

# Saint Matthew Island Blue King Crab Stock Assessment 2016

D'Arcy Webber

Jie Zheng

James Ianelli

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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 pounds) 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 carapace length (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.

Table 1: Status and catch specifications (1000 tonnes) (scenario 1). MSST is minimum stock-size threshold, MMB is mature male biomass, TAC is total allowable catch, OFL is over fishing limit, ABC is the annual b catch.

Year	MSST	Biomass (MMB)	TAC	Retained catch	Total male catch	OFL	ABC
2011/12	1.50	5.03	1.15	0.85	0.95	1.70	1.54
2012/13	1.80	2.85	0.74	0.73	0.82	1.02	0.92
2013/14	1.50	3.01	0.00	0.00	0.00	0.56	0.45
2014/15	1.86	2.48	0.30	0.14	0.15	0.43	0.34
2015/16		2.45				0.28	0.22

## 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 5 discrete seasons. Season length in Gmacs is controlled simply by changing the proportion of natural mortality that is applied during each season.

### Changes in Assessment Results

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

No general comments relative to crab assessments were applied in this draft preliminary assessment.

## CPT and SSC Comments Specific to the SMBKC Stock Assessment

Comment: The SSC is not convinced that the model runs with extra CV are very informative. The inclusion of extra CV seems to be rather arbitrary based on the numbers of points that fall within confidence intervals estimated from trawl surveys. The SSC recommends coming up with some alternative way to consider extra variability, which could be informed by simulation testing.

Response:

Comment: The descriptions of seasons in the model is confusing and currently reads as if  $M$  differs among seasons (see page 39). More justification is needed on how seasons are defined and how they were selected, as well as clarification on  $M$  during these seasons.

Response: This description has been amended and justification provided in the appendix.

Comment: During the presentation to the SSC, uncertainty was expressed about the origins of the growth transition matrix, but page 7 of the report indicates that the matrix was derived by Otto and Cummiskey (1990). As this matrix is critical to the model, the origin and integrity of the growth transition matrix should be carefully explained in the assessment for fall 2016. In some other models, the transition matrix can be estimated. If there are doubts about the veracity of the transition matrix, perhaps this can be explored in the modeling framework.

Response: The report is correct, the growth matrix was derived by Otto and Cummiskey (1990) and used in this assessment.

Comment: The selectivities were constrained so that they do not exceed 1.0, but the tables of log-transformed parameter estimates do not indicate that this upper bound was approached. This should be clarified.

Response:

Comment: It would be helpful to include a table of NMFS trawl survey CPUE by crab stage, just as was provided for the ADF&G pot survey (Table 1).

Response:

Comment: Page 10 refers to a table of observed and estimated sample size, but no such table was provided.

Response:

Comment: As with the 2015 model, GMACS consistently overestimates trawl survey estimates of male biomass in the last decade, whereas GMACS tends to underestimate the last couple of pot survey estimates (Figure 9, 12). This is also reflected in patterns in residuals, and the proportions of stage-3 crab tend to be overestimated in recent years (Figure 14). These patterns should be discussed in the assessment.

Response:

Comment: The report contains very little description and interpretation of results. Moreover, not all figures are cited in the document. The document should highlight the major features of the results and offer some explanation, as well.

Response:

Comment: A brief explanation was provided about the future outlook (page 12) that indicated a declining stock. However, stock trends shown in Figure 24 generally suggest population growth since 1993. Closer examination of Tables 9-11 suggest that trends depend somewhat on model run and life stage. Statements about future outlook should be qualified and refer to figures and tables and explain any differences in outcomes.

Response:

Comment: The SSC discussed the possibility that these patterns could be indicative of spatial patterns in stock distribution. The trawl survey covers a much larger geographic distribution than the pot survey (Figure 4). Crab distribution may vary with sex (females tend to be found close to shore) and life stage. Thus, the

trawl and pot surveys may sample the crab stock differentially. Moreover, the geographic distributions of these stages may vary with stock density and temperature. It could be informative to conduct some spatial analyses, which could include: (1) estimation of survey catchability as a function of temperature, (2) a stock assessment model run that includes pot surveys and only those trawl stations that fall within the pot survey distribution as a comparison the runs that include the full trawl survey data, and (3) analysis of the spatial distribution of surveyed crabs by stage at high and low biomass and during warm and cold years.

Response:

Comment: Andre Punt pointed out the need to use a fixed-iteration Newton's method to calculate OFL, not bisection, to keep the calculation differentiable so that OFL can be reported as an sdreport variable.

Response: This has been done and the OFL is reported as an sdreport variable.

Comment: Regarding general code development, the CPT had the following requests:

1. 1-year projection for calculating Tier 3 or 4 OFLs
2. specify catchability as a fixed or estimated parameter or use the analytic calculation for the MLE
3. specify priors (e.g., gamma) using mean and variance/standard deviation for all parameters to ease specifying priors
4. include an option to calculate dynamic B MSY
5. add the ability to "jitter" initial parameter values
6. add the ability to conduct retrospective analyses
7. add ability to estimate bycatch fishing mortality rates when observer data are missing but effort data is available
8. allow different phases for "rec\_ini", "rec\_dev" estimation

Response:

Comment: the CPT requests that some evaluation should also be included in the September report to the CPT which compares against the previous assessment model corrected for the error.

Response:

Comment: *The SSC and CPT requested the following models for review at the spring 2016 meeting:*

1. Base: try to match 2015 model but prevent dome shaped selex
2. Base + add CV for both surveys
3. Above + Francis re-weighting
4. Above + remove M spike

Response: *Models 1, 2, and 4 above are included and evaluated in this document. The software to implement the 3rd model requesting Francis re-weighting is incomplete but should be available for the September 2016 meeting.*

## 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.).



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

## 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,

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

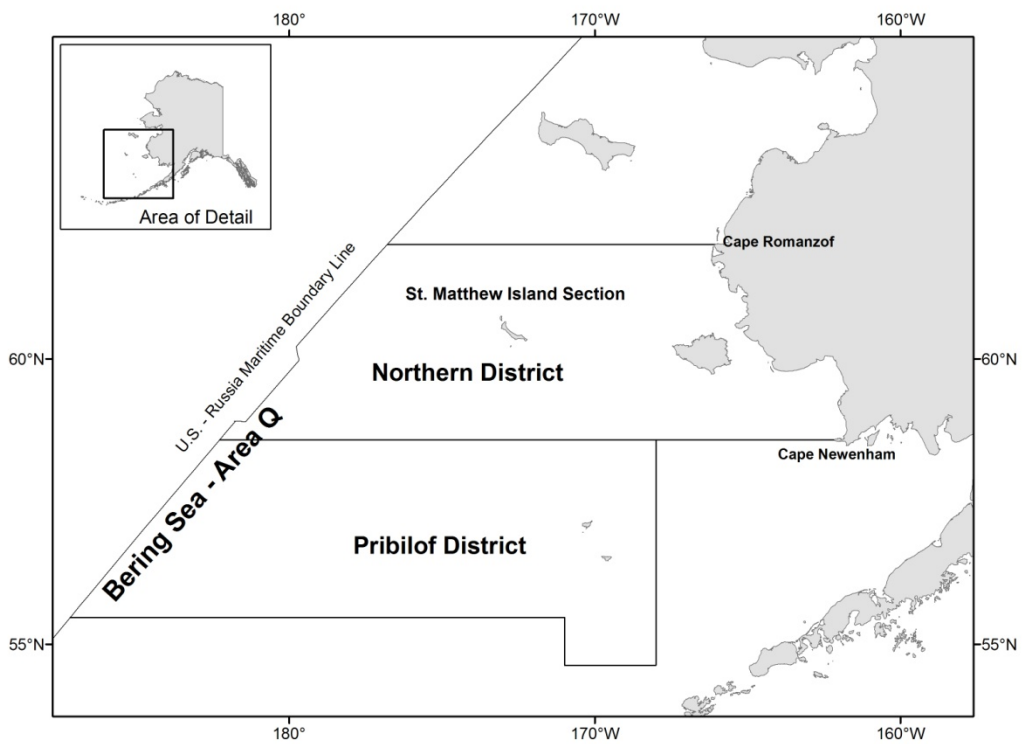


Figure 2: King crab Registration Area Q (Bering Sea).

*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 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 (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

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

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).

## 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).

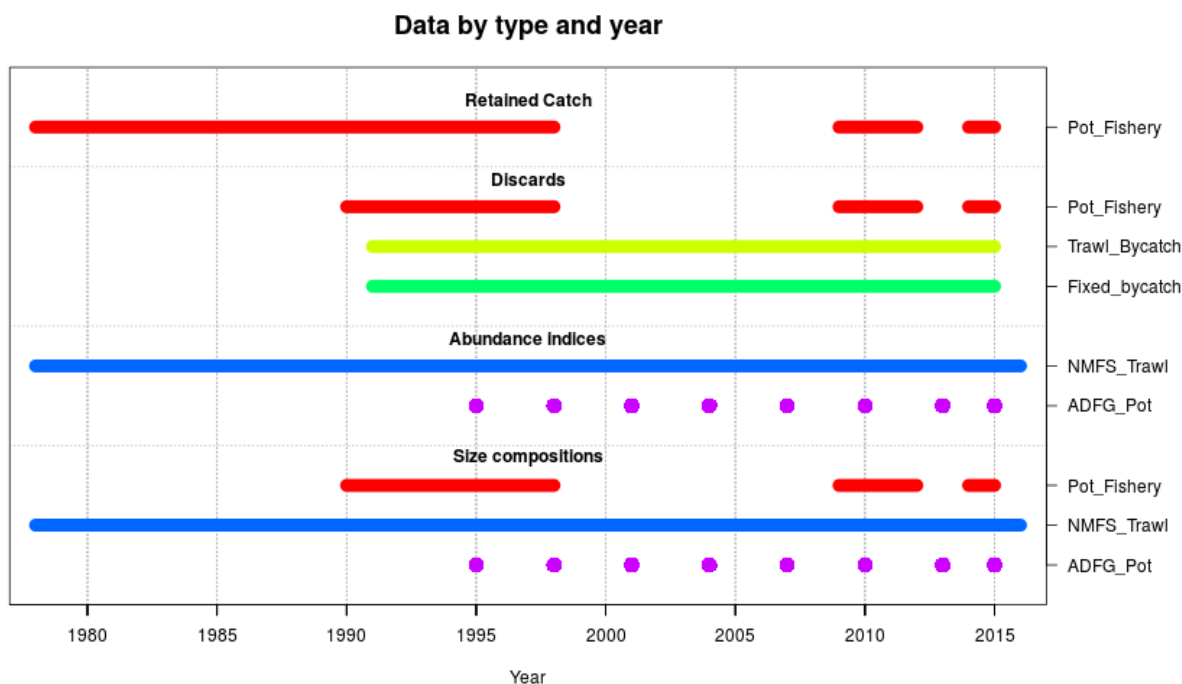


Figure 3: Data extent for the SMBKC assessment.

### 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 2); 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.

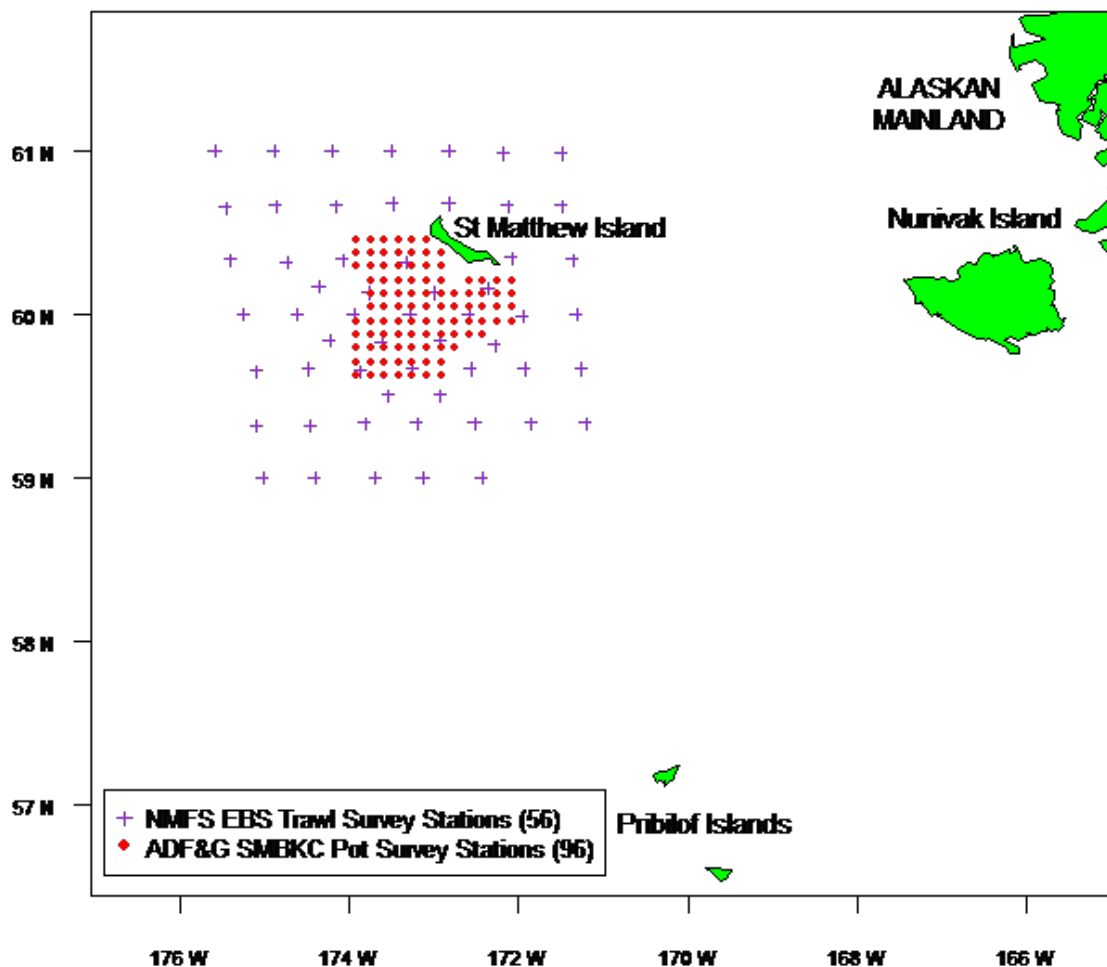


Figure 4: Trawl and pot-survey stations used in the SMBKC stock assessment.

