Bristol Bay Red King Crab Stock Assessment 2017

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Executive Summary

1. **Stock**: Red king crab (RKC), *Paralithodes camtschaticus*, in Bristol Bay, Alaska.
2. **Catch**: The domestic RKC fishery began to expand in the late 1960s and peaked in 1980 with a catch of 129.95 million lbs (58,943 t). The catch declined dramatically in the early 1980s and remained at low levels during the last three decades. The retained catch in 2015/16 was about 10 million lbs (4,500 t), similar to the catch in 2014/15. The magnitude of bycatch from groundfish trawl fisheries has been stable and small relative to stock abundance during the last 10 years.
3. **Stock biomass**: Estimated mature biomass increased dramatically in the mid 1970s and decreased precipitously in the early 1980s. Estimated mature crab abundance had increased during 1985-2009 with mature females being about three times more abundant in 2009 than in 1985 and mature males being about two times more abundant in 2009 than in 1985. Estimated mature abundance has steadily declined since 2009.
4. **Recruitment**: Estimated recruitment was high during 1970s and early 1980s and has generally been low since 1985. During 1984-2016, in only 6 years were estimated recruitments above the historical average for 1976-2016. Estimated recruitment was low during the last 10 years.
5. **Management performance**: Status and catch specifications (1,000 t) (scenario 2) are given below. Total male catch has been estimated as the sum of fishery-reported retained catch, estimated male discard mortality in the directed fishery, and estimated male bycatch mortality in the Tanner crab and groundfish fisheries. The stock was above the minimum stock-size threshold (MSST) in 2016/17 and is hence not overfished. Overfishing did not occur in 2016/17 (Tables 1 and 2).
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).

A. Summary of Major Changes

Changes in Management of the Fishery

There were no new changes in management of the fishery.

Table 1: Status and catch specifications (1000 tons) (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 catch	OFL	ABC
2012/13	13.19^{A}	29.05^{A}	3.56	3.62	3.9	7.96	7.17
2013/14	12.85^{B}	27.12^{B}	3.90	3.99	4.56	7.07	6.36
2014/15	13.03^{C}	27.25^{C}	4.49	4.54	5.44	6.82	6.14
2015/16	12.89^{D}	27.68^{D}	4.52	4.61	5.34	6.73	6.06
2016/17		24.00^{D}				6.64	5.97

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

Year	MSST	Biomass (MMB_{mating})	TAC	Retained catch	Total catch	OFL	ABC
2012/13	29.1^{A}	64.0^{A}	7.85	7.98	8.59	17.55	15.8
2013/14	28.3^{B}	59.9^{B}	8.6	8.8	10.05	15.58	14.02
2014/15	28.7^{C}	60.1^{C}	9.99	10.01	11.99	15.04	13.53
2015/16	28.4^{D}	61.0^{D}	9.97	10.17	11.77	14.84	13.36
2016/17		52.9^{D}				14.63	13.17

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

Changes to the Input Data

a. The new 2016 NMFS trawl survey data and BSFRF side-by-side trawl survey data during 2013-2016 were used.

b. Catch and biomass data were updated to include the 2016/17 information.

c. The Tanner crab fishery was split out from the directed fishery bycatch data
d. The groundfish "fixed-gear" fishery was split from the trawl-gear bycatch dataa

Changes in Assessment Methodology

This assessment was done using Gmacs. 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 4 discrete seasons. 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 BBRKC model is provided in Appendix A.

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

Year	Tier	B_{MSY}	Biomass (MMB_{mating})	B/B_{MSY}	F_{OFL}	γ	Basis for B_{MSY}	Natural mortality
2012/13	3b	27.5	26.3	0.96	0.31	1.0	1984-2012	0.18
2013/14	3b	26.4	25.0	0.95	0.27	1.0	1984-2013	0.18
2014/15	3b	25.7	24.7	0.96	0.28	1.0	1984-2014	0.18
2015/16	3b	26.1	24.7	0.95	0.27	1.0	1984-2015	0.18
2016/17	3b	25.8	24.0	0.93	0.27	1.0	1984-2016	0.18

Table 4: Basis for the OFL (millions of lbs) (scenario **Gmacs base**).

Year	Tier	B_{MSY}	Biomass (MMB_{mating})	B/B_{MSY}	F_{OFL}	γ	Basis for B_{MSY}	Natural mortality
2012/13	3b	60.7	58.0	0.96	0.31	1.0	1984-2012	0.18
2013/14	3b	58.2	55.0	0.95	0.27	1.0	1984-2013	0.18
2014/15	3b	56.7	54.4	0.96	0.28	1.0	1984-2014	0.18
2015/16	3b	57.5	54.4	0.95	0.27	1.0	1984-2015	0.18
2016/17	3b	56.8	52.9	0.93	0.27	1.0	1984-2016	0.18

Changes in Assessment Results

B. Responses to SSC and CPT Comments

CPT and SSC Comments on Assessments in General

Comment: *To come*

Response:

CPT and SSC Comments Specific to the BBRKC Stock Assessment

Comment: * [to come] The SSC and CPT requested the following models for review at the spring 2017 meeting:*

1. *Base: try to match 2016 model*
2. *Evaluate M*

Response: Models 1, 2, and 3 are all included and evaluated in this document as the **Gmacs base**, **Gmacs M**, and **Gmacs Mvary** scenarios.

C. Introduction

Scientific