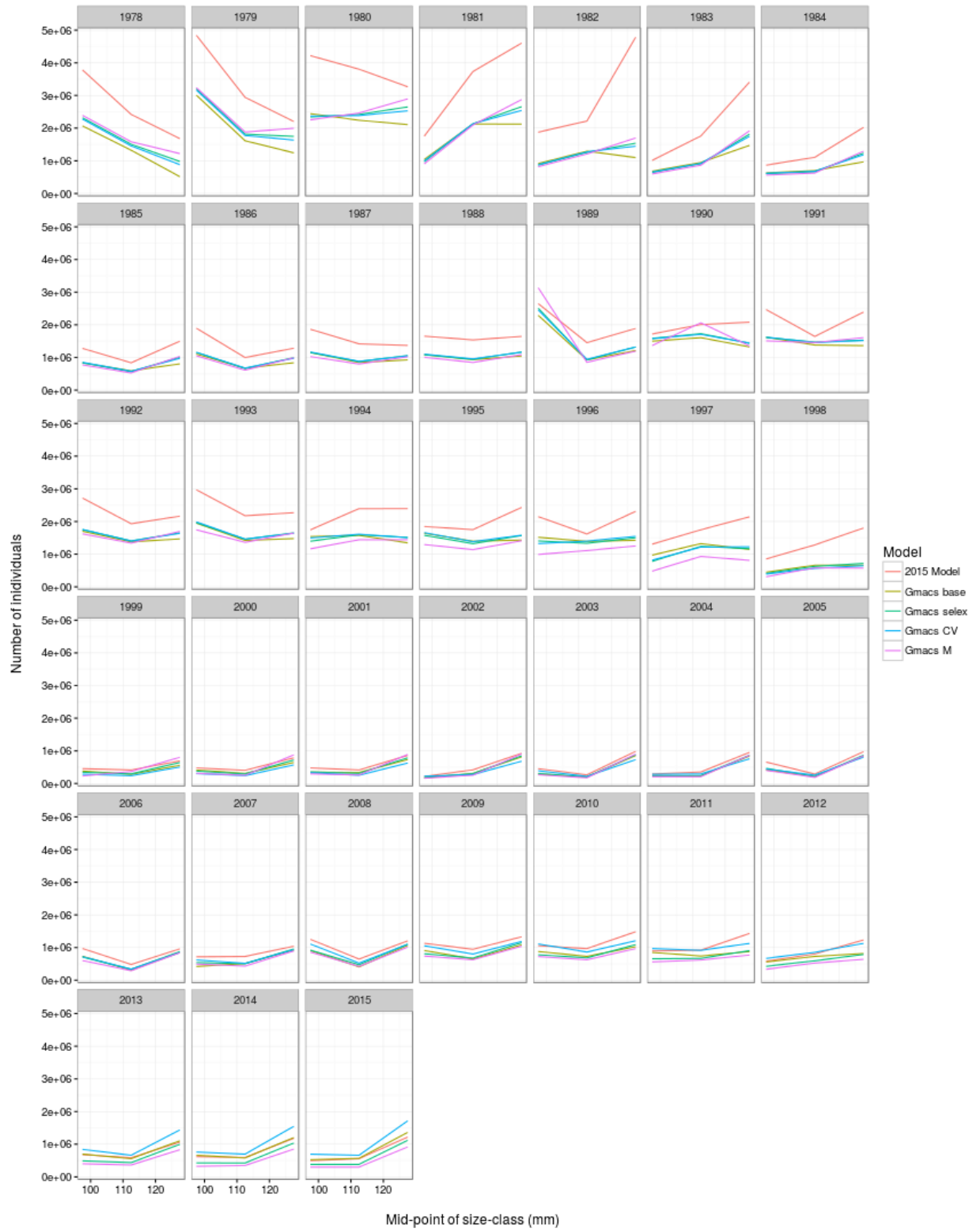


Figure 27: Numbers by stage each year (15 February) in each of the models including the 2015 model.

