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 tonne (1.167 million pound) TAC. Following three more years of modest harvests supported by a fishery catch per unit effort (CPUE) of around 10 crab per pot lift, the fishery was again closed in 2013/14 due to declining trawl-survey estimates of abundance and concerns about the health of the stock. The directed fishery resumed again in 2014/15 with a TAC of 300 tonnes (0.655 million pounds), but the fishery performance was relatively poor with a retained catch of 140 tonnes (0.309 million pounds). The retained catch in 2015/16 was even lower at 48 tonnes (0.105 million pounds).
3. **Stock biomass**: Following a period of low numbers (below 30% of the 1978-2016 mean of 5,865 tonnes) after the stock was declared overfished in 1999, trawl-survey indices of SMBKC stock abundance and biomass generally increased to well above average from 2007-2012. In 2013 the survey biomass estimate was low (~40% of the mean value) but was followed by average biomass estimates in 2014 and 2015 (with sampling CVs of 77% and 45%, respectively). The 2016 survey biomass estimate was 3,500 tonnes (7.7 million lbs with a CV of 39%). This value represents about 60% of the long term mean with the most recent 3-year average surveys at 87% of the mean value. This suggests a general decline in biomass compared to the recent peak survey estimate of nearly twice the average. The assessment model estimates dampen the interannual variability observed in the survey biomass and suggest that the stock (in survey biomass units) is presently at about 45% of the long term model-predicted survey biomass average. The trend from these values suggest a slight decline.
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 was 0.723 million. Survey recruitment was 0.992 million in 2015, but the majority of this survey estimate is from one tow with a great deal of uncertainty. In 2016, survey recruitment declined to 0.535 million.
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 2015/16 and is hence not overfished. Overfishing did not occur in 2015/16 (Tables 1 and 2).

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

Table 1: Status and catch specifications (1000 tonnes) (scenario **Gmacs base**). Notes: A - calculated from the assessment reviewed by the Crab Plan Team in September 2013, B - calculated from the assessment reviewed by the Crab Plan Team in September 2014, C - calculated from the assessment reviewed by the Crab Plan Team in September 2015, D - calculated from the assessment reviewed by the Crab Plan Team in September 2016.

Year	MSST	Biomass (MMB_{mating})	TAC	Retained catch	Total male catch	OFL	ABC
2012/13	1.80^{A}	2.85^{A}	0.74	0.73	0.82	1.02	0.92
2013/14	1.50^{B}	3.01^{B}	0.00	0.00	0.00	0.56	0.45
2014/15	1.86^{C}	2.48^{C}	0.30	0.14	0.15	0.43	0.34
2015/16	1.84^{D}	2.11^{D}	0.19	0.05	0.05	0.28	0.22
2016/17		2.23^{D}				0.14	0.11

Table 2: Status and catch specifications (million pounds) (scenario **Gmacs base**).

Year	MSST	Biomass (MMB_{mating})	TAC	Retained catch	Total male catch	OFL	ABC
2012/13	4.0^{A}	6.29^{A}	1.630	1.616	1.81	2.24	2.02
2013/14	3.4^{B}	6.64^{B}	0.000	0.000	0.0006	1.24	0.99
2014/15	4.1^{C}	5.47^{C}	0.655	0.309	0.329	0.94	0.75
2015/16	4.0^{D}	4.65^{D}	0.41	0.105	0.105	0.62	0.49
2016/17		4.91^{D}				0.31	0.25

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 (Table 3).

Table 3: Basis for the OFL (1000 tonnes) (scenario **Gmacs base**).

Year	Tier	B_{MSY}	Biomass (MMB_{mating})	B/B_{MSY}	F_{OFL}	γ	Basis for B_{MSY}	Natural mortality
2012/13	4a	3.56	5.63	1.56	0.18	1	1978-2012	0.18
2013/14	4b	3.06	3.01	0.98	0.18	1	1978-2013	0.18
2014/15	4b	3.28	2.71	0.82	0.14	1	1978-2014	0.18
2015/16	4b	3.71	2.45	0.66	0.11	1	1978-2015	0.18
2016/17	4b	3.67	2.23	0.61	0.09	1	1978-2016	0.18

A. Summary of Major Changes

Changes in Management of the Fishery

There are no new changes in management of the fishery.

Changes to the Input Data

Data used in this assessment have been updated to include the most recently available fishery and survey numbers. This assessment makes use of two new survey data points including the 2016 NMFS trawl-survey estimate of abudance, and the 2016 ADF&G pot survey CPUE. Both of these surveys have associated size compositon data. The assessment also uses updated 1993-2015 groundfish and fixed gear bycatch estimates based on AKRO data. The 2015/16 directed fishery catch data and associated size composition data were also used.

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 model and the previous model. One of the major differences being that natural and fishing mortality are continuous within 5 discrete seasons (using the "correct" catch equation rather than being applied as a pulse). Season length in Gmacs is controlled by changing the proportion of natural mortality that is applied during each season. A detailed outline of the Gmacs implementation of the SMBKC model is provided in Appendix A.

Changes in Assessment Results

One of the Gmacs model scenarios (**Gmacs match**) attempts to match the 2015 assessment as closely as possible by specifying the same (or similar) dynamics and some of the same (fixed) parameter values. There are some minor differences between the 2015 model and the **Gmacs match** model, but given that Gmacs and the 2015 model have different underpinning population dynamics, these differences should be of little concern. Four other Gmacs scenarios are presented as well, each providing a slightly different fit to the data.

B. Responses to SSC and CPT Comments

CPT and SSC Comments on Assessments in General

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

1. *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:

1. Done
2. Done
3. Not yet implemented
4. Not yet implemented
5. Not yet implemented
6. Not yet implemented
7. Not yet implemented
8. Done

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 F_{OFL} and OFL have both been reported as an sdreport variables in this document.

CPT and SSC Comments Specific to the SMBKC Stock Assessment

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: The error in the 2015 was fixed and this model was run again. Comparisons between the Gmacs models and the 2015 model are presented throughout this document. One of the Gmacs model scenarios (**Gmacs match**) attempts to match the 2015 assessment as closely as possible by specifying the same (or similar) dynamics and some of the same (fixed) parameter values.

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 selectivity*
2. *Base + add CV for both surveys*
3. *Above + Francis re-weighting*
4. *Above + remove M spike*

Response: Models 1, 3, and 4 are all included and evaluated in this document as the **Gmacs base**, **Gmacs Francis**, and **Gmacs M** scenarios. Model 2 was not included in this document for two reasons. Firstly, if doing Francis iterative re-weighting then additional CV should not be added as well (as the two methods basically do the same thing). Secondly, the SSC recommended against the model runs with additional CV (see the comment from the SSC below).

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: All model runs that estimate additional CV were dropped from this document. Instead we provide three model runs that use the Francis iterative re-weighting method to re-weight the length-frequency data relative to the abundance indices. These runs are the **Gmacs Francis**, **Gmacs M**, and **Gmacs force** scenarios. The final Gmacs scenario (**Gmacs force**) is an exploratory model run that upweights both the trawl-survey and pot survey abundance indices (it upweights the pot survey more than the trawl survey).

Comment: *The descriptions of seasons in the model is confusing and currently reads as if M differs among seasons. 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 updated and justification provided in Appendix A.

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: After fixing the error in the 2015 SMBKC model code, it was found that the NMFS trawl survey selectivity does exceed 1 for stage-2 crab. The **Gmacs match** scenario does allow selectivity to be greater than 1 (it uses the same fixed selectvity values as the 2015 model). At the request of the CPT an upper bound of 1 was specified for the remaining Gmacs scenarios. Tables 14, 15, 16, and 17 all show that this upper bound was approached for at least one selectivity parameter in all of these scenarios.

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: This table has been added.

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

Response: This table has been added.

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: Done.

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: In the past Jie has tried to estimate survey catchability as a function of temperature with little success. We will try again this year, but this run will not be presented in this document.

C. Introduction

Scientific Name

The blue king crab is a lithodid crab, *Paralithodes platypus* (Brant 1850).

Distribution

Blue king crab are sporadically distributed throughout the North Pacific Ocean from Hokkaido, Japan, to southeastern Alaska (Figure 1). In the eastern Bering Sea small populations are distributed around St. Matthew Island, the Pribilof Islands, St. Lawrence Island, and Nunivak Island. Isolated populations also exist in some other cold water areas of the Gulf of Alaska (NPFMC 1998). The St. Matthew Island Section for blue king crab is within Area Q2 (Figure 2), which is the Northern District of the Bering Sea king crab registration area and includes the waters north of Cape Newenham (58°39' N. lat.) and south of Cape Romanzof (61°49' N. lat.).

Stock Structure

The Alaska Department of Fish and Game (ADF&G) Gene Conservation Laboratory division has detected regional population differences between blue king crab collected from St. Matthew Island and the Pribilof Islands[2]. NMFS tag-return data from studies on blue king crab in the Pribilof Islands and St. Matthew

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

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

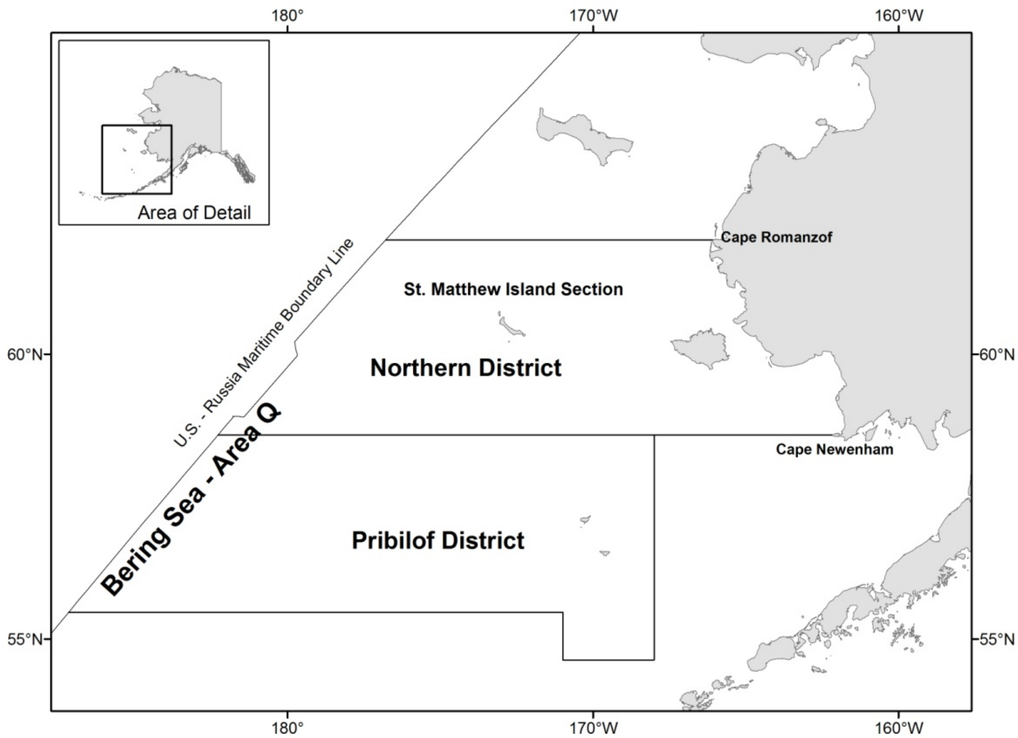

Figure 2: King crab Registration Area Q (Bering Sea).

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 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 4).

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 8). 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 (460,859 pounds) with a reported effort of 10,697 pot lifts and an estimated CPUE of 9.9 retained individual crab per pot lift. The fishery remained open the next three years with modest harvests and similar CPUE, but large declines in the NMFS trawl-survey estimate of stock abundance raised concerns about the health of the stock, prompting ADF&G to close the fishery again for the 2013/14 season. Due to an abundance 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,

Table 4: The 1978/79 to 2015/16 directed St. Matthew Island blue king crab pot fishery. The Guideline Harvest Level (GHL) and Total Allowable Catch (TAC) are in millions of pounds. Harvest includes deadloss. Catch per unit effort (CPUE) in this table is simply the harvest number / pot lifts. The average weight is the harvest weight / harvest number in pounds. The average CL is the average of retained crab in mm from dockside sampling of delivered crab. Source: Fitch et al 2012; ADF&G Dutch Harbor staff, pers. comm.

			Harvest					
Year	Dates	GHL/TAC	Crab	Pounds	Pot lifts	CPUE	avg wt	avg CL
1978/79	07/15 - 09/03		436,126	1,984,251	43,754	10	4.5	132.2
1979/80	07/15 - 08/24		52,966	210,819	9,877	5	4.0	128.8
1980/81	07/15 - 09/03			CONFIDENTIAL				
1981/82	07/15 - 08/21		1,045,619	4,627,761	58,550	18	4.4	NA
1982/83	08/01 - 08/16		1,935,886	8,844,789	165,618	12	4.6	135.1
1983/84	08/20 - 09/06	8.0	1,931,990	9,454,323	133,944	14	4.9	137.2
1984/85	09/01 - 09/08	2.0-4.0	841,017	3,764,592	73,320	11	4.5	135.5
1985/86	09/01 - 09/06	0.9-1.9	436,021	2,175,087	46,988	9	5.0	139.0
1986/87	09/01 - 09/06	0.2-0.5	219,548	1,003,162	22,073	10	4.6	134.3
1987/88	09/01 - 09/05	0.6-1.3	227,447	1,039,779	28,230	8	4.6	134.1
1988/89	09/01 - 09/05	0.7-1.5	280,401	1,236,462	21,678	13	4.4	133.3
1989/90	09/01 - 09/04	1.7	247,641	1,166,258	30,803	8	4.7	134.6
1990/91	09/01 - 09/07	1.9	391,405	1,725,349	26,264	15	4.4	134.3
1991/92	09/16 - 09/20	3.2	726,519	3,372,066	37,104	20	4.6	134.1
1992/93	09/04 - 09/07	3.1	545,222	2,475,916	56,630	10	4.5	134.1
1993/94	09/15 - 09/21	4.4	630,353	3,003,089	58,647	11	4.8	135.4
1994/95	09/15 - 09/22	3.0	827,015	3,764,262	60,860	14	4.9	133.3
1995/96	09/15 - 09/20	2.4	666,905	3,166,093	48,560	14	4.7	135.0
1996/97	09/15 - 09/23	4.3	660,665	3,078,959	91,085	7	4.7	134.6
1997/98	09/15 - 09/22	5.0	939,822	4,649,660	81,117	12	4.9	139.5
1998/99	09/15 - 09/26	4.0	635,370	2,968,573	91,826	7	4.7	135.8
1999/00 - 2008/09				FISHERY CLOSED				
2009/10	10/15 - 02/01	1.17	103,376	460,859	10,697	10	4.5	134.9
2010/11	10/15 - 02/01	1.60	298,669	1,263,982	29,344	10	4.2	129.3
2011/12	10/15 - 02/01	2.54	437,862	1,881,322	48,554	9	4.3	130.0
2012/13	10/15 - 02/01	1.63	379,386	1,616,054	37,065	10	4.3	129.8
2013/14				FISHERY CLOSED				
2014/15	10/15 - 02/05	0.66	69,109	308,582	10,133	7	4.5	132.3
2015/16	10/19 - 11/28	0.41	24,076	105,010	5,475	4	4.4	132.6

with estimated total bycatch in terms of number of crab captured sometimes more than twice as high as the catch of legal crab (Moore et al. 2000; ADF&G Crab Observer Database). Pot-lift sampling by ADF&G crab observers (Gaeuman 2013; ADF&G Crab Observer Database) indicates similar bycatch rates of discarded male crab since the reopening of the fishery (Table 5), with total male discard mortality in the 2012/13 directed fishery estimated at about 12% (88 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 6).

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

Table 5: Observed proportion of crab by size class during the ADF&G crab observer pot-lift sampling. Source: ADF&G Crab Observer Database.

Year	Total pot lifts	Pot lifts sampled	Number of crab (90 mm+ CL)	Stage 1	Stage 2	Stage 3
1990/91	26,264	10	150	0.113	0.393	0.493
1991/92	37,104	125	3,393	0.133	0.177	0.690
1992/93	56,630	71	1,606	0.191	0.268	0.542
1993/94	58,647	84	2,241	0.281	0.210	0.510
1994/95	60,860	203	4,735	0.294	0.271	0.434
1995/96	48,560	47	663	0.148	0.212	0.640
1996/97	91,085	96	489	0.160	0.223	0.618
1997/98	81,117	133	3,195	0.182	0.205	0.613
1998/99	91,826	135	1.322	0.193	0.216	0.591
1999/00 - 2008/09			FISHERY CLOSED			
2009/10	10,484	989	19,802	0.141	0.324	0.535
2010/11	29,356	2,419	45,466	0.131	0.315	0.553
2011/12	48,554	3,359	58,666	0.131	0.305	0.564
2012/13	37,065	2,841	57,298	0.141	0.318	0.541
2013/14			FISHERY CLOSED			
2014/15	10,133	895	9,906	0.094	0.228	0.679
2015/16	5,475	419	3,248	0.115	0.252	0.633

D. Data

Summary of New Information

Data used in this assessment have been updated to include the most recently available fishery and survey numbers. This assessment makes use of two new survey data points including the 2016 NMFS trawl-survey estimate of abudance, and the 2016 ADF&G pot survey CPUE. Both of these surveys have associated size compositon data. The assessment also uses updated 1993-2015 groundfish and fixed gear bycatch estimates based on AKRO data. The 2015/16 directed fishery catch data and associated size composition data were also used. The data used in each of the new models is shown in Figure 3.

Major Data Sources

Major data sources used in this assessment include annual directed-fishery retained-catch statistics from fish tickets (1978/79-1998/99, 2009/10-2012/13, and 2014/15-2015/16; Table 4); results from the annual NMFS eastern Bering Sea trawl survey (1978-2016; Table 8); results from the triennial ADF&G SMBKC pot survey (every third year during 1995-2013), the 2015 pot survey, and the 2016 pot survey (Table 7); size-frequency information from ADF&G crab-observer pot-lift sampling (1990/91-1998/99, 2009/10-2012/13, and 2014/15-2015/16; Table 5); and NMFS groundfish-observer bycatch biomass estimates (1992/93-2015/16; Table 6).

Figure 4 maps stations from which SMBKC trawl-survey and pot-survey data were obtained. Further information concerning the NMFS trawl survey as it relates to commercial crab species is available in Daly et al. (2014); see Gish et al. (2012) for a description of ADF&G SMBKC pot-survey methods. It should be noted that the two surveys cover different geographic regions and that each has in some years encountered proportionally large numbers of male blue king crab in areas 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.

