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[1]. The fishery was closed for 10 years after the stock was declared overfished in 1999. Fishing resumed in 2009/10 with a fishery-reported retained catch of 209 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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[1]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.

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 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

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

CPT and SSC Comments Specific to SMBKC Stock Assessment

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.).
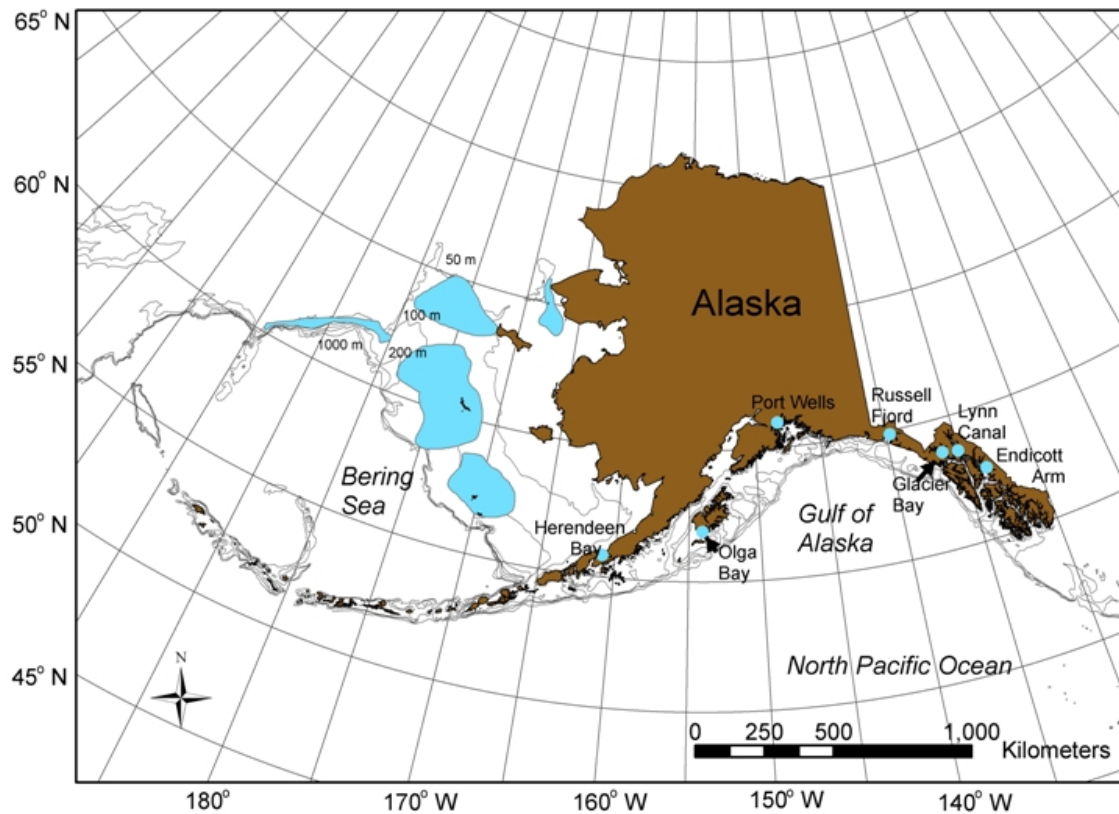

Figure 1: Distribution of blue king crab (*Paralithodes platypus*) in the Gulf of Alaska, Bering Sea, and Aleutian Islands waters (shown in blue).
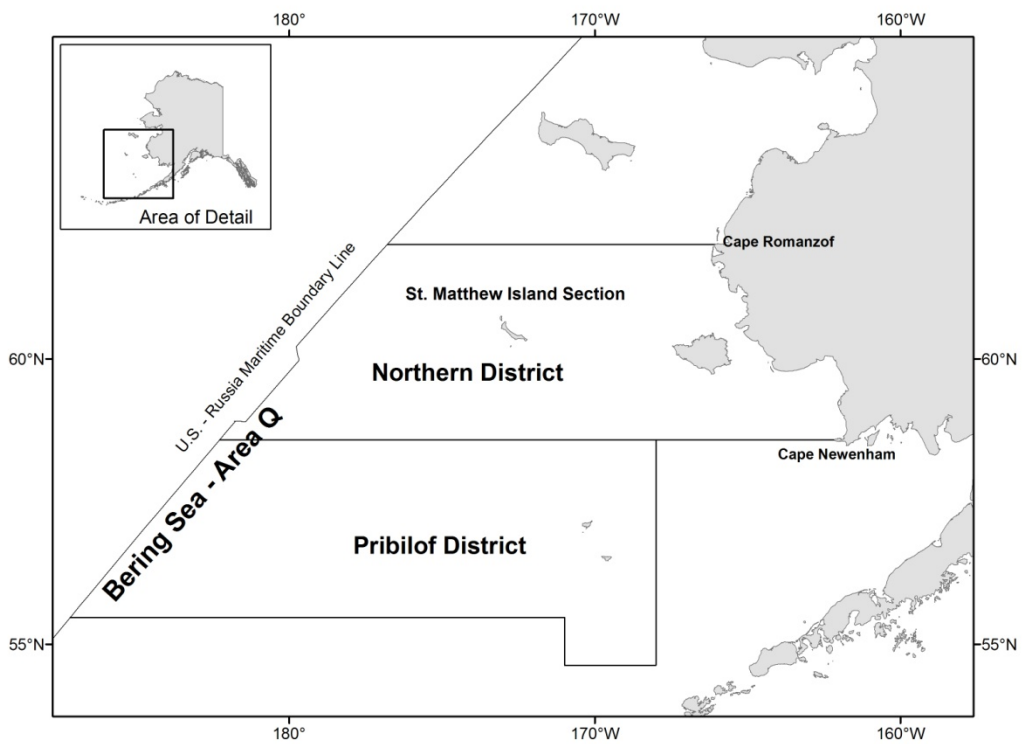
Figure 2: King crab Registration Area Q (Bering Sea).

Stock Structure

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

Life History

Like the red king crab, *Paralithodes camtshaticus*, the blue king crab is considered a shallow water species by comparison with other lithodids such as golden king crab, *Lithodes aequispinus*, and the scarlet king crab, *Lithodes couesi* (Donaldson and Byersdorfer 2005). Adult male blue king crab are found at an average depth of 70 m (NPFMC 1998). The reproductive cycle appears to be annual for the first two reproductive cycles and biennial thereafter (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. Spermataphore diameter also increased with increasing CL with an asymptote at ~ 100 mm CL. They noted, however, that although spermataphore presence indicates physiological sexual maturity, it may not be an indicator of functional sexual maturity. For purposes of management of the St. Matthew Island blue king crab fishery, the State of Alaska uses 105 mm CL to define the lower size bound of functionally mature males (Pengilly and Schmidt 1995). Otto and Cummiskey (1990) report an average growth increment of 14.1 mm CL for adult SMBKC males.

Management History

The SMBKC fishery developed subsequent to baseline ecological studies associated with oil exploration (Otto 1990). Ten U.S. vessels harvested 545 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

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

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[3]. Some bycatch of discarded blue king crab has also been observed historically in the eastern Bering Sea snow crab fishery, but in recent years it has generally been negligible, 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).

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.

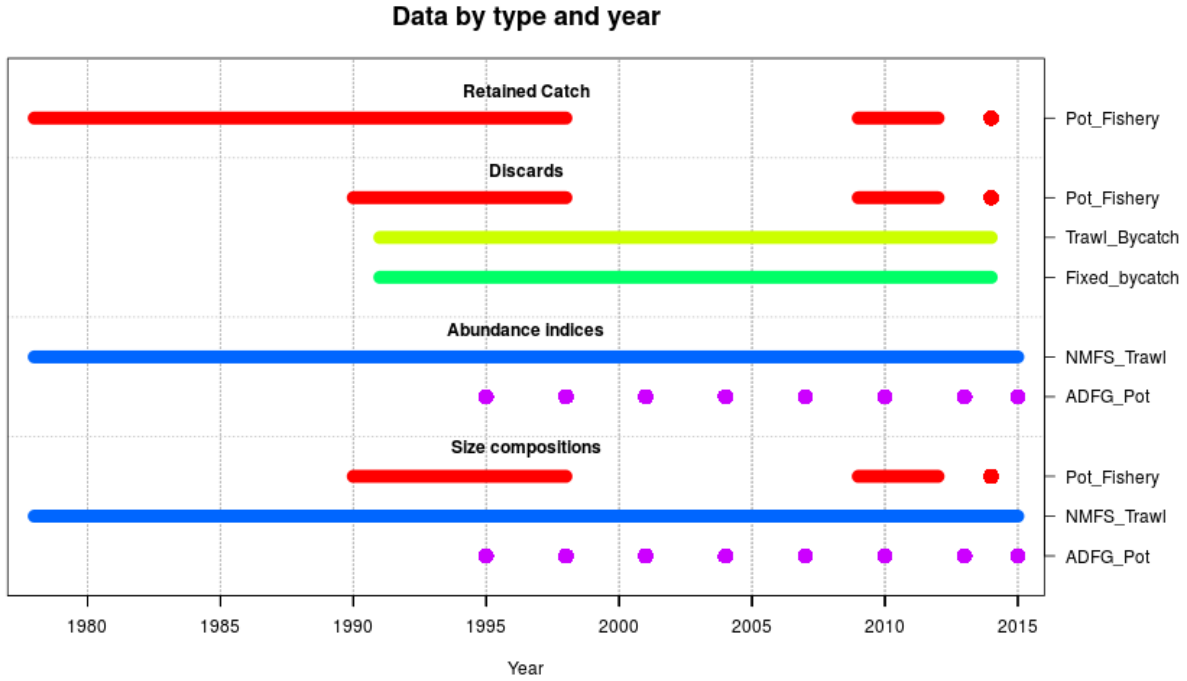[3]D. Pengilly, ADF&G, pers. comm.

Figure 3: Data extent for the SMBKC 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.

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

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

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 CV**: 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.

5. **Gmacs M**: natural mortality (M) is fixed at 0.18 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.

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

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 3, 4, 5, and 6. Negative log likelihood values and management measures for the four Gmacs scenarios are compared in Table 8. Estimated abundances by stage and mature male biomasses for three of the scenarios are listed in Tables 9, 10, and 11.

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 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 3, 4, 5, and 6. 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 α and β, F_{OFL} is determined by the control rule

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

where B is quantified as mature-male biomass (MMB) at mating with time of mating assigned a nominal date of 15 February. Note that as B itself is a function of the fishing mortality F_{OFL}, 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 $M = 0.18$ yr^{-1} in setting the F_{MSY} proxy value γM. The parameters α and β are assigned their default values $\alpha = 0.10$ and $\beta = 0.25$. The F_{OFL}, OFL, 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 3: Model parameter estimates and standard deviations (SD) for the **Gmacs match** model.