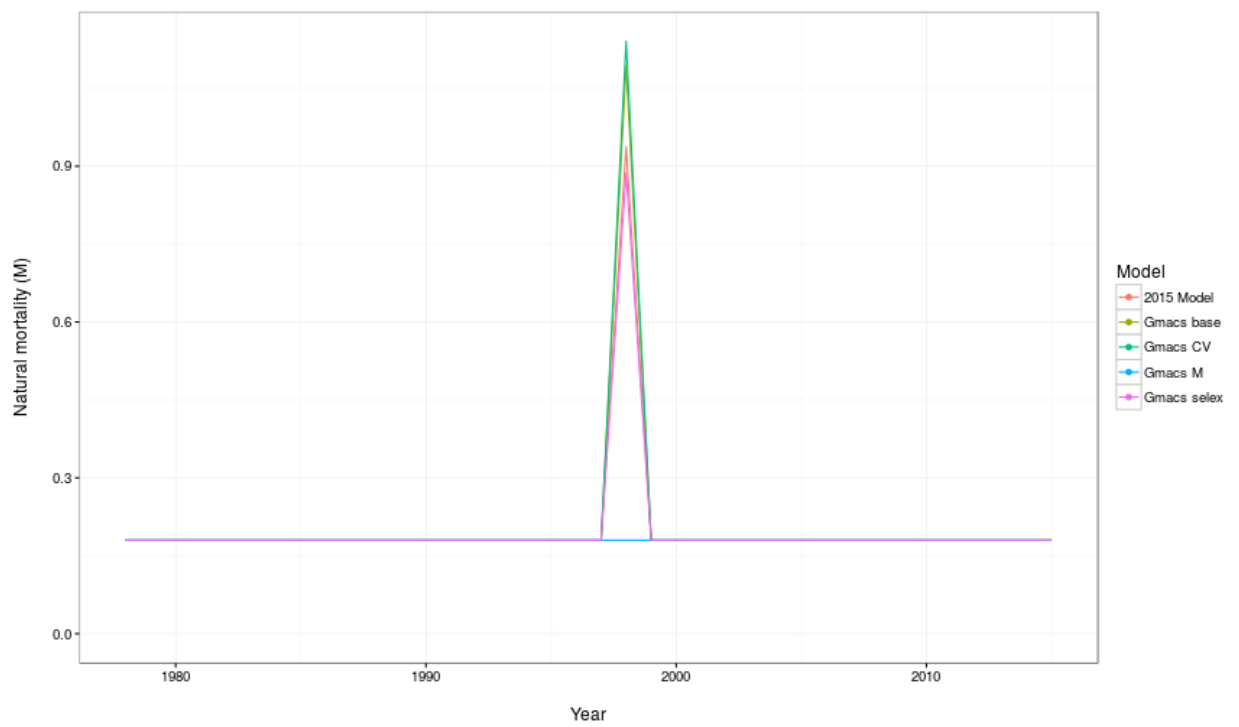


Figure 28: Time-varying natural mortality ( $M_t$ ). Estimated pulse period occurs in 1998/99 (i.e.  $M_{1998}$ ).

# Appendix A: SMBKC Model Description

## 1. Introduction

The Gmacs model has been specified to account only for male crab at least 90 mm in carapace length (CL). These are partitioned into three stages (size-classes) determined by CL measurements of (1) 90-104 mm, (2) 105-119 mm, and (3) 120+ mm. For management of the St. Matthew Island blue king crab (SMBKC) fishery, 120 mm CL is used as the proxy value for the legal measurement of 5.5 mm in 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

Each model year is split into four seasons. MMB is measured 15 February. To accomodate this, four seasons were defined.

Within the model, the beginning of the crab year is assumed contemporaneous with the NMFS trawl survey, nominally assigned a date of 1 July. With boldface lowercase letters indicating vector quantities we designate the vector of stage abundances during season  $t$  and year  $y$  as

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

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

$$\mathbf{G} = \begin{bmatrix} 1 - \pi_{12} - \pi_{13} & \pi_{12} & \pi_{13} \\ 0 & 1 - \pi_{23} & \pi_{23} \\ 0 & 0 & 1 \end{bmatrix}, \quad (4)$$

with  $\pi_{jk}$  equal to the proportion of stage- $j$  crab that molt and grow into stage- $k$  within a season or year. Similarly, the survival matrix  $\mathbf{S}_{t,y}$  during season  $t$  and year  $y$  is

$$\mathbf{S}_{t,y} = \begin{bmatrix} 1 - e^{-Z_{1,t,y}} & 0 & 0 \\ 0 & 1 - e^{-Z_{2,t,y}} & 0 \\ 0 & 0 & 1 - e^{-Z_{3,t,y}} \end{bmatrix}, \quad (5)$$

where  $Z_{l,t,y}$  represents the combination of natural mortality  $M_{t,y}$  and fishing mortality  $F_{t,y}$  during season  $t$  and year  $y$ . 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, thus

$$\mathbf{r}_{t,y} = [\bar{R}, 0, 0]^\top. \quad (6)$$

In this formulation of the model, all recruits are assumed to be to stage-1. The basic population dynamics underlying Gmacs can thus be described as

$$\begin{aligned} \mathbf{n}_{t+1,y} &= \mathbf{S}_{t,y} \mathbf{n}_{t,y}, & \text{if } t < 4 \\ \mathbf{n}_{t,y+1} &= \mathbf{G}_t \mathbf{S}_{t,y} \mathbf{n}_{t,y} + \mathbf{r}_{t,y}, & \text{if } t = 4 \end{aligned} \quad (7)$$