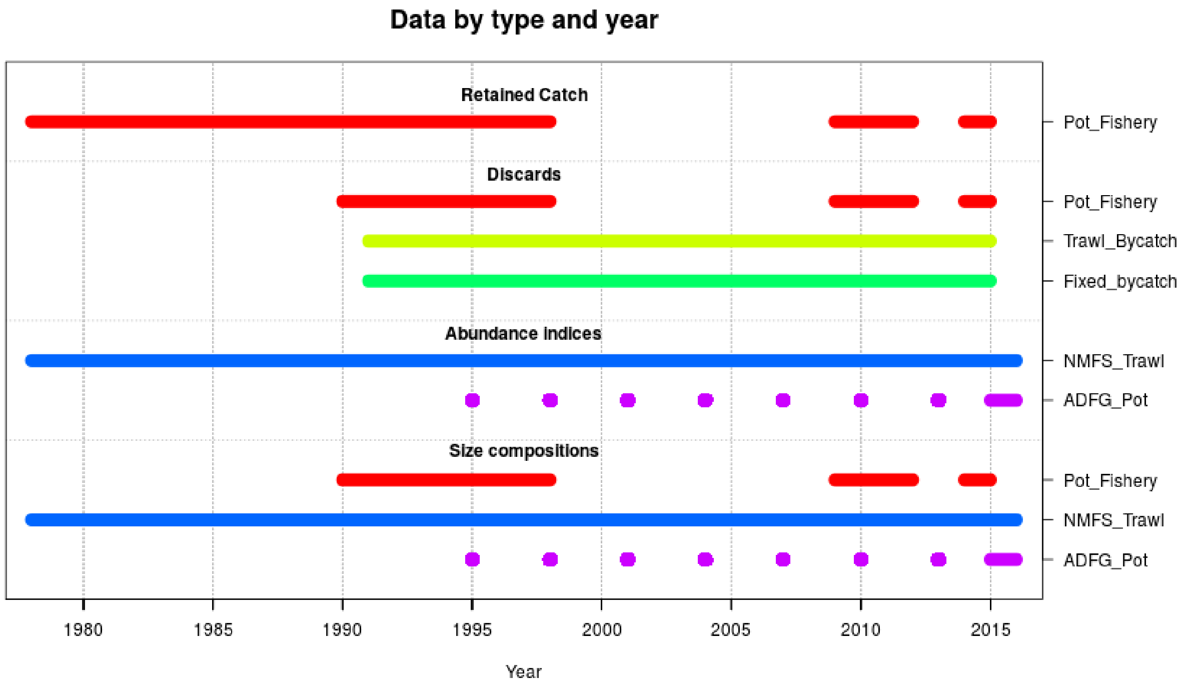

Figure 3: Data extent for the SMBKC assessment.

Other Data Sources

Recent model configurations developed for SMBKC makes use of a growth transition matrix based on Otto and Cummiskey (1990), the same growth transition matrix is used in this assessment. Other relevant data sources, including assumed population and fishery parameters, are presented in Appendix A, which also provides a detailed description of the model configuration used for this assessment.

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.

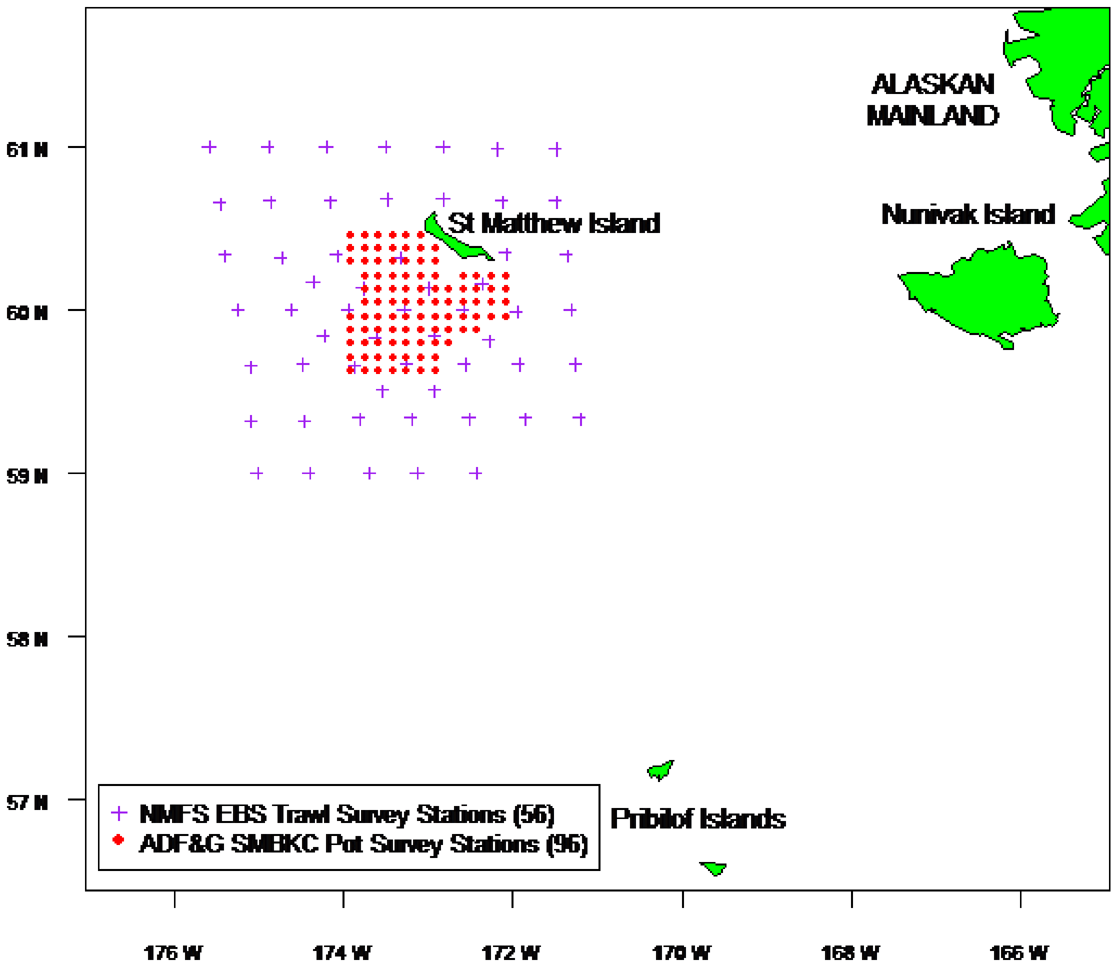

Figure 4: Trawl and pot-survey stations used in the SMBKC stock assessment.

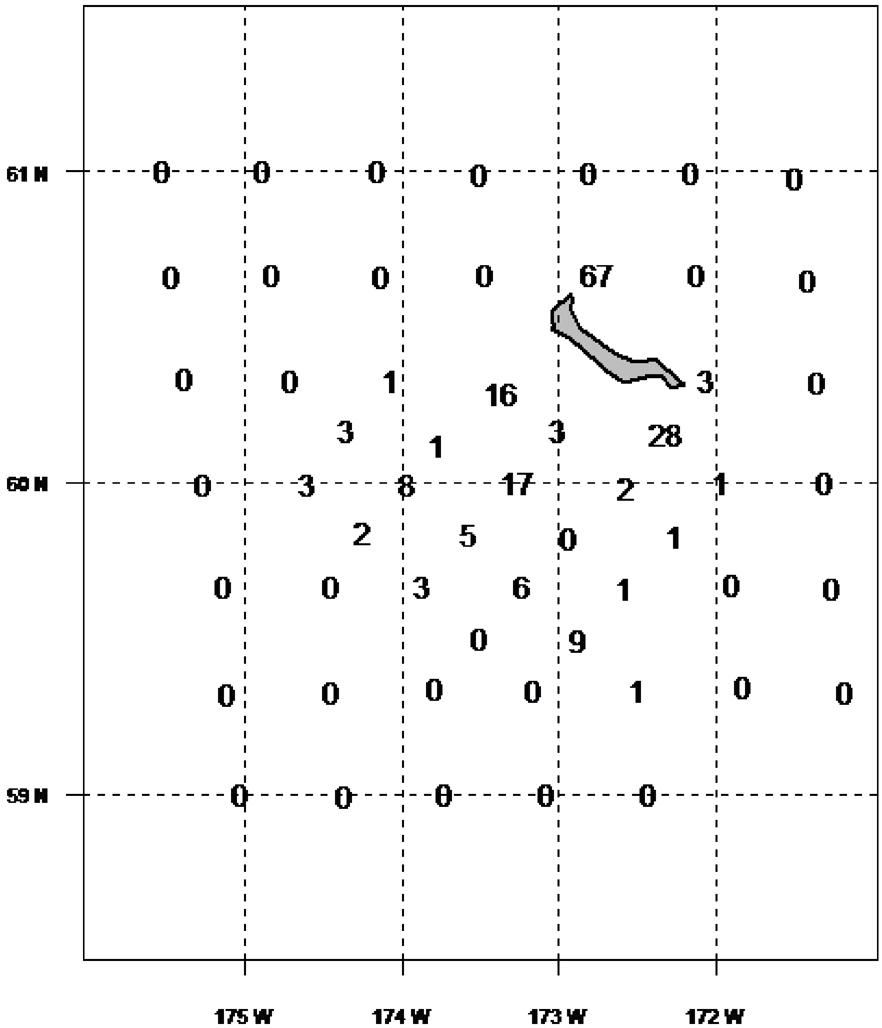

Figure 5: Catches of 181 male blue king crab measuring at least 90 mm CL from the 2014 NMFS trawl-survey at the 56 stations used to assess the SMBKC stock. Note that the area north of St. Matthew Island, which includes the large catch of 67 crab at station R-24, is not represented in the ADF&G pot-survey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

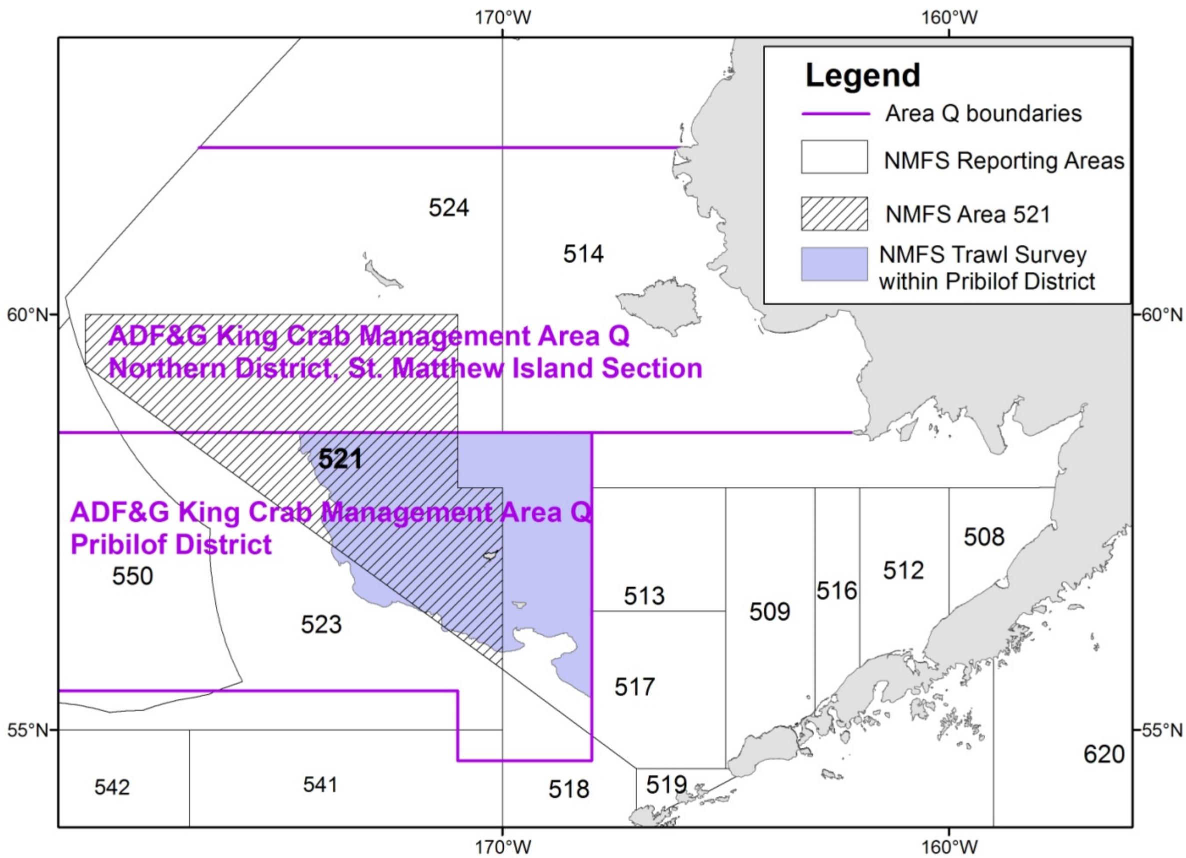

Figure 6: NFMS Bering Sea reporting areas. Estimates of SMBKC bycatch in the groundfish fisheries are based on NMFS observer data from reporting areas 524 and 521.

Table 6: Groundfish SMBKC male bycatch biomass (tonnes) estimates. Trawl includes pelagic trawl and non-pelagic trawl types. Source: J. Zheng, ADF&G, and author estimates based on data from R. Foy, NMFS. AKRO estimates used after 2008/09.

Year	Trawl bycatch	Fixed gear bycatch
1978	0.000	0.000
1979	0.000	0.000
1980	0.000	0.000
1981	0.000	0.000
1982	0.000	0.000
1983	0.000	0.000
1984	0.000	0.000
1985	0.000	0.000
1986	0.000	0.000
1987	0.000	0.000
1988	0.000	0.000
1989	0.000	0.000
1990	0.000	0.000
1991	3.538	0.045
1992	1.996	2.268
1993	1.542	0.000
1994	0.318	0.091
1995	0.635	0.136
1996	0.000	0.045
1997	0.000	0.181
1998	0.000	0.907
1999	0.000	1.361
2000	0.000	0.000
2001	0.000	0.862
2002	0.726	0.408
2003	0.998	1.134
2004	0.091	0.635
2005	0.000	0.590
2006	2.812	1.451
2007	0.045	69.717
2008	0.272	6.622
2009	0.635	7.530
2010	0.363	9.571
2011	0.181	0.590
2012	0.000	0.590
2013	0.181	0.272
2014	0.000	0.272
2015	0.000	0.635

Table 7: 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 seven triennial ADF&G SMBKC pot surveys and the 2015 and 2016 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
2016	0.083	0.192	0.725	2.378	0.186	777

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

	Abundance					Biomass		
	Stage-1	Stage-2	Stage-3			Total		Number
Year	(90-104 mm)	(105-119 mm)	(120+ mm)	Total	CV	(90+ mm CL)	CV	of crabs
1978	2.213	1.991	1.521	5.726	0.411	15.064	0.394	157
1979	3.061	2.281	1.808	7.150	0.472	17.615	0.463	178
1980	2.856	2.563	2.541	7.959	0.572	22.017	0.507	185
1981	0.483	1.213	2.263	3.960	0.368	14.443	0.402	140
1982	1.669	2.431	5.884	9.984	0.401	35.763	0.344	271
1983	1.061	1.651	3.345	6.057	0.332	21.240	0.298	231
1984	0.435	0.497	1.452	2.383	0.175	8.976	0.179	105
1985	0.379	0.376	1.117	1.872	0.216	6.858	0.210	93
1986	0.203	0.447	0.374	1.025	0.428	3.124	0.388	46
1987	0.325	0.631	0.715	1.671	0.302	5.024	0.291	71
1988	0.410	0.816	0.957	2.183	0.285	6.963	0.252	81
1989	2.169	1.154	1.786	5.109	0.314	13.974	0.271	208
1990	1.053	1.031	2.338	4.422	0.302	14.837	0.274	170
1991	1.147	1.665	2.233	5.046	0.259	15.318	0.248	197
1992	1.074	1.382	2.291	4.746	0.206	15.638	0.201	220
1993	1.521	1.828	3.276	6.626	0.185	21.051	0.169	324
1994	0.883	1.298	2.257	4.438	0.187	14.416	0.176	211
1995	1.025	1.188	1.741	3.953	0.187	12.574	0.178	178
1996	1.238	1.891	3.064	6.193	0.263	20.746	0.241	285
1997	1.165	2.228	3.789	7.182	0.367	24.084	0.337	296
1998	0.660	1.661	2.849	5.170	0.373	17.586	0.355	243
1998	0.223	0.222	0.558	1.003	0.192	3.515	0.182	52
2000	0.282	0.285	0.740	1.307	0.303	4.623	0.310	61
2001	0.419	0.502	0.938	1.859	0.243	6.242	0.245	91
2002	0.111	0.230	0.640	0.981	0.311	3.820	0.320	38
2003	0.449	0.280	0.465	1.194	0.399	3.454	0.336	65
2004	0.247	0.184	0.562	0.993	0.369	3.360	0.305	48
2005	0.319	0.310	0.501	1.130	0.403	3.620	0.371	42
2006	0.917	0.642	1.240	2.798	0.339	8.585	0.334	126
2007	2.518	2.020	1.193	5.730	0.420	14.266	0.385	250
2008	1.352	0.801	1.457	3.609	0.289	10.261	0.284	167
2009	1.573	2.161	1.410	5.144	0.263	13.892	0.256	251
2010	3.937	3.253	2.458	9.648	0.544	24.539	0.466	388
2011	1.800	3.255	3.207	8.263	0.587	24.099	0.558	318
2012	0.705	1.970	1.808	4.483	0.361	13.669	0.339	193
2013	0.335	0.452	0.807	1.593	0.215	5.043	0.217	74
2014	0.723	1.627	1.809	4.160	0.503	13.292	0.449	181
2015	0.992	1.269	1.979	4.240	0.774	12.958	0.770	153
2016	0.535	0.660	1.178	2.373	0.447	7.685	0.393	108

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 first 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

Five different Gmacs model scenarios were considered, in this document results from these models and the 2015 model are compared. The models inlcude:

1. **2015 Model**: the 2015 provided by Jie. Note that an error was found in the 2015 model code[4]. This error was fixed before making comparisons. Fixing this error caused the NMFS trawl survey selectivity to exceed 1 for stage-2 crab.
2. **Gmacs match**: tries to match as closely as possible with the 2015 Model by fixing the stage-1 and stage-2 selectivity parameters and the catchability coefficient (q) for the ADF&G pot survey at those values estimated in the 2015 model (and allows the NMFS trawl survey selectivity to exceed 1 for stage-2 crab). The parameters that are estimated in this model include the average recruitment ($\bar{R}$), the recruitment deviations (δ_y^R), the initial numbers in each stage ($\boldsymbol{n}^0$), the natural mortality deviation

[4]The error in the 2015 model code was in the population dynamics function where the growth transition matrix is applied to the numbers at length to calculate the numbers during the following time-step, specifically ‘`N(t+1,3)=TM(2,3)*NN(2)+NN(3);`‘ which should be ‘`N(t+1,3)=TM(1,3)*NN(1)+TM(2,3)*NN(2)+NN(3);`‘.