Parameter	Estimate	SD
Natural mortality (M) deviation in 1998/99	1.6690000	0.1241800
$\log(\bar{R})$	13.4240000	0.0593130
$\log(N_1)$	14.8690000	0.1697000
$\log(N_2)$	14.4400000	0.1945700
$\log(N_3)$	14.2420000	0.2020800
ADF&G pot survey catchability (q)	0.0043422	0.0003041
$\bar{F}_{\text{pot}}$	-1.4009000	0.0514780
$\bar{F}_{\text{trawl bycatch}}$	-11.7030000	0.2114300
$\bar{F}_{\text{fixed bycatch}}$	-9.5859000	0.2086200

Table 4: 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	1.6821000	0.1280100
$\log(\bar{R})$	13.4430000	0.0606560
$\log(N_1)$	14.8350000	0.1709400
$\log(N_2)$	14.4420000	0.1994600
$\log(N_3)$	14.1470000	0.2110100
ADF&G pot survey catchability (q)	0.0041236	0.0003206
$\log(\bar{F}_{\text{pot}})$	-1.4013000	0.0545840
$\log(\bar{F}_{\text{trawl bycatch}})$	-11.7310000	0.2118100
$\log(\bar{F}_{\text{fixed bycatch}})$	-9.6157000	0.2089100
Stage-1 directed pot selectivity 1978-2008	-0.7422000	0.1739900
Stage-2 directed pot selectivity 1978-2008	-0.3988200	0.1266200
Stage-1 directed pot selectivity 2009-2015	-0.7586000	0.1816100
Stage-2 directed pot selectivity 2009-2015	-0.0000000	0.0000255
Stage-1 NMFS trawl selectivity	-0.2616500	0.0665400
Stage-2 NMFS trawl selectivity	-0.0000000	0.0000079
Stage-1 ADF&G pot selectivity	-0.8554800	0.1469900
Stage-2 ADF&G pot selectivity	-0.0959220	0.0842330

```
## Error in data.frame(Parameter, Estimate, SD): arguments imply differing number of rows: 19, 17
```

```
## Error in data.frame(Model, Parameter, Estimate): arguments imply differing number of rows: 60, 64
```

Table 5: 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	1.6821000	0.1280100
$\log(\bar{R})$	13.4430000	0.0606560
$\log(N_1)$	14.8350000	0.1709400
$\log(N_2)$	14.4420000	0.1994600
$\log(N_3)$	14.1470000	0.2110100
ADF&G pot survey catchability (q)	0.0041236	0.0003206
$\log(\bar{F}_{\text{pot}})$	-1.4013000	0.0545840
$\log(\bar{F}_{\text{trawl bycatch}})$	-11.7310000	0.2118100
$\log(\bar{F}_{\text{fixed bycatch}})$	-9.6157000	0.2089100
Stage-1 directed pot selectivity 1978-2008	-0.7422000	0.1739900
Stage-2 directed pot selectivity 1978-2008	-0.3988200	0.1266200
Stage-1 directed pot selectivity 2009-2015	-0.7586000	0.1816100
Stage-2 directed pot selectivity 2009-2015	-0.0000000	0.0000255
Stage-1 NMFS trawl selectivity	-0.2616500	0.0665400
Stage-2 NMFS trawl selectivity	-0.0000000	0.0000079
Stage-1 ADF&G pot selectivity	-0.8554800	0.1469900
Stage-2 ADF&G pot selectivity	-0.0959220	0.0842330

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

Parameter	Estimate	SD
$\log(\bar{R})$	13.5090000	0.0605460
$\log(N_1)$	14.8130000	0.2039400
$\log(N_2)$	14.4510000	0.2297100
$\log(N_3)$	14.1530000	0.2369600
ADF&G pot survey catchability (q)	0.0057246	0.0010926
$\log(\bar{F}_{\text{pot}})$	-1.3622000	0.0573600
$\log(\bar{F}_{\text{trawl bycatch}})$	-11.7450000	0.2119100
$\log(\bar{F}_{\text{fixed bycatch}})$	-9.6349000	0.2085400
Stage-1 directed pot selectivity 1978-2008	-0.5002000	0.1840100
Stage-2 directed pot selectivity 1978-2008	-0.3838900	0.1508900
Stage-1 directed pot selectivity 2009-2015	-0.9469300	0.1991800
Stage-2 directed pot selectivity 2009-2015	-0.0000000	0.0001032
Stage-1 NMFS trawl selectivity	-0.2190300	0.0623010
Stage-2 NMFS trawl selectivity	-0.0000000	0.0000081
Stage-1 ADF&G pot selectivity	-1.0707000	0.1385700
Stage-2 ADF&G pot selectivity	-0.1466100	0.0966060

Table 7: Comparisons of model parameter estimates for the four Gmacs model scenarios.

Parameter	Estimate	SD
$\log(\bar{R})$	13.509	0.061
$\log(N_1)$	14.813	0.204
$\log(N_2)$	14.451	0.230
$\log(N_3)$	14.153	0.237
ADF&G pot survey catchability (q)	0.006	0.001
$\log(\bar{F}_{\text{pot}})$	-1.362	0.057
$\log(\bar{F}_{\text{trawl bycatch}})$	-11.745	0.212
$\log(\bar{F}_{\text{fixed bycatch}})$	-9.635	0.209
Stage-1 directed pot selectivity 1978-2008	-0.500	0.184
Stage-2 directed pot selectivity 1978-2008	-0.384	0.151
Stage-1 directed pot selectivity 2009-2015	-0.947	0.199
Stage-2 directed pot selectivity 2009-2015	-0.000	0.000
Stage-1 NMFS trawl selectivity	-0.219	0.062
Stage-2 NMFS trawl selectivity	-0.000	0.000
Stage-1 ADF&G pot selectivity	-1.071	0.139
Stage-2 ADF&G pot selectivity	-0.147	0.097

Table 8: 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	-66.71	-66.82	-66.64	-67.11
Pot Discarded Catch	5.34	4.64	4.03	3.76
Trawl bycatch Discarded Catch	22.05	22.05	22.05	22.05
Fixed bycatch Discarded Catch	20.88	20.87	20.87	20.85
NMFS Trawl Survey	-10.59	-11.82	-3.90	-7.68
ADF&G Pot Survey CPUE	51.01	48.61	49.81	0.18
Directed Pot LF	-12.07	-12.08	11.12	10.80
NMFS Trawl LF	14.89	20.48	53.15	35.09
ADF&G Pot LF	-5.48	-5.15	1.74	-1.75
Recruitment deviations	55.44	55.35	56.31	54.22
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	108.54	112.69	178.62	100.47
Total estimated parameters	272.00	280.00	278.00	278.00
MMB_2015	2800.16	2828.62	2242.09	5268.40
Fofl	0.34	0.34	0.30	0.36

Table 9: 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

Table 10: 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	2559761	1667653	976628	4379
1979	4101172	2222508	2054121	6299
1980	3482746	3059350	3189711	10121
1981	1344971	3028561	4597417	10558
1982	1412505	1766244	4619438	7507
1983	1261075	1576524	2388452	4442
1984	681995	1356564	1288645	3012
1985	596216	839171	1001411	2698
1986	880484	627588	1340506	2684
1987	1258820	707767	1152010	3150
1988	1123866	631832	830347	3437
1989	1207615	925487	998729	3925
1990	1107484	992104	1140360	4880
1991	2546151	981827	1598415	4865
1992	1651241	1771015	1864734	5036
1993	1474217	1580991	1312749	5230
1994	1665692	1474538	1494443	4953
1995	1781985	1443725	1627933	4925
1996	2066038	1527972	2315723	4741
1997	1510048	1678805	2367335	4108
1998	1348103	1498483	1366227	2815
1999	1607651	1367785	1546438	1637
2000	1486582	1365583	1489635	1790
2001	853182	1338991	2143270	1960
2002	593201	927650	1755163	2080
2003	324940	508035	584693	1982
2004	340235	286997	631107	2004
2005	389319	288232	704385	1955
2006	361222	326940	796293	2109
2007	130383	313309	864339	2498
2008	116363	279619	771398	2698
2009	315846	171925	863110	2865
2010	202118	236246	837664	2700
2011	469920	199349	865723	2394
2012	749396	332832	868441	2142
2013	668307	296817	774470	2517
2014	445102	511501	921126	2587
2015	959892	421655	1068712	2800

Table 11: 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	2474644	1669508	852421	4098
1979	4022190	2169623	1931186	6016
1980	3509075	2997101	3053057	9768
1981	1367493	3022837	4452588	10263
1982	1470104	1777137	4497514	7269
1983	1312500	1586233	2278759	4282
1984	720054	1392060	1198121	2940
1985	611034	872637	946772	2659
1986	874731	647436	1312663	2660
1987	1282256	711068	1138102	3150
1988	1144790	634778	817894	3463
1989	1229369	939530	991132	3977
1990	1132887	1009106	1143110	4975
1991	2600416	1002395	1612053	4959
1992	1646768	1808641	1891644	5128
1993	1470223	1614582	1336687	5332
1994	1676911	1484145	1533756	5077
1995	1803514	1453353	1666830	5047
1996	2109123	1543779	2356130	4856
1997	1511599	1708507	2413037	4249
1998	1349489	1525002	1406877	2925
1999	1619769	1378162	1597524	1680
2000	1525688	1375904	1538408	1849
2001	867337	1365461	2194587	2026
2002	618716	944452	1812505	2157
2003	336229	513139	610635	2057
2004	365349	292222	648676	2068
2005	400729	304225	724096	2011
2006	380285	339102	822755	2202
2007	135753	328161	894398	2617
2008	121157	292878	798235	2832
2009	312109	179636	895163	3009
2010	205657	236678	867967	2801
2011	524921	201573	892442	2463
2012	781645	364803	897138	2200
2013	697100	325345	800102	2574
2014	470406	539494	963066	2635
2015	995078	445292	1120285	2829