## 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.

Table 2: 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

## 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:** the 2015 provided by Jie (note that an error was found in the code, this error was fixed before making comparisons).
2. **Gmacs match:** tries to match as closely as possible the 2015 Model.
3. **Gmacs base:** directed pot, NMFS trawl survey and ADF&G pot survey selectivities are estimated for stage-1 and stage-2 crab. These selectivities are bounded so that they cannot be greater than 1.
4. **Gmacs M:** natural mortality ( $M$ ) is fixed at  $0.18 \text{ yr}^{-1}$  during all years as well as estimating additional CV is estimated for both the NMFS trawl survey and the ADF&G pot survey and estimating the directed pot, NMFS trawl survey and ADF&G pot survey selectivities for stage-1 and stage-2 crab. These selectivities are bounded so that they cannot be greater than 1.
5. **Gmacs Francis:** additional CV is estimated for both the NMFS trawl survey and 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. These selectivities are bounded so that they cannot be greater than 1.

Scenario	Selectivity estimated	Additional CV	Estimate $M_{1998}$
Gmacs match	No	No	Yes
Gmacs base	Yes	No	Yes
Gmacs M	Yes	Yes	No
Gmacs Francis	Yes	Yes	Yes

## 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 4, 5, 6, and 7. Negative log likelihood values and management measures for the four Gmacs scenarios are compared in Table 9. Estimated abundances by stage and mature male biomasses for three of the scenarios are listed in Tables 10, ??, and ??.

The scenarios that estimated stage-1 and stage-2 selectivities fit the data better. The scenario with additional CV for the pot survey CPUE fit the trawl survey data better and resulted in higher abundance and biomass estimates in the most recent years. Estimated directed pot and trawl survey selectivities  $> 1.0$  for stage-2 crab are 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 ( $> 89 \text{ mm CL}$ ) 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, 18, and 20 for the Gmacs base model. Fits to retained catch biomass and bycatch death biomass are shown for all Gmacs scenarios in Figure 22. Estimated recruitment and mature male biomass are compared in Figures 23 and 24, 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 23). Estimated recruitment during recent years is generally low in all scenarios. Estimated mature male biomass 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 24).

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 4, 5, 6, and 7. 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

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

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

where  $B$  is quantified as mature-male biomass (MMB) at mating with time of mating assigned a nominal date of 15 February. Note that as  $B$  itself is a function of the fishing mortality  $F_{OFL}$ , 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 1978-2016, 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, 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.

## K. References

- Alaska Department of Fish and Game (ADF&G). 2013. Crab observer training and deployment manual. Alaska Department of Fish and Game Shellfish Observer Program, Dutch Harbor. Unpublished.
- Collie, J.S., A.K. Delong, and G.H. Kruse. 2005. Three-stage catch-survey analysis applied to blue king crabs. Pages 683-714 [In] Fisheries assessment and management in data-limited situations. University of Alaska Fairbanks, Alaska Sea Grant Report 05-02, Fairbanks.
- Daly, B., R. Foy, and C. Armistead. 2014. The 2013 eastern Bering Sea continental shelf bottom trawl survey: results for commercial crab species. NOAA Technical Memorandum, NMFS-AFSC.
- Donaldson, W.E., and S.C. Byersdorfer. 2005. Biological field techniques for lithodid crabs. University of Alaska Fairbanks, Alaska Sea Grant Report 05-03, Fairbanks.
- Fitch, H., M. Deiman, J. Shaishnikoff, and K. Herring. 2012. Annual management report for the commercial and subsistence shellfish fisheries of the Bering Sea, 2010/11. Pages 75-1776 [In] Fitch, H., M. Schwenzfeier, B. Baechler, T. Hartill, M. Salmon, M. Deiman, E.
- Evans, E. Henry, L. Wald, J. Shaishnikoff, K. Herring, and J. Wilson. 2012. Annual management report for the commercial and subsistence shellfish fisheries of the Aleutian Islands, Bering Sea and the Westward

Region's Shellfish Observer Program, 2010/11. Alaska Department of Fish and Game, Fishery Management Report No. 12-22, Anchorage.

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

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

Gaeuman, W.B. 2013. Summary of the 2012/13 mandatory crab observer program database for the Bering Sea/Aleutian Islands commercial crab fisheries. Alaska Department of Fish and Game, Fishery Data Series No. 13-54, Anchorage. Gish, R.K., V.A. Vanek, and D. Pengilly. 2012. Results of the 2010 triennial St. Matthew Island blue king crab pot survey and 2010/11 tagging study. Alaska Department of Fish and Game, Fishery Management Report No. 12-24, Anchorage.

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

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

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

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

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

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

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

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

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

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

Schirripa, M.J., C.P. Goodyear, and R.M. Methot. 2009. Testing different methods of incorporating climate data into the assessment of US West Coast sablefish. *ICES Journal of Marine Science*, 66: 1605-1613.

- Somerton, D.A., and R.A. MacIntosh. 1983. The size at sexual maturity of blue king crab, *Paralithodes platypus*, in Alaska. *Fishery Bulletin* 81: 621-828.
- Wilderbuer, T., D. G. Nichol, and J. Ianelli. 2013. Assessment of the yellowfin sole stock in the Bering Sea and Aleutian Islands. Pages 619-708 in 2013 North Pacific Groundfish Stock Assessment and Fishery Evaluation Reports for 2014. North Pacific Fishery Management Council, Anchorage.
- Zheng, J. 2005. A review of natural mortality estimation for crab stocks: data-limited for every stock? Pages 595-612 [In] *Fisheries Assessment and Management in Data-Limited Situations*. University of Alaska Fairbanks, Alaska Sea Grant Program Report 05-02, Fairbanks.
- Zheng, J., and G.H. Kruse. 2002. Assessment and management of crab stocks under uncertainty of massive die-offs and rapid changes in survey catchability. Pages 367-384 [In] A.J. Paul, E.G. Dawe, R. Elnor, G.S. Jamieson, G.H. Kruse, R.S. Otto, B. Sainte-Marie, T.C. Shirley, and D. Woodby (eds.). *Crabs in Cold Water Regions: Biology, Management, and Economics*. University of Alaska Fairbanks, Alaska Sea Grant Report 02-01, Fairbanks.
- Zheng, J., M.C. Murphy, and G.H. Kruse. 1997. Application of catch-survey analysis to blue king crab stocks near Pribilof and St. Matthew Islands. *Alaska Fish. Res. Bull.* 4:62-74.

Table 4: Model parameter estimates and standard deviations (SD) for the **Gmacs match** model.

Parameter	Estimate	SD
Natural mortality ( $M$ ) deviation in 1998/99	1.6846000	0.1213800
$\log(\bar{R})$	13.4540000	0.0592040
$\log(N_1)$	14.8800000	0.1697300
$\log(N_2)$	14.4510000	0.1945100
$\log(N_3)$	14.2540000	0.2024800
ADF&G pot survey catchability ( $q$ )	0.0041661	0.0002893
$\bar{F}_{\text{pot}}$	-1.5264000	0.0514520
$\bar{F}_{\text{trawl bycatch}}$	-12.2700000	0.0816670
$\bar{F}_{\text{fixed bycatch}}$	-9.1722000	0.0818210
Fofl	0.1225500	0.0147360
OFL	1627.7000000	372.5200000

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

Parameter	Estimate	SD
Natural mortality ( $M$ ) deviation in 1998/99	1.7000000	0.1248400
$\log(\bar{R})$	13.4760000	0.0601940
$\log(N_1)$	14.8460000	0.1710600
$\log(N_2)$	14.4560000	0.1994900
$\log(N_3)$	14.1610000	0.2118200
ADF&G pot survey catchability ( $q$ )	0.0039794	0.0003066
$\log(\bar{F}_{\text{pot}})$	-1.5302000	0.0542120
$\log(\bar{F}_{\text{trawl bycatch}})$	-12.2980000	0.0826750
$\log(\bar{F}_{\text{fixed bycatch}})$	-9.2005000	0.0828250
Stage-1 directed pot selectivity 1978-2008	-0.7307800	0.1735700
Stage-2 directed pot selectivity 1978-2008	-0.3835600	0.1265400
Stage-1 directed pot selectivity 2009-2015	-0.7405000	0.1644900
Stage-2 directed pot selectivity 2009-2015	-0.0000000	0.0000164
Stage-1 NMFS trawl selectivity	-0.2573000	0.0671840
Stage-2 NMFS trawl selectivity	-0.0000000	0.0000074
Stage-1 ADF&G pot selectivity	-0.9158600	0.1441200
Stage-2 ADF&G pot selectivity	-0.0950260	0.0834040
Fofl	0.1228400	0.0159430
OFL	1645.4000000	397.7500000



Table 6: Model parameter estimates and standard deviations (SD) for the **Gmacs CV** model that estimates stage-1 and stage-2 selectivity.

Parameter	Estimate	SD
$\log(R)$	13.3150000	0.0556410
$\log(N_1)$	14.8280000	0.2067900
$\log(N_2)$	14.5480000	0.2258600
$\log(N_3)$	14.2250000	0.2373600
ADF&G pot survey catchability ( $q$ )	0.0046689	0.0003108
$\log(\bar{F}_{\text{pot}})$	-1.4363000	0.0560500
$\log(\bar{F}_{\text{trawl bycatch}})$	-12.1960000	0.0806440
$\log(\bar{F}_{\text{fixed bycatch}})$	-9.0982000	0.0807370
Stage-1 directed pot selectivity 1978-2008	-0.5226300	0.1830300
Stage-2 directed pot selectivity 1978-2008	-0.3710800	0.1497500
Stage-1 directed pot selectivity 2009-2015	-0.6209300	0.1763000
Stage-2 directed pot selectivity 2009-2015	-0.0000000	0.0000168
Stage-1 NMFS trawl selectivity	-0.1159700	0.0609900
Stage-2 NMFS trawl selectivity	-0.0000000	0.0000050
Stage-1 ADF&G pot selectivity	-0.8885000	0.1374100
Stage-2 ADF&G pot selectivity	-0.0000000	0.0000826
Fofl	0.1013900	0.0136470
OFL	1087.8000000	266.6900000

Table 7: Model parameter estimates and standard deviations (SD) for the **Gmacs M** model that estimates stage-1 and stage-2 selectivity.

Parameter	Estimate	SD
$\log(R)$	13.5250000	0.0598530
$\log(N_1)$	14.8260000	0.2041200
$\log(N_2)$	14.4710000	0.2292100
$\log(N_3)$	14.1710000	0.2377600
ADF&G pot survey catchability ( $q$ )	0.0055894	0.0010667
$\log(\bar{F}_{\text{pot}})$	-1.5052000	0.0566500
$\log(\bar{F}_{\text{trawl bycatch}})$	-12.3160000	0.0831970
$\log(\bar{F}_{\text{fixed bycatch}})$	-9.2199000	0.0832740
Stage-1 directed pot selectivity 1978-2008	-0.4806300	0.1839700
Stage-2 directed pot selectivity 1978-2008	-0.3626100	0.1507800
Stage-1 directed pot selectivity 2009-2015	-0.9017600	0.1828300
Stage-2 directed pot selectivity 2009-2015	-0.0000000	0.0000362
Stage-1 NMFS trawl selectivity	-0.2103000	0.0617130
Stage-2 NMFS trawl selectivity	-0.0000000	0.0000072
Stage-1 ADF&G pot selectivity	-1.0795000	0.1362900
Stage-2 ADF&G pot selectivity	-0.1406000	0.0958480

Table 8: Comparisons of model parameter estimates for the four Gmacs model scenarios.

Model	Parameter	Estimate
Gmacs match	Natural mortality ( $M$ ) deviation in 1998/99	1.685
Gmacs match	$\log(\bar{R})$	13.454
Gmacs match	$\log(N_1)$	14.880
Gmacs match	$\log(N_2)$	14.451
Gmacs match	$\log(N_3)$	14.254
Gmacs match	ADF&G pot survey catchability ( $q$ )	0.004
Gmacs match	$\log(\bar{F}_{\text{pot}})$	-1.526
Gmacs match	$\log(\bar{F}_{\text{trawl bycatch}})$	-12.270
Gmacs match	$\log(\bar{F}_{\text{fixed bycatch}})$	-9.172
Gmacs base	Natural mortality ( $M$ ) deviation in 1998/99	1.700
Gmacs base	$\log(\bar{R})$	13.476
Gmacs base	$\log(N_1)$	14.846
Gmacs base	$\log(N_2)$	14.456
Gmacs base	$\log(N_3)$	14.161
Gmacs base	ADF&G pot survey catchability ( $q$ )	0.004
Gmacs base	$\log(\bar{F}_{\text{pot}})$	-1.530
Gmacs base	$\log(\bar{F}_{\text{trawl bycatch}})$	-12.298
Gmacs base	$\log(\bar{F}_{\text{fixed bycatch}})$	-9.200
Gmacs base	Stage-1 directed pot selectivity 1978-2008	-0.731
Gmacs base	Stage-2 directed pot selectivity 1978-2008	-0.384
Gmacs base	Stage-1 directed pot selectivity 2009-2015	-0.741
Gmacs base	Stage-2 directed pot selectivity 2009-2015	-0.000
Gmacs base	Stage-1 NMFS trawl selectivity	-0.257
Gmacs base	Stage-2 NMFS trawl selectivity	-0.000
Gmacs base	Stage-1 ADF&G pot selectivity	-0.916
Gmacs base	Stage-2 ADF&G pot selectivity	-0.095
Gmacs CV	Natural mortality ( $M$ ) deviation in 1998/99	-
Gmacs CV	$\log(\bar{R})$	13.315
Gmacs CV	$\log(N_1)$	14.828
Gmacs CV	$\log(N_2)$	14.548
Gmacs CV	$\log(N_3)$	14.225
Gmacs CV	ADF&G pot survey catchability ( $q$ )	0.005
Gmacs CV	$\log(\bar{F}_{\text{pot}})$	-1.436
Gmacs CV	$\log(\bar{F}_{\text{trawl bycatch}})$	-12.196
Gmacs CV	$\log(\bar{F}_{\text{fixed bycatch}})$	-9.098
Gmacs CV	Stage-1 directed pot selectivity 1978-2008	-0.523
Gmacs CV	Stage-2 directed pot selectivity 1978-2008	-0.371
Gmacs CV	Stage-1 directed pot selectivity 2009-2015	-0.621
Gmacs CV	Stage-2 directed pot selectivity 2009-2015	-0.000
Gmacs CV	Stage-1 NMFS trawl selectivity	-0.116
Gmacs CV	Stage-2 NMFS trawl selectivity	-0.000
Gmacs CV	Stage-1 ADF&G pot selectivity	-0.888
Gmacs CV	Stage-2 ADF&G pot selectivity	-0.000
Gmacs M	Natural mortality ( $M$ ) deviation in 1998/99	-
Gmacs M	$\log(\bar{R})$	13.525
Gmacs M	$\log(N_1)$	14.826
Gmacs M	$\log(N_2)$	14.471
Gmacs M	$\log(N_3)$	14.171
Gmacs M	ADF&G pot survey catchability ( $q$ )	0.006
Gmacs M	$\log(\bar{F}_{\text{pot}})$	-1.505
Gmacs M	$\log(\bar{F}_{\text{trawl bycatch}})$	-12.316
Gmacs M	$\log(\bar{F}_{\text{fixed bycatch}})$	-9.220
Gmacs M	Stage-1 directed pot selectivity 1978-2008	-0.481
Gmacs M	Stage-2 directed pot selectivity 1978-2008	-0.363
Gmacs M	Stage-1 directed pot selectivity 2009-2015	-0.902
Gmacs M	Stage-2 directed pot selectivity 2009-2015	-0.000
Gmacs M	Stage-1 NMFS trawl selectivity	-0.210

Table 9: Comparisons of negative log-likelihood values and management measures for the four Gmacs model scenarios. Biomass and OFL are in tonnes.