1998 (δ^M_{1998}), and the fishing mortalities for the directed pot fishery, the trawl bycatch fishery, and the fixed bycatch fishery ($\bar{F}^{\text{df}}$, $\bar{F}^{\text{tb}}$, $\bar{F}^{\text{fb}}$, $\delta^{\text{df}}_{t,y}$, $\delta^{\text{tb}}_{t,y}$, $\delta^{\text{fb}}_{t,y}$).

3. **Gmacs base**: directed pot, NMFS trawl survey and ADF&G pot survey selectivities are estimated for stage-1 and stage-2 crab (and fixed at 1 for stage-3 crab). These selectivities are bounded so that they cannot be greater than 1. This model also estimates the catchability coefficient (q) for the ADF&G pot survey as well as the average recruitment ($\bar{R}$), the recruitment deviations (δ^R_y), the initial numbers in each stage ($\boldsymbol{n}^0$), the natural mortality deviation 1998 (δ^M_{1998}), and the fishing mortalities for the directed pot fishery, the trawl bycatch fishery, and the fixed bycatch fishery ($\bar{F}^{\text{df}}$, $\bar{F}^{\text{tb}}$, $\bar{F}^{\text{fb}}$, $\delta^{\text{df}}_{t,y}$, $\delta^{\text{tb}}_{t,y}$, $\delta^{\text{fb}}_{t,y}$).
4. **Gmacs Francis**: is the same as above except that it also uses the Francis iterative re-weighting method (Francis 2011), to re-weight the size-composition data relative to the abundance indices. The trawl survey and pot survey weights were left as is (i.e. a weight of 1) because upweighting these series resulted in worse standard deviation of the normalised residual (SDNR) and median of the absolute residual (MAR) values for each of the surveys. Down-weighting the two surveys actually improved the SDNR and MAR values, but it would be unwise to down-weight either of these series.
5. **Gmacs M**: is the same as above except that natural mortality (M) is fixed at 0.18 yr^{-1} during all years. The Francis weights for each of the size-compostitons were recalculated and applied again in this model.
6. **Gmacs force**: is an exploratory scenario that the same as above except the NMFS trawl survey is up-weighted by $\lambda^{\text{NMFS}} = 1.5$ and the ADF&G pot survey is up-weighted by $\lambda^{\text{ADFG}} = 2$. After this, the Francis weights for each of the size-compostitons were recalculated and applied again in this model. This scenario should not be used for overfishing determination as it upweights the trawl and pot survey abundance indices to force a better fit to each of these data sets and provide some contrast among the Gmacs model runs. This scenario forces a better fit to the trawl and pot surveys at the expense of the SDNR (and MAR) for each of these series.

Table 9 outlines the major features of each of the models.

Table 9: Outline of the major features of the five different Gmacs scenarios.

Scenario	Selectivity estimated	Use Francis LF weighting	Estimate M_{1998}
Gmacs match	No	No	Yes
Gmacs base	Yes	No	Yes
Gmacs Francis	Yes	Yes	Yes
Gmacs M	Yes	Yes	No
Gmacs force	Yes	Yes	No

Results

Results for all Gmacs scenarios are provided with comparisons to the 2015 model. We recommend that the **Gmacs M** scenario be used for overfishing determination in 2016, based on the fit to the data and the plausibility of parameter estimates.

a. Effective sample sizes and weighting factors.

Observed and estimated effective sample sizes are compared in Table 12. Effective sample sizes are also shown on size-composition plots (Figures 14, 15, and 16).

Data weighting factors, SDNRs, and MARs are presented in Table 19. The SDNR for the trawl survey is acceptable at 1.44 in the **Gmacs match** scenario, and improves to 1.41 and 1.36 in the **Gmacs base** and **Gmacs Francis** scenarios. In the **Gmacs M** model the SDNR of the trawl survey is slightly worse at 1.54, and is much worse in the exploratory **Gmacs force** scenario at 2.26. The SDNRs for the pot surveys show much the same pattern between each of the scenarios, but are much higher values (ranging from 3.77 to 5.94). These values are very high, and whilst they can be improved by down-weighting the pot survey, it is recommended that they be left as they are as the pot survey is one of the most important data series in this model. The MAR for the trawl and pot surveys shows the same pattern among each of the scenarios as the SDNR. The SDNR (and MAR) values for the trawl survey and pot survey size compositions were excellent, ranging from 0.79 to 1.35 (except for in the **Gmacs force** scenario where the weights were a little high). The SDNRs for the directed pot fishery size compositions are a little low, ranging from 0.65 to 0.8. However, the SDNRs (and MARs) were not used when weighting the size composition data sets in those scenarios that used the Francis weighting method (i.e. in the **Gmacs Francis**, **Gmacs M**, and **Gmacs Force** scenarios). Instead, the Francis size composition weights were used (Francis 2011). In all model scenarios, the Francis weights match the weights that were actually applied to each of the size composition data sets.

b. Tables of estimates.

Model parameter estimates for each of the Gmacs scenarios are summarized in Tables 13, 14, 15, 16, and 17. These parameter estimates are compared in Table 18. Negative log-likelihood values and management measures for each of the Gmacs scenarios are compared in Tables 20 and 10.

There is little difference in the parameter estimates within the **Gmacs match** and **Gmacs base** scenarios. This is reflected in the log-likelihood components and the management quantities. The parameter estimates in the **Gmacs M** scenario are a little different to the previous scenarios, particularly the estimate of the ADF&G pot survey catchability (q) (see Table 18).

c. Graphs of estimates.

Estimated (and fixed) selectivities are compared in Figure 7.

The various model fits to total male (> 89 mm CL) trawl survey biomass are compared in Figures 8 and 9. The fits to pot survey CPUE are compared in Figures 10 and 11. Standardized residuals of total male trawl survey biomass and pot survey CPUE are plotted in Figures 12 and 13.

Fits to stage compositions for trawl survey, pot survey, and commercial observer data are shown in Figures 14, 15, and 16 for the all scenarios. Bubble plots of stage composition residuals for trawl survey, pot survey, and commercial observer data are shown for the **Gmacs base**, **Gmacs Francis**, **Gmacs M**, and **Gmacs force** scenarios in Figures 17, 18, 19, and 20, respectively.

Fits to retained catch numbers and bycatch biomass are shown for all Gmacs scenarios in Figure 21.

Estimated recruitment is compared in Figure 22. Estimated abundances by stage and mature male biomasses for all scenarios (including the 2015 model) are shown in Figures 26 and 23. Estimated natural mortality each year (M_t) is presented in Figure 27.

d. Graphic evaluation of the fit to the data.

There is little difference between model estimated survey biomass in the gmacs scenarios when compared with the 2015 model (Figures 8 and 10). Looking at the model fits to the NMFS trawl survey biomass (Figure 8), the **Gmacs match** scenario is the most similar to the 2015 model, and the **Gmacs base** model is very similar as well. In all scenarios, Gmacs produces a better fit during the mid-late 1980s. However, since about 2010 Gmacs estimates a slighly lower survey biomass than the 2015 model in an attempt to better fit the ADF&G pot survey CPUE (Figure 10). The two Gmacs scenarios that do not attempt to estimate natural mortality in 1998/99 (**Gmacs M** and **Gmacs force**) predict lower survey biomass from 1992 to 1998 than the other scenarios and the 2015 model. These same two runs also predict a lower survey biomass in recent years (since about 2010). While these two models may result in slightly worse fits to the data, they do not risk over-fitting the data in the same way the other scenarios do. As exptected the model that upweights the

NMFS survey biomass and ADF&G pot survey CPUE (**Gmacs force**) provides a better fit to the survey biomass during the mid-late 1980s and a much better fit to the pot survey CPUE in the most recent two years (Figures 8, 9, 10, and 11). Keep in mind that this scenario was only included for exploratory purposes and forcing these weights resulted in worse SDNR and MAR values for the two abundance indices.

Estimated recruitment to the model is variable over time (Figure 22). Estimated recruitment during recent years is generally low in all scenarios. Estimated mature male biomass on 15 February also fluctuates strongly over time (Figure 23).

e. Retrospective and historic analyses.

Gmacs retrospective analyses under development.

f. Uncertainty and sensitivity analyses.

Estimated standard deviations of parameters and selected management measures for the five Gmacs scenarios are summarized in Tables 13, 14, 15, 16, and 17. Probabilities for mature male biomass and OFL in 2016 are illustrated in Section F.

g. Comparison of alternative model scenarios.

Both the **Gmacs match** and **Gmacs base** scenarios provide adequate matches between the 2015 model and its Gmacs equivalent. In fact, despite a few minor differences, estimates produced by the 2015 model are generally encompassed the in the uncertainty bounds of the **Gmacs match** model.

Looking at the plot of mature male biomass (Figure 23), the **Gmacs force** scenario stands out as being quite different to the other models (including the 2015 model). This scenario results in a lower MMB from the mid-1908s through to the late-1990s, and is again lower in the most recent 5 years. This scenario upweights both the trawl survey and the pot survey abundance indices (it upweights the pot survey more than the trawl survey) and represents a model run that places greater trust in the abundance indices, particularly the pot survey, than other data sources.

Although the **Gmacs M** scenario presents a worse fit to the data, particularly the NMFS trawl-survey time series, this model does not simply allow a better fit to by estimating an unconstrained pulse in natural mortality. Allowing a better fit in this way is a bit like estimating catchability (q) every year, it is not recommended. Although doing so produces a better fit to the model, it reduces predictive power and support for such a phenomena, anecdotal or otherwise, seems to be limited. It also raises concerns about what the implications would be for an "average" true natural mortality which can affect the management measures.

In summary, we recommend that the **Gmacs M** scenario be used for overfishing determination for this stock in 2016.

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} (therefore numerical approximation of F_{OFL} is required). As implemented for this assessment, all calculations proceed according to the model equations given in Appendix A. F_{OFL} is taken to be full-selection fishing mortality in the directed pot fishery and groundfish trawl and fixed-gear fishing mortalities set at their model geometric mean values over years for which there are data-based estimates of bycatch-mortality biomass.

The currently recommended Tier 4 convention is to use the full assessment period, currently 1978-2016, to define a B_{MSY} proxy in terms of average estimated MMB and to set $\gamma = 1.0$ with assumed stock natural mortality $M = 0.18$ yr^{-1} in setting the F_{MSY} proxy value γM. The parameters α and β are assigned their default values $\alpha = 0.10$ and $\beta = 0.25$. The F_{OFL}, OFL, ABC, and MMB in 2016 for all scenarios are summarized in Table 10. ABC is 80% of the OFL.

Table 10: Comparisons of management measures for the five Gmacs model scenarios. Biomass and OFL are in tonnes.

Component	Gmacs match	Gmacs base	Gmacs Francis	Gmacs M	Gmacs force
MMB_{2016}	2240.516	2229.091	2206.231	1804.758	1439.655
B_{MSY}	3681.513	3671.965	3597.328	3459.060	3325.722
F_{OFL}	0.089	0.088	0.089	0.073	0.057
OFL_{2016}	140.623	140.253	141.374	95.567	62.115
ABC_{2016}	112.499	112.203	113.099	76.454	49.692

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.

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Table 11: Mean weight (kg) by stage in used in all of the models (provided as a vector of weights at length each year to Gmacs).

Year	Stage-1	Stage-2	Stage-3
1978	0.7	1.2	1.9
1979	0.7	1.2	1.7
1980	0.7	1.2	1.9
1981	0.7	1.2	1.9
1982	0.7	1.2	1.9
1983	0.7	1.2	2.1
1984	0.7	1.2	1.9
1985	0.7	1.2	2.1
1986	0.7	1.2	1.9
1987	0.7	1.2	1.9
1988	0.7	1.2	1.9
1989	0.7	1.2	2.0
1990	0.7	1.2	1.9
1991	0.7	1.2	2.0
1992	0.7	1.2	1.9
1993	0.7	1.2	2.0
1994	0.7	1.2	1.9
1995	0.7	1.2	2.0
1996	0.7	1.2	2.0
1997	0.7	1.2	2.1
1998	0.7	1.2	2.0
1999	0.7	1.2	1.9
2000	0.7	1.2	1.9
2001	0.7	1.2	1.9
2002	0.7	1.2	1.9
2003	0.7	1.2	1.9
2004	0.7	1.2	1.9
2005	0.7	1.2	1.9
2006	0.7	1.2	1.9
2007	0.7	1.2	1.9
2008	0.7	1.2	1.9
2009	0.7	1.2	1.9
2010	0.7	1.2	1.8
2011	0.7	1.2	1.8
2012	0.7	1.2	1.8
2013	0.7	1.2	1.9
2014	0.7	1.2	1.9
2015	0.7	1.2	1.9
2016	0.7	1.2	1.9

Table 12: Observed and assumed sample sizes for observer data from the directed pot fishery, the NMFS trawl survey, and the ADF&G pot survey.

	Observed sample sizes			Assumed sample sizes		
Year	Observer pot	NMFS trawl	ADF&G pot	Observer pot	NMFS trawl	ADF&G pot
1978		157			50	
1979		178			50	
1980		185			50	
1981		140			50	
1982		271			50	
1983		231			50	
1984		105			50	
1985		93			46.5	
1986		46			23	
1987		71			35.5	
1988		81			40.5	
1989		208			50	
1990	150	170		15	50	
1991	3393	197		25	50	
1992	1606	220		25	50	
1993	2241	324		25	50	
1994	4735	211		25	50	
1995	663	178	4624	25	50	100
1996	489	285		25	50	
1997	3195	296		25	50	
1998	1323	243	4812	25	50	100
1999		52			26	
2000		61			30.5	
2001		91	3255		45.5	100
2002		38			19	
2003		65			32.5	
2004		48	640		24	100
2005		42			21	
2006		126			50	
2007		250	3319		50	100
2008		167			50	
2009	19802	251		50	50	
2010	45466	388	3920	50	50	100
2011	58667	318		50	50	
2012	57282	193		50	50	
2013		74	2167		37	100
2014	9906	181		50	50	
2015	3248	153	1077	50	50	100
2016		108	777		50	100

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

Parameter	Estimate	SD
Natural mortality deviation in 1998/99 (δ^M_{1998})	1.668	0.116
$\log(\bar{R})$	13.390	0.048
$\log(n^0_1)$	14.894	0.169
$\log(n^0_2)$	14.477	0.194
$\log(n^0_3)$	14.285	0.200
$\log(\bar{F}^{\text{df}})$	-1.519	0.045
$\log(\bar{F}^{\text{tb}})$	-12.228	0.068
$\log(\bar{F}^{\text{fb}})$	-9.130	0.068
F_{OFL}	0.089	0.009
OFL	140.620	25.900

Table 14: Model parameter estimates, selected derived quantities, and their standard deviations (SD) for the **Gmacs base** model.

Parameter	Estimate	SD
Natural mortality deviation in 1998/99 (δ^M_{1998})	1.669	0.127
$\log(\bar{R})$	13.399	0.059
$\log(n^0_1)$	14.860	0.171
$\log(n^0_2)$	14.524	0.197
$\log(n^0_3)$	14.224	0.210
ADF&G pot survey catchability ($q \times 1000$)	3.967	0.304
$\log(\bar{F}^{\text{df}})$	-1.512	0.054
$\log(\bar{F}^{\text{tb}})$	-12.245	0.082
$\log(\bar{F}^{\text{fb}})$	-9.147	0.082
log Stage-1 directed pot selectivity 1978-2008	-0.713	0.174
log Stage-2 directed pot selectivity 1978-2008	-0.406	0.127
log Stage-1 directed pot selectivity 2009-2016	-0.629	0.164
log Stage-2 directed pot selectivity 2009-2016	-0.000	0.000
log Stage-1 NMFS trawl selectivity	-0.203	0.067
log Stage-2 NMFS trawl selectivity	-0.000	0.000
log Stage-1 ADF&G pot selectivity	-0.856	0.135
log Stage-2 ADF&G pot selectivity	-0.106	0.078
F_{OFL}	0.088	0.011
OFL	140.250	32.767

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

Parameter	Estimate	SD
Natural mortality deviation in 1998/99 (δ^M_{1998})	1.675	0.135
$\log(\bar{R})$	13.394	0.059
$\log(n^0_1)$	14.836	0.205
$\log(n^0_2)$	14.544	0.226
$\log(n^0_3)$	14.235	0.236
ADF&G pot survey catchability ($q \times 1000$)	3.881	0.307
$\log(\bar{F}^{\mathrm{df}})$	-1.483	0.057
$\log(\bar{F}^{\mathrm{tb}})$	-12.245	0.082
$\log(\bar{F}^{\mathrm{fb}})$	-9.148	0.082
log Stage-1 directed pot selectivity 1978-2008	-0.628	0.183
log Stage-2 directed pot selectivity 1978-2008	-0.423	0.149
log Stage-1 directed pot selectivity 2009-2016	-0.512	0.176
log Stage-2 directed pot selectivity 2009-2016	-0.000	0.000
log Stage-1 NMFS trawl selectivity	-0.143	0.061
log Stage-2 NMFS trawl selectivity	-0.000	0.000
log Stage-1 ADF&G pot selectivity	-0.870	0.134
log Stage-2 ADF&G pot selectivity	-0.050	0.091
F_{OFL}	0.090	0.011
OFL	141.370	32.875

Table 16: Model parameter estimates, selected derived quantities, and their standard deviations (SD) for the **Gmacs M** model.

Parameter	Estimate	SD
$\log(\bar{R})$	13.245	0.054
$\log(n^0_1)$	14.836	0.207
$\log(n^0_2)$	14.608	0.223
$\log(n^0_3)$	14.280	0.236
ADF&G pot survey catchability ($q \times 1000$)	4.573	0.301
$\log(\bar{F}^{\mathrm{df}})$	-1.421	0.056
$\log(\bar{F}^{\mathrm{tb}})$	-12.154	0.080
$\log(\bar{F}^{\mathrm{fb}})$	-9.056	0.080
log Stage-1 directed pot selectivity 1978-2008	-0.510	0.183
log Stage-2 directed pot selectivity 1978-2008	-0.396	0.150
log Stage-1 directed pot selectivity 2009-2016	-0.502	0.175
log Stage-2 directed pot selectivity 2009-2016	-0.000	0.000
log Stage-1 NMFS trawl selectivity	-0.063	0.060
log Stage-2 NMFS trawl selectivity	-0.000	0.000
log Stage-1 ADF&G pot selectivity	-0.812	0.132
log Stage-2 ADF&G pot selectivity	-0.000	0.000
F_{OFL}	0.073	0.010
OFL	95.567	22.394

Table 17: Model parameter estimates, selected derived quantities, and their standard deviations (SD) for the **Gmacs force** model.