Aside from natural mortality and molting and growth, only the directed fishery and some limited bycatch mortality in the groundfish fisheries are assumed to affect the stock. Nontrivial bycatch mortality with another fishery, as occurred in 2012/13, is assumed to be accounted for in the model in the estimate of groundfish bycatch mortality. The directed fishery is modeled as a mid-season pulse occurring at time  $\pi_t$  with full-selection fishing mortality  $F_t$  relative to stage-3 crab. Year- $t$  directed-fishery removals from the stock are computed as

$$R_t^{df} = H^{df} S^{df} (1 - e^{F_t^{df}}) e^{-\tau_t M} N_t$$

where the diagonal matrices

$$\mathbf{H}^{df} = \begin{bmatrix} h^{df} & 0 & 0 \\ 0 & h^{df} & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (8)$$

account for stage selectivities  $s_1^{df}$  and  $s_2^{df}$  and discard handling mortality  $h^{df}$  in the directed fishery, both assumed constant over time. Yearly stage removals resulting from bycatch mortality in the groundfish trawl and fixed-gear fisheries are calculated as Feb 15 (0.63 yr) pulse effects in terms of the respective fishing mortalities  $F_t^{gt}$  and  $F_t^{gf}$  by

### 3. Model Data

Data inputs used in model estimation are listed in Table 1XX. All quantities relate to male SMBKC  $\leq 90$ mm CL.

### 4. Model Parameters

Estimated parameters with scenarios 8 and 10 are listed in Table 2XX and include an estimated parameter for natural mortality ( $M$ ) in 1998/99 assuming an anomalous mortality event in that year, as hypothesized by Zheng and Kruse (2002), with natural mortality otherwise fixed at  $0.18 \text{ yr}^{-1}$ .

In any year with no directed fishery, and hence zero retained catch,  $F_t^{df}$  is set to zero rather than model estimated. Similarly, for years in which no groundfish bycatch data are available,  $F_t^{gf}$  and  $F_t^{gt}$  are imputed to be the geometric means of the estimates from years for which there are data. Table 3XX lists additional externally determined parameters used in model computations.

In all scenarios, the stage-transition matrix is

$$\begin{bmatrix} 0.2 & 0.7 & 0.1 \\ 0 & 0.4 & 0.6 \\ 0 & 0 & 1 \end{bmatrix} \quad (9)$$

which includes molting probabilities.

The combination of the growth matrix and molting probabilities results in the stage-transition matrix for scenarios 3-11. Molting probability for stage 1 for scenarios 8, 9, 10, 11 during 1978-2000 is assumed to be 0.91 estimated from the tagging data and ratio of molting probabilities of stages 2 to stage 1 is fixed as 0.69231 from the tagging data as well. For scenarios 0 and 1, stage-transition matrix

Both surveys are assigned a nominal date of 1 July, the start of the crab year. The directed fishery is treated as a season midpoint pulse. Groundfish bycatch is likewise modeled as a pulse effect, occurring at the nominal time of mating, February 15, which is also the reference date for calculation of federal management biomass quantities.



Table 10: Model bounds, initial values, priors and estimation phase.

Parameter	LB	Initial value	UB	Prior type	Prior par1	Prior par2	Phase
$Mdev_{1998}$	0	0.0		Random walk	0	10	2
$\log(R_0)$	-7	14.3	30	Uniform	-7	30	2
$\log(\bar{R})$	-7	10.0	20	Uniform	-7	20	1
$\log(N_1)$	5	14.0	15	Uniform	5	15	1
$\log(N_2)$	5	14.0	15	Uniform	5	15	1
$\log(N_3)$	5	14.0	15	Uniform	5	15	1
$q_{pot}$	0	4.0	5	Uniform	0	5	4
Add CV ADFG pot	0	0.0	10	Gamma	1	100	4
Stage-1 1978-2008	0	0.4	2	Uniform	0	2	4
Stage-2 1978-2008	0	0.7	2	Uniform	0	2	4
Stage-1 2009-2015	0	0.3	2	Uniform	0	2	4
Stage-2 2009-2015	0	0.8	2	Uniform	0	2	4
Stage-1 NMFS	0	0.7	2	Uniform	0	2	4
Stage-2 NMFS	0	0.9	2	Uniform	0	2	4
Stage-1 ADFG	0	0.3	2	Uniform	0	2	4
Stage-2 ADFG	0	0.7	2	Uniform	0	2	4

## 5. Model Objective Function and Weighting Scheme

The objective function consists of a sum of eight “negative log-likelihood” terms characterizing the hypothesized error structure of the principal data inputs with respect to their true, i.e., model-predicted, values and four “penalty” terms associated with year-to-year variation in model recruit abundance and fishing mortality in the directed fishery and groundfish trawl and fixed-gear fisheries. See Table 1, where upper and lower case letters designate model-predicted and data-computed quantities, respectively, and boldface letters again indicate vector quantities. Sample sizes  $n_t$  (observed number of male SMBKC  $\leq 90$  mm CL) and estimated coefficients of variation  $\hat{c}v_t$  were used to develop appropriate variances for stage-proportion and abundance-index components. The weights  $\lambda_j$  appearing in the objective function component expressions in Table 1 play the role of “tuning” parameters in the modeling procedure.

Table 4XX. Log-likelihood and penalty components of base-model objective function. The  $\lambda_k$  are weights, described in text; the neff t are effective sample sizes, also described in text. All summations are with respect to years over each data series.

Component	Distribution	Form
Legal retained-catch biomass	Lognormal	$-0.5 \sum (\log(c_t/C_t)^2 / \log(1 + cv_c^2))$
Dis. Pot bycatch biomass	Lognormal	

## 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.