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.
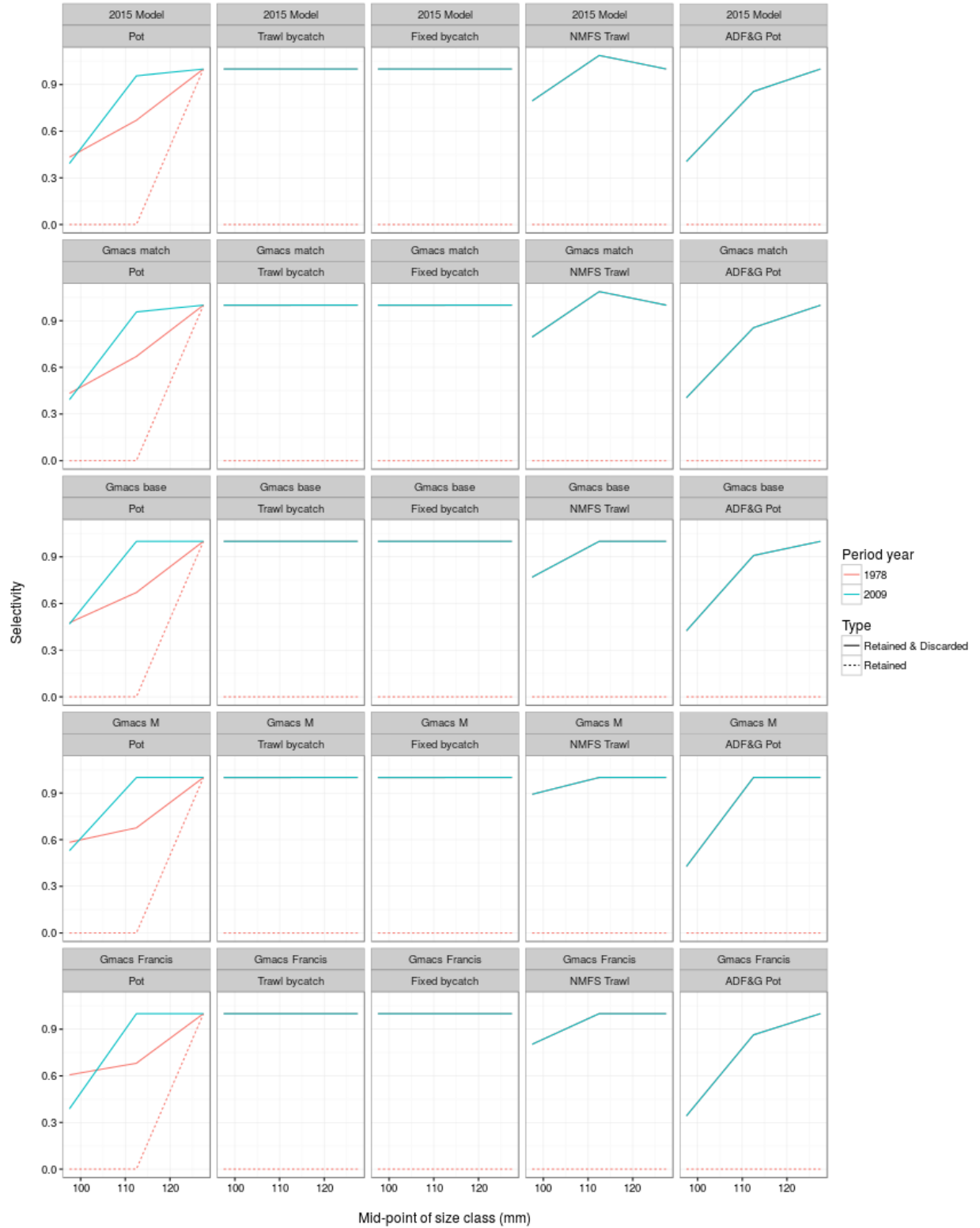
Figure 7: Comparisons of the estimated (and fixed to match the 2015 model selectivities in the Gmacs base scenario) stage-1 and stage-2 selectivities for each of the different model scenarios (the stage-3 selectivities are all fixed at 1). Estimated selectivities are shown for the directed pot fishery, 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.
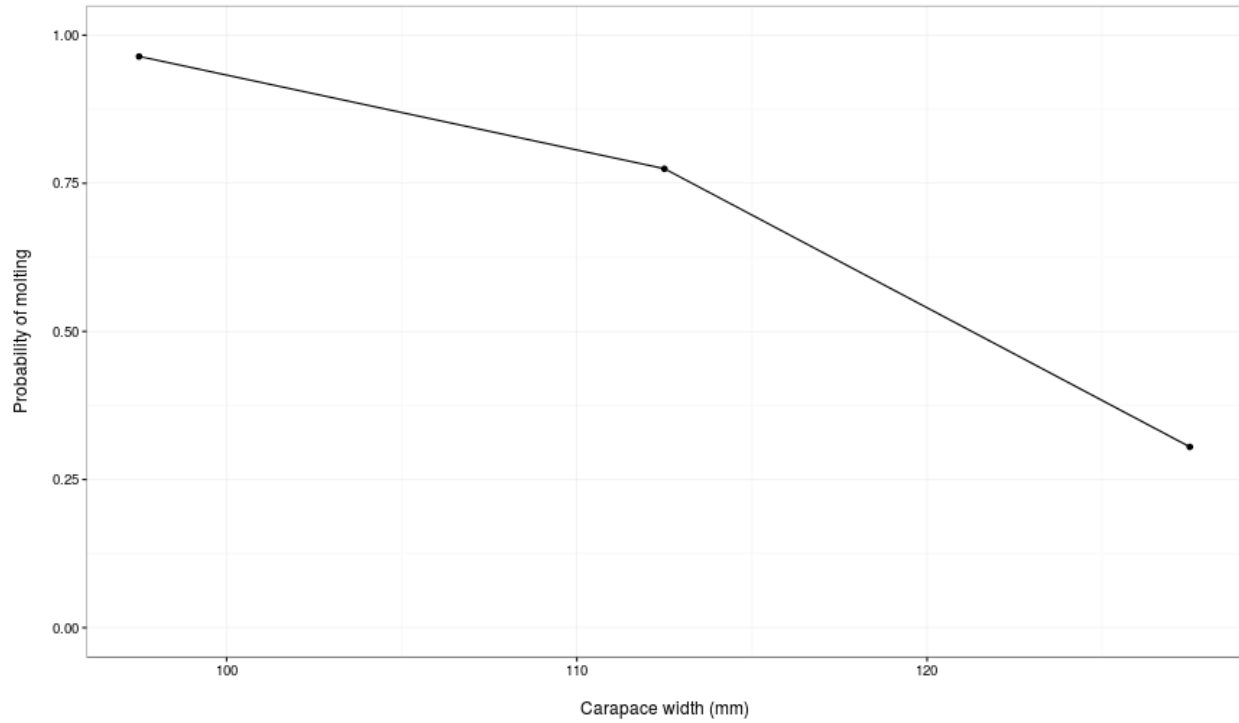
Figure 8: Molting probabilities by stage used in all of the Gmacs model scenarios.
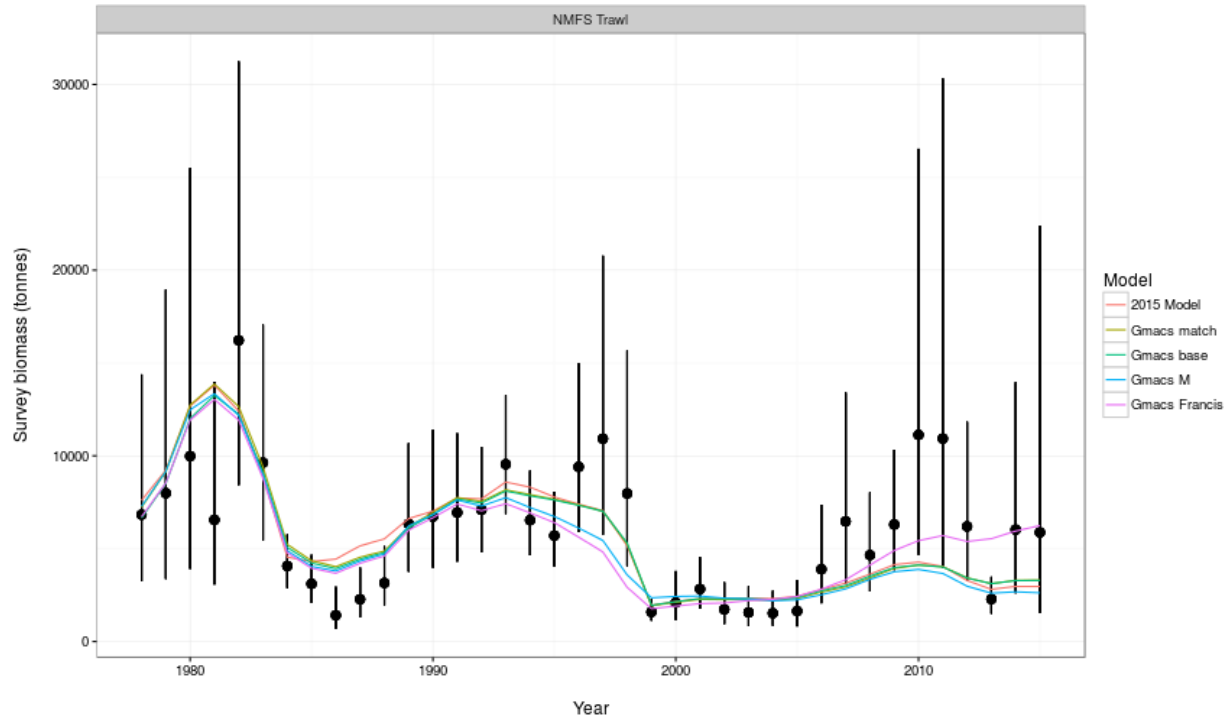
Figure 9: Comparisons of area-swept estimates of total male survey biomass (tonnes) and model predictions for the 2015 model and each of the Gmacs model scenarios. The error bars are plus and minus 2 standard deviations.
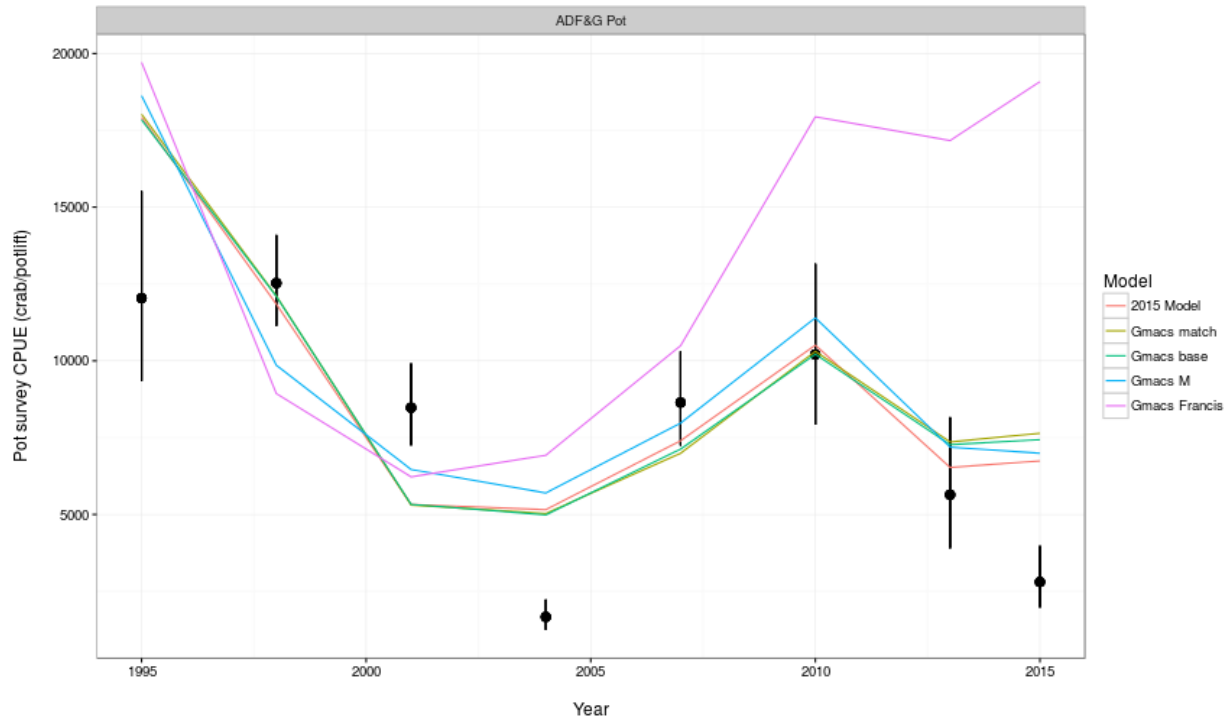
Figure 10: Comparisons of total male pot survey CPUEs and model predictions for the 2015 model and each of the Gmacs model scenarios. The additional CV for the pot survey CPUE in the Gmacs CV scenario is not shown. The error bars are plus and minus 2 standard deviations.
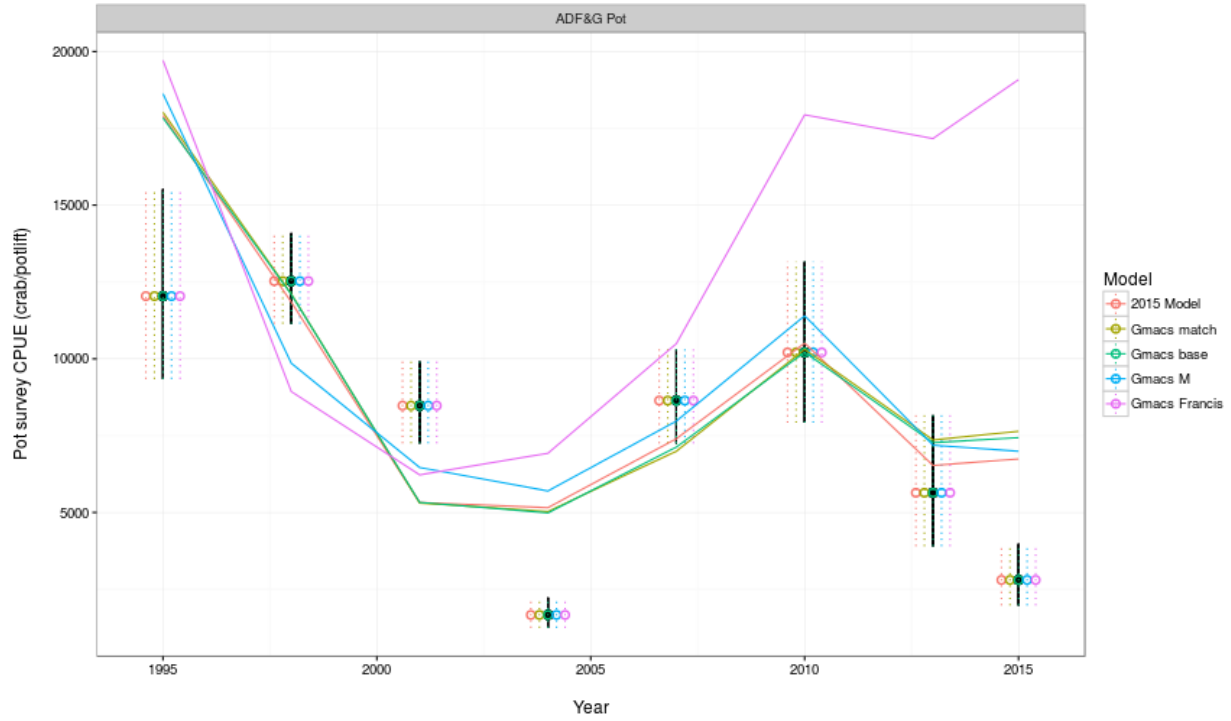
Figure 11: Comparisons of total male pot survey CPUEs and model predictions for the 2015 model and each of the Gmacs model scenarios. The additional CV for the pot survey CPUE is shown. The error bars are plus and minus 2 standard deviations.
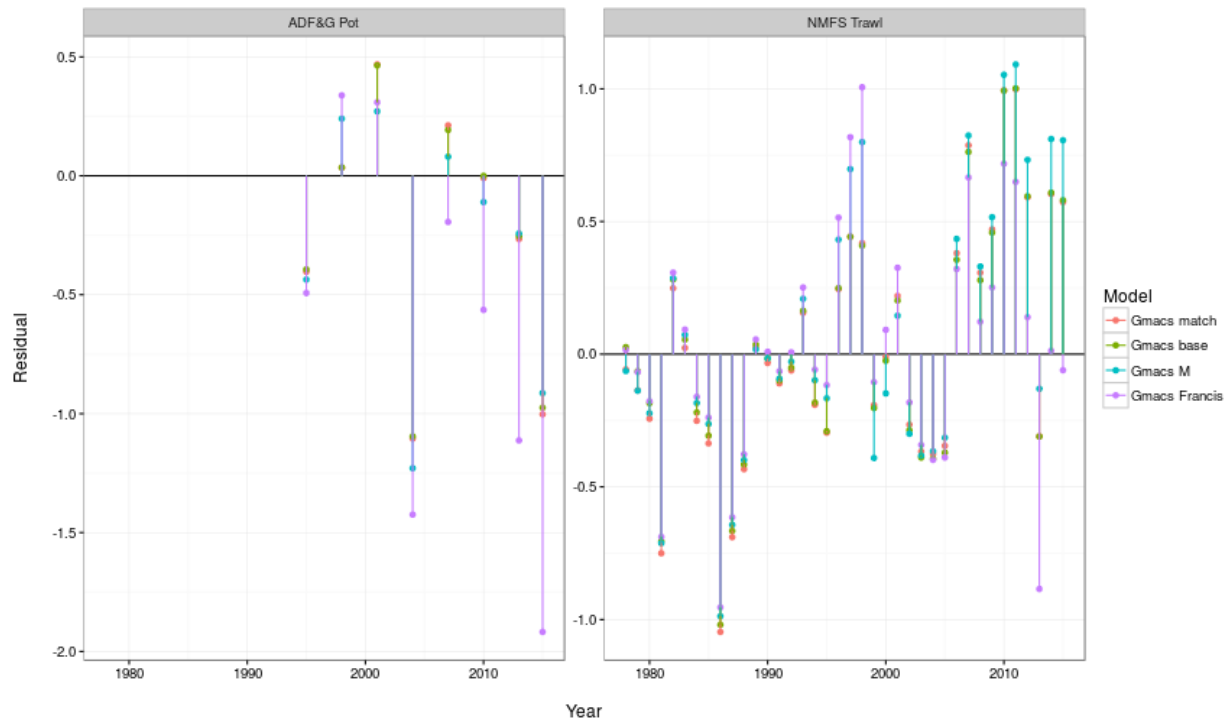
Figure 12: Standardized residuals for area-swept estimates of total male survey biomass and total male pot survey CPUEs for each of the Gmacs model scenarios.
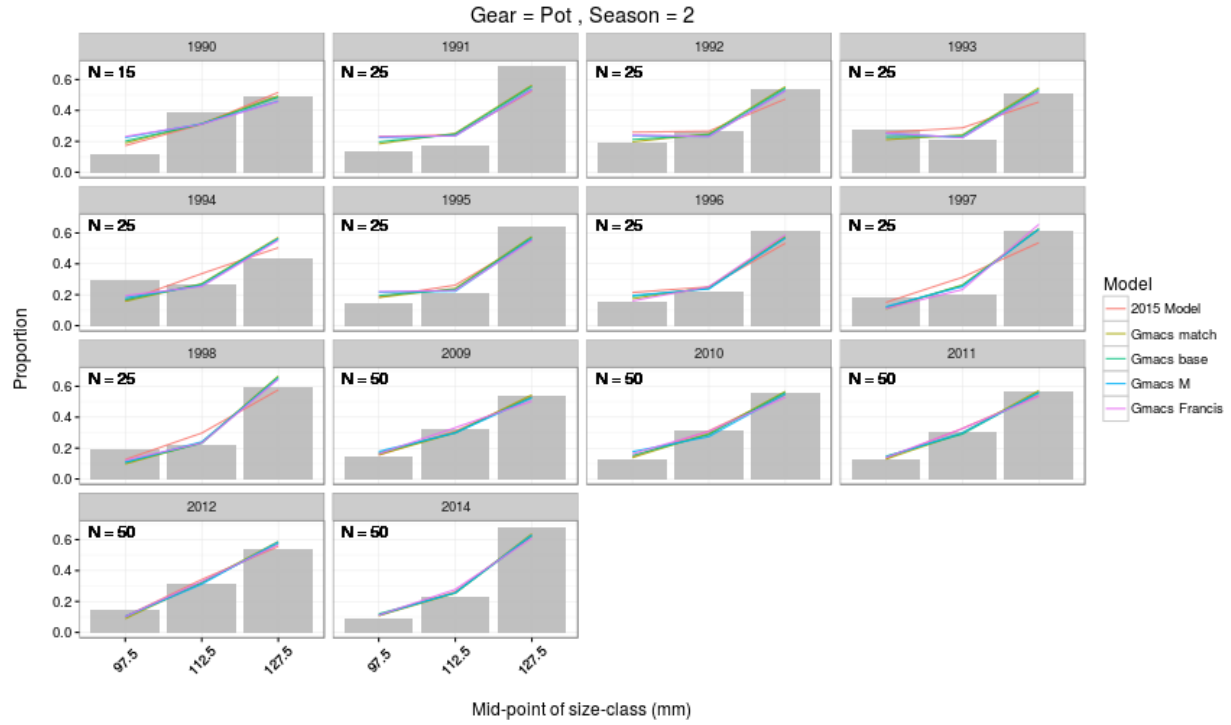
Figure 13: Observed and model estimated size-frequencies of SMBKC by year retained in the directed pot fishery for the 2015 model and each of the Gmacs model scenarios.
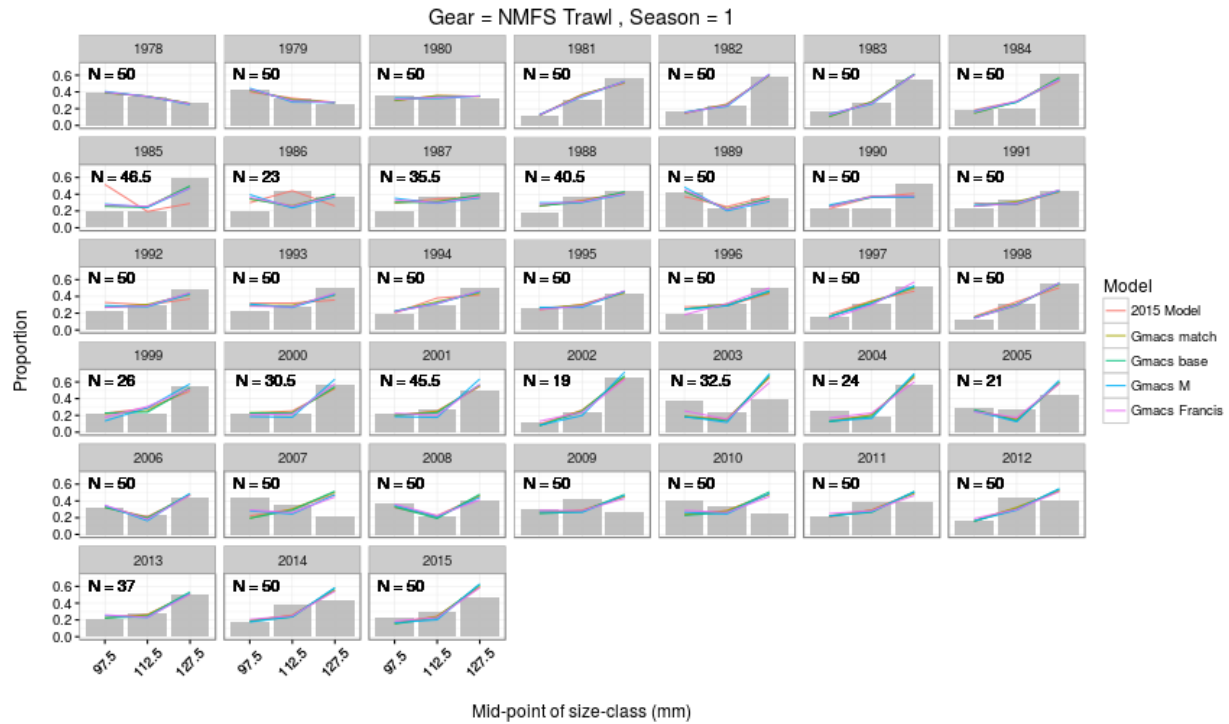
Figure 14: Observed and model estimated size-frequencies of discarded male SMBKC by year in the NMFS trawl survey for the 2015 model and each of the Gmacs model scenarios.
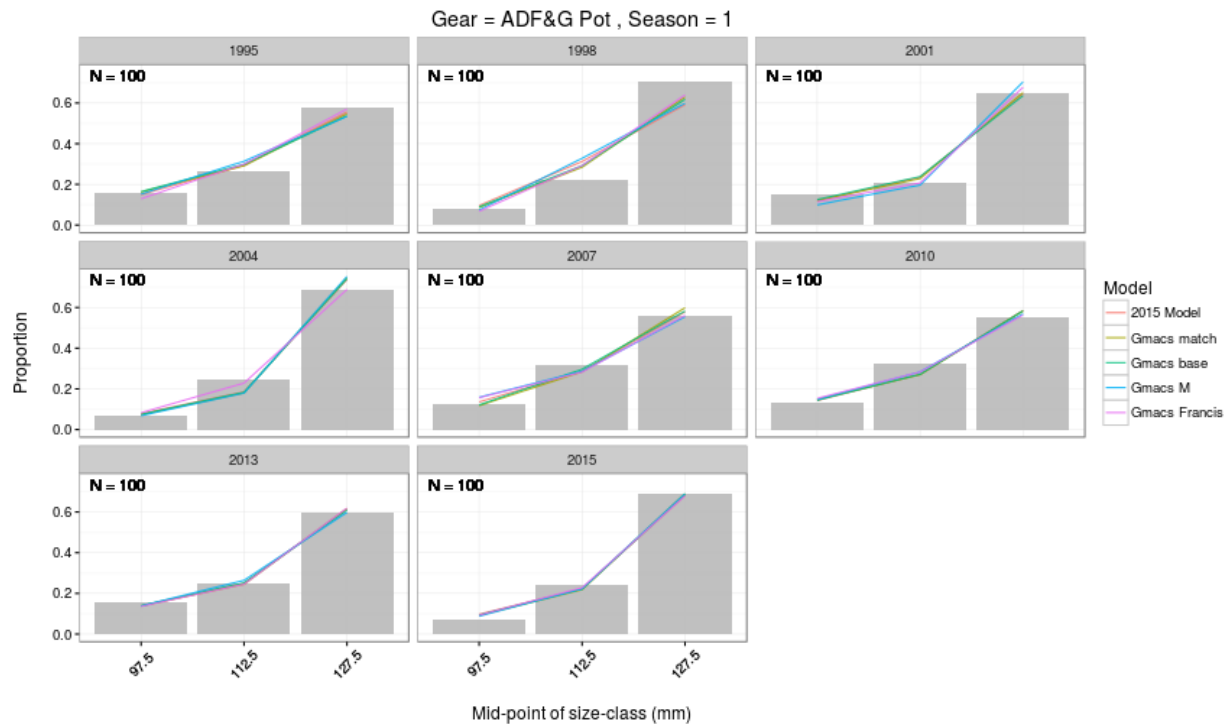
Figure 15: Observed and model estimated size-frequencies of discarded SMBKC by year in the ADF&G pot survey for the 2015 model and each of the Gmacs model scenarios.
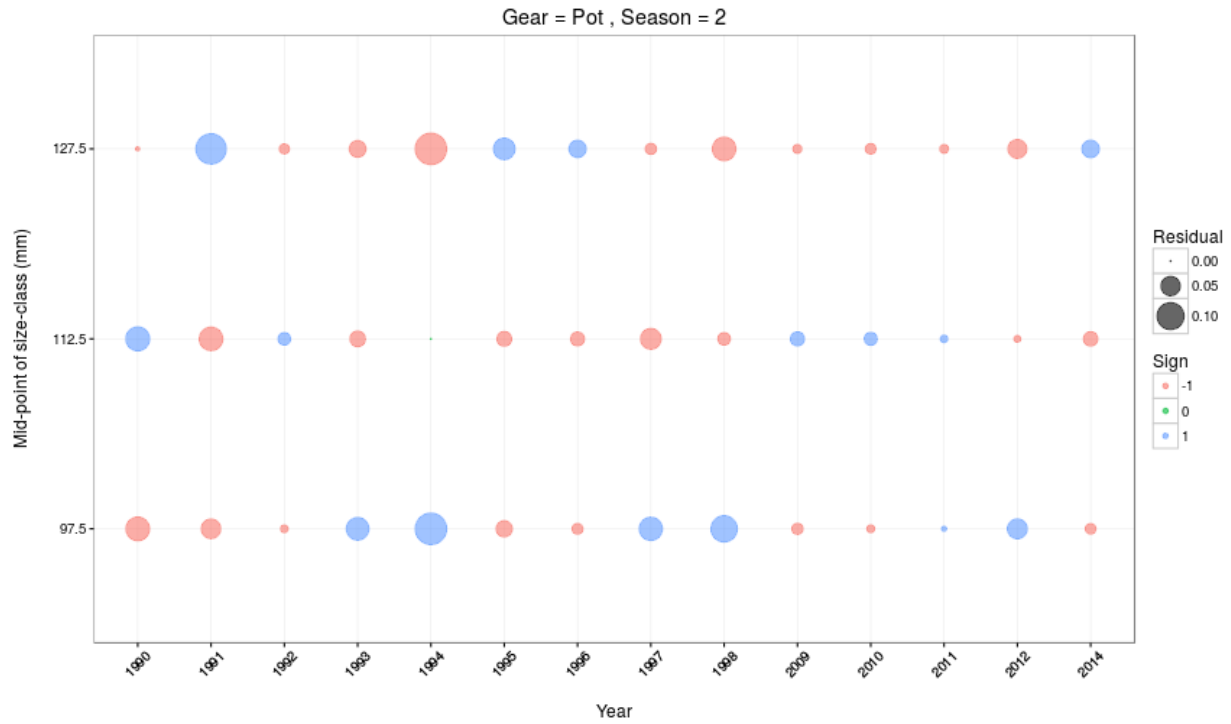
Figure 16: Bubble plots of residuals by stage and year for the directed pot fishery size composition data for St. Mathew Island blue king crab (SMBKC) in the **Gmacs match** model.
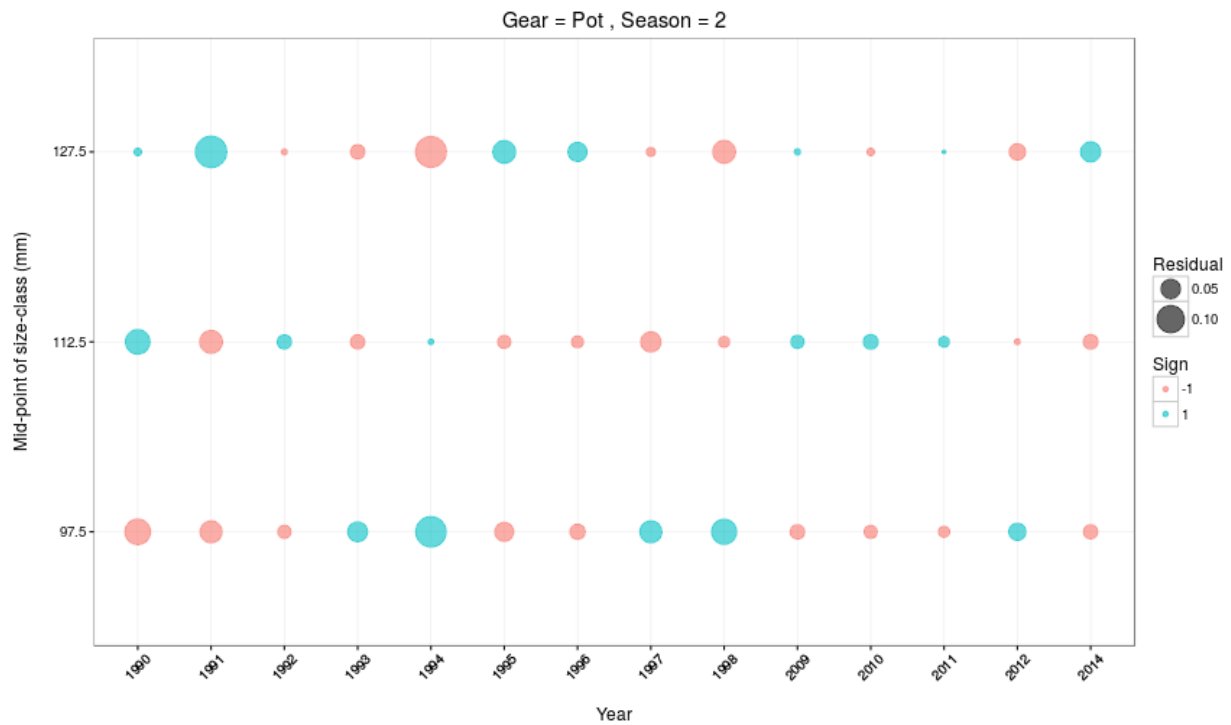
Figure 17: Bubble plots of residuals by stage and year for the directed pot fishery size composition data for St. Mathew Island blue king crab (SMBKC) in the **Gmacs base** model.
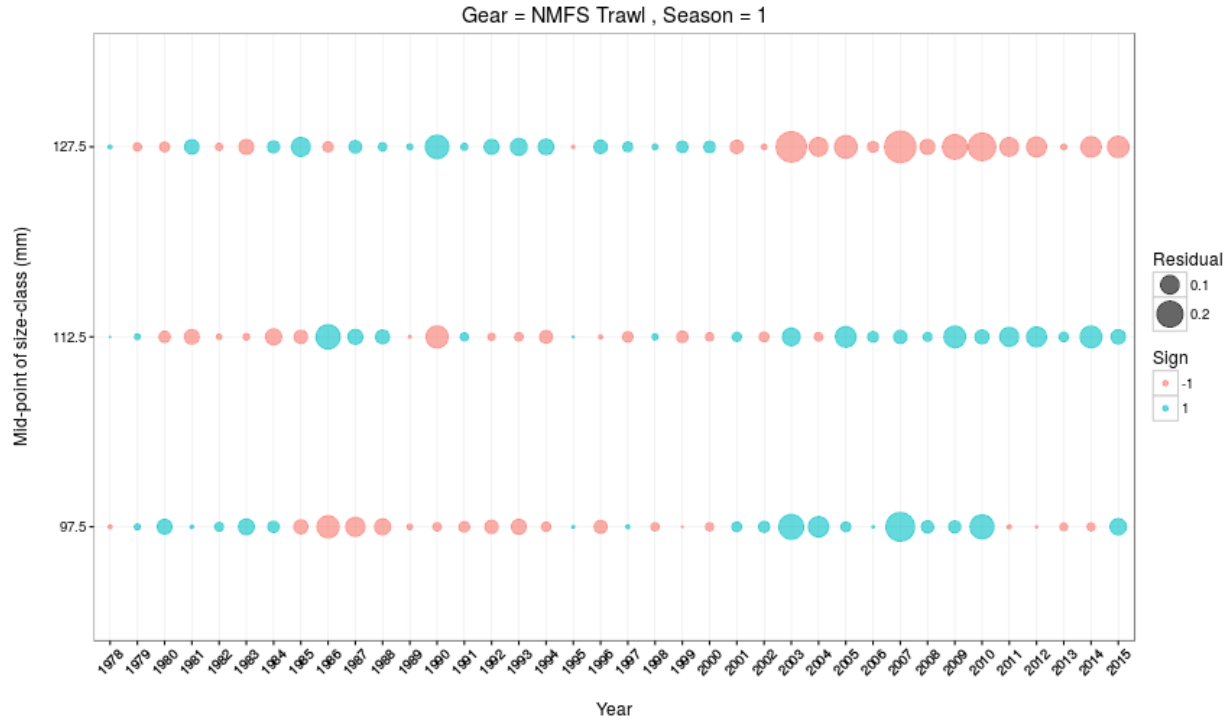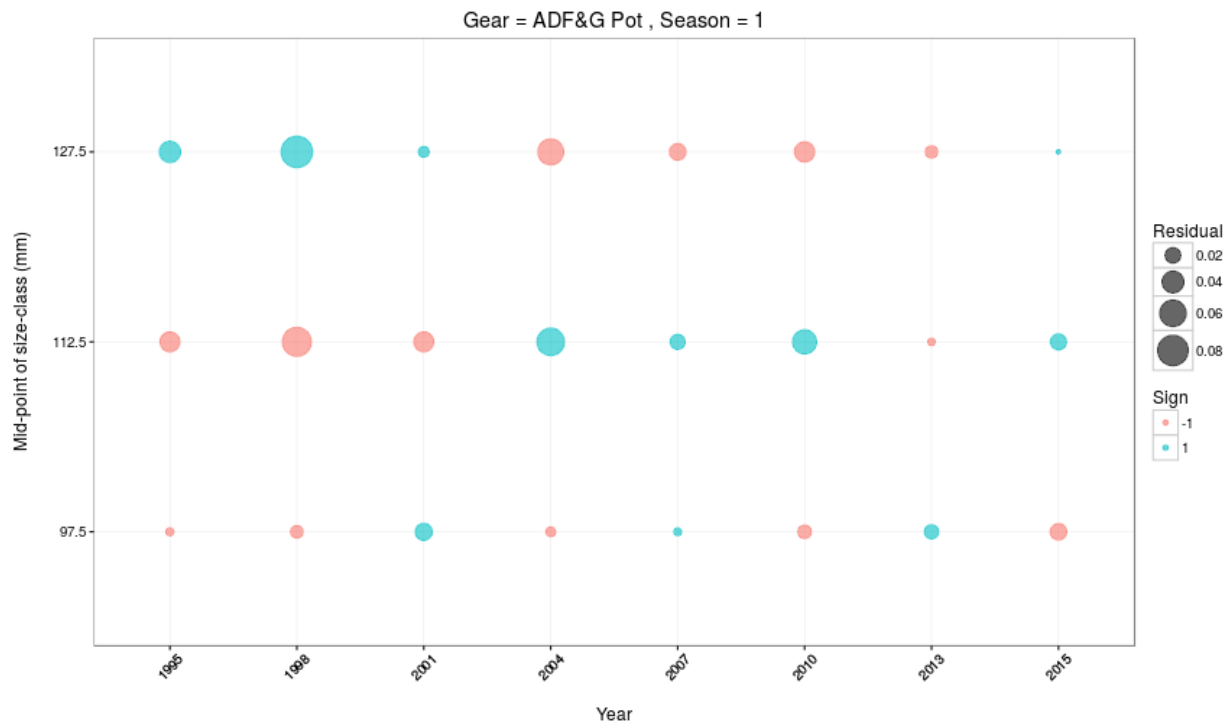
Figure 18: Bubble plots of residuals by stage and year for the NMFS trawl survey size composition data for St. Mathew Island blue king crab (SMBKC) in the **Gmacs base** model.
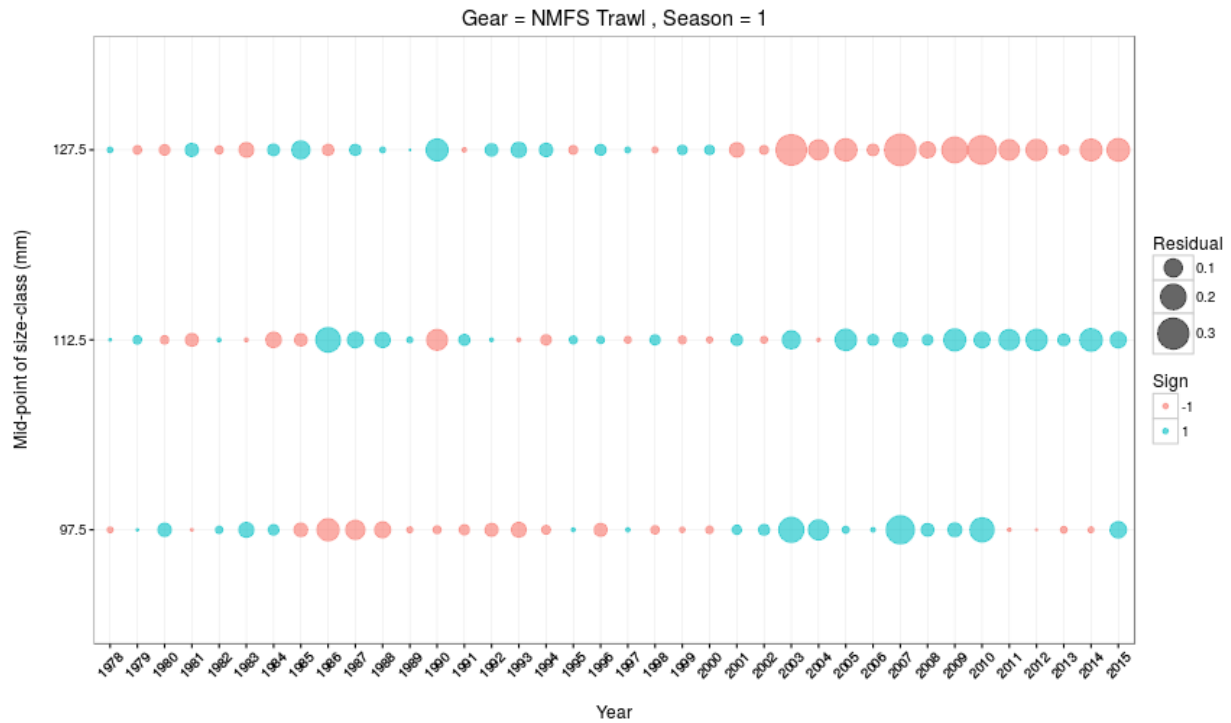
Figure 19: Bubble plots of residuals by stage and year for the NMFS trawl survey size composition data for St. Mathew Island blue king crab (SMBKC) in the **Gmacs selex** model.
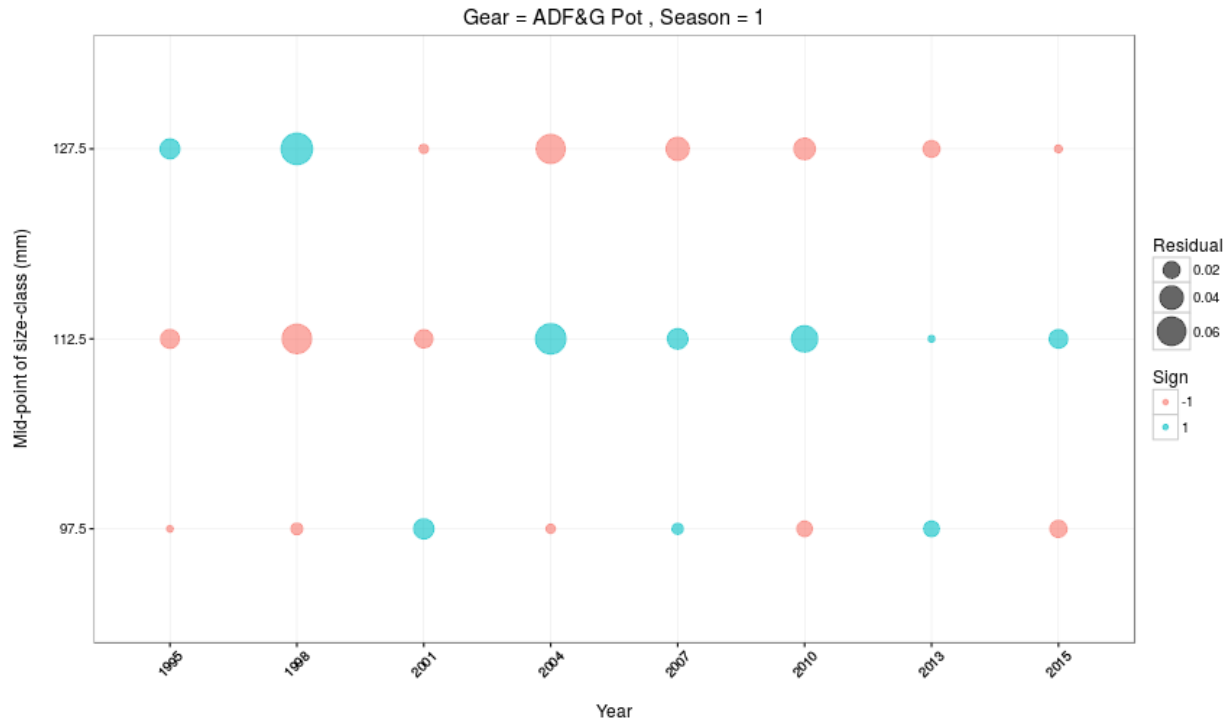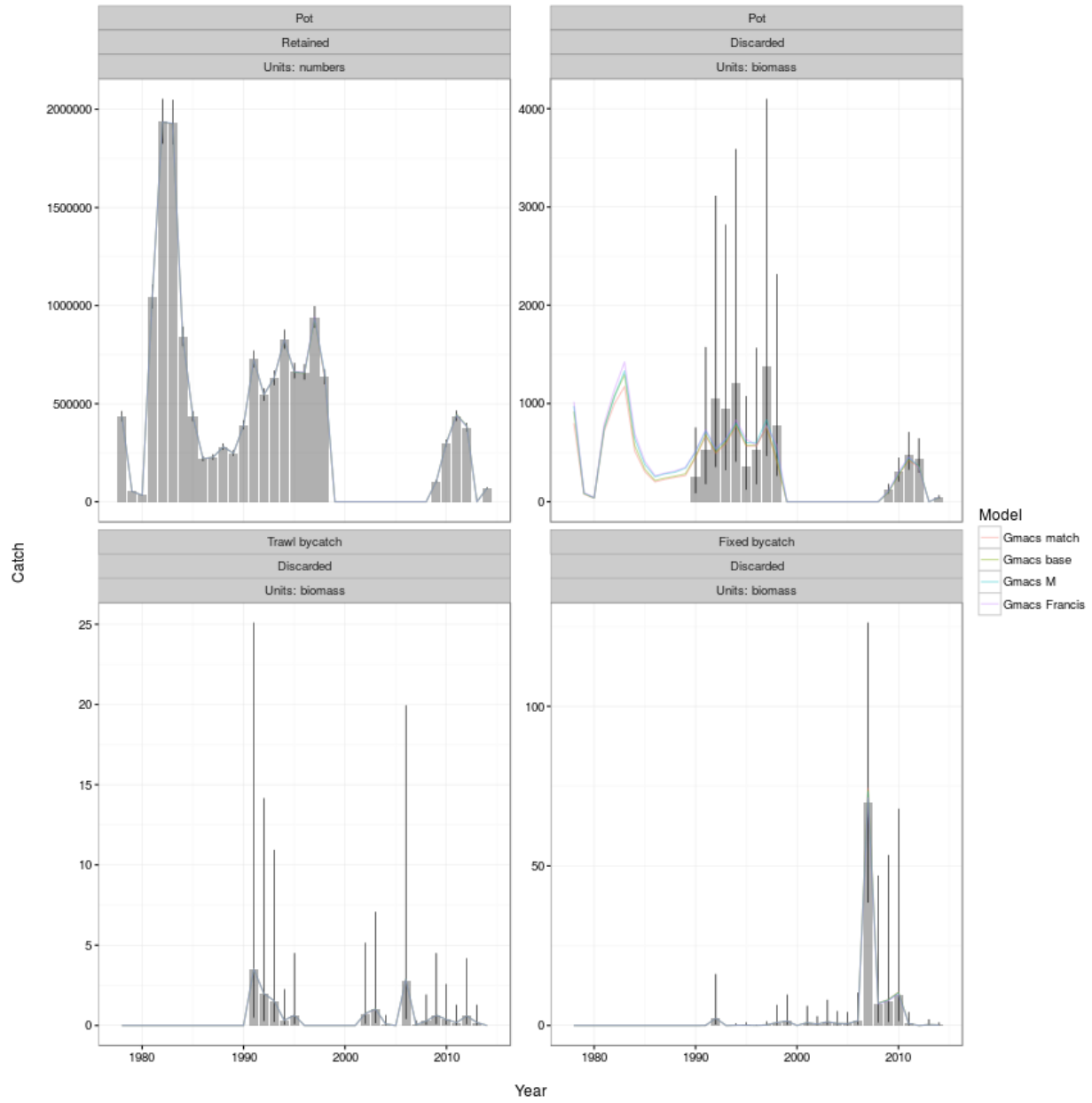
Figure 20: Bubble plots of residuals by stage and year for the ADF&G pot survey size composition data for St. Mathew Island blue king crab (SMBKC) in the **Gmacs base** model.