Parameter	Estimate	SD
$\log(\bar{R})$	13.110	0.049
$\log(n_1^0)$	14.785	0.207
$\log(n_2^0)$	14.600	0.217
$\log(n_3^0)$	14.255	0.228
ADF&G pot survey catchability ($q \times 1000$)	4.129	0.190
$\log(\bar{F}^{\text{df}})$	-1.335	0.044
$\log(\bar{F}^{\text{tb}})$	-12.168	0.070
$\log(\bar{F}^{\text{fb}})$	-9.069	0.070
log Stage-1 directed pot selectivity 1978-2008	-0.639	0.179
log Stage-2 directed pot selectivity 1978-2008	-0.507	0.147
log Stage-1 directed pot selectivity 2009-2016	-0.223	0.168
log Stage-2 directed pot selectivity 2009-2016	-0.000	0.000
log Stage-1 NMFS trawl selectivity	-0.012	0.059
log Stage-2 NMFS trawl selectivity	-0.000	0.000
log Stage-1 ADF&G pot selectivity	-0.478	0.163
log Stage-2 ADF&G pot selectivity	-0.000	0.000
F_{OFL}	0.057	0.005
OFL	62.115	8.838

Table 18: Comparisons of model parameter estimates for the five Gmacs model scenarios.

Parameter	Match	Base	Francis	M	Force
ADF&G pot survey catchability (q)	-	3.967	3.881	4.573	4.129
$\log(\bar{F}^{\text{df}})$	-1.519	-1.512	-1.483	-1.421	-1.335
$\log(\bar{F}^{\text{fb}})$	-9.130	-9.147	-9.148	-9.056	-9.069
$\log(\bar{F}^{\text{tb}})$	-12.228	-12.245	-12.245	-12.154	-12.168
$\log(\bar{R})$	13.390	13.399	13.394	13.245	13.110
$\log(n_1^0)$	14.894	14.860	14.836	14.836	14.785
$\log(n_2^0)$	14.477	14.524	14.544	14.608	14.600
$\log(n_3^0)$	14.285	14.224	14.235	14.280	14.255
log Stage-1 ADF&G pot selectivity	-	-0.856	-0.870	-0.812	-0.478
log Stage-1 directed pot selectivity 1978-2008	-	-0.713	-0.628	-0.510	-0.639
log Stage-1 directed pot selectivity 2009-2015	-	-0.629	-0.512	-0.502	-0.223
log Stage-1 NMFS trawl selectivity	-	-0.203	-0.143	-0.063	-0.012
log Stage-2 ADF&G pot selectivity	-	-0.106	-0.050	-0.000	-0.000
log Stage-2 directed pot selectivity 1978-2008	-	-0.406	-0.423	-0.396	-0.507
log Stage-2 directed pot selectivity 2009-2015	-	-0.000	-0.000	-0.000	-0.000
log Stage-2 NMFS trawl selectivity	-	-0.000	-0.000	-0.000	-0.000
Natural mortality deviation in 1998/99 (δ_{1998}^{M})	1.668	1.669	1.675	-	-

Table 19: Comparisons of data weights, Francis LF weights (i.e. the new weights that should be applied to the LFs), SDNR values, and MAR values for the five Gmacs model scenarios. Note that in the Gmacs Francis, M and Force scenarios, the Francis LF weights and the LF weights applied to each size composition are the same as the size compositions have been re-weighted using the Francis method.

Component	Match	Base	Francis	M	Force
NMFS trawl survey weight	1.00	1.00	1.00	1.00	1.50
ADF&G pot survey weight	1.00	1.00	1.00	1.00	2.00
Directed pot LF weight	1.00	1.00	1.75	1.59	1.35
NMFS trawl survey LF weight	1.00	1.00	0.54	0.55	0.28
ADF&G pot survey LF weight	1.00	1.00	1.82	1.31	0.39
Francis weight for directed pot LF	1.72	1.75	1.75	1.59	1.35
Francis weight for NMFS trawl survey LF	0.54	0.53	0.54	0.55	0.28
Francis weight for ADF&G pot survey LF	2.17	2.22	1.82	1.31	0.39
SDNR NMFS trawl survey	1.44	1.41	1.35	1.54	2.26
SDNR ADF&G pot survey	3.95	3.87	3.79	3.79	6.02
SDNR directed pot LF	0.68	0.64	0.66	0.69	0.81
SDNR NMFS trawl survey LF	1.22	1.27	1.27	1.32	1.74
SDNR ADF&G pot survey LF	0.78	0.80	0.90	0.98	1.63
MAR NMFS trawl survey	1.06	1.10	1.14	1.27	1.69
MAR ADF&G pot survey	3.03	2.90	2.71	3.42	4.75
MAR directed pot LF	0.47	0.45	0.54	0.51	0.57
MAR NMFS trawl survey LF	0.55	0.55	0.68	0.69	1.04
MAR ADF&G pot survey LF	0.53	0.53	0.48	0.58	0.88

Table 20: Comparisons of negative log-likelihood values for the five Gmacs model scenarios.

Component	Match	Base	Francis	M	Force
Pot Retained Catch	-69.05	-69.19	-69.24	-69.06	-67.31
Pot Discarded Catch	6.44	6.00	6.19	5.72	8.25
Trawl bycatch Discarded Catch	-6.88	-6.88	-6.88	-6.88	-6.88
Fixed bycatch Discarded Catch	-6.85	-6.86	-6.86	-6.87	-6.86
NMFS Trawl Survey	-6.21	-7.60	-10.33	1.49	41.40
ADF&G Pot Survey CPUE	56.31	53.35	50.38	52.51	149.86
Directed Pot LF	-12.12	-12.98	11.30	11.75	14.80
NMFS Trawl LF	16.82	22.39	52.14	55.70	93.15
ADF&G Pot LF	-7.05	-6.49	0.35	1.38	12.65
Recruitment deviations	57.24	57.11	57.04	58.08	62.34
F penalty	14.49	14.49	14.49	14.49	14.49
M penalty	6.47	6.47	6.47	0.00	0.00
Prior	13.72	13.71	13.71	13.71	13.71
Total	63.34	63.53	118.76	132.02	329.59
Total estimated parameters	282.00	291.00	291.00	289.00	289.00

Table 21: Population abundances ($\boldsymbol{n}$) by crab stage in numbers of crab at the time of the survey and mature male biomass (MMB) in tonnes on 15 February for the **2015 model**.

Year	n_1	n_2	n_3	MMB
1978	3018380	1953510	1597980	4075
1979	3919060	2341120	2147490	5802
1980	3467980	3064710	3243990	9074
1981	1395090	3047670	4504000	9239
1982	1368260	1777680	4466940	6370
1983	707216	1318650	3036760	3355
1984	683165	782950	1543430	1990
1985	2244990	616447	986160	1686
1986	1338560	1445520	916977	2727
1987	1432180	1228070	1383660	3375
1988	1306640	1222920	1677970	3723
1989	2279000	1148700	1865710	4245
1990	1445840	1690250	2098040	4744
1991	2024880	1377550	2361620	4400
1992	2321500	1583990	2169580	4531
1993	2514290	1829500	2290170	4977
1994	1465290	2012460	2447020	4912
1995	1572620	1462710	2400370	4768
1996	1807950	1360970	2267560	4351
1997	1086810	1459480	2125050	3718
1998	684461	1059430	1727860	1804
1999	373686	342335	653347	1560
2000	412027	332743	748221	1725
2001	380490	352080	826139	1889
2002	169056	340032	898096	2008
2003	336657	212374	934340	1942
2004	235762	267626	914402	1963
2005	525625	227222	917421	1927
2006	799432	383194	923952	2099
2007	590277	594788	1029430	2455
2008	1019370	530589	1177800	2720
2009	928263	772468	1333420	2992
2010	873520	791923	1475900	2755
2011	723104	753585	1409700	2350
2012	458036	646078	1187950	1959
2013	532334	461243	984254	2294
2014	466341	465305	1097620	2327
2015	389087	424535	1123020	2511

Table 22: Population abundances ($\boldsymbol{n}$) by crab stage in numbers of crab at the time of the survey (1 July, season 1) and mature male biomass (MMB) in tonnes on 15 February for the **Gmacs match** model.

Year	n_1	n_2	n_3	MMB
1978	2940912	1937321	1599485	4443
1979	4214746	2366729	2186198	6293
1980	3530461	3255079	3319758	9985
1981	1339907	3151773	4671239	10382
1982	1423213	1836341	4716859	7421
1983	703526	1445516	3354759	4515
1984	627868	894099	1961366	3104
1985	933225	665758	1432033	2802
1986	1338578	768053	1239446	2797
1987	1329964	1039251	1346574	3294
1988	1226021	1124816	1564678	3617
1989	2674536	1092640	1736620	4139
1990	1666073	1928817	2012719	5144
1991	1762209	1618513	2457709	5111
1992	1851674	1570399	2396923	5251
1993	2090492	1606677	2482221	5419
1994	1515487	1758741	2518683	5130
1995	1675780	1473533	2412962	5059
1996	1511565	1471942	2333159	4852
1997	853687	1375503	2256106	4212
1998	614040	958573	1853684	2887
1999	363364	313057	693876	1650
2000	409999	316943	766549	1791
2001	375285	345618	833361	1948
2002	132240	334836	900466	2060
2003	328086	189126	930652	1952
2004	211796	254862	898980	1968
2005	467209	208953	896146	1911
2006	745199	342948	892153	2052
2007	436309	549673	978199	2416
2008	921106	432887	1113856	2568
2009	819128	682462	1222934	2679
2010	757131	706071	1339466	2456
2011	643942	677524	1270850	2089
2012	363765	602723	1067516	1762
2013	457408	413959	889357	2032
2014	450828	405706	988406	2041
2015	358504	399119	1006285	2106
2016	354174	342919	1048939	2241

Table 23: Population abundances ($\boldsymbol{n}$) by crab stage in numbers of crab at the time of the survey (1 July, season 1) and mature male biomass (MMB) in tonnes on 15 February for the **Gmacs base** model.

Year	n_1	n_2	n_3	MMB
1978	2842553	2030682	1504270	4369
1979	4115791	2340416	2145183	6194
1980	3529677	3188432	3264045	9803
1981	1338669	3129048	4591236	10207
1982	1469061	1828043	4638329	7259
1983	754807	1469572	3288146	4406
1984	637458	932143	1921506	3073
1985	890400	684083	1418367	2795
1986	1336767	749141	1233575	2764
1987	1287378	1031877	1332012	3258
1988	1179403	1097457	1545228	3550
1989	2660962	1056248	1702720	4031
1990	1673077	1908726	1964979	5034
1991	1754214	1615905	2408100	5012
1992	1871458	1564858	2352908	5161
1993	2128922	1616393	2443968	5354
1994	1515844	1784461	2494344	5112
1995	1695295	1482349	2404947	5052
1996	1570907	1486308	2331832	4864
1997	874137	1415011	2266545	4276
1998	627570	983746	1883218	2960
1999	377384	320461	711071	1690
2000	416083	327613	785793	1839
2001	386596	352741	855291	1997
2002	136181	343829	923298	2113
2003	332125	194435	954559	2003
2004	214753	258999	921946	2015
2005	507024	212065	917650	1955
2006	757084	367265	915000	2123
2007	499106	564749	1010460	2494
2008	936580	474418	1153889	2690
2009	783535	705391	1278475	2801
2010	746606	692962	1394496	2534
2011	635953	667031	1309638	2144
2012	370619	594551	1094544	1800
2013	458732	415238	908815	2068
2014	418921	406908	1005411	2072
2015	349833	380865	1018496	2107
2016	348100	331752	1049276	2229

Table 24: Population abundances ($\boldsymbol{n}$) by crab stage in numbers of crab at the time of the survey (1 July, season 1) and mature male biomass (MMB) in tonnes on 15 February for the **Gmacs Francis** model.

Year	n_1	n_2	n_3	MMB
1978	2773168	2071022	1521277	4448
1979	4012989	2313326	2173811	6211
1980	3413859	3119273	3265792	9726
1981	1266941	3038223	4548361	10022
1982	1331165	1755763	4551046	7009
1983	791158	1364802	3167440	4038
1984	618917	918397	1770041	2774
1985	863252	668643	1283094	2498
1986	1272386	728106	1110514	2507
1987	1305290	987205	1213303	2982
1988	1185055	1093003	1425180	3326
1989	2719838	1058063	1600648	3834
1990	1613495	1943754	1885470	4929
1991	1762108	1592769	2354212	4882
1992	1844861	1561733	2296818	5052
1993	2103441	1599792	2393250	5236
1994	1486360	1764014	2441442	4989
1995	1690546	1458279	2347702	4913
1996	1622928	1475489	2271336	4736
1997	935254	1441812	2214730	4199
1998	669720	1028431	1857664	2958
1999	381531	336633	708798	1704
2000	419237	335440	792346	1860
2001	384401	357200	864950	2020
2002	138770	344035	933418	2132
2003	313516	196017	963331	2021
2004	212181	248653	928509	2016
2005	441285	207104	917732	1949
2006	756886	327175	907090	2063
2007	672313	551242	983749	2431
2008	904835	570126	1139817	2771
2009	783866	718806	1312023	2874
2010	805014	697650	1429325	2598
2011	579876	702727	1346472	2246
2012	350190	573694	1138922	1850
2013	472316	396333	933205	2091
2014	384581	408534	1017443	2095
2015	336647	361332	1026497	2100
2016	331572	317518	1045055	2206

Table 25: Population abundances ($\boldsymbol{n}$) by crab stage in numbers of crab at the time of the survey (1 July, season 1) and mature male biomass (MMB) in tonnes on 15 February for the **Gmacs M** model.

Year	n_1	n_2	n_3	MMB
1978	2773253	2208566	1590814	4739
1979	4014131	2359326	2300824	6476
1980	3379208	3135309	3395032	9990
1981	1228349	3023321	4661453	10215
1982	1323065	1728220	4634844	7138
1983	784869	1350865	3223131	4136
1984	607531	910065	1809304	2838
1985	841161	659203	1310956	2545
1986	1307055	712036	1127309	2521
1987	1300481	1002107	1222198	3016
1988	1165518	1095169	1439700	3355
1989	2727774	1047363	1612268	3845
1990	1547353	1944818	1890505	4939
1991	1662327	1554450	2353529	4838
1992	1702967	1490607	2268954	4919
1993	1870927	1493083	2322598	4977
1994	1238827	1592424	2309599	4549
1995	1364594	1256220	2130915	4263
1996	1126489	1217400	1962080	3853
1997	589494	1065317	1785668	2903
1998	358607	700474	1281907	1987
1999	221539	443567	901902	2186
2000	316604	277655	993851	2171
2001	318313	277885	995729	2175
2002	124507	278909	997380	2178
2003	285292	165930	982925	2023
2004	188770	222113	927435	1984
2005	392829	184552	901578	1893
2006	662876	291311	878246	1968
2007	596329	484331	933816	2262
2008	860536	503685	1058218	2544
2009	713011	670698	1206874	2639
2010	726949	640149	1311503	2341
2011	509971	637872	1212988	1952
2012	292388	511149	989859	1536
2013	392793	341635	773318	1747
2014	310713	343762	849839	1732
2015	267290	296500	847866	1725
2016	259047	255305	857560	1805

Table 26: Population abundances ($\boldsymbol{n}$) by crab stage in numbers of crab at the time of the survey (1 July, season 1) and mature male biomass (MMB) in tonnes on 15 February for the **Gmacs force** model.

Year	n_1	n_2	n_3	MMB
1978	2637916	2191610	1551721	4645
1979	3863213	2274538	2248369	6291
1980	3292168	3018741	3296119	9668
1981	1168317	2933483	4513144	9838
1982	1260806	1663115	4461823	6736
1983	697016	1292723	3042386	3703
1984	510866	839282	1622052	2408
1985	682666	579036	1111094	2041
1986	1059689	592580	906957	1969
1987	1194847	817564	957766	2307
1988	1169196	971750	1117773	2628
1989	2931393	1008278	1282244	3158
1990	1541046	2050811	1612480	4554
1991	1680312	1586167	2174252	4534
1992	1712905	1511681	2137214	4696
1993	1887221	1505911	2224169	4798
1994	1164232	1606230	2234610	4423
1995	1104599	1217221	2068310	4106
1996	1885521	1052380	1872486	3503
1997	759491	1453992	1695142	3170
1998	415152	929690	1420442	2487
1999	168540	553203	1126248	2729
2000	302700	283309	1231754	2622
2001	258218	271643	1196115	2542
2002	76507	241698	1156604	2434
2003	169306	125449	1093257	2184
2004	95781	140823	989597	2008
2005	554693	103039	904989	1808
2006	816129	358709	853769	1999
2007	622382	596360	959983	2437
2008	830704	556086	1138229	2752
2009	677685	670804	1297453	2797
2010	615176	619586	1384128	2436
2011	424614	565768	1252168	1931
2012	239781	437169	974564	1421
2013	282938	286169	714646	1583
2014	218293	261004	763856	1491
2015	162491	214817	726441	1429
2016	141604	166746	706359	1440

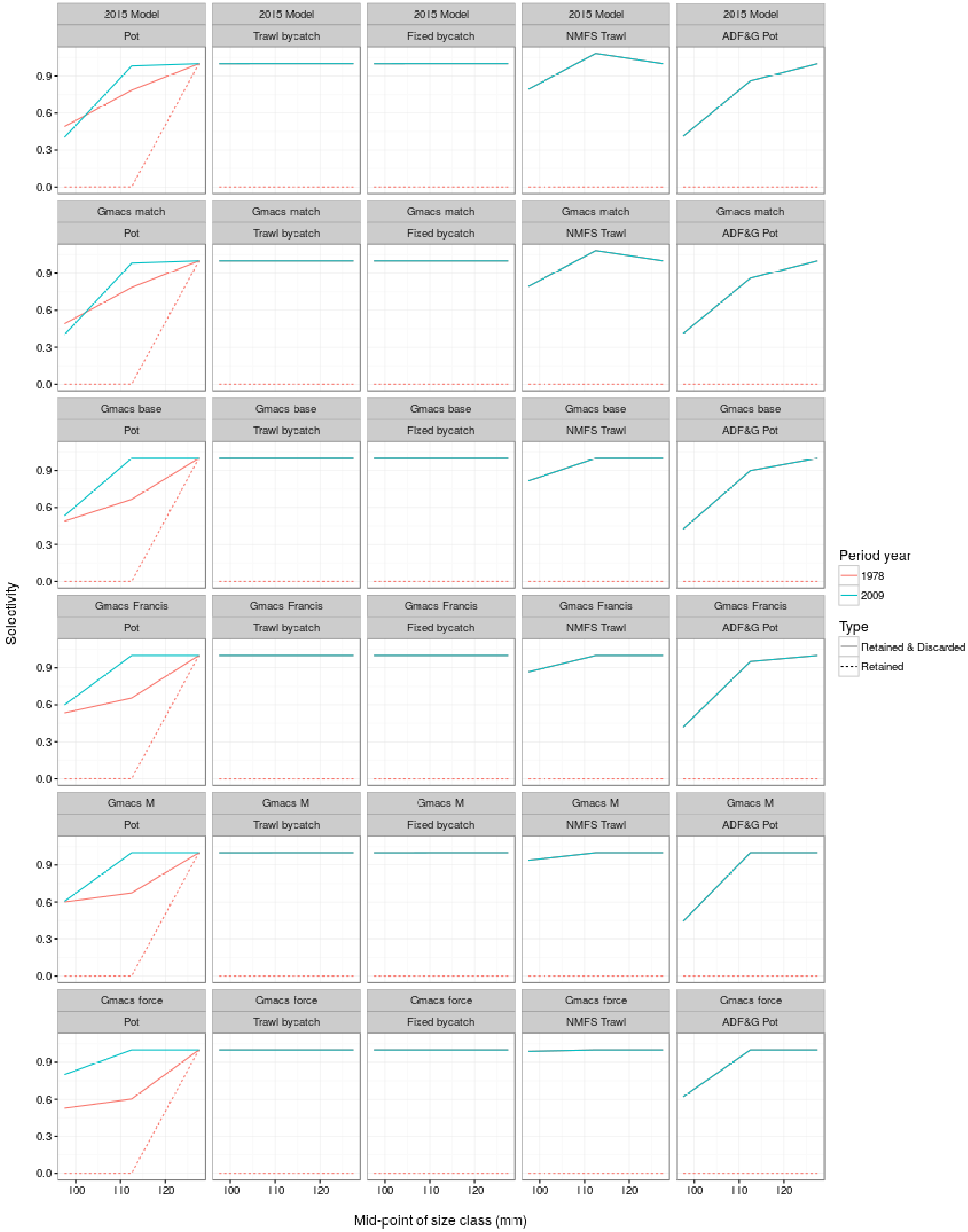

Figure 7: Comparisons of the estimated (and fixed to match the 2015 model selectivities in the Gmacs base scenario) stage-1 and stage-2 selectivities for each of the different model scenarios (the stage-3 selectivities are all fixed at 1). Estimated selectivities are shown for the directed pot fishery, 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 2009-2016.