Component	Gmacs match	Gmacs base	Gmacs CV	Gmacs M
Pot Retained Catch	-69.25	-69.36	-69.17	-69.66
Pot Discarded Catch	6.95	5.83	5.42	4.41
Trawl bycatch Discarded Catch	-6.88	-6.88	-6.88	-6.88
Fixed bycatch Discarded Catch	-6.86	-6.86	-6.87	-6.88
NMFS Trawl Survey	-11.84	-12.91	-4.36	-7.21
ADF&G Pot Survey CPUE	52.65	50.47	52.15	0.07
Directed Pot LF	-13.37	-13.14	11.63	10.98
NMFS Trawl LF	13.39	18.62	52.96	35.50
ADF&G Pot LF	-4.77	-4.50	2.18	-1.34
Recruitment deviations	56.48	56.32	57.19	55.43
F penalty	14.49	14.49	14.49	14.49
M penalty	6.47	6.47	0.00	0.00
Prior	12.82	15.59	15.59	15.59
Total	50.29	54.14	124.33	44.51
Total estimated parameters	283.00	291.00	289.00	289.00
\$MMB_2016\$	2946.43	2970.95	2372.22	5303.58
Fofl	0.12	0.12	0.10	0.18
OFL	1627.70	1645.36	1087.75	4114.46

Table 10: 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	3032380	1959650	1609350	4105
1979	3935440	2351410	2162280	5838
1980	3483360	3078760	3263590	9125
1981	1399440	3061830	4529080	9304
1982	1395390	1786860	4497980	6427
1983	726237	1329510	3064220	3382
1984	683934	775568	1553320	1989
1985	2205160	605801	984896	1669
1986	1303830	1410240	904641	2670
1987	1387260	1197070	1354150	3290
1988	1263250	1187840	1635410	3613
1989	2252400	1113040	1810310	4105
1990	1424190	1664200	2032870	4603
1991	1988020	1357180	2293490	4250
1992	2333220	1553010	2098930	4368
1993	2503120	1824300	2215840	4826
1994	1446940	2001220	2380110	4771
1995	1553850	1443750	2334010	4623
1996	1759330	1342640	2201930	4209
1997	1044040	1423500	2056840	3531
1998	656793	1013930	1642390	1717
1999	364932	338232	632065	1516
2000	400439	326253	727657	1681
2001	369769	343135	804742	1840
2002	165003	330775	874845	1956
2003	329593	206912	909941	1891
2004	231656	261670	890695	1913
2005	509789	222831	894291	1880
2006	778720	372468	901109	2046
2007	580634	579094	1003240	2390
2008	1005230	519548	1147060	2652
2009	919126	760501	1301030	2920
2010	868450	782376	1441940	2684
2011	712542	745364	1374460	2271
2012	446333	632141	1149010	1870
2013	517648	445721	939761	2196
2014	449804	451532	1051450	2229
2015	377699	410207	1076110	2410
2016				



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.

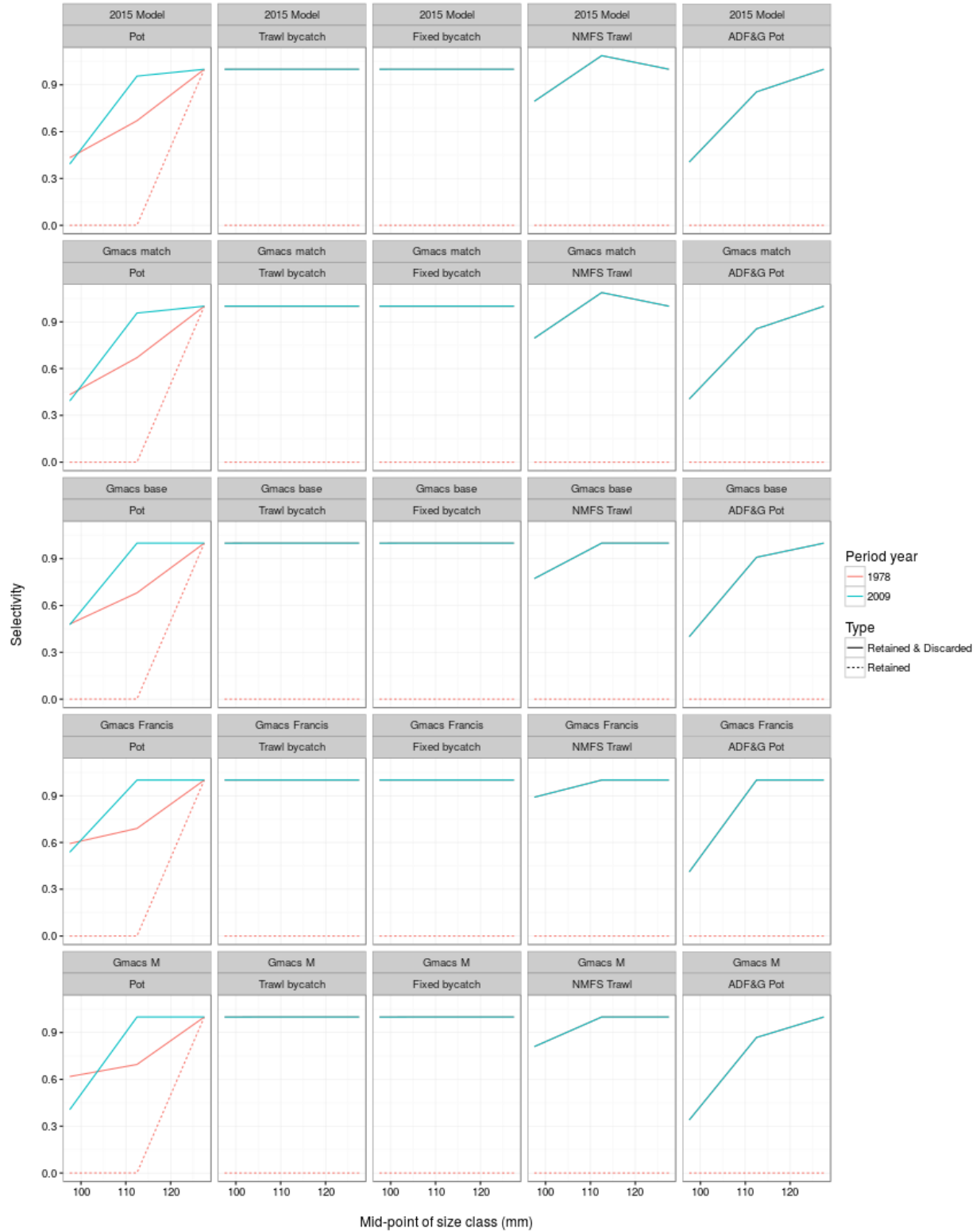


Figure 7: Comparisons of the estimated (and fixed to match the 2015 model selectivities in the Gmacs base scenario) stage-1 and stage-2 selectivities for each of the different model scenarios (the stage-3 selectivities are all fixed at 1). Estimated selectivities are shown for the directed pot fishery,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

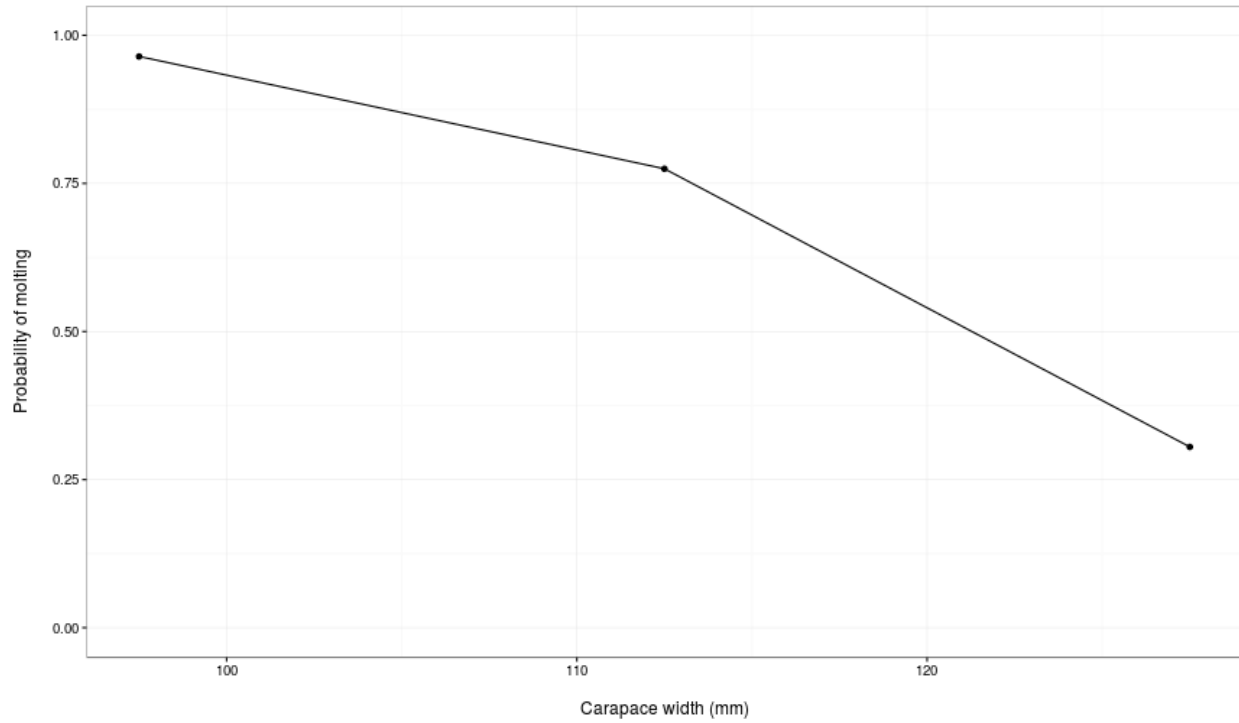


Figure 8: Molting probabilities by stage used in all of the Gmacs model scenarios.

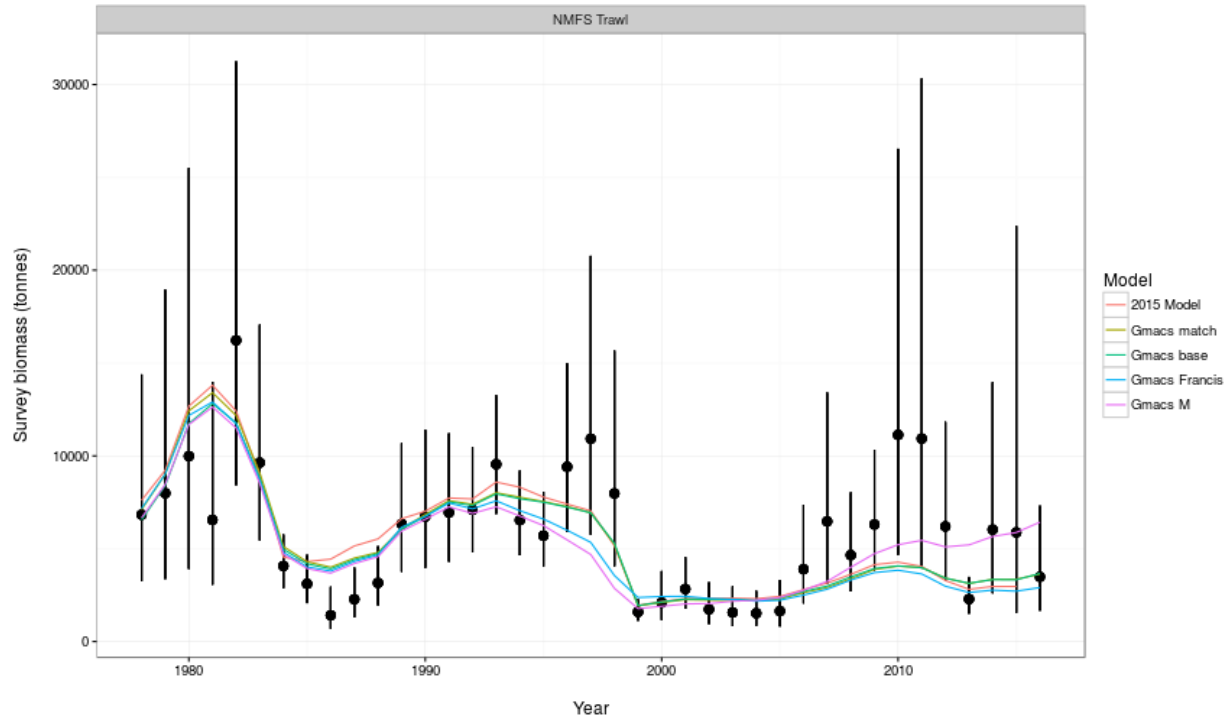


Figure 9: Comparisons of area-swept estimates of total male survey biomass (tonnes) and model predictions for the 2015 model and each of the Gmacs model scenarios. The error bars are plus and minus 2 standard deviations.