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.
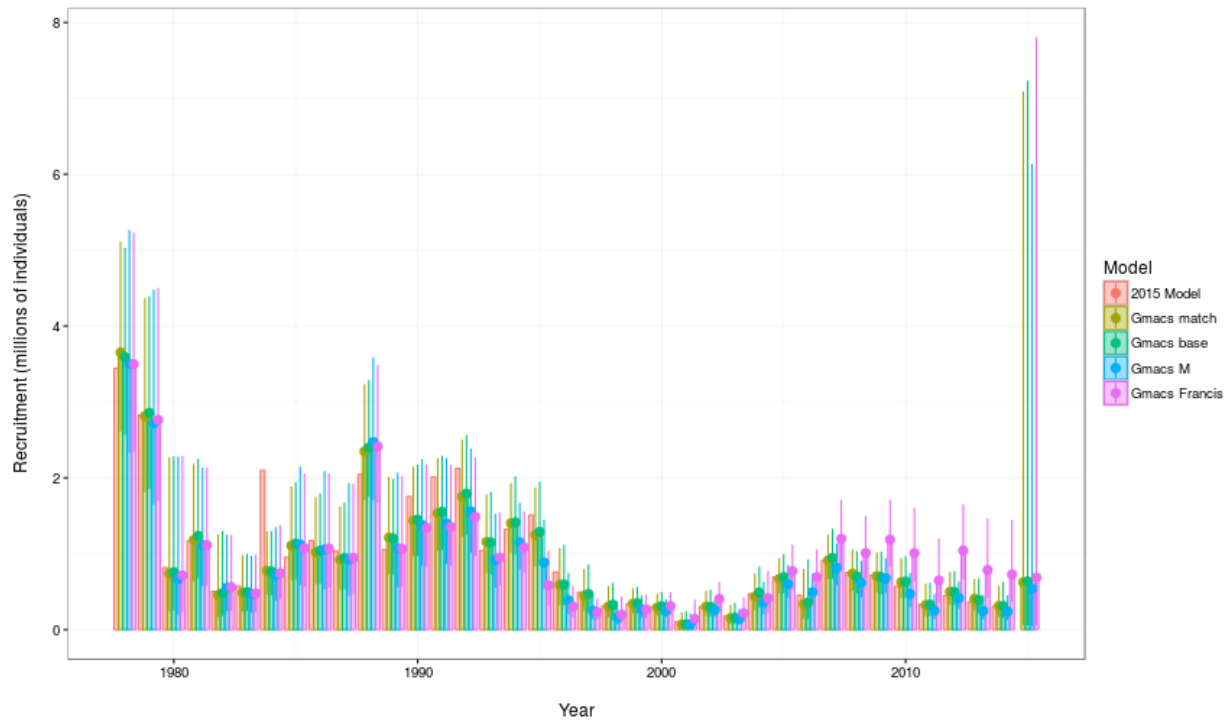
Figure 23: Estimated recruitment time series during 1979-2015 in each of the scenarios.
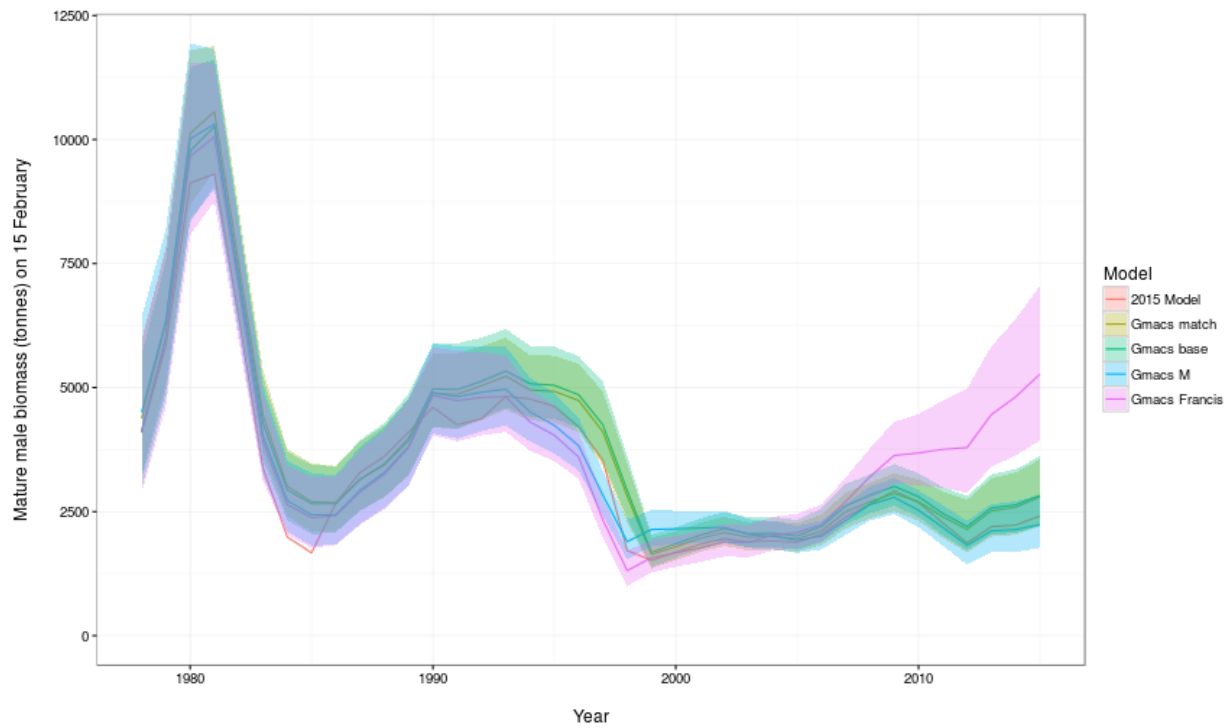
Figure 24: Estimated mature male biomass (MMB) time series on 15 February during 1978-2015 for each of the model scenarios.
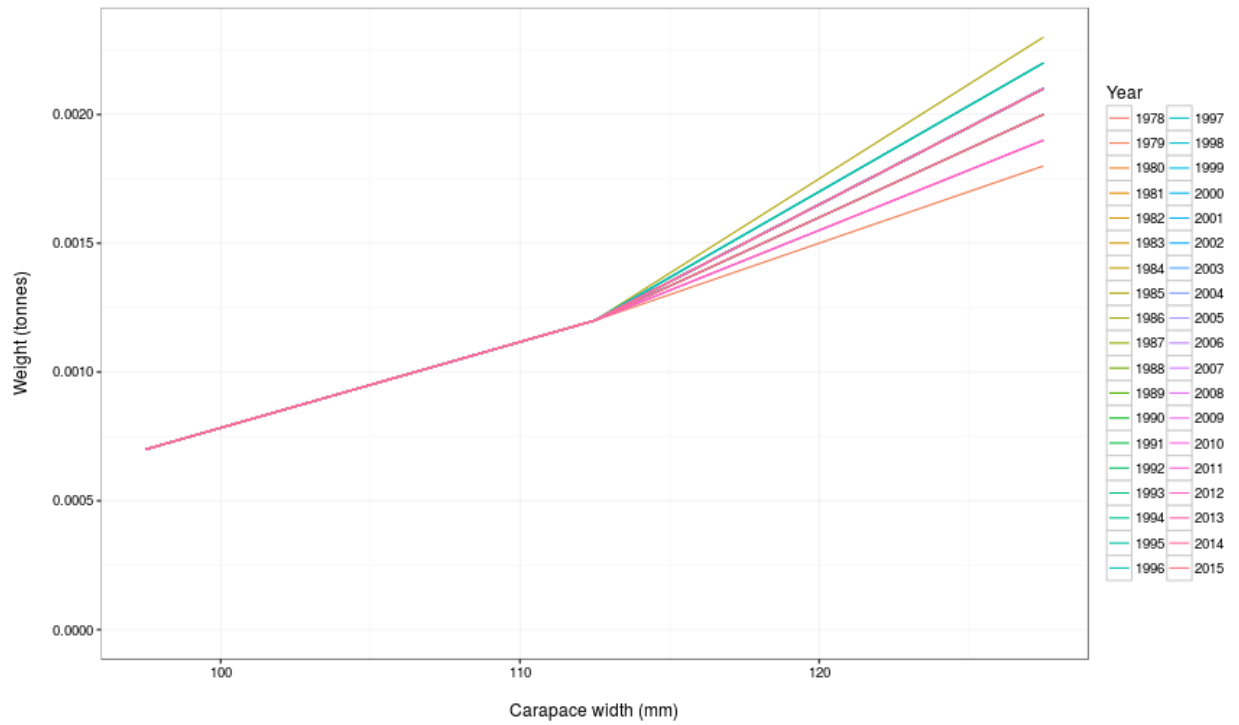
Figure 25: Relationship between carapace width (mm) and weight (kg) in all of the models (provided as a vector of weights at length to Gmacs).
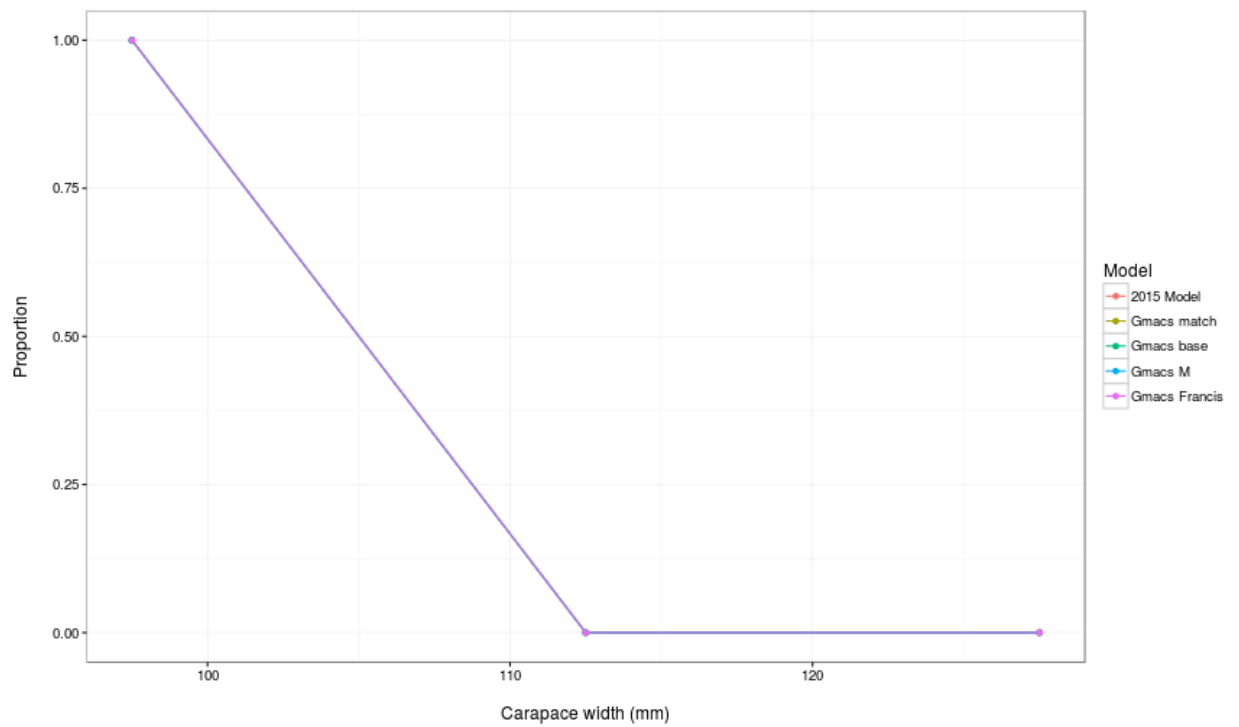