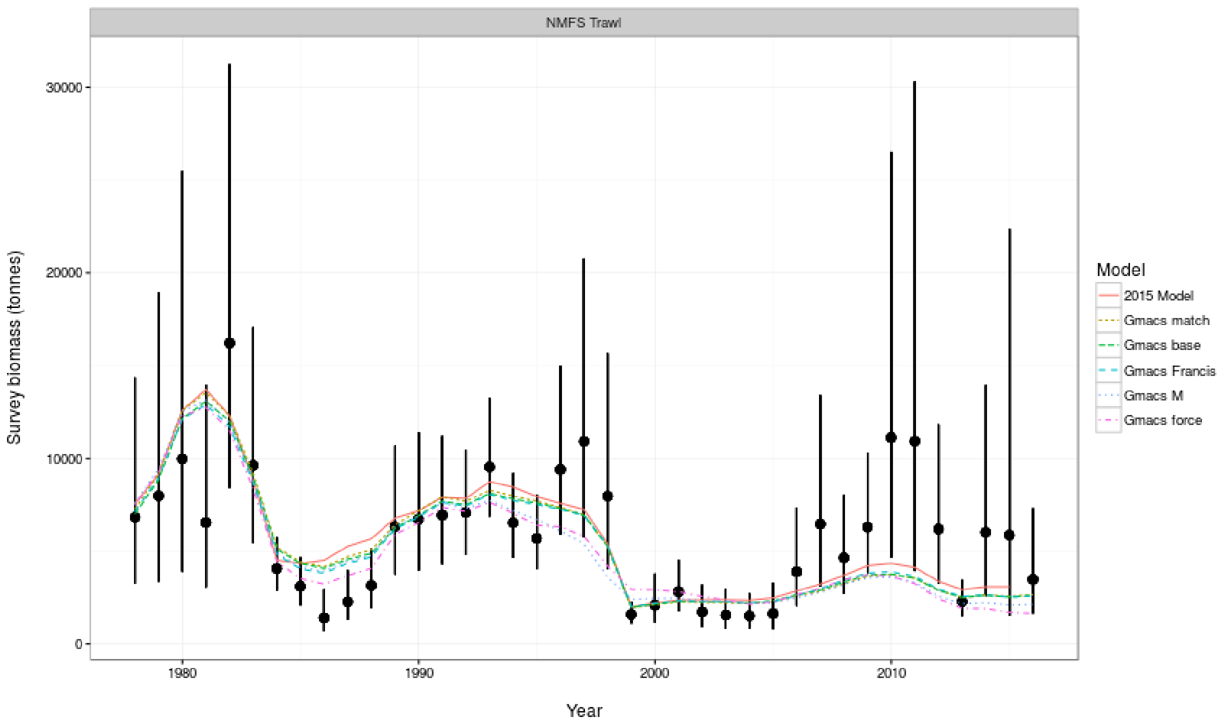

Figure 8: Comparisons of area-swept estimates of total male survey biomass (tonnes) and model predictions for the 2015 model and each of the Gmacs model scenarios. The error bars are plus and minus 2 standard deviations.

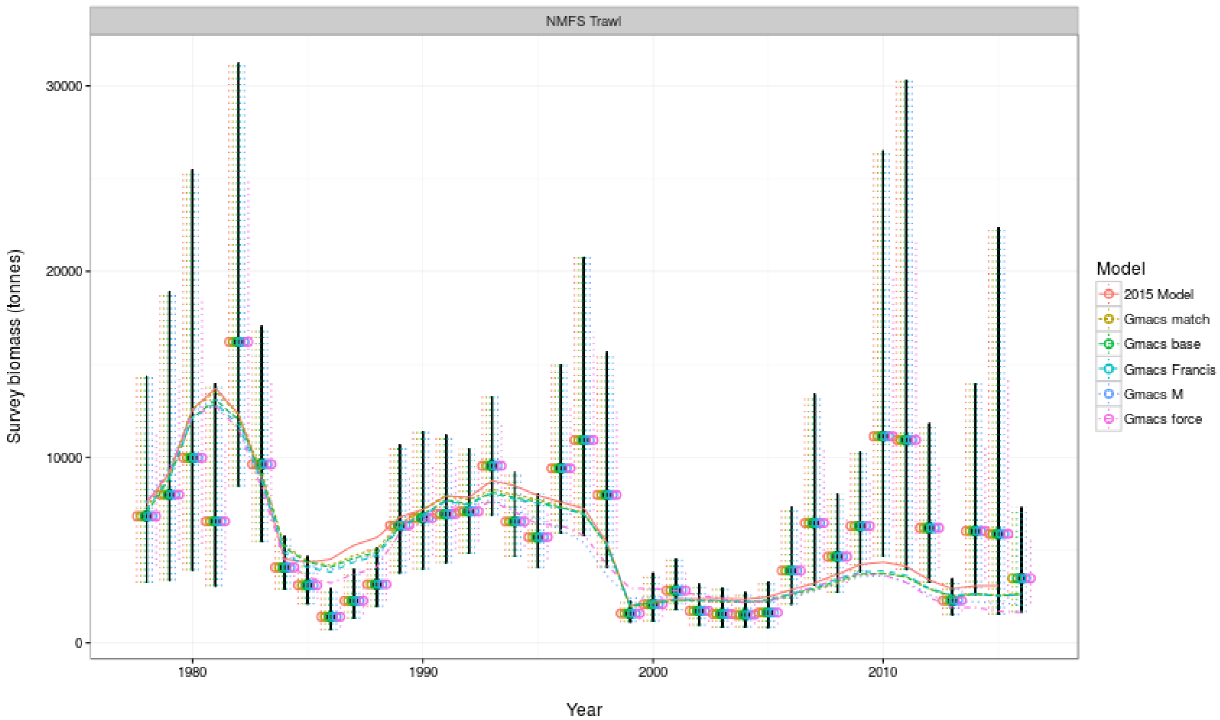

Figure 9: Comparisons of area-swept estimates of total male survey biomass (tonnes) and model predictions for the 2015 model and each of the Gmacs model scenarios. The solid black error bars are plus and minus 2 standard deviations derived using the original survey CVs. The dotted error bars are plus and minus 2 standard deviations but represent the weighted survey CVs.

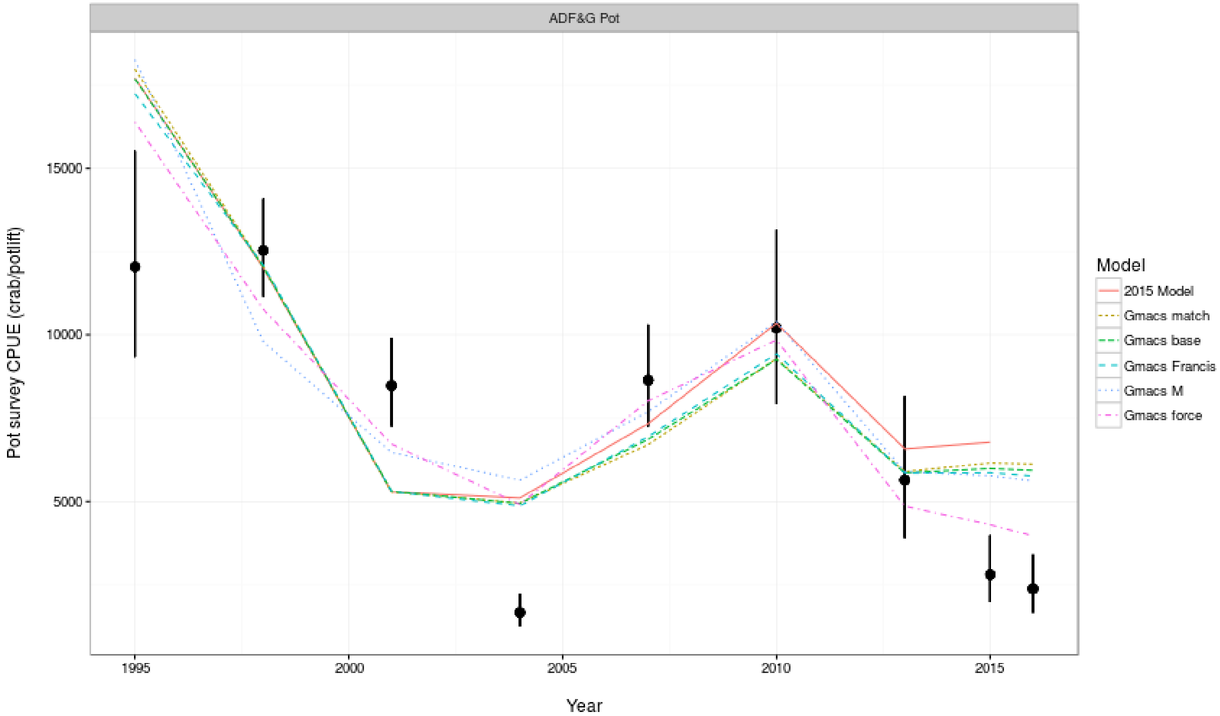

Figure 10: Comparisons of total male pot survey CPUEs and model predictions for the 2015 model and each of the Gmacs model scenarios. The error bars are plus and minus 2 standard deviations.

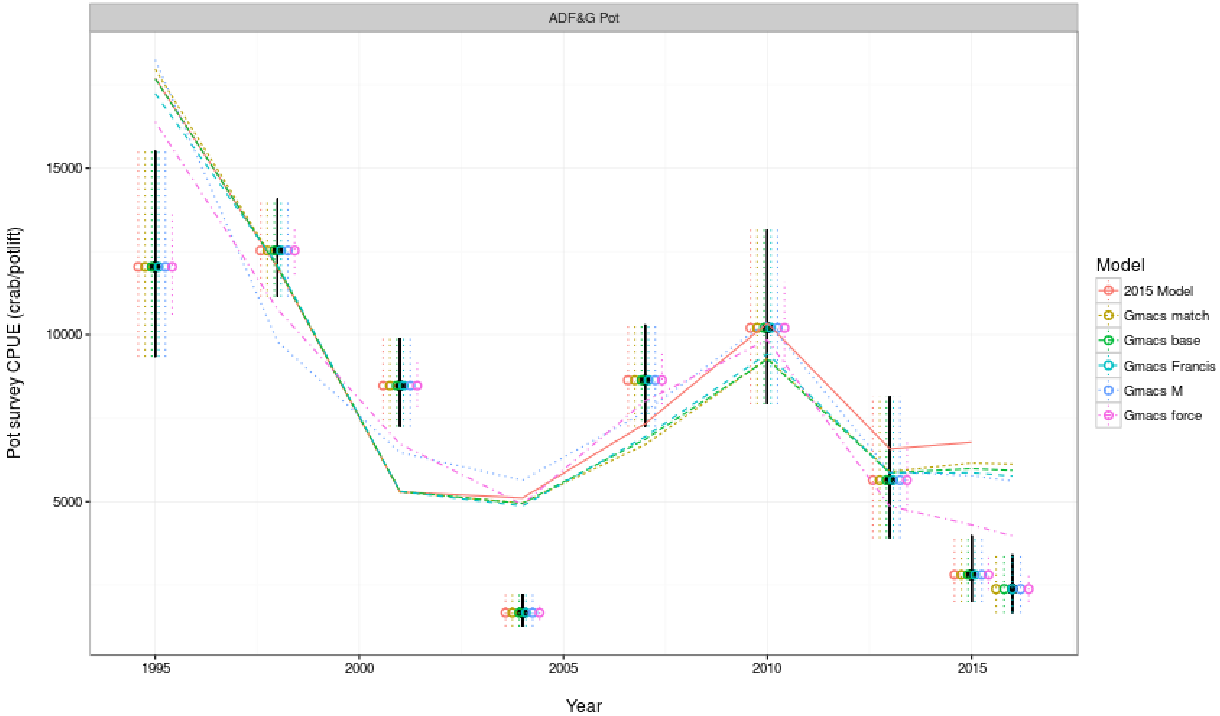

Figure 11: Comparisons of total male pot survey CPUEs and model predictions for the 2015 model and each of the Gmacs model scenarios. The solid black error bars are plus and minus 2 standard deviations derived using the original survey CVs. The dotted error bars are plus and minus 2 standard deviations but represent the weighted survey CVs.

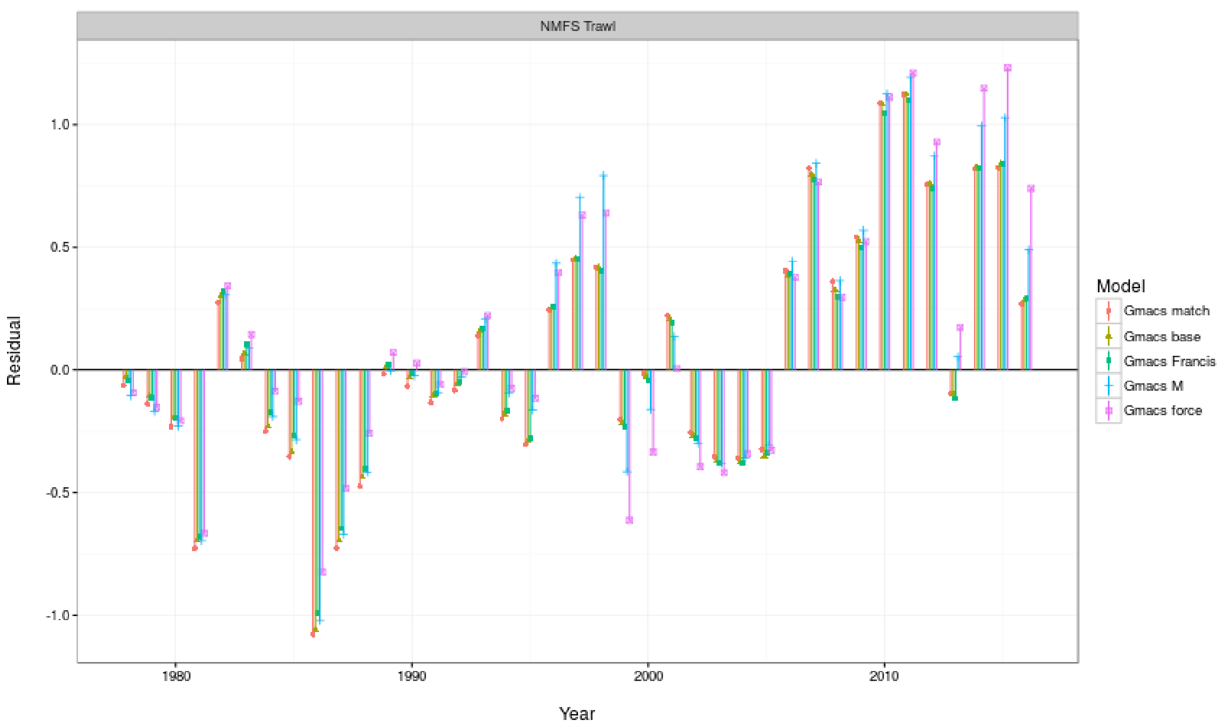

Figure 12: Standardized residuals for area-swept estimates of total male survey biomass for each of the Gmacs model scenarios.