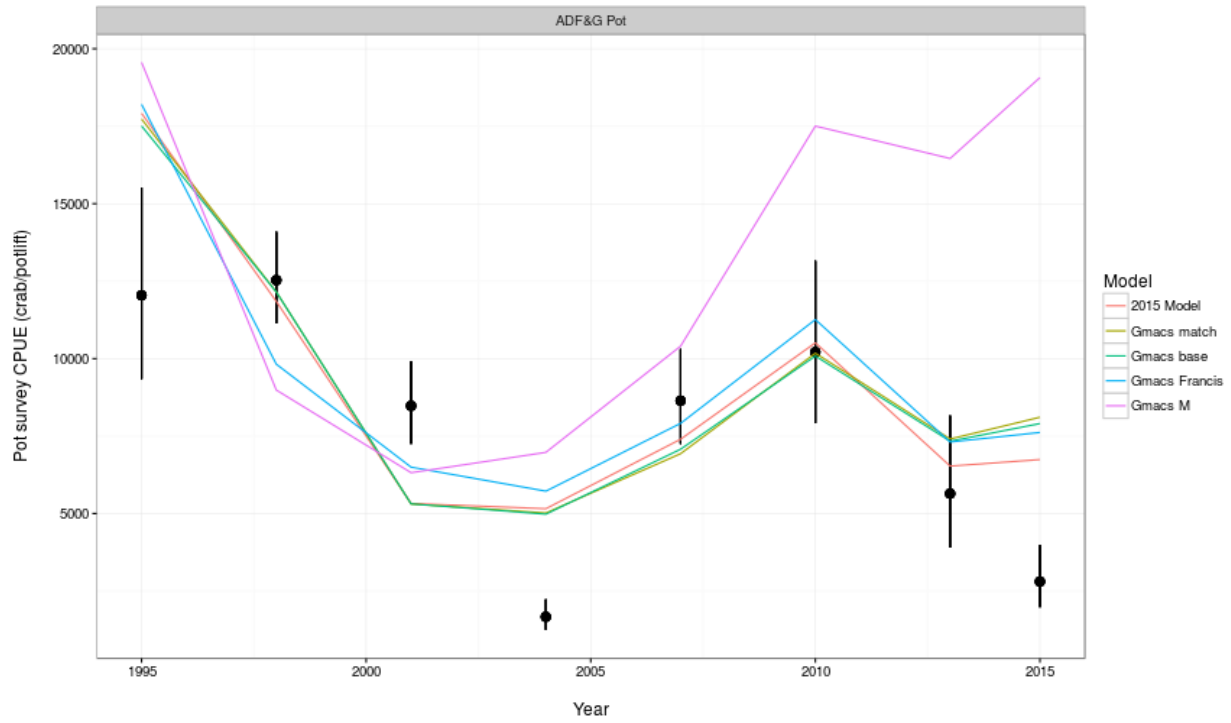


Figure 10: Comparisons of total male pot survey CPUEs and model predictions for the 2015 model and each of the Gmacs model scenarios. The additional CV for the pot survey CPUE in the Gmacs CV scenario is not shown. The error bars are plus and minus 2 standard deviations.

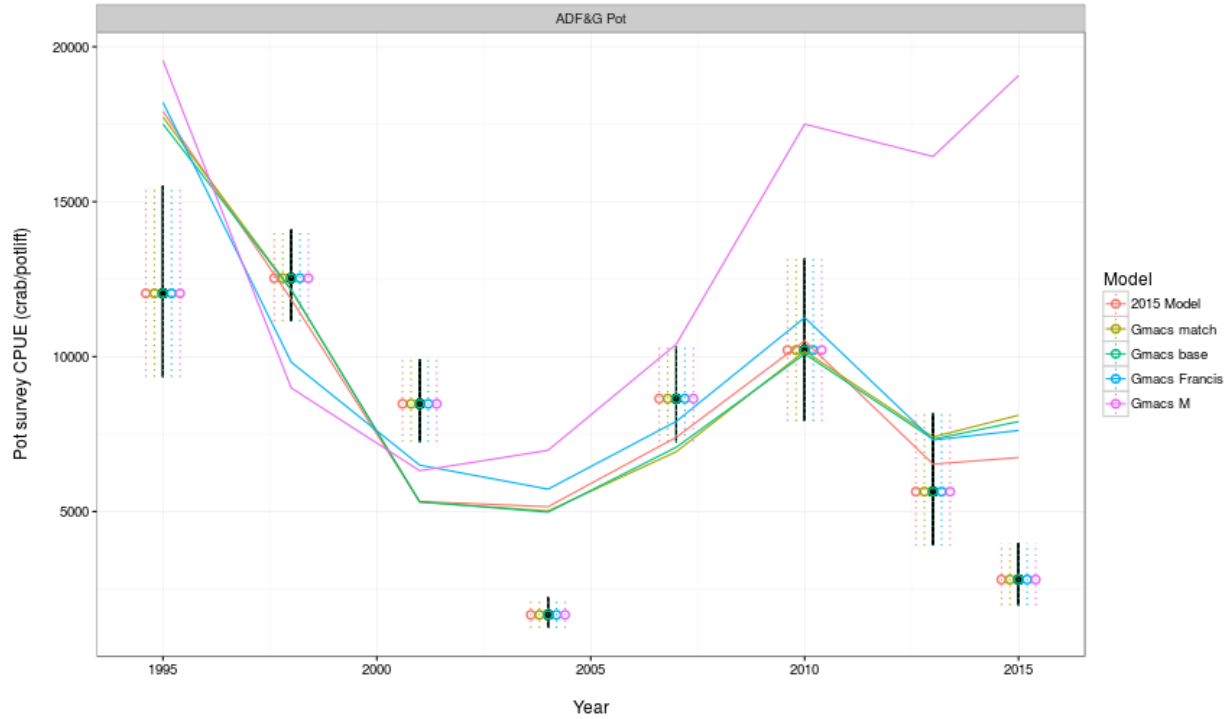


Figure 11: Comparisons of total male pot survey CPUEs and model predictions for the 2015 model and each of the Gmacs model scenarios. The additional CV for the pot survey CPUE is shown. The error bars are plus and minus 2 standard deviations.

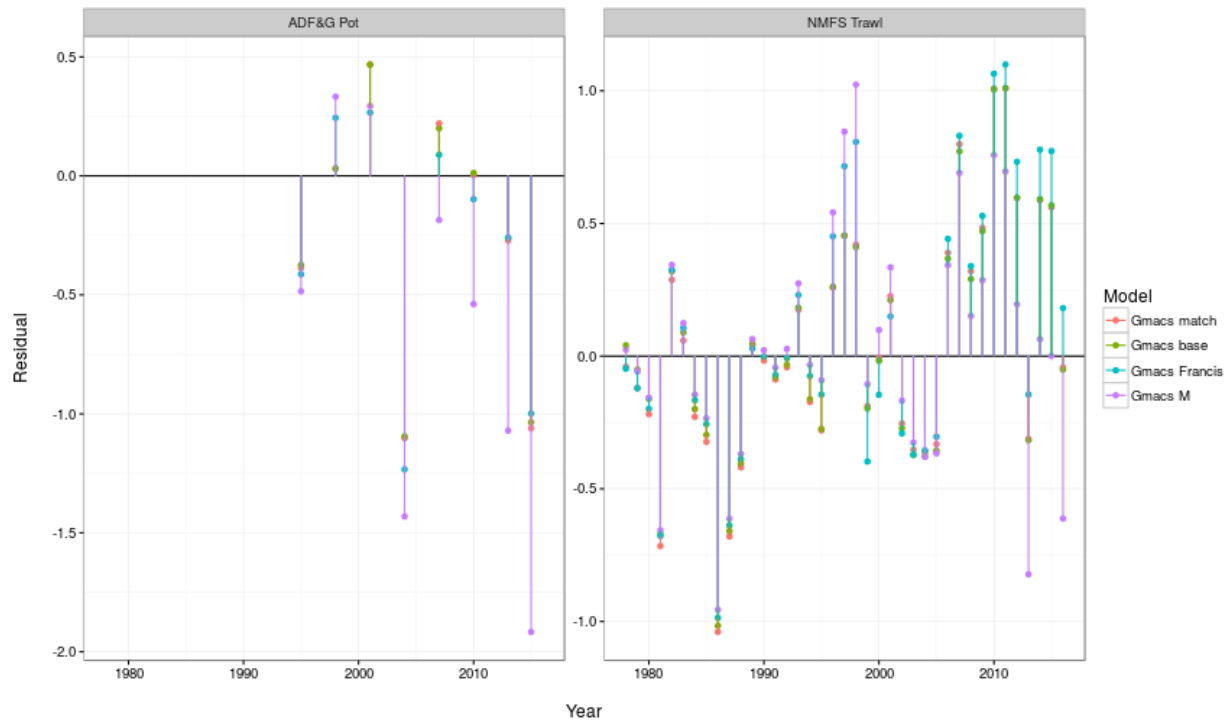


Figure 12: Standardized residuals for area-swept estimates of total male survey biomass and total male pot survey CPUEs for each of the Gmacs model scenarios.

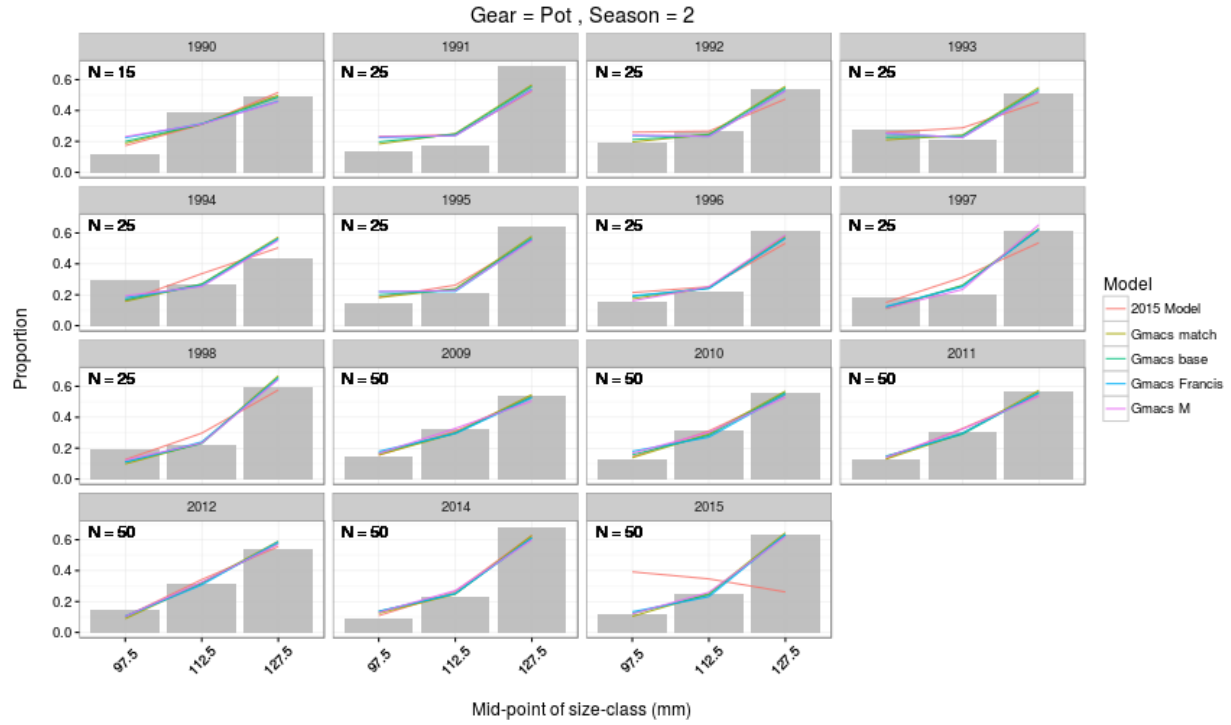


Figure 13: Observed and model estimated size-frequencies of SMBKC by year retained in the directed pot fishery for the 2015 model and each of the Gmacs model scenarios.

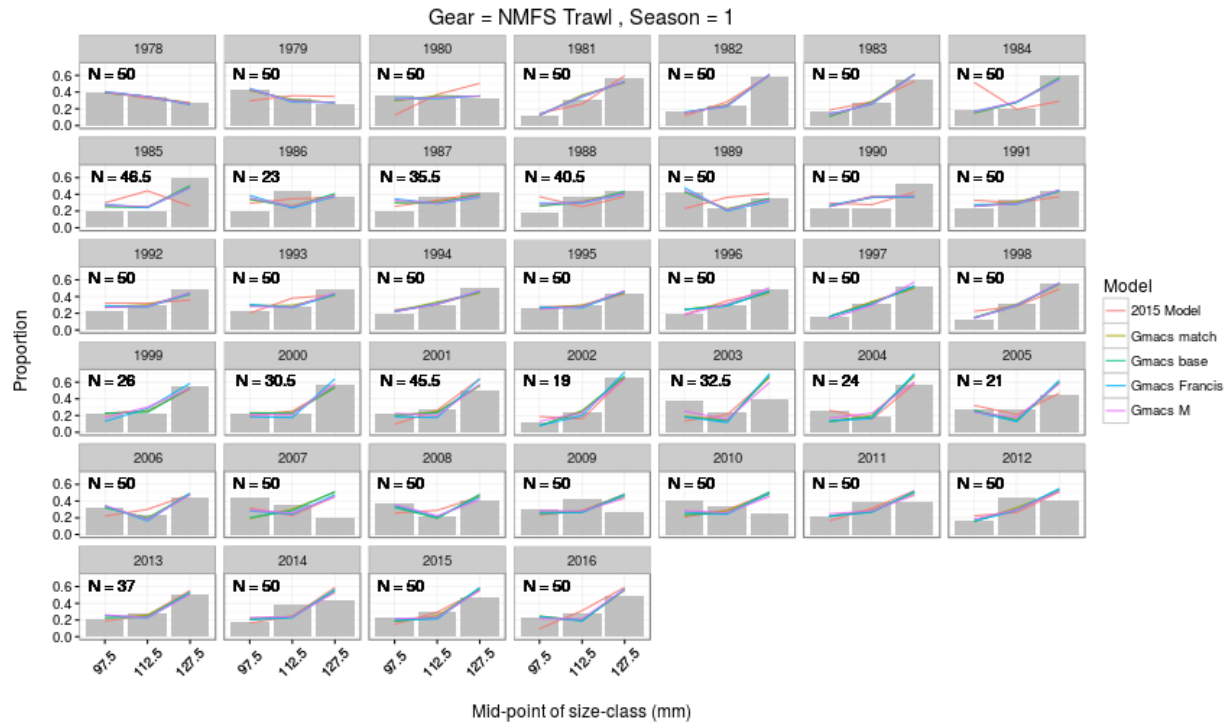


Figure 14: Observed and model estimated size-frequencies of discarded male SMBKC by year in the NMFS trawl survey for the 2015 model and each of the Gmacs model scenarios.