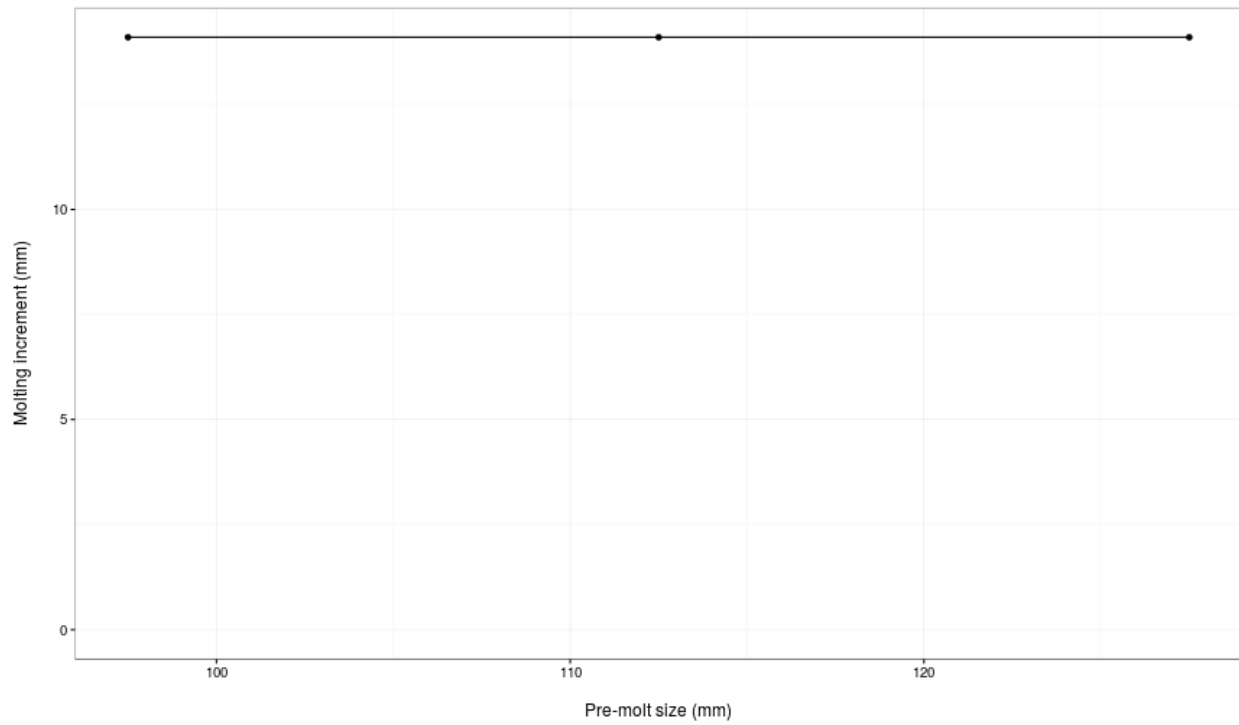Figure 26: Distribution of carapace width (mm) at recruitment.
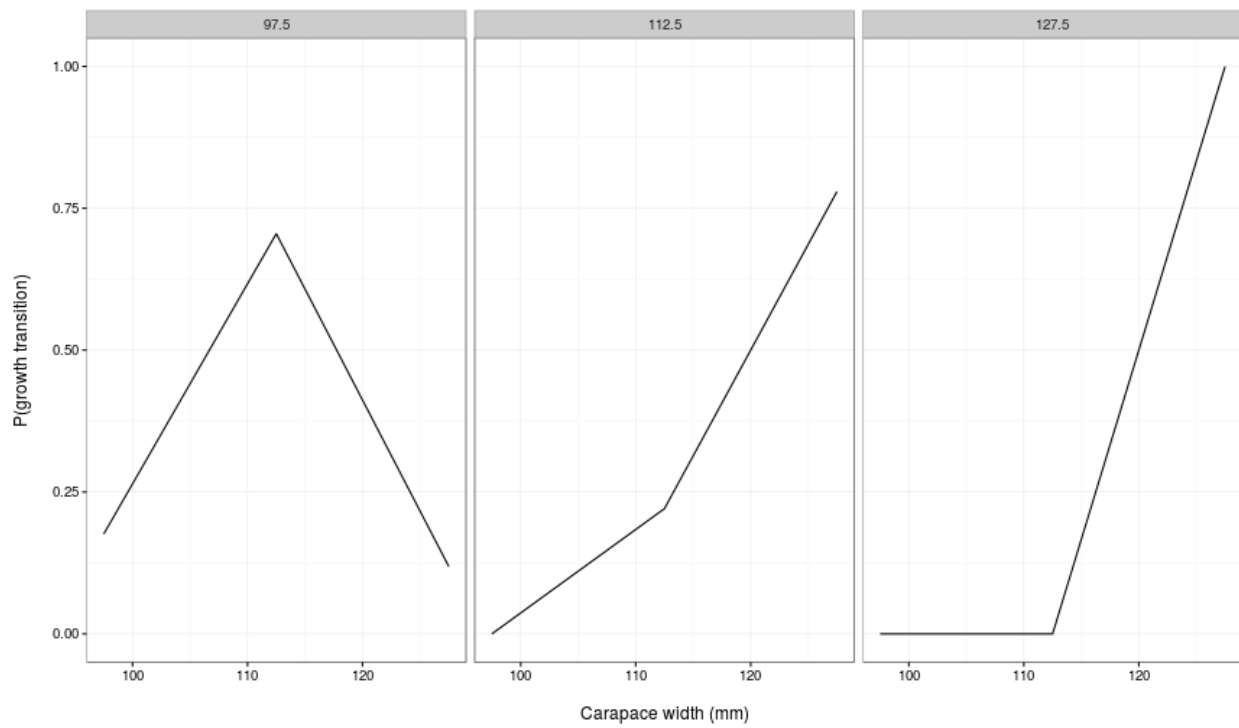
Figure 27: Growth increment (mm) each molt.