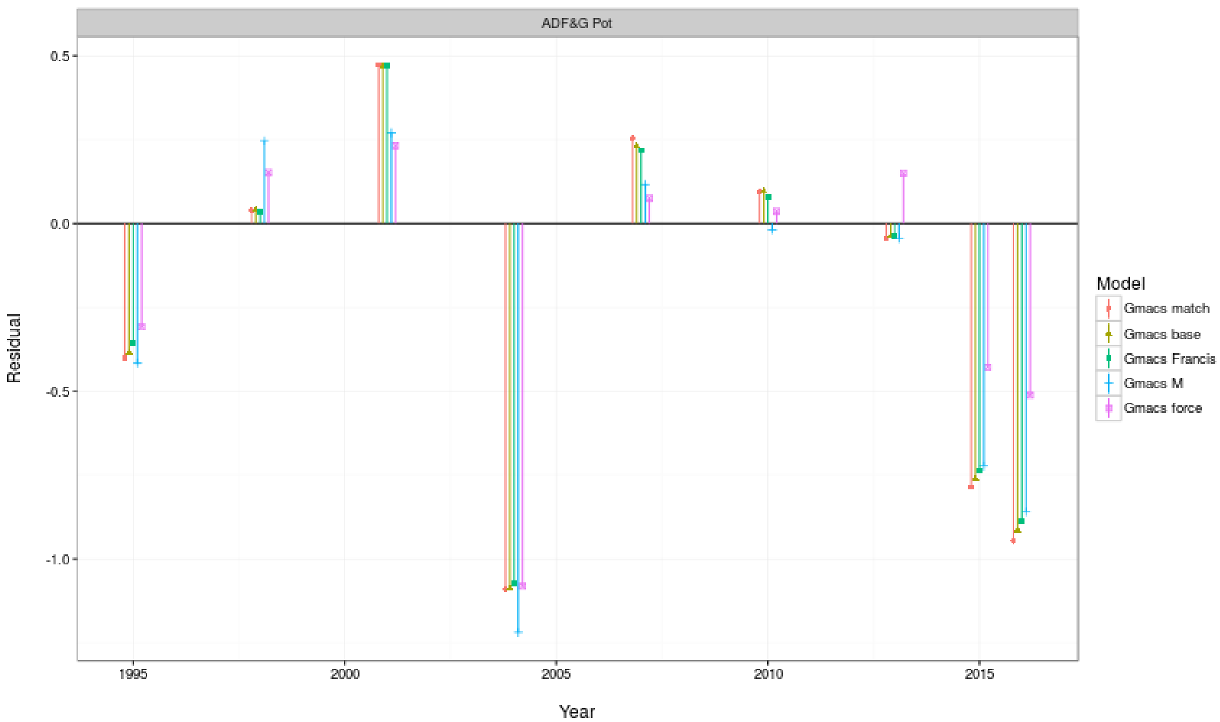

Figure 13: Standardized residuals for total male pot survey CPUEs for each of the Gmacs model scenarios.

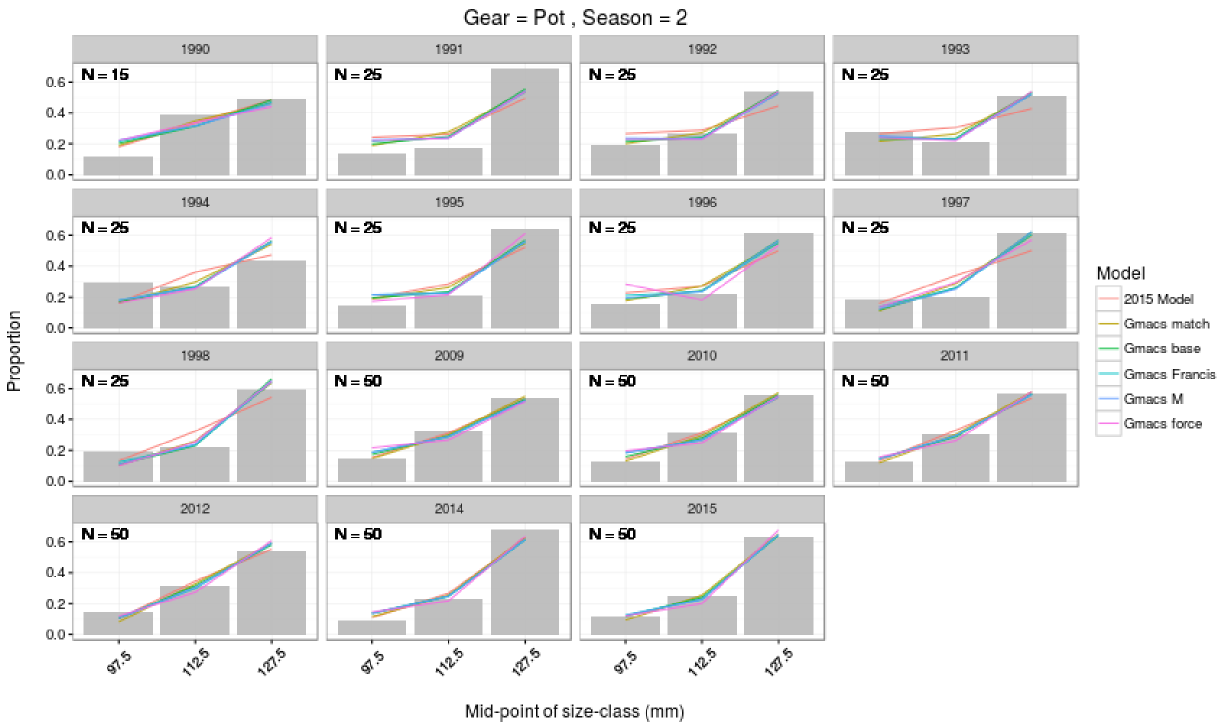

Figure 14: Observed and model estimated size-frequencies of SMBKC by year retained in the directed pot fishery for the 2015 model and each of the Gmacs model scenarios. Note that there is no model estimated size-frequency for the 2015 model during the 2015 year.

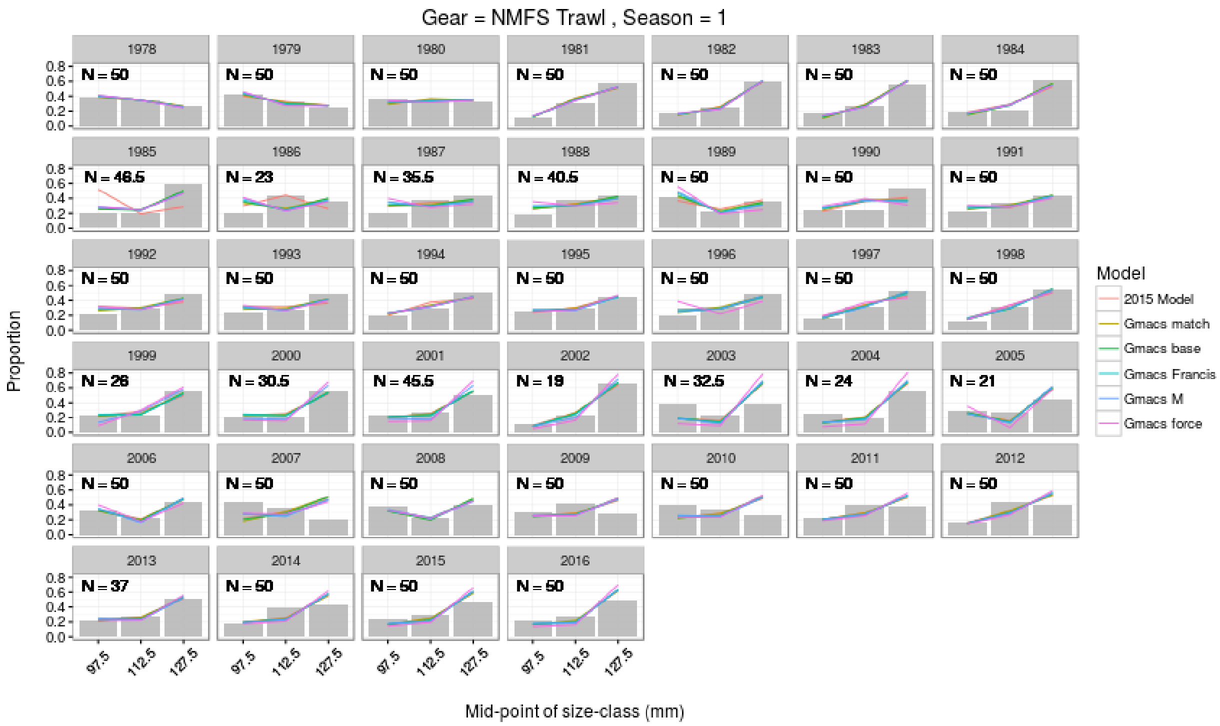

Figure 15: Observed and model estimated size-frequencies of discarded male SMBKC by year in the NMFS trawl survey for the 2015 model and each of the Gmacs model scenarios. Note that there is no model estimated size-frequency for the 2015 model during the 2016 year.

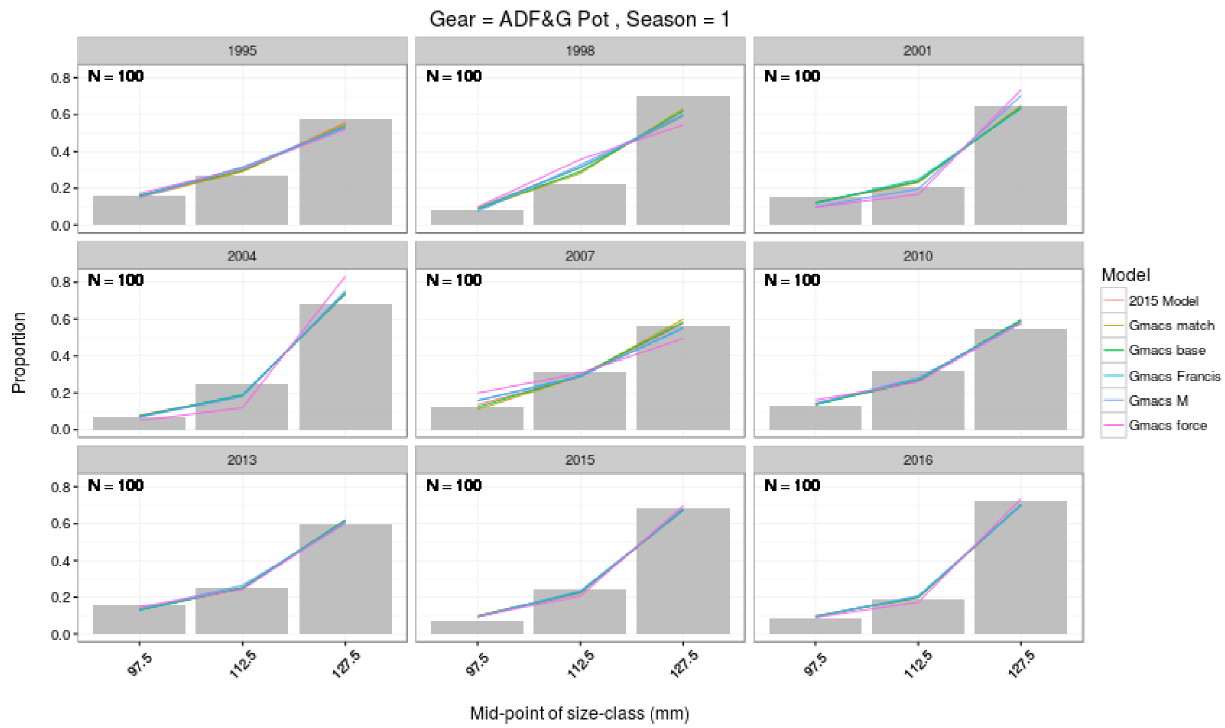

Figure 16: Observed and model estimated size-frequencies of discarded SMBKC by year in the ADF&G pot survey for the 2015 model and each of the Gmacs model scenarios. Note that there is no model estimated size-frequency for the 2015 model during the 2016 year.

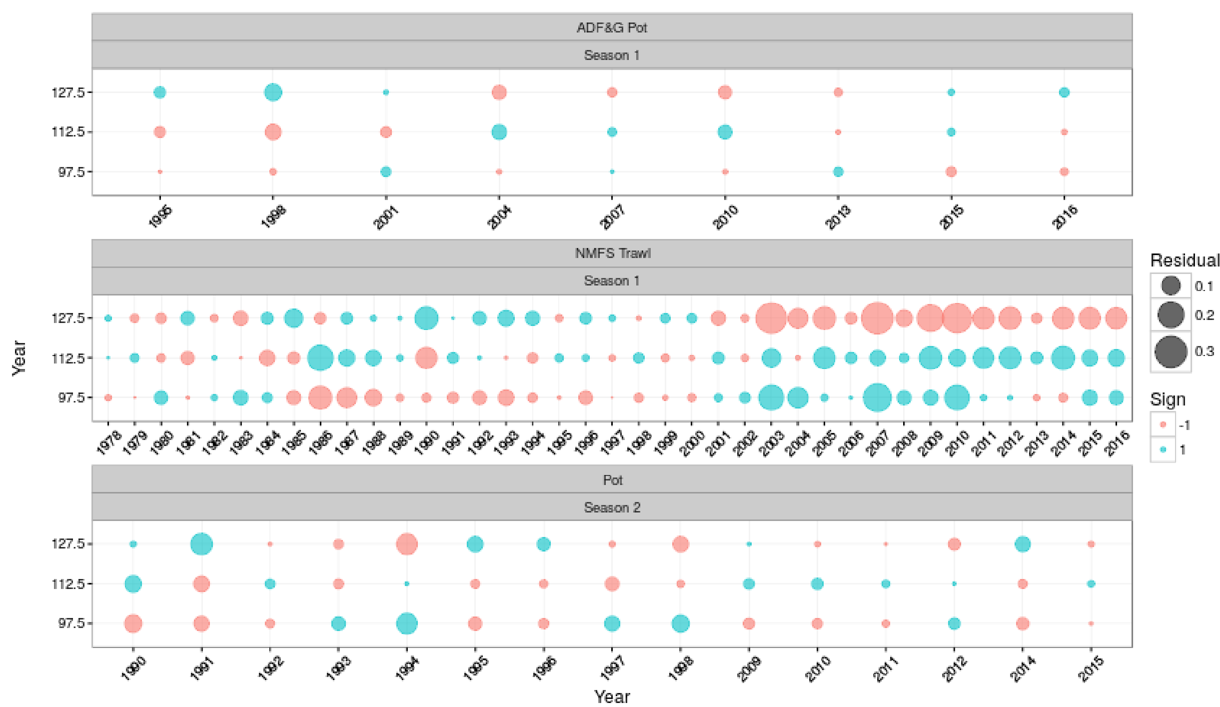

Figure 17: Bubble plots of residuals by stage and year for the directed pot fishery size composition data for St. Mathew Island blue king crab (SMBKC) in the **Gmacs base** model.

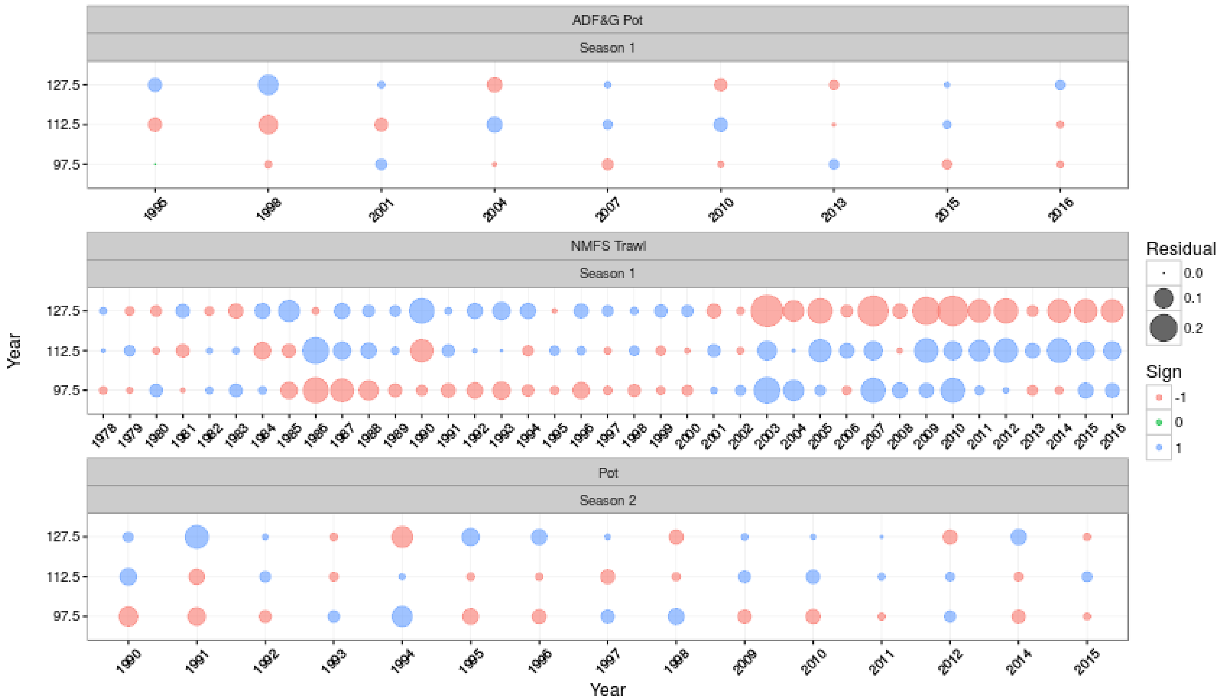

Figure 18: Bubble plots of residuals by stage and year for the NMFS trawl survey size composition data for St. Mathew Island blue king crab (SMBKC) in the **Gmacs Francis** model.

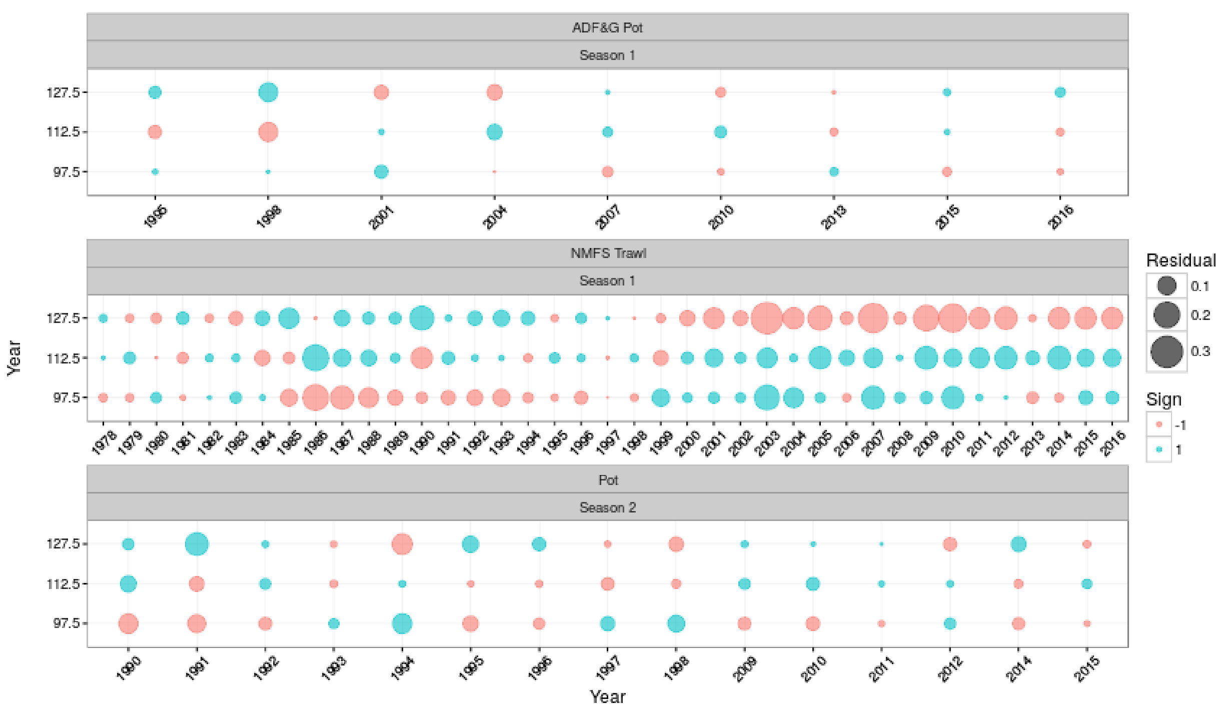

Figure 19: Bubble plots of residuals by stage and year for the NMFS trawl survey size composition data for St. Mathew Island blue king crab (SMBKC) in the **Gmacs M** model.