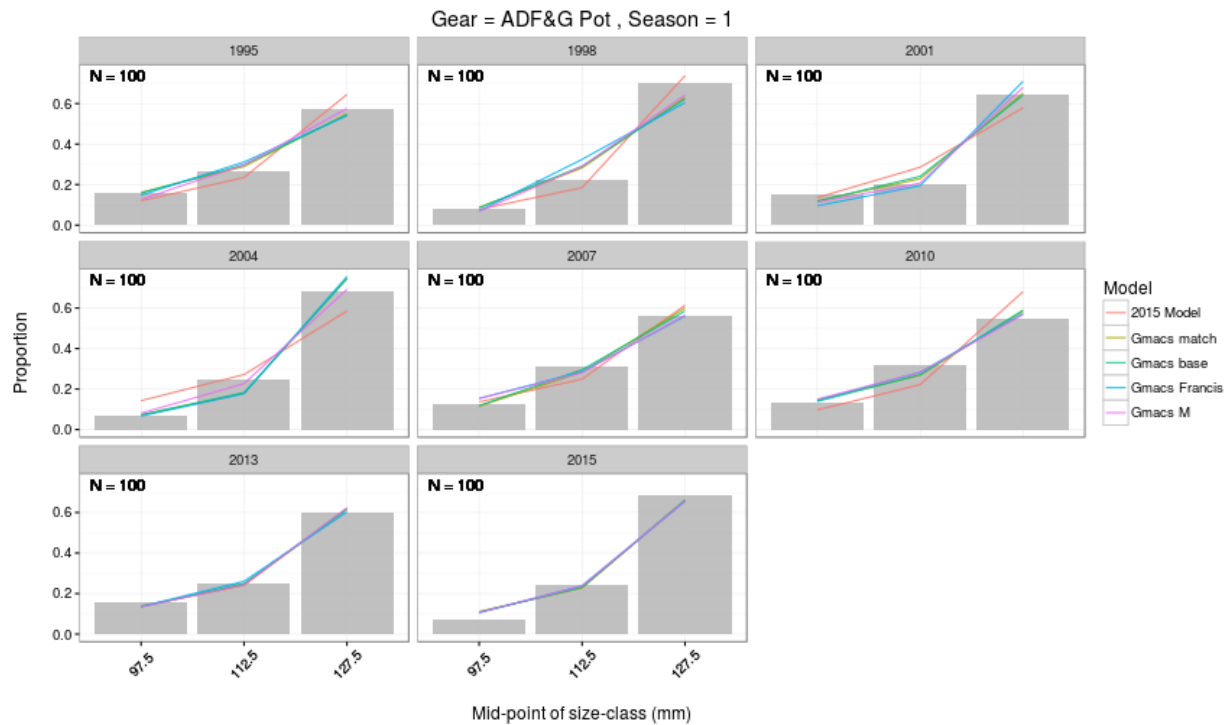


Figure 15: Observed and model estimated size-frequencies of discarded SMBKC by year in the ADF&G pot survey for the 2015 model and each of the Gmacs model scenarios.

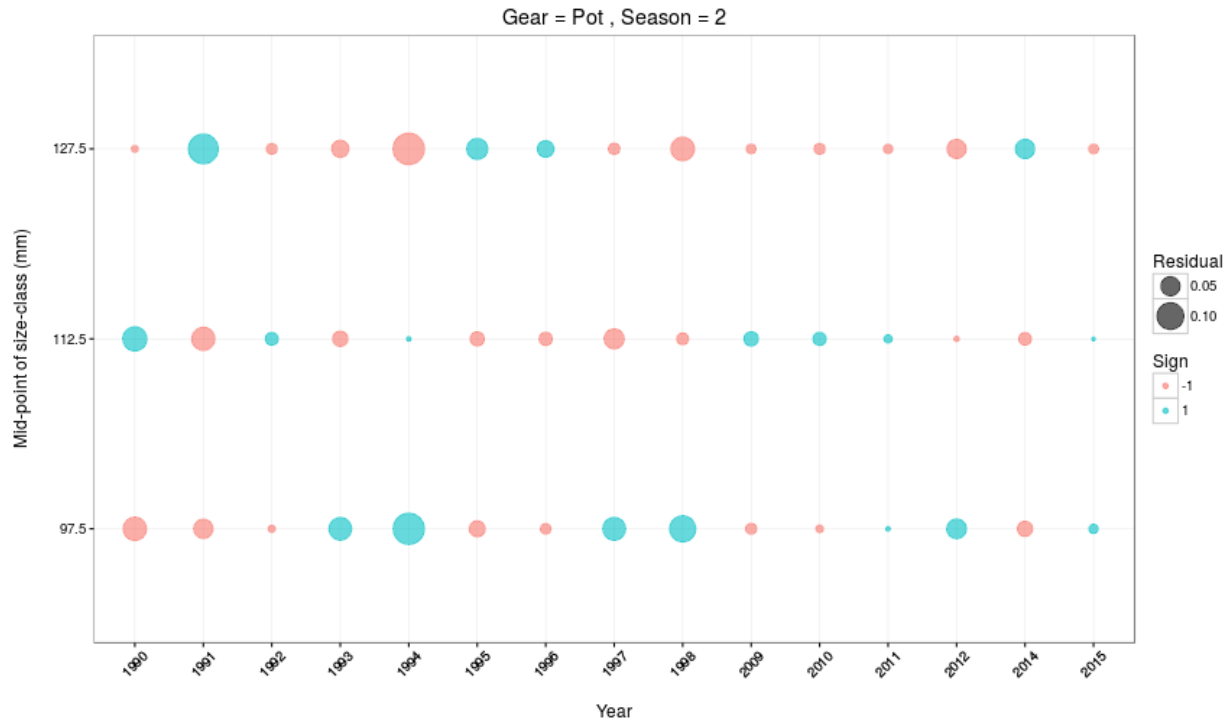


Figure 16: Bubble plots of residuals by stage and year for the directed pot fishery size composition data for St. Mathew Island blue king crab (SMBKC) in the **Gmacs match** model.

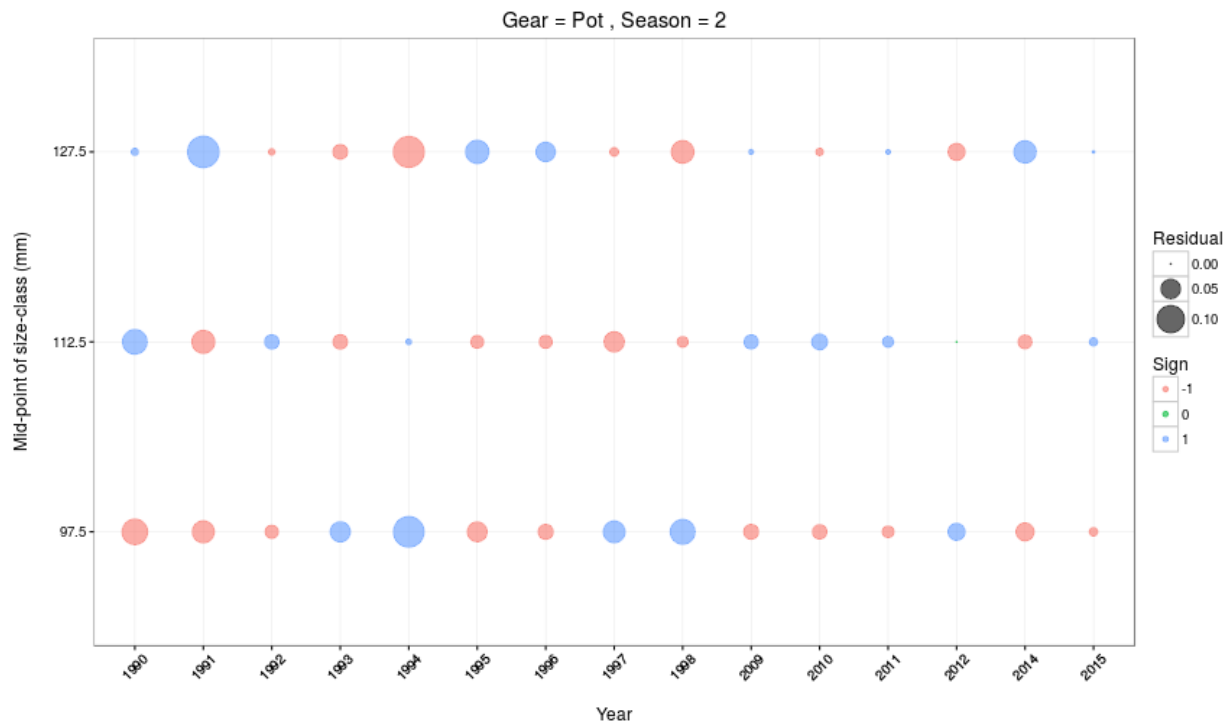


Figure 17: Bubble plots of residuals by stage and year for the directed pot fishery size composition data for St. Mathew Island blue king crab (SMBKC) in the **Gmacs base** model.

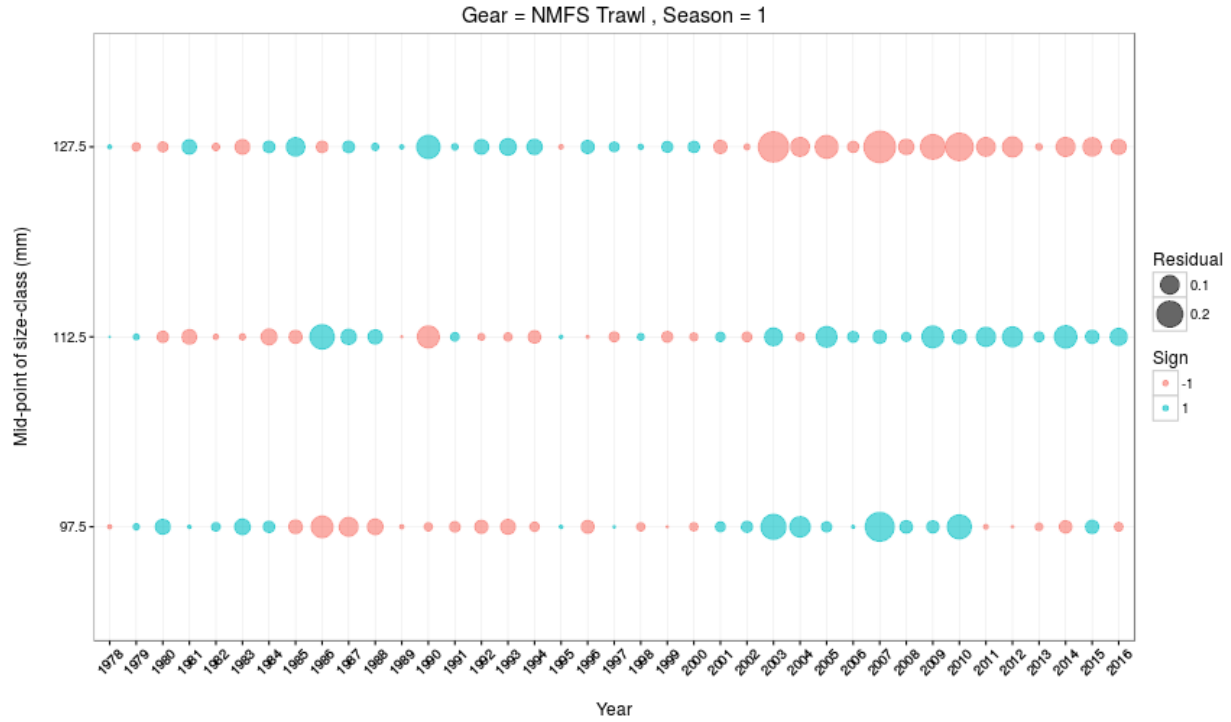


Figure 18: Bubble plots of residuals by stage and year for the NMFS trawl survey size composition data for St. Mathew Island blue king crab (SMBKC) in the **Gmacs base** model.

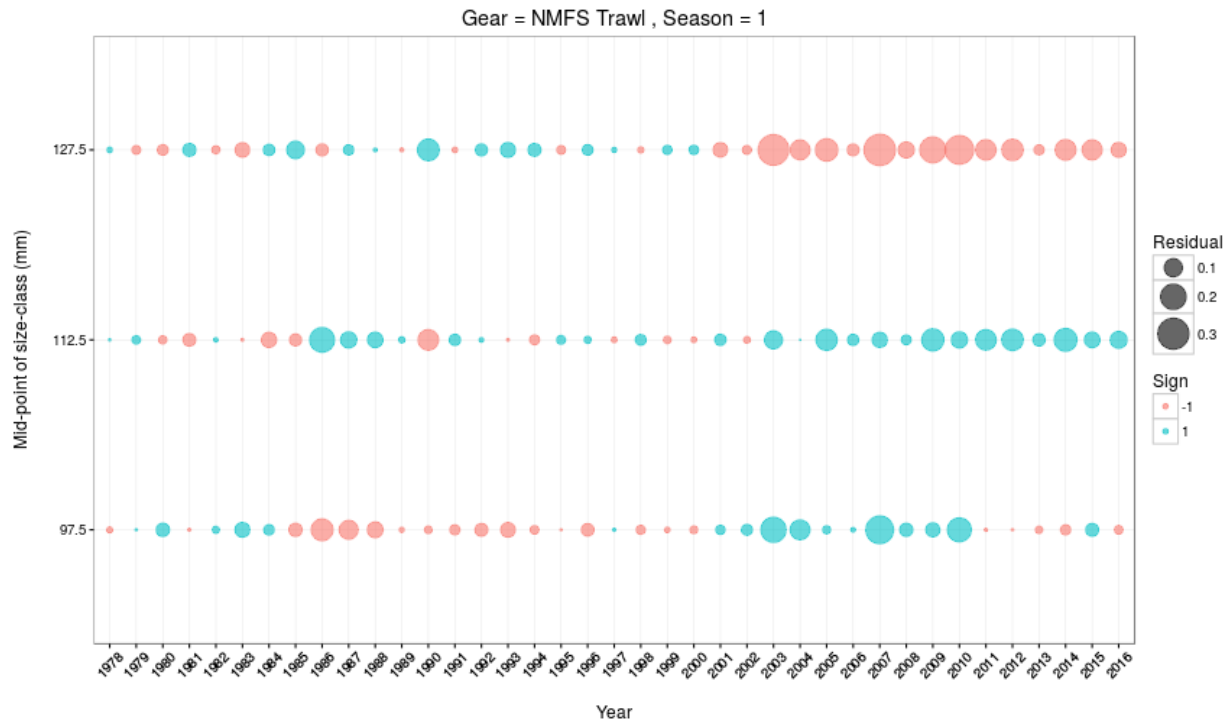


Figure 19: Bubble plots of residuals by stage and year for the NMFS trawl survey size composition data for St. Mathew Island blue king crab (SMBKC) in the **Gmacs selex** model.