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).
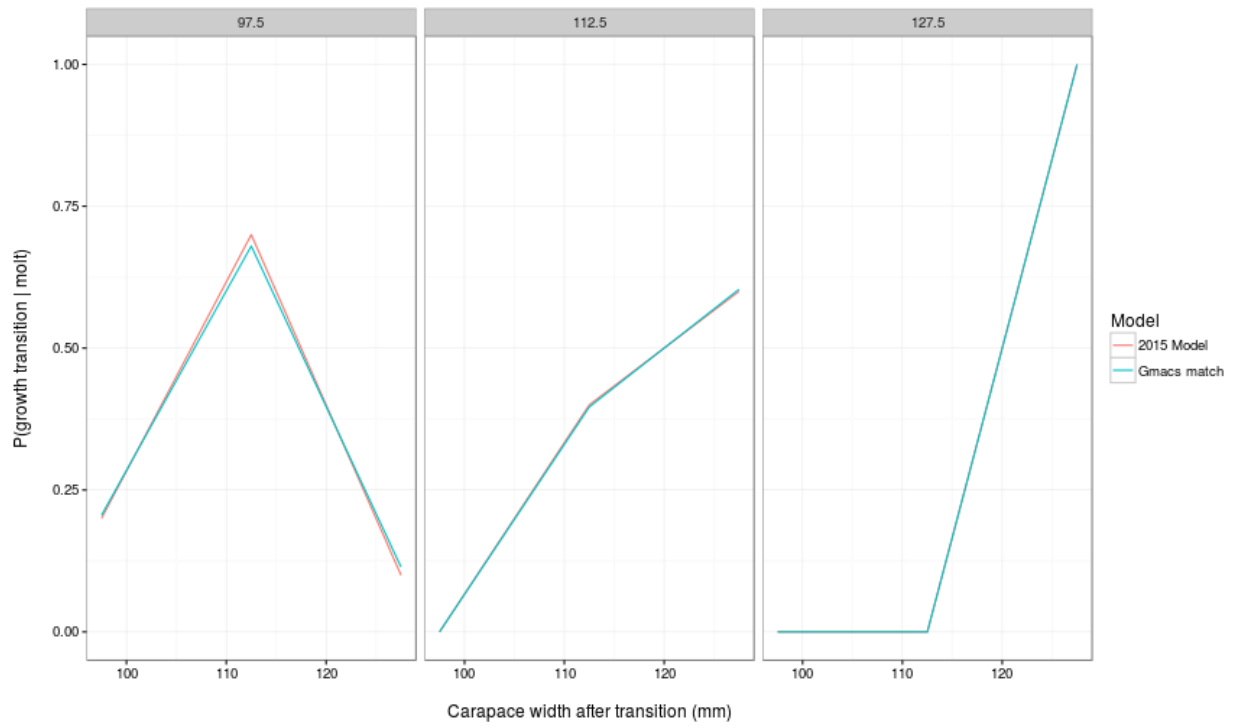
35