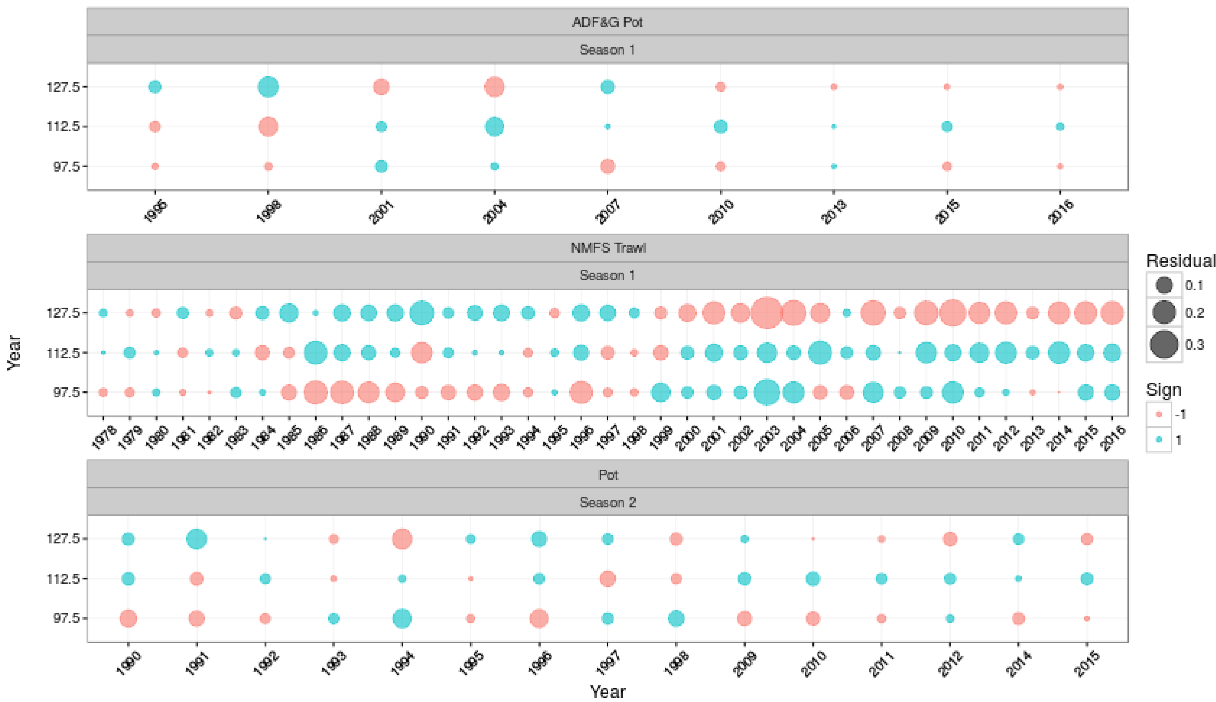

Figure 20: Bubble plots of residuals by stage and year for the ADF&G pot survey size composition data for St. Mathew Island blue king crab (SMBKC) in the **Gmacs force** model.

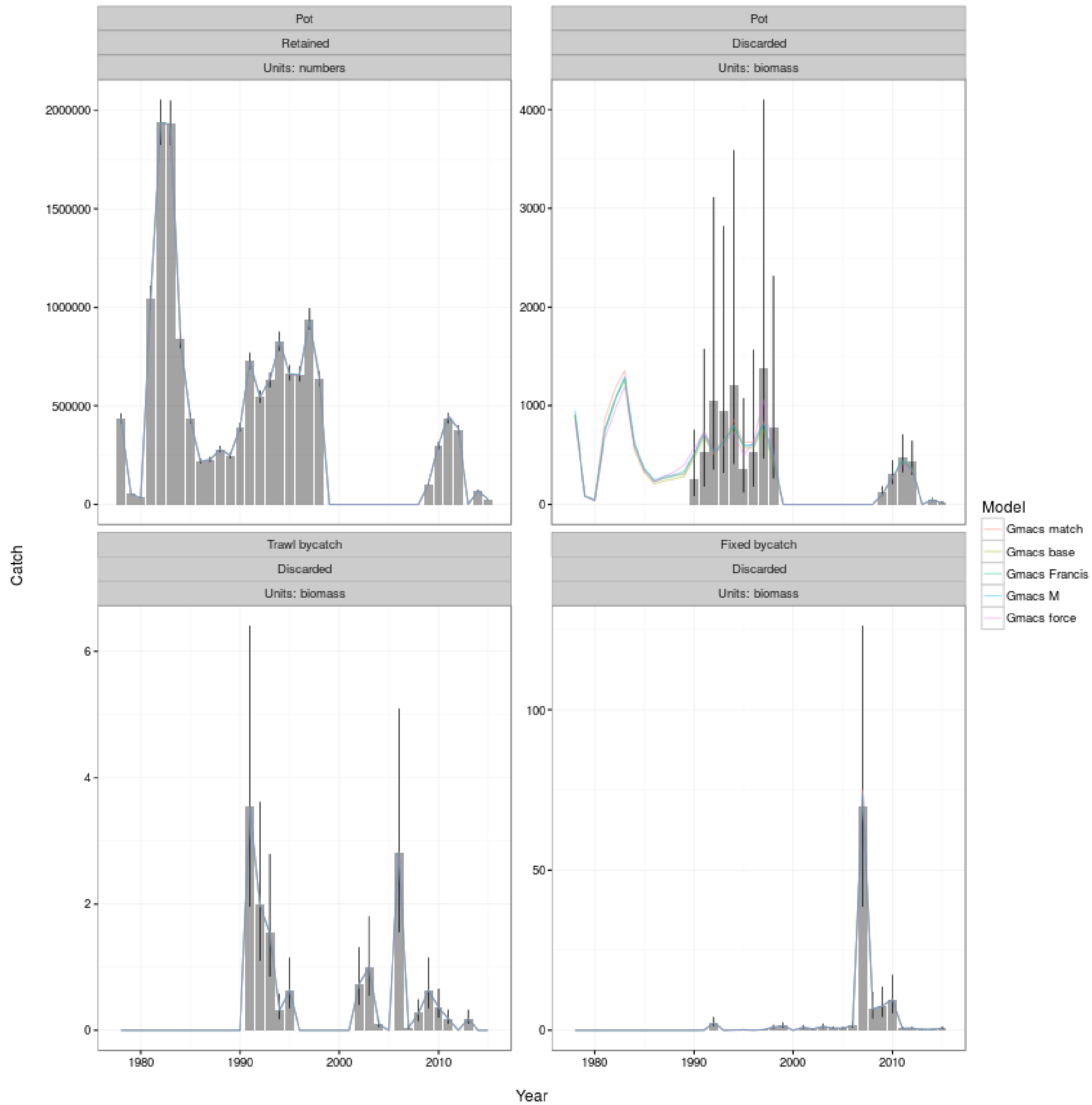

Figure 21: Comparison of observed and model predicted retained catch and bycatches in each of the Gmacs models. Note that difference in units between each of the panels, some panels are expressed in numbers of crab, some as biomass (tonnes).

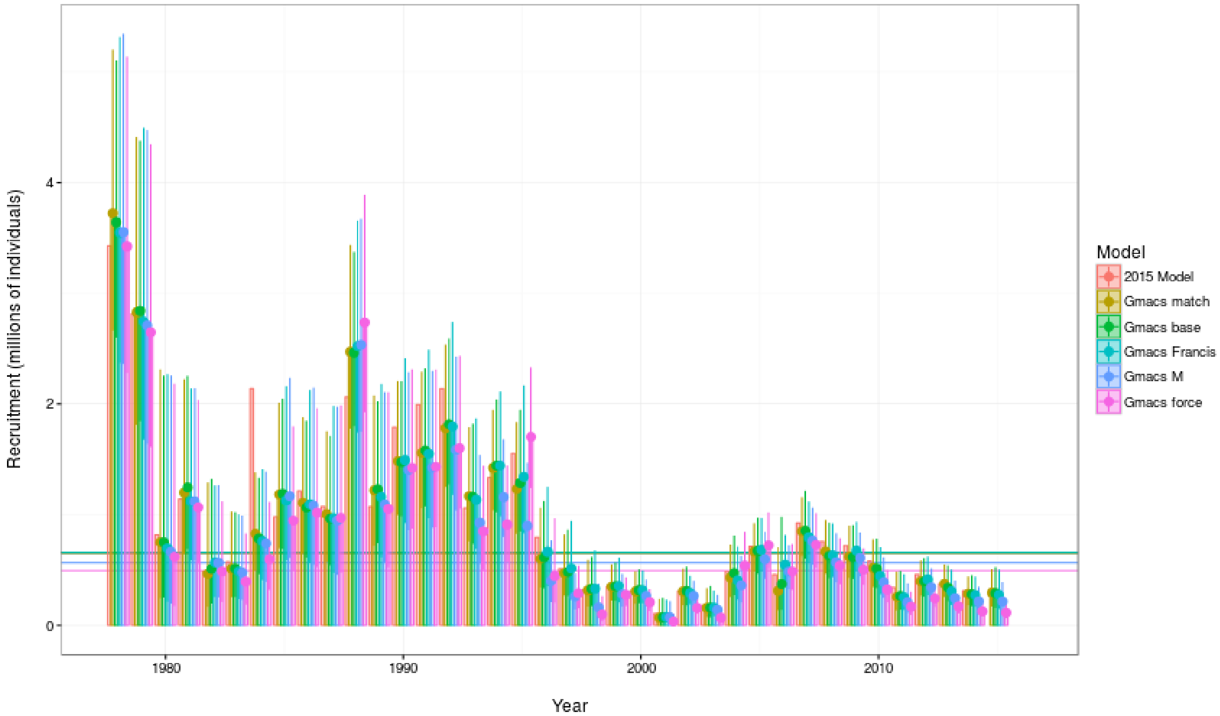

Figure 22: Comparisons of estimated recruitment time series during 1979-2016 in each of the scenarios. The solid horizontal lines in the background represent the estimate of the average recruitment parameter ($\bar{R}$) in each model scenario.

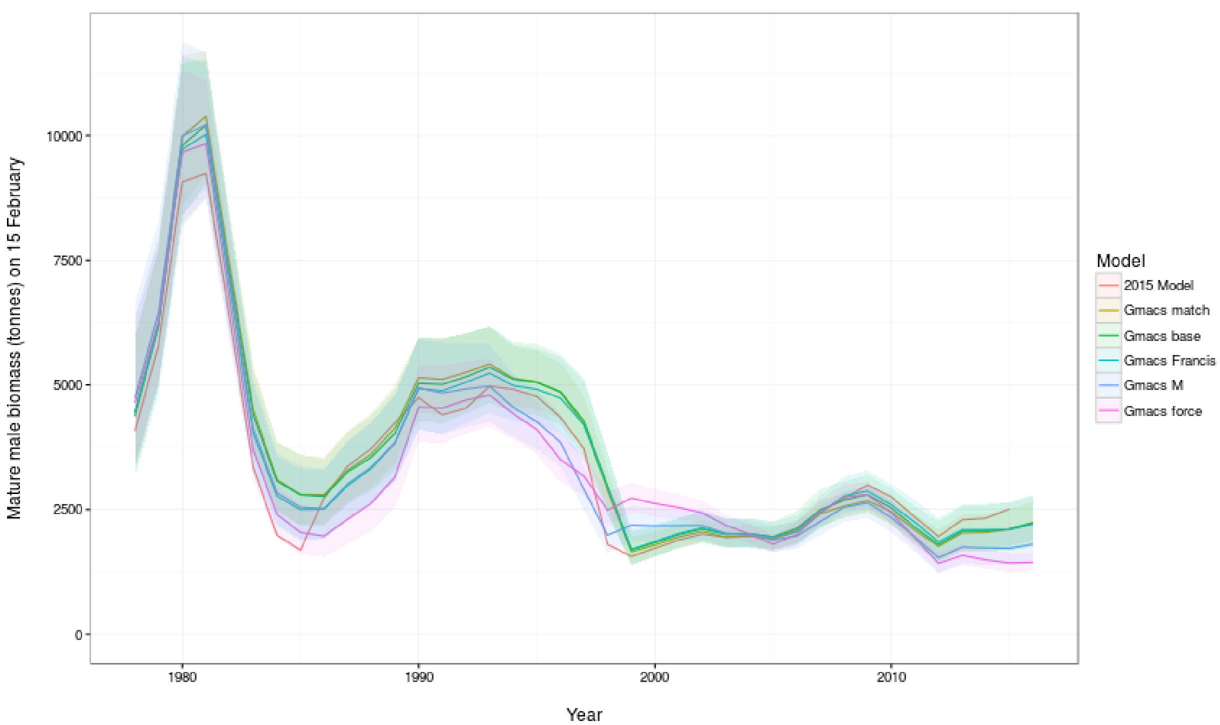

Figure 23: Comparisons of estimated mature male biomass (MMB) time series on 15 February during 1978-2016 for each of the model scenarios.

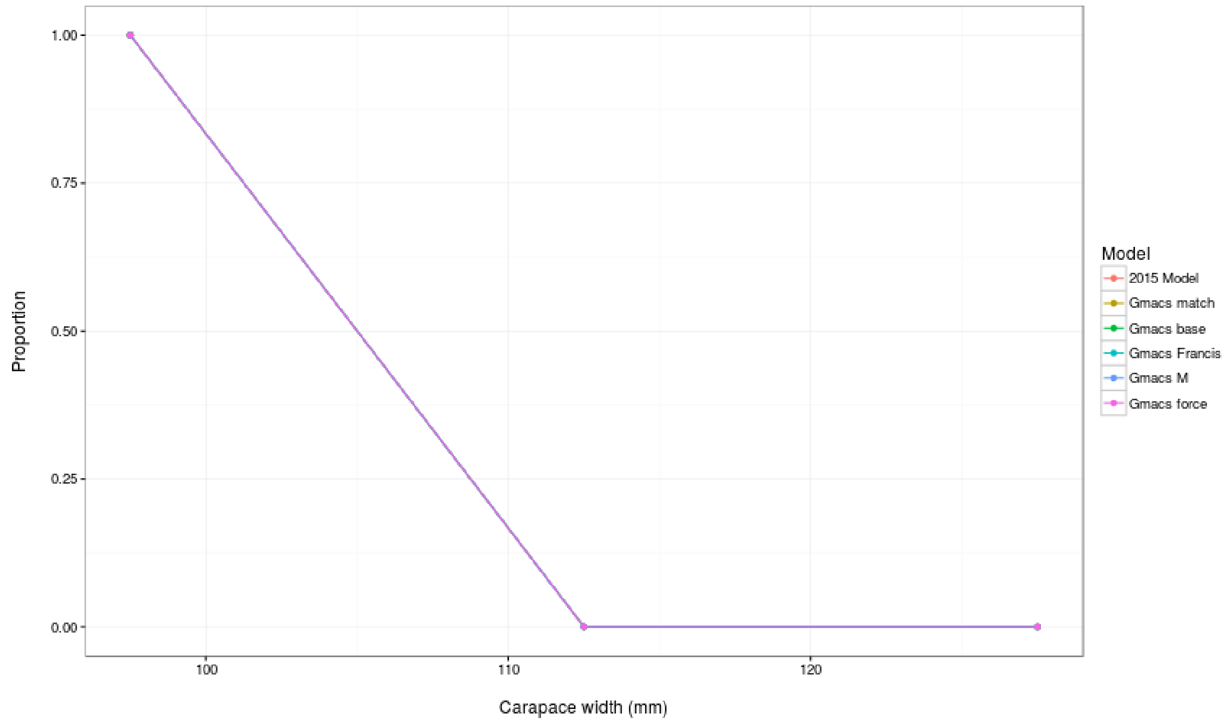

Figure 24: Distribution of carapace width (mm) at recruitment.

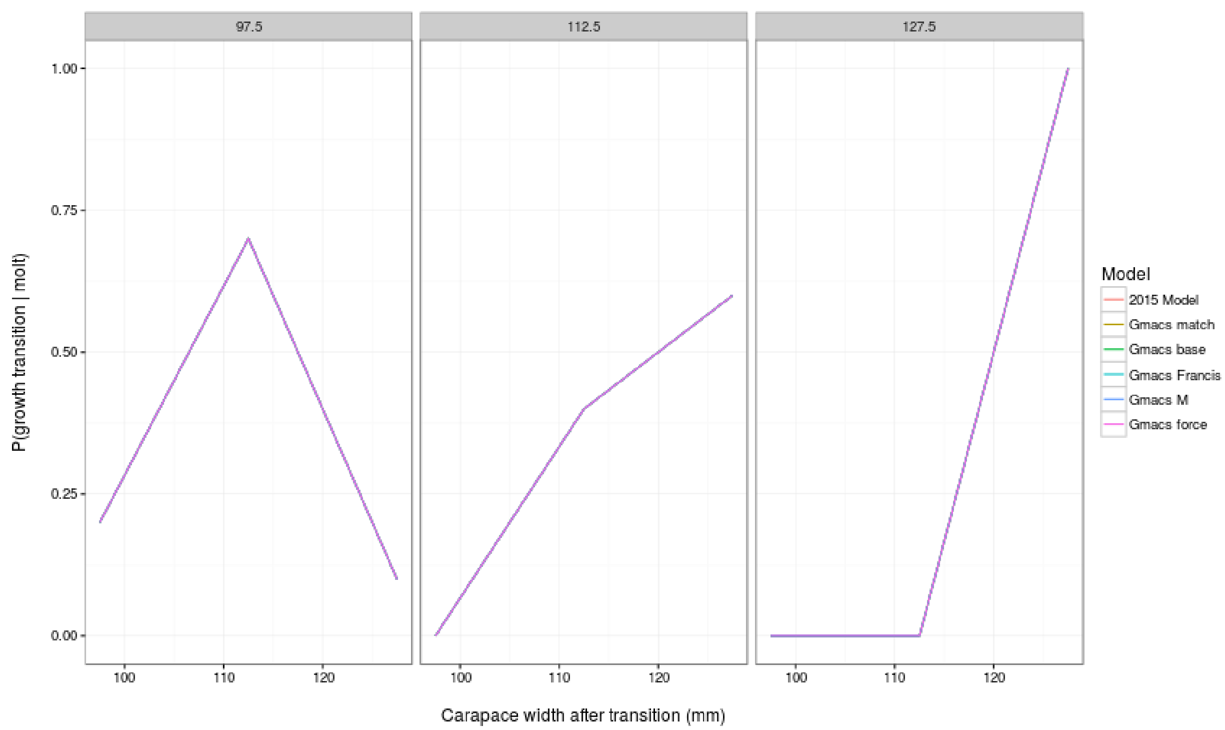

Figure 25: Probability of size transition by stage (i.e. the combination of the growth matrix and molting probabilities). Each of the panels represent the stage before a transition. The x-axes represent the stage after a transition. The size transition matrix was provided as an input directly to Gmacs (as it was during the 2015 SMBKC assessment).