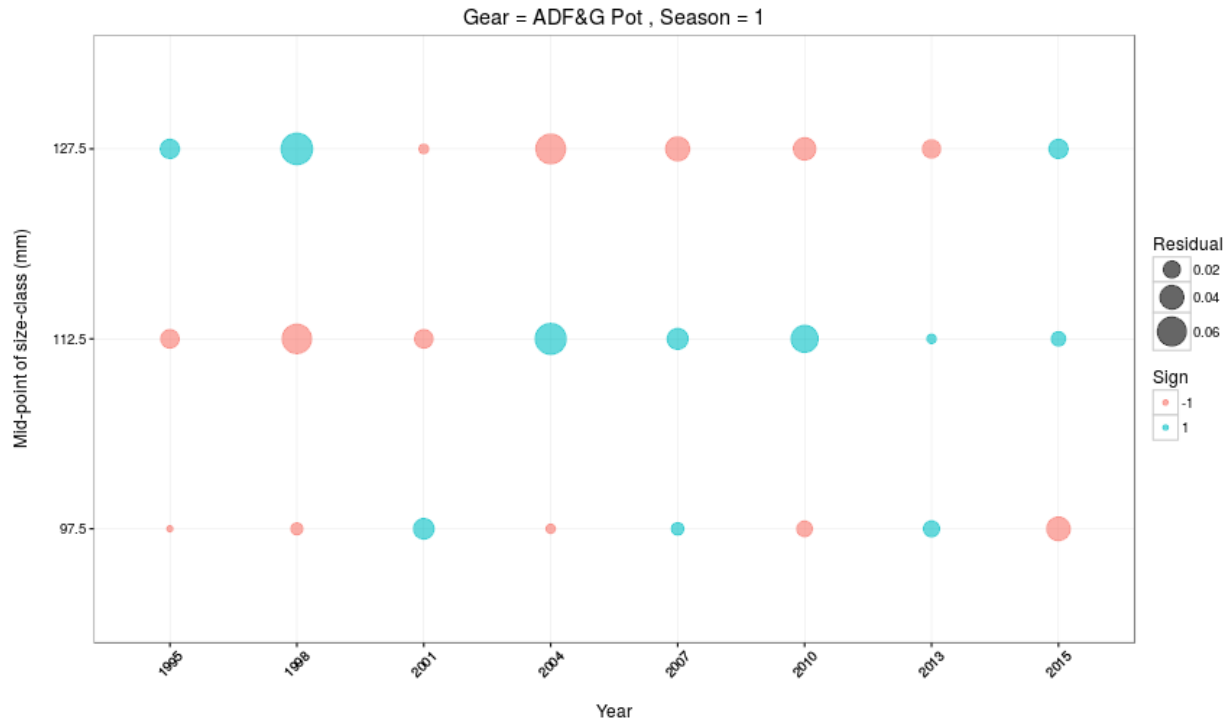


Figure 20: Bubble plots of residuals by stage and year for the ADF&G pot survey size composition data for St. Mathew Island blue king crab (SMBKC) in the **Gmacs base** model.

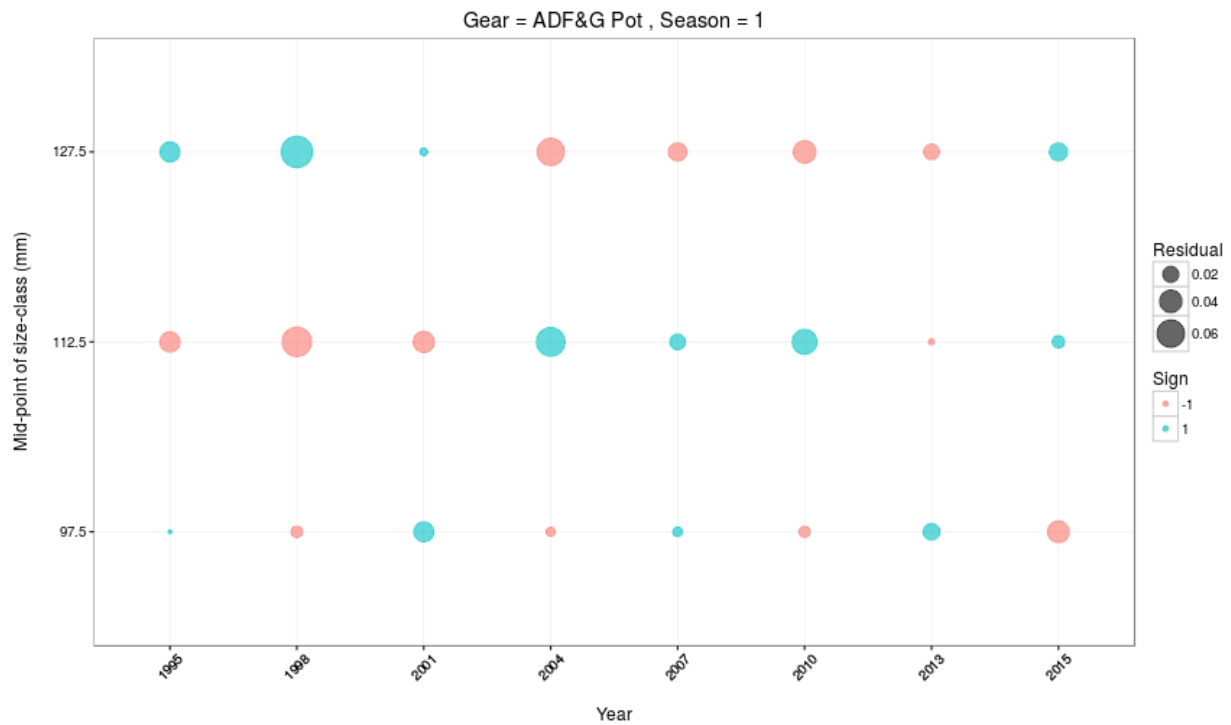


Figure 21: Bubble plots of residuals by stage and year for the ADF&G pot survey size composition data for St. Mathew Island blue king crab (SMBKC) in the **Gmacs selex** model.

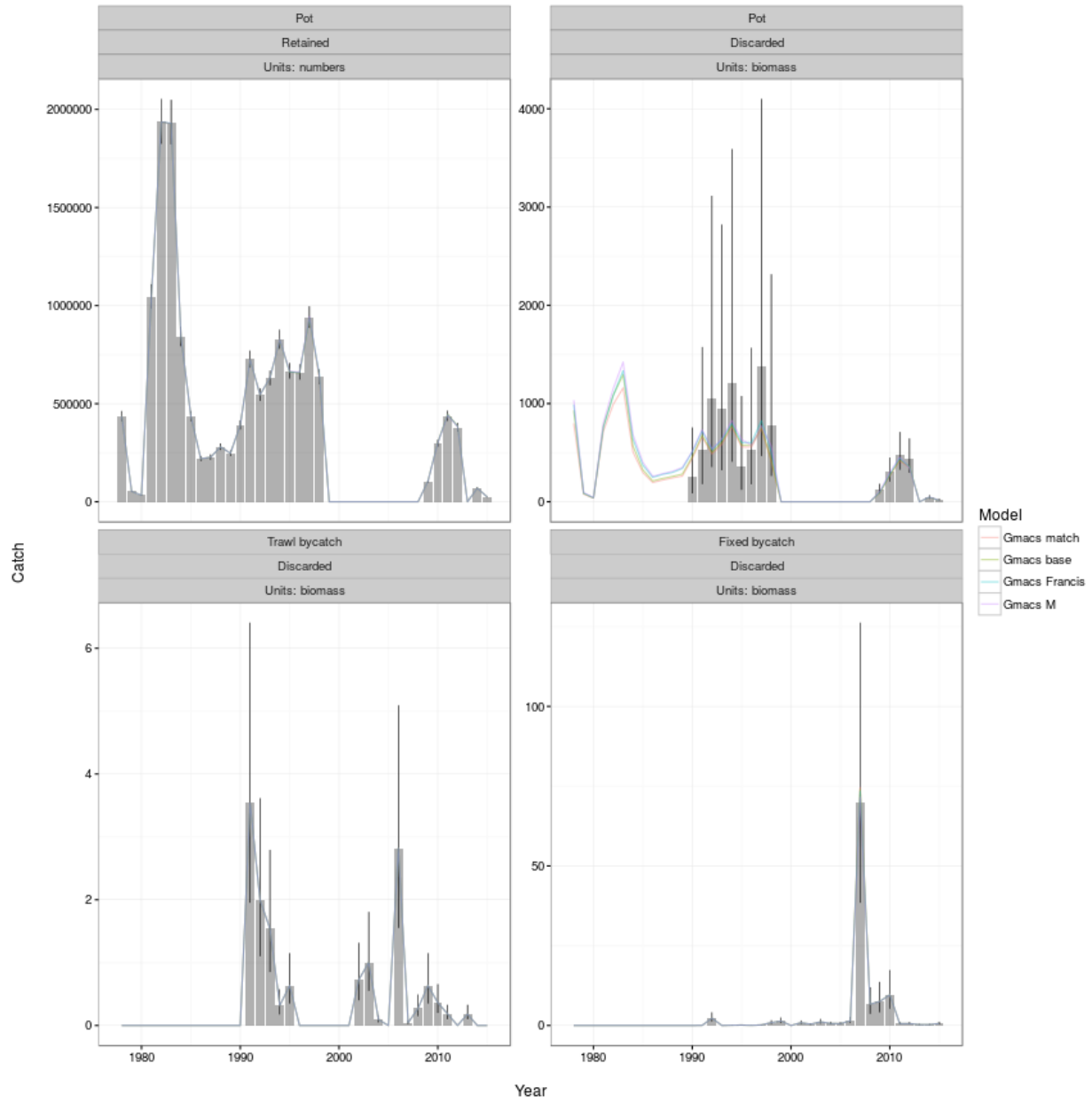


Figure 22: Comparison of observed and model predicted retained catch and bycatches in each of the Gmacs models. Note that difference in units between each of the panels.



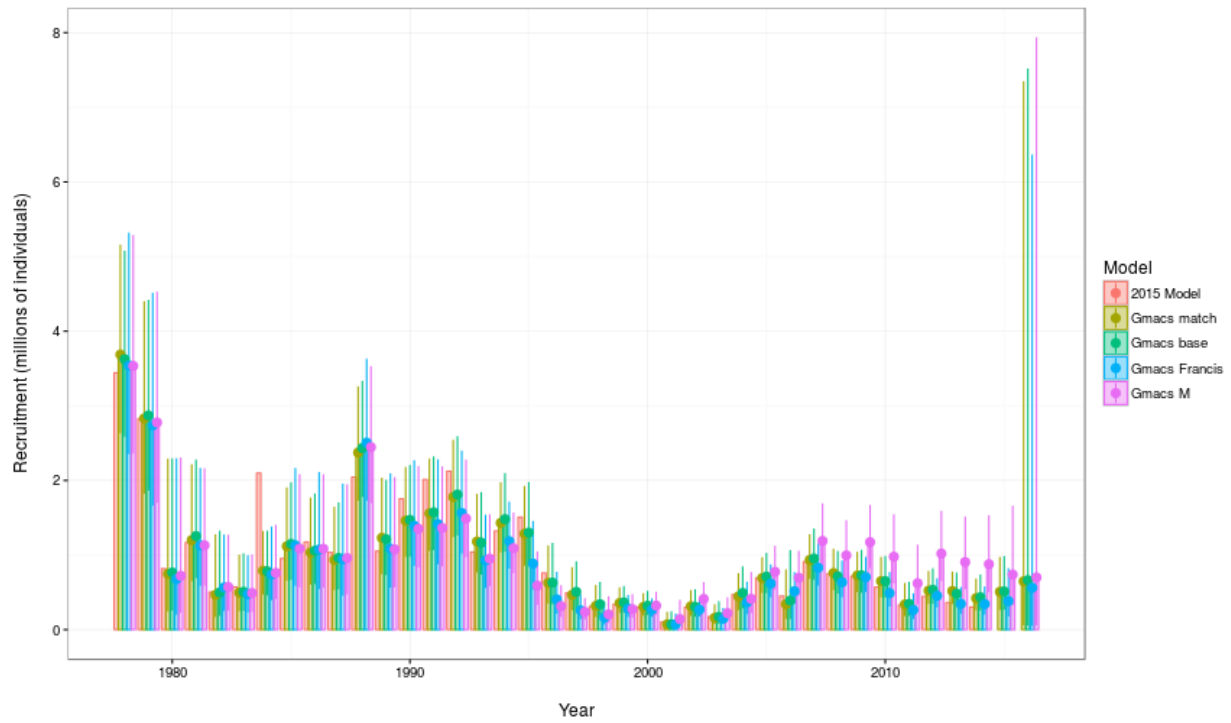


Figure 23: Estimated recruitment time series during 1979-2015 in each of the scenarios.

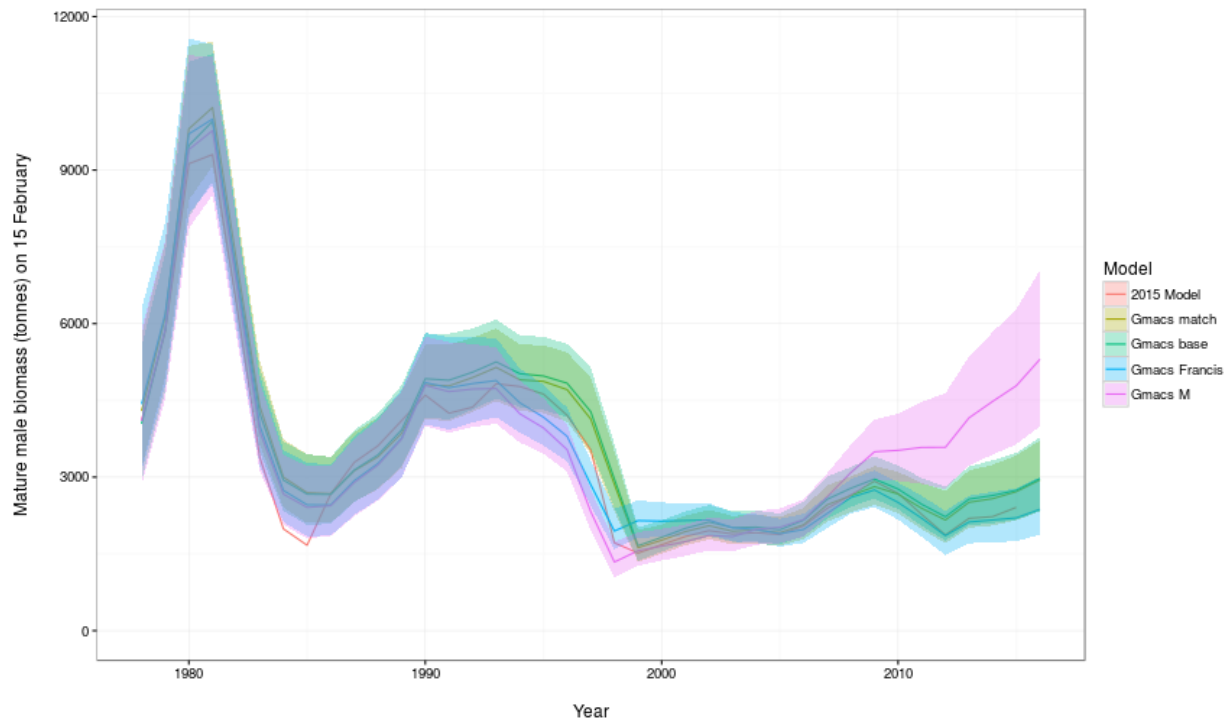


Figure 24: Estimated mature male biomass (MMB) time series on 15 February during 1978-2015 for each of the model scenarios.