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.
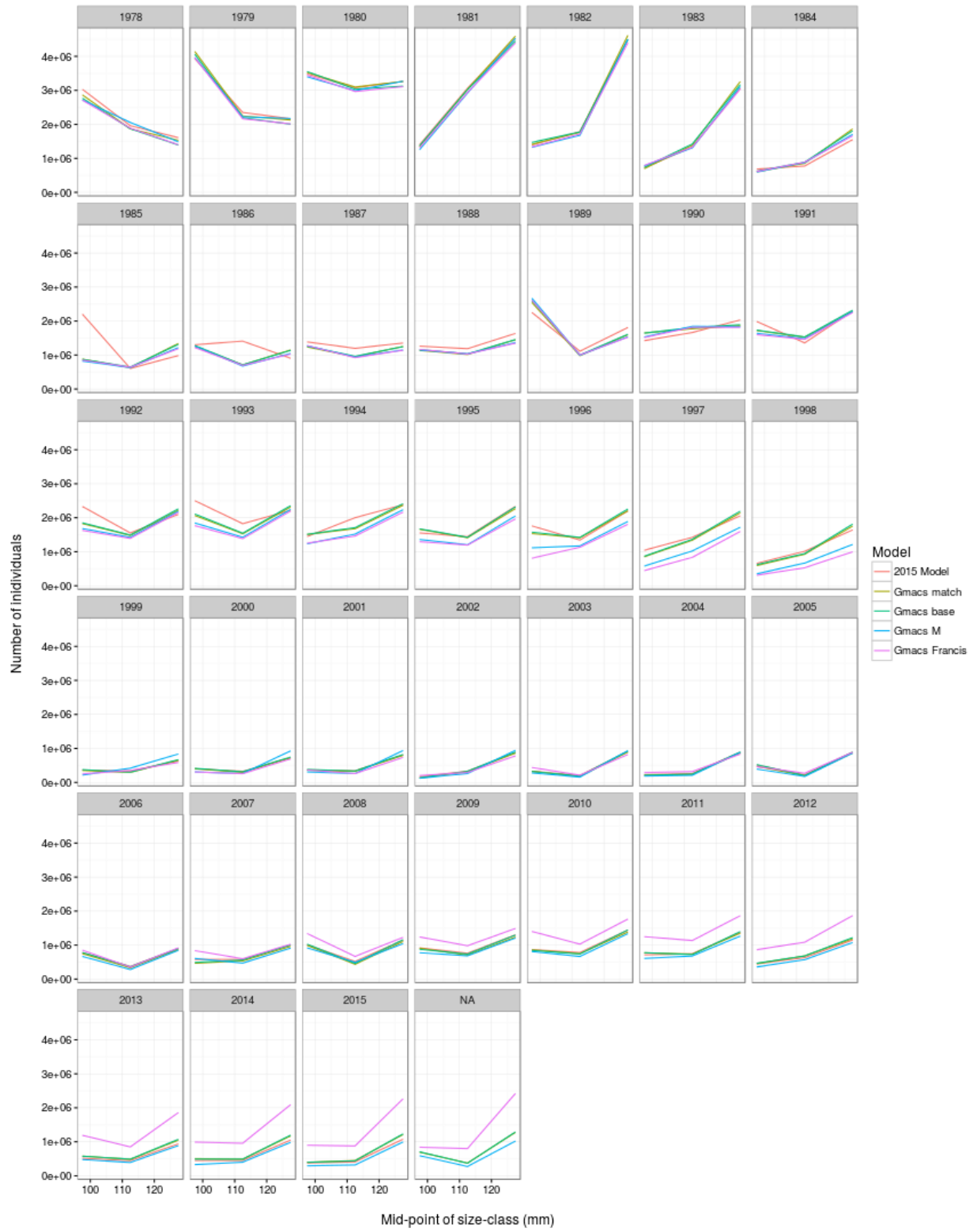
Figure 30: Numbers by stage each year (15 February) in each of the models including the 2015 model.
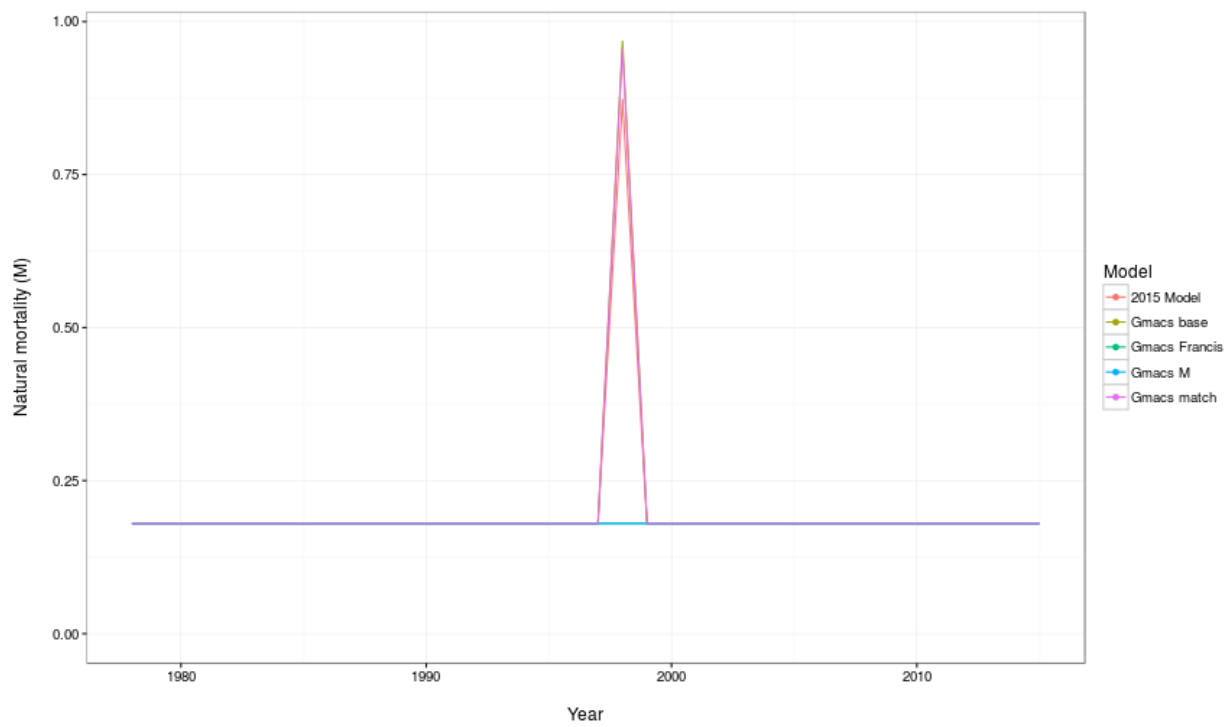
Figure 31: Time-varying natural mortality (M_t). Estimated pulse period occurs in 1998/99 (i.e. M_{1998}).