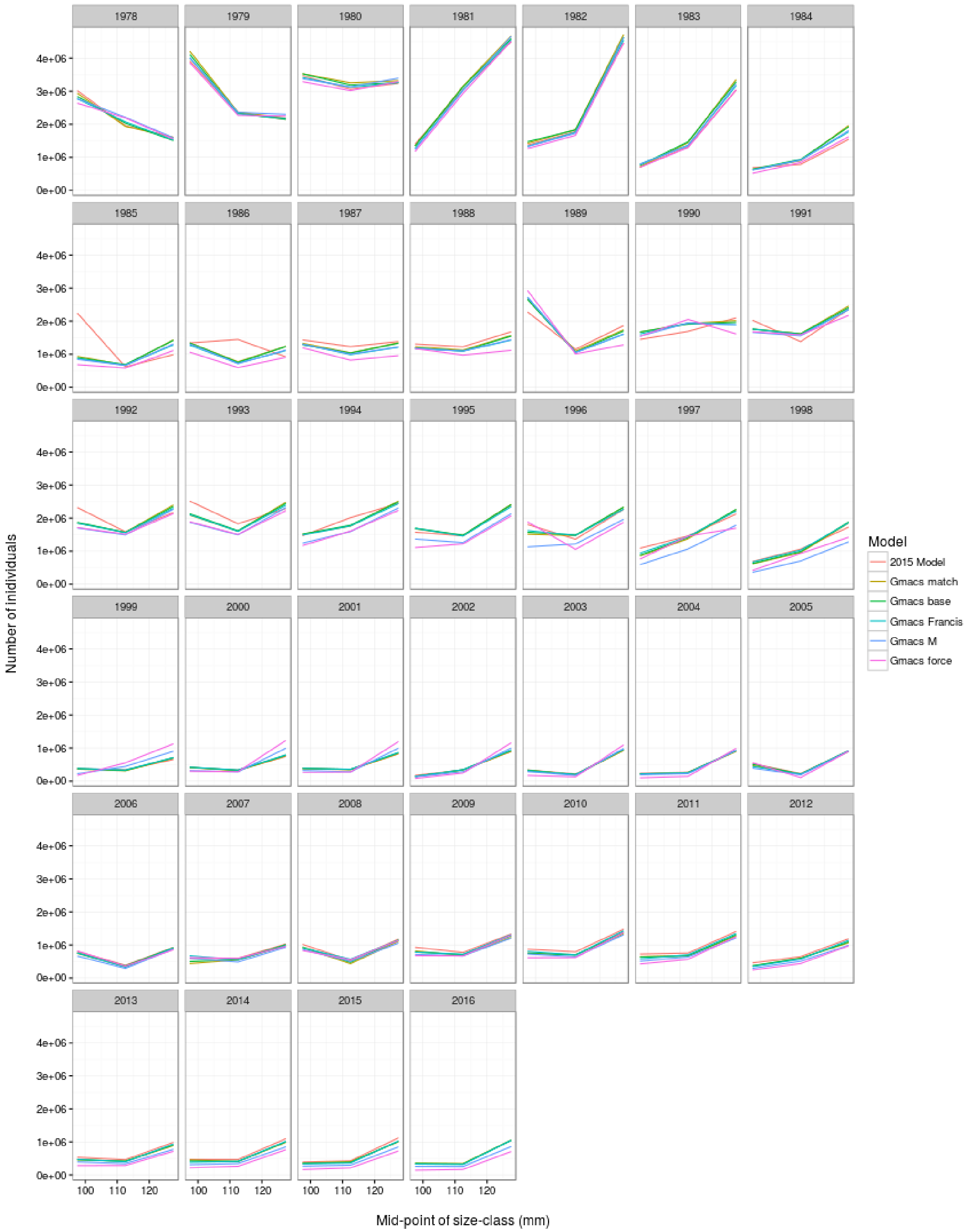

Figure 26: Numbers by stage each year (at the beginning of the model year, i.e. 1 July, season 1) in each of the models including the 2015 model.

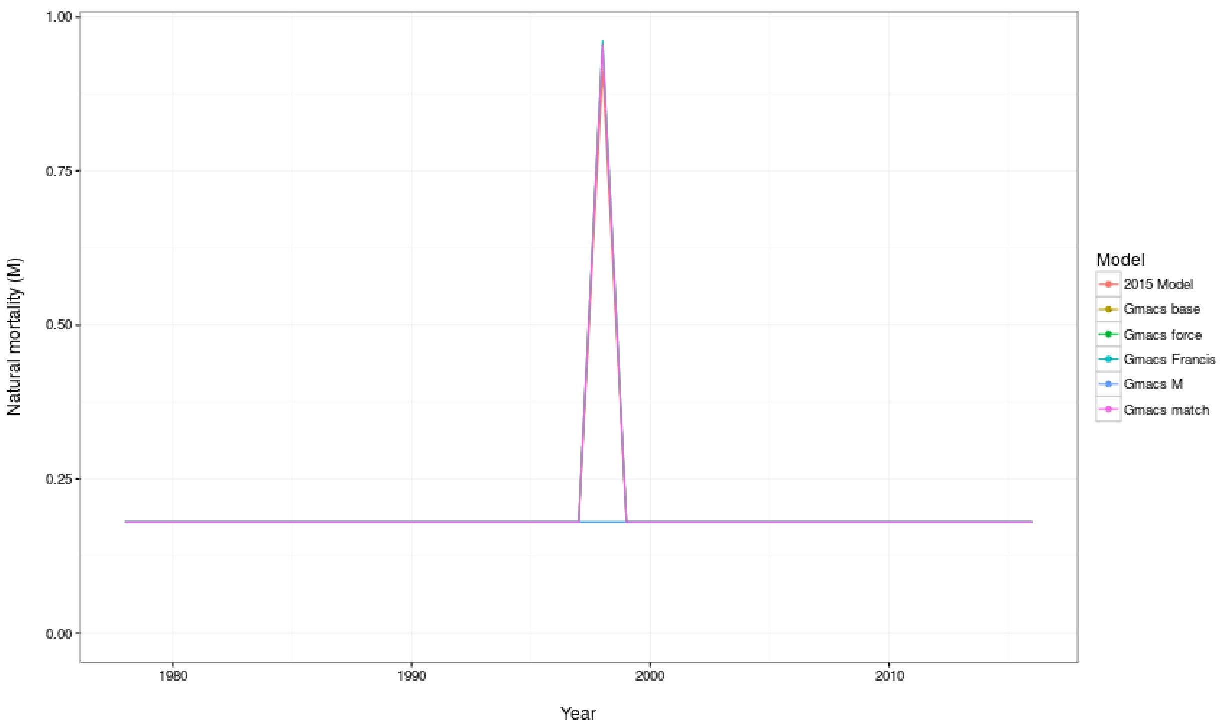

Figure 27: Time-varying natural mortality (M_t). Estimated pulse period occurs in 1998/99 (i.e. M_{1998}).

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, which is the reference date for calculation of federal management biomass quantities. To accommodate this, each model year is split into 5 seasons (t) and a proportion of the natural mortality (τ_t) is applied in each of these seasons where $\sum_{t=1}^{t=5} \tau_t = 1$. 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
   - τ_2 ranges from 0.05 to 0.44 depending on the time of year the fishery begins each year (i.e. a higher value indicates the fishery begins later in the year; see Table 4)
3. Season 3
   - $\tau_3 = 0$
   - Fishing mortality applied
4. Season 4
   - $\tau_4 = 0.63 - \sum_{i=1}^{i=4} \tau_i$
   - Calculate MMB (15 February)
5. Season 5
   - $\tau_5 = 0.37$
   - Growth and molting
   - Recruitment (all to stage-1)

The proportion of natural mortality (τ_t) applied during each season in the model is provided in Table 27. The beginning of the year (1 July) to the date that MMB is measured (15 February) is 63% of the year. Therefore 63% of the natural mortality must be applied before the MMB is calculated. Because the timing of the fishery is different each year τ_2 is different each year and thus τ_4 differs each year.

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

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

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

$$\phi_l = \left[1, 0, 0\right]^\top , \tag{3}$$

and the recruitment is

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

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

$$\delta_y^R \sim (N) \left(0, \sigma_R^2\right) . \tag{5}$$

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

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

with π_{jk} equal to the proportion of stage-j crab that molt and grow into stage-k within a season or year.

The natural mortality each season t and year y is

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

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

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

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

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

where $\delta_{t,y}^{\text{df}}$, $\delta_{t,y}^{\text{tb}}$, and $\delta_{t,y}^{\text{fb}}$ are the fishing mortality deviations for each of the fisheries, each season t during each year y, $\bar{F}^{\text{df}}$, $\bar{F}^{\text{tb}}$, and $\bar{F}^{\text{fb}}$ are the average fishing mortalities for each fishery. The total mortality $Z_{l,t,y}$ represents the combination of natural mortality $M_{t,y}$ and fishing mortality $F_{t,y}$ during season t and year y

$$\boldsymbol{Z}_{t,y} = Z_{l,t,y} = M_{t,y} + F_{t,y}. \tag{10}$$

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

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

The basic population dynamics underlying Gmacs can thus be described as

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

3. Model Data

Data inputs used in model estimation are listed in Table 28.

4. Model Parameters

Table 29 lists fixed (externally determined) parameters used in model computations. In all scenarios, the stage-transition matrix is

$$\boldsymbol{G} = \begin{bmatrix} 0.2 & 0.7 & 0.1 \\ 0 & 0.4 & 0.6 \\ 0 & 0 & 1 \end{bmatrix} \tag{13}$$

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

Estimated parameters are listed in Table 30 and include an estimated natural mortality deviation parameter in 1998/99 (δ^M_{1998}) assuming an anomalous mortality event in that year, as hypothesized by Zheng and Kruse (2002), with natural mortality otherwise fixed at 0.18 yr^{-1}.

5. Model Objective Function and Weighting Scheme

The objective function consists of the sum of several "negative log-likelihood" terms characterizing the hypothesized error structure of the principal data inputs (Table 20).

Gmacs calculates standard deviation of the normalised residual (SDNR) values and median of the absolute residual (MAR) values for all abundance indices and size compositions to help the user come up with resonable likelihood weights. For an abundance data set to be well fitted, the SDNR should not be much greater than 1 (a value much less than 1, which means that the data set is fitted better than was expected, is not a cause for concern). What is meant by "much greater than 1" depends on m (the number of years in the data set). Francis (2011) suggests upper limits of 1.54, 1.37, and 1.26 for m = 5, 10, and 20, respectively. Although an SDNR not much greater than 1 is a necessary condition for a good fit, it is not sufficient. It is important to plot the observed and expected abundances to ensure that the fit is good.

Gmacs also calculates Francis weights for each of the size composition data sets supplied (Francis 2011). If the user wishes to use the Francis iterative re-weighting method, first the weights applied to the abundance indices should be adjusted by trial and error until the SDNR (and/or MAR) are adequte. Then the Francis weights supplied by Gmacs should be used as the new likelihood weights for each of the size composition data sets the next time the model is run. The user can then iteratively adjust the abudance index and size composition weights until adequate SDNR (and/or MAR) values are achieved, given the Francis weights.

6. Estimation

The model was implemented using the software AD Model Builder (Fournier et al. 2012), with parameter estimation by minimization of the model objective function using automatic differentiation. Parameter estimates and standard deviations provided in this document are AD Model Builder reported values assuming maximum likelihood theory asymptotics.

Table 27: Proportion of the natural mortality (τ_t) that is applied during each season (t) in the model.

Year	Season 1	Season 2	Season 3	Season 4	Season 5
1978	0.00	0.07	0.00	0.56	0.37
1979	0.00	0.06	0.00	0.57	0.37
1980	0.00	0.07	0.00	0.56	0.37
1981	0.00	0.05	0.00	0.58	0.37
1982	0.00	0.07	0.00	0.56	0.37
1983	0.00	0.12	0.00	0.51	0.37
1984	0.00	0.10	0.00	0.53	0.37
1985	0.00	0.14	0.00	0.49	0.37
1986	0.00	0.14	0.00	0.49	0.37
1987	0.00	0.14	0.00	0.49	0.37
1988	0.00	0.14	0.00	0.49	0.37
1989	0.00	0.14	0.00	0.49	0.37
1990	0.00	0.14	0.00	0.49	0.37
1991	0.00	0.18	0.00	0.45	0.37
1992	0.00	0.14	0.00	0.49	0.37
1993	0.00	0.18	0.00	0.45	0.37
1994	0.00	0.18	0.00	0.45	0.37
1995	0.00	0.18	0.00	0.45	0.37
1996	0.00	0.18	0.00	0.45	0.37
1997	0.00	0.18	0.00	0.45	0.37
1998	0.00	0.18	0.00	0.45	0.37
1999	0.00	0.18	0.00	0.45	0.37
2000	0.00	0.18	0.00	0.45	0.37
2001	0.00	0.18	0.00	0.45	0.37
2002	0.00	0.18	0.00	0.45	0.37
2003	0.00	0.18	0.00	0.45	0.37
2004	0.00	0.18	0.00	0.45	0.37
2005	0.00	0.18	0.00	0.45	0.37
2006	0.00	0.18	0.00	0.45	0.37
2007	0.00	0.18	0.00	0.45	0.37
2008	0.00	0.18	0.00	0.45	0.37
2009	0.00	0.44	0.00	0.19	0.37
2010	0.00	0.44	0.00	0.19	0.37
2011	0.00	0.44	0.00	0.19	0.37
2012	0.00	0.44	0.00	0.19	0.37
2013	0.00	0.44	0.00	0.19	0.37
2014	0.00	0.44	0.00	0.19	0.37
2015	0.00	0.44	0.00	0.19	0.37
2016	0.00	0.44	0.00	0.19	0.37

Table 28: Data inputs used in model estimation.

Data	Years	Source
Directed pot-fishery retained-catch number (not biomass)	1978/79 - 1998/99 2009/10 - 2015/16	Fish tickets (fishery closed 1999/00 - 2008/09)
Groundfish trawl bycatch biomass	1992/93 - 2015/16	NMFS groundfish observer program
Groundfish fixed-gear bycatch biomass	1992/93 - 2015/16	NMFS groundfish observer program
NMFS trawl-survey biomass index (area-swept estimate) and CV	1978-2016	NMFS EBS trawl survey
ADF&G pot-survey abundance index (CPUE) and CV	Triennial 1995-2016	ADF&G SMBKC pot survey
NMFS trawl-survey stage proportions and total number of measured crab	1978-2016	NMFS EBS trawl survey
ADF&G pot-survey stage proportions and total number of measured crab	Triennial 1995-2016	ADF&G SMBKC pot survey
Directed pot-fishery stage proportions and total number of measured crab	1990/91 - 1998/99 2009/10 - 2015/16	ADF&G crab observer program (fishery closed 1999/00 - 2008/09)

Table 29: Fixed model parameters for all scenarios.

Parameter	Symbol	Value	Source/rationale
Trawl-survey catchability	q	1.0	Default
Natural mortality	M	0.18 yr^{-1}	NPFMC (2007)
Size transition matrix	$\boldsymbol{G}$	Equation 13	Otto and Cummiskey (1990)
Stage-1 and stage-2 mean weights	w_1, w_2	0.7, 1.2 kg	Length-weight equation (B. Foy, NMFS) applied to stage midpoints
Stage-3 mean weight	$w_{3,y}$	Depends on year Table 11	Fishery reported average retained weight from fish tickets, or its average, and mean weights of legal males
Recruitment SD	σ_R	1.2	High value
Natural mortality SD	σ_M	10.0	High value (basically free parameter)
Directed fishery handling mortality		0.2	2010 Crab SAFE
Groundfish trawl handling mortality		0.8	2010 Crab SAFE
Groundfish fixed-gear handling mortality		0.5	2010 Crab SAFE
SD of directed fishery fishing mortality deviations	σ_{df}	50	
SD of trawl bycatch fishing mortality deviations	σ_{tb}	50	
SD of fixed gear bycatch fishing mortality deviations	σ_{fb}	50	

Table 30: The lower bound (LB), upper bound (UB), initial value, prior, and estimation phase for each estimated model parameter.

Parameter	LB	Initial value	UB	Prior	Phase
Average recruitment $\log(\bar{R})$	-7	10.0	20	Uniform(-7,20)	1
Stage-1 initial numbers $\log(n_1^0)$	5	14.5	20	Uniform(5,20)	1
Stage-2 initial numbers $\log(n_2^0)$	5	14.0	20	Uniform(5,20)	1
Stage-3 initial numbers $\log(n_3^0)$	5	13.5	20	Uniform(5,20)	1
ADF&G pot survey catchability q	0	4.0	5	Uniform(0,5)	1
Stage-1 directed fishery selectivity 1978-2008	0	0.4	1	Uniform(0,1)	3
Stage-2 directed fishery selectivity 1978-2008	0	0.7	1	Uniform(0,1)	3
Stage-1 directed fishery selectivity 2009-2015	0	0.4	1	Uniform(0,1)	3
Stage-2 directed fishery selectivity 2009-2015	0	0.7	1	Uniform(0,1)	3
Stage-1 NMFS trawl survey selectivity	0	0.4	1	Uniform(0,1)	4
Stage-2 NMFS trawl survey selectivity	0	0.7	1	Uniform(0,1)	4
Stage-1 ADF&G pot survey selectivity	0	0.4	1	Uniform(0,1)	4
Stage-2 ADF&G pot survey selectivity	0	0.7	1	Uniform(0,1)	4
Natural mortality deviation during 1998 δ_{1998}^M	-3	0.0	3	Normal(0, σ_M^2)	4
Recruitment deviations δ_y^R	-7	0.0	7	Normal(0, σ_R^2)	3
Average directed fishery fishing mortality $\bar{F}^{\mathrm{df}}$	-	0.2	-	-	1
Average trawl bycatch fishing mortality $\bar{F}^{\mathrm{tb}}$	-	0.001	-	-	1
Average fixed gear bycatch fishing mortality $\bar{F}^{\mathrm{fb}}$	-	0.001	-	-	1