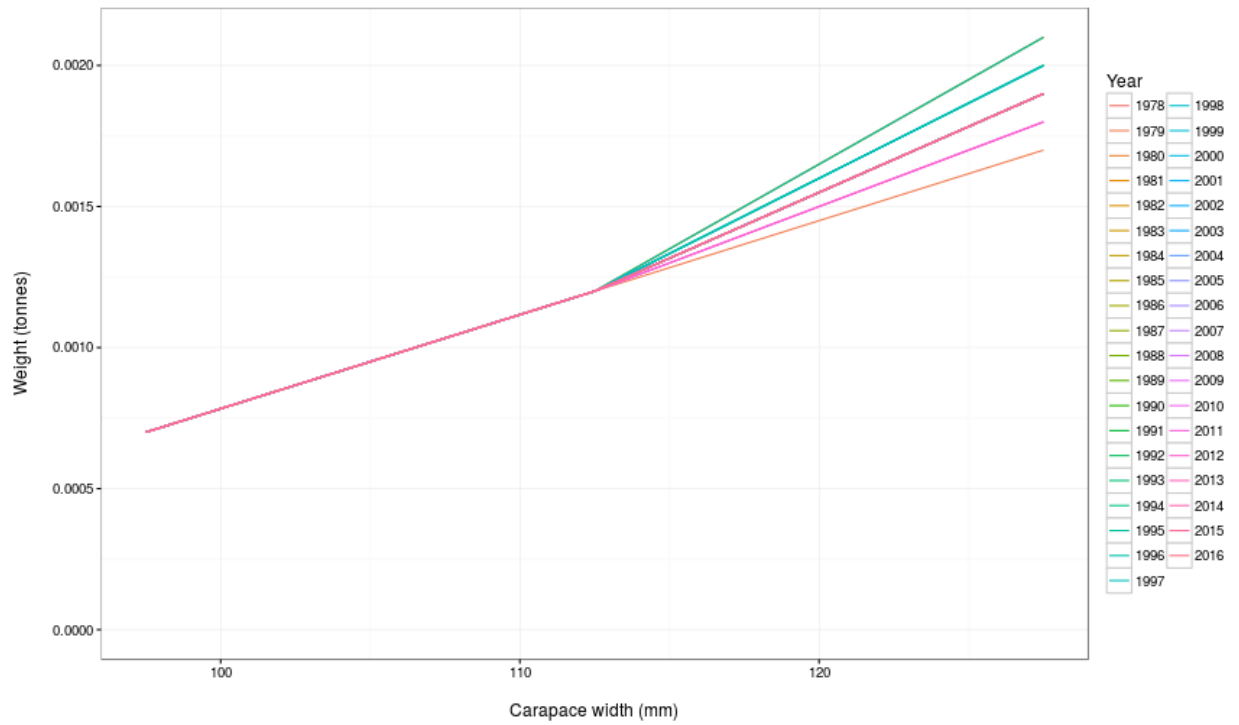


Figure 25: Relationship between carapace width (mm) and weight (kg) in all of the models (provided as a vector of weights at length to Gmacs).

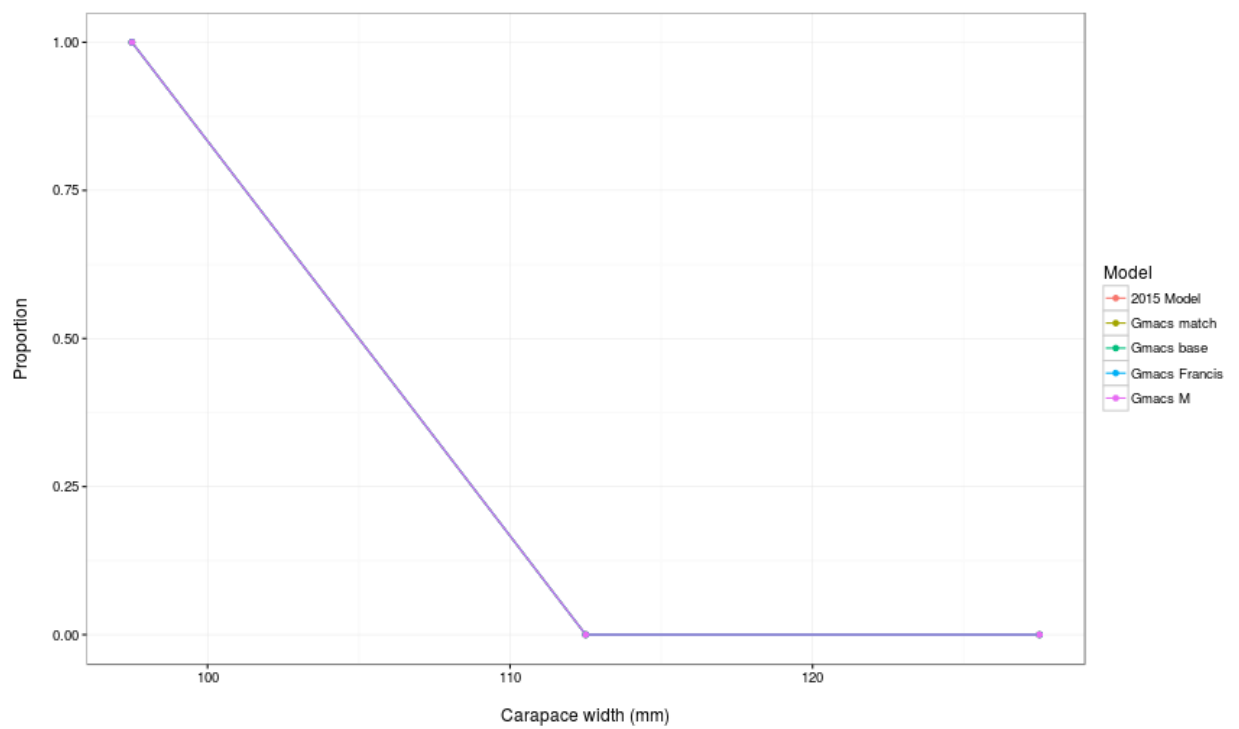


Figure 26: Distribution of carapace width (mm) at recruitment.

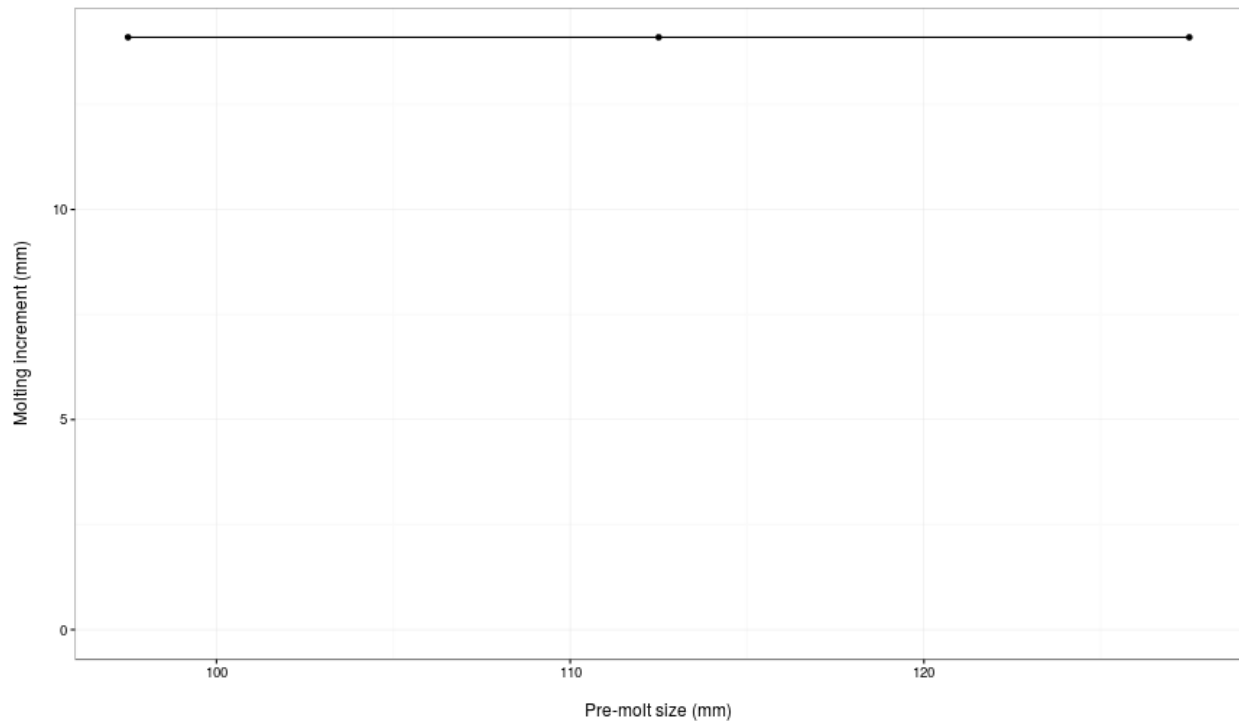


Figure 27: Growth increment (mm) each molt.

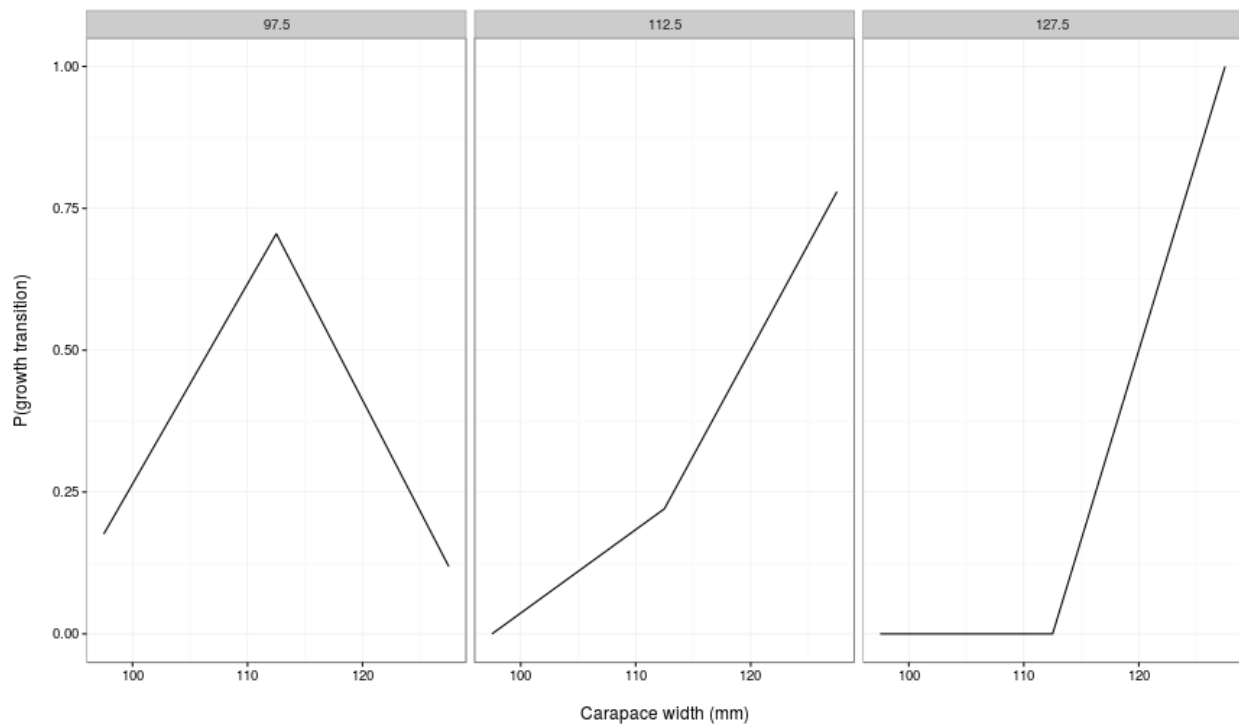


Figure 28: Probability of growth transition by stage. Each of the panels represent the stage before growth. The x-axes represent the stage after a growth (ignoring the probability of molting).

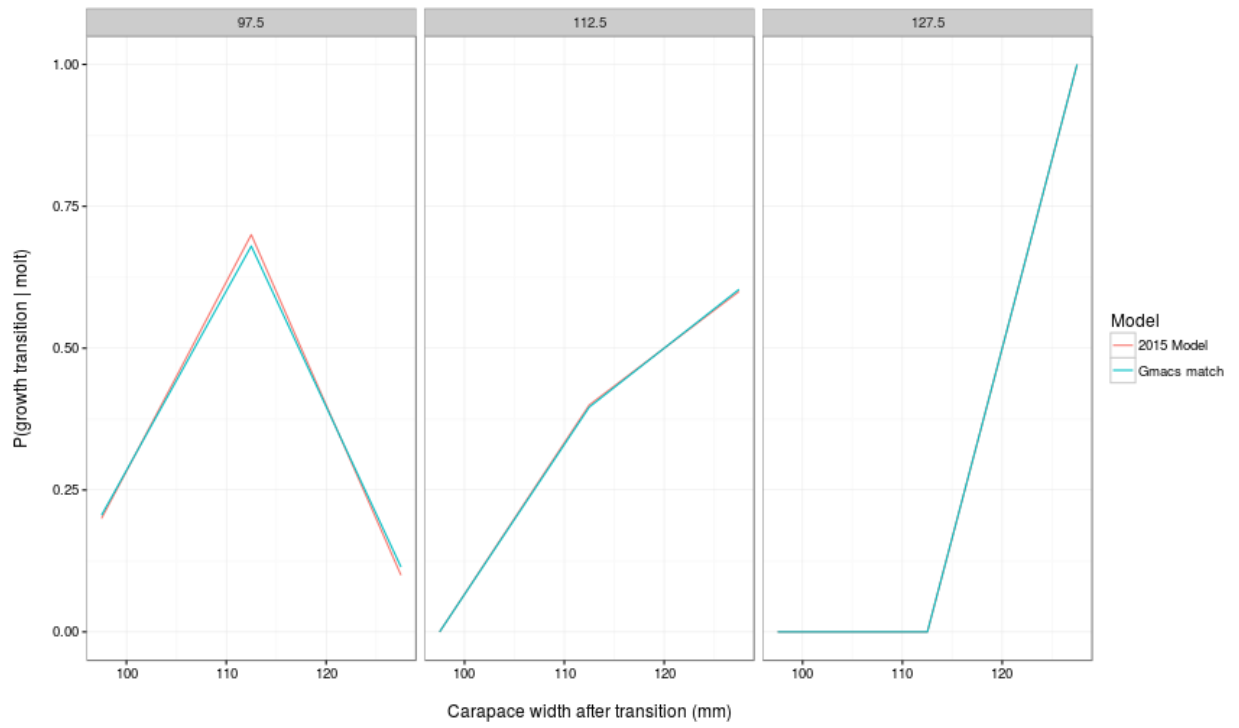


Figure 29: Probability of size transition by stage (i.e. the combination of the growth matrix and molting probabilities). Each of the panels represent the stage before a transition. The x-axes represent the stage after a transition.