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. 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 (τ) is applied in each of these seasons:

1. Season 1
   - Beginning of the SMBKC fishing year (1 July)
   - Surveys

2. Season 2
   - $\tau = 0.44$

3. Season 3
   - Fishing mortality applied

4. Season 4
   - $\tau = 0.185$
   - Calculate MMB (15 February)

5. Season 5
   - $\tau = 0.375$
   - Growth and molting
   - Recruitment (all to stage-1)

Put the table if tau here.

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

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

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

$$G = \begin{bmatrix} 1 - \pi_{12} - \pi_{13} & \pi_{12} & \pi_{13} \\ 0 & 1 - \pi_{23} & \pi_{23} \\ 0 & 0 & 1 \end{bmatrix}, \tag{3}$$

with π_{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 $\boldsymbol{S}_{t,y}$ during season t and year y is

$$S_{t,y} = \begin{bmatrix} 1 - e^{-Z_{1,t,y}} & 0 & 0 \\ 0 & 1 - e^{-Z_{2,t,y}} & 0 \\ 0 & 0 & 1 - e^{-Z_{3,t,y}} \end{bmatrix}, \tag{4}$$

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 $\boldsymbol{r}_{t,y}$. The SMBKC formulation of Gmacs specifies recruitment to stage-1 only, thus

$$r_{t,y} = \left[\bar{R}, 0, 0\right]^{\top}, \tag{5}$$

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

$$\begin{aligned} n_{t+1,y} &= S_{t,y} n_{t,y}, & \text{if } t < 4 \\ n_{t,y+1} &= G S_{t,y} n_{t,y} + r_{t,y}, & \text{if } t = 4 \end{aligned} \tag{6}$$

The natural mortality

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

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

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

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

3. Model Data

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

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

4. Model Parameters

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

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 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

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

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.

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

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 $\widehat{cv}_t$ were used to develop appropriate variances for stage-proportion and abundance-index components. The weights λ_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 λ_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	$-0.5 \sum \left(\log(c_t/C_t)^2 / \log(1+cv_c^2) \right)$
Dis. Pot bycatch biomass	Lognormal	

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

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

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

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

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 χ^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 expectected 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.