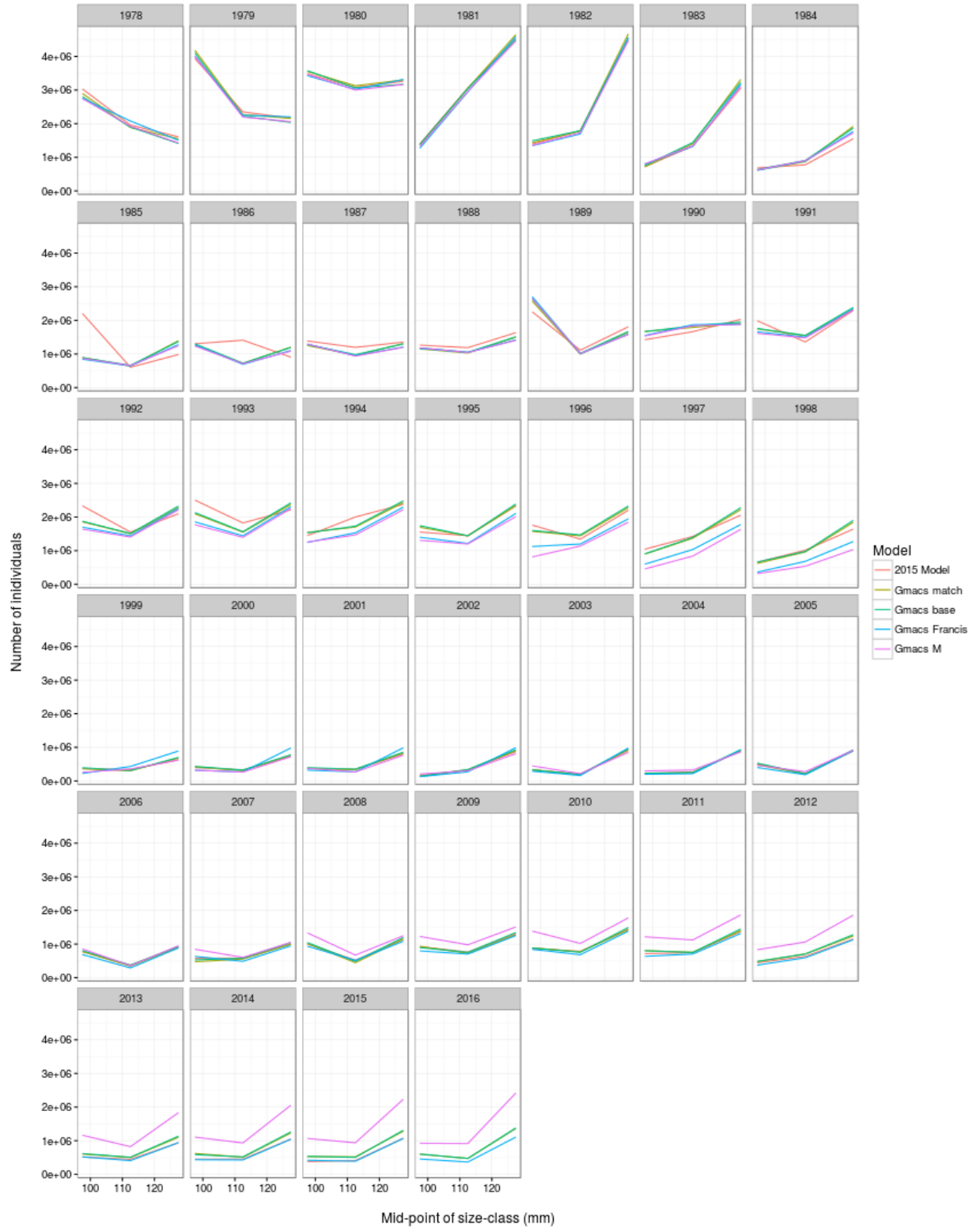


Figure 30: Numbers by stage each year (15 February) in each of the models including the 2015 model.

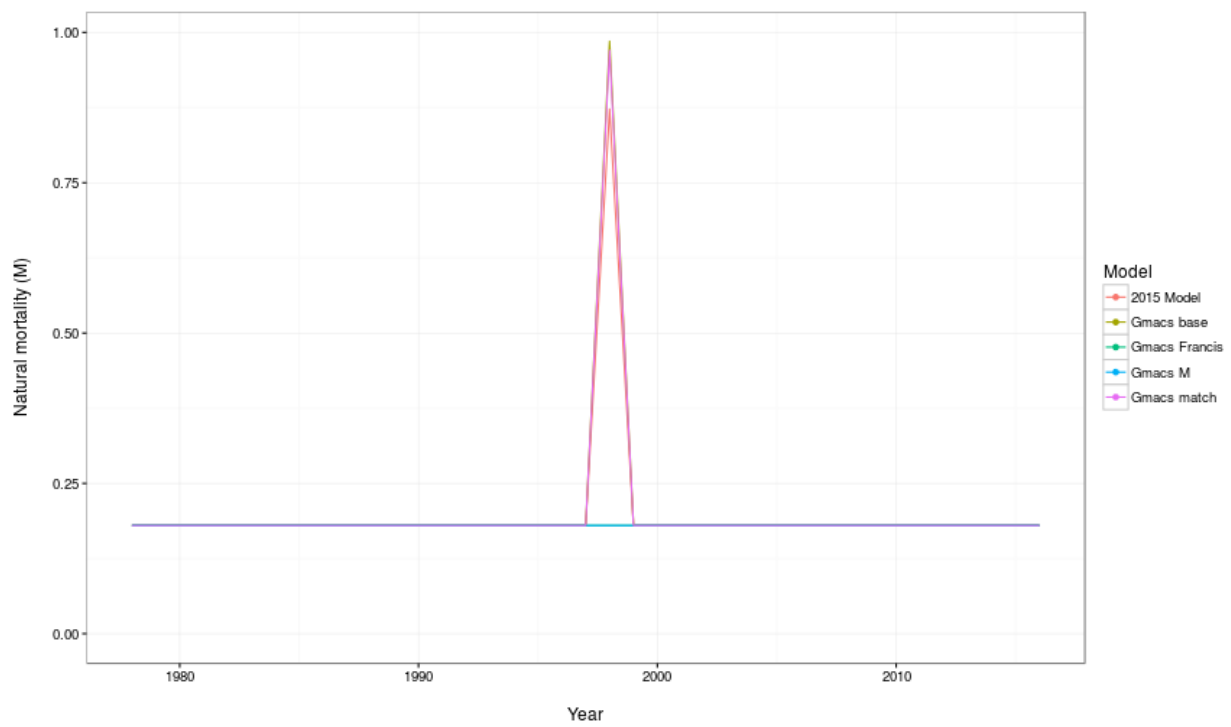


Figure 31: Time-varying natural mortality ( $M_t$ ). Estimated pulse period occurs in 1998/99 (i.e.  $M_{1998}$ ).

# 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

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 measured 15 February. To accomodate this, each model year is split into five seasons and a proportion of the natural mortality ( $\tau_i$ ) is applied in each of these seasons where  $\sum_{i=1}^5 \tau_i = 1$ . Each model year consists of the following processes:

### 1. Season 1

- Beginning of the SMBKC fishing year (1 July)
- $\tau_1 = 0$
- Surveys

### 2. Season 2

- $\tau_2$  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)

### 3. Season 3

- $\tau_3 = 0$
- Fishing mortality applied

### 4. Season 4

- $\tau_4 = 0.63 - \sum_{i=1}^4 \tau_i$
- Calculate MMB (15 February)

### 5. Season 5

- $\tau_5 = 0.37$
- Growth and molting
- Recruitment (all to stage-1)

The proportion of natural mortality ( $\tau$ ) applied during each season in the model is provided in Table 11. 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  $\tau_2$  is different each year and thus  $\tau_4$  differs each year.

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

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

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

$$\mathbf{G} = \begin{bmatrix} 1 - \pi_{12} - \pi_{13} & \pi_{12} & \pi_{13} \\ 0 & 1 - \pi_{23} & \pi_{23} \\ 0 & 0 & 1 \end{bmatrix}, \quad (3)$$

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

$$\mathbf{S}_{t,y} = \begin{bmatrix} 1 - e^{-Z_{1,t,y}} & 0 & 0 \\ 0 & 1 - e^{-Z_{2,t,y}} & 0 \\ 0 & 0 & 1 - e^{-Z_{3,t,y}} \end{bmatrix}, \quad (4)$$

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

$$\mathbf{r}_{t,y} = [\bar{R}, 0, 0]^\top, \quad (5)$$

where  $\bar{R}$  is the average annual recruitment. The basic population dynamics underlying Gmacs can thus be described as

$$\begin{aligned} \mathbf{n}_{t+1,y} &= \mathbf{S}_{t,y} \mathbf{n}_{t,y}, & \text{if } t < 4 \\ \mathbf{n}_{t,y+1} &= \mathbf{G} \mathbf{S}_{t,y} \mathbf{n}_{t,y} + \mathbf{r}_{t,y}, & \text{if } t = 4 \end{aligned} \quad (6)$$

The natural mortality

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

where  $\bar{M}_t = 0, 0.44$  and

The 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.

### 3. Model Data

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

$$y = \{\text{catch}, \text{cpue}, \text{lfs}\}$$



## 4. Model Parameters

$$\theta = \{R_0, \bar{R}, \mathbf{n}_0, q_{\text{pot}}, cv, Mdev, sel\}$$

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,  $F_t^{\text{df}}$  is set to zero rather than model estimated. Similarly, for years in which no groundfish bycatch data are available,  $F_t^{\text{gf}}$  and  $F_t^{\text{gt}}$  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.

Both surveys are assigned a nominal date of 1 July, the start of the crab year. The directed fishery is not treated as a season midpoint pulse. Groundfish bycatch is likewise not modeled as a pulse effect, occurring at the nominal time of mating, 15 February, which is also the reference date for calculation of federal management biomass quantities.

## 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 2, 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  $\leq 90 \text{ mm CL}$ ) and estimated coefficients of variation  $\hat{cv}_t$  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 2 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  $n_t$  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	

$$\sigma_i = \frac{1}{\lambda} \sqrt{\log(1.0 + c_i^2)} \quad (10)$$

$$\delta_i = \frac{\log(obs_i/pred_i)}{\sigma_i} + 0.5\sigma_i \quad (11)$$

The standard deviation of the normalized (or standardized) residuals (SDNR) is calculated as

$$sdnr = \sqrt{\frac{1}{n} \sum_{i=1}^n (\delta_i - \bar{\delta})^2} \quad (12)$$

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). Since the normalized residuals are (approximately) normally distributed, a reasonable guideline is that the SDNR should be less than  $\chi^2$ , where  $c2; m1$  is the 95th percentile of a  $c2$  distribution with  $m - 1$  degrees of freedom (e.g., this means 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.

```
The MAR is dvector tmp = fabs(tmpVec); dvector w = sort(tmp); out(2) = w(floor(0.5*(size_count(w)+1)));
// MAR
```

MAR, Francis weighting

## 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 11: Proportion of the natural mortality ( $\tau$ ) that is applied during each season in the model.

Season 1	Season 2	Season 3	Season 4	Season 5
0.00	0.07	0.00	0.56	0.37
0.00	0.06	0.00	0.57	0.37
0.00	0.07	0.00	0.56	0.37
0.00	0.05	0.00	0.58	0.37
0.00	0.07	0.00	0.56	0.37
0.00	0.12	0.00	0.51	0.37
0.00	0.10	0.00	0.53	0.37
0.00	0.14	0.00	0.49	0.37
0.00	0.14	0.00	0.49	0.37
0.00	0.14	0.00	0.49	0.37
0.00	0.14	0.00	0.49	0.37
0.00	0.14	0.00	0.49	0.37
0.00	0.14	0.00	0.49	0.37
0.00	0.18	0.00	0.45	0.37
0.00	0.14	0.00	0.49	0.37
0.00	0.18	0.00	0.45	0.37
0.00	0.18	0.00	0.45	0.37
0.00	0.18	0.00	0.45	0.37
0.00	0.18	0.00	0.45	0.37
0.00	0.18	0.00	0.45	0.37
0.00	0.18	0.00	0.45	0.37
0.00	0.18	0.00	0.45	0.37
0.00	0.18	0.00	0.45	0.37
0.00	0.18	0.00	0.45	0.37
0.00	0.18	0.00	0.45	0.37
0.00	0.18	0.00	0.45	0.37
0.00	0.18	0.00	0.45	0.37
0.00	0.18	0.00	0.45	0.37
0.00	0.18	0.00	0.45	0.37
0.00	0.18	0.00	0.45	0.37
0.00	0.18	0.00	0.45	0.37
0.00	0.18	0.00	0.45	0.37
0.00	0.18	0.00	0.45	0.37
0.00	0.44	0.00	0.19	0.37
0.00	0.44	0.00	0.19	0.37
0.00	0.44	0.00	0.19	0.37
0.00	0.44	0.00	0.19	0.37
0.00	0.44	0.00	0.19	0.37
0.00	0.44	0.00	0.19	0.37
0.00	0.44	0.00	0.19	0.37
0.00	0.44	0.00	0.19	0.37
0.00	0.44	0.00	0.19	0.37

Table 12: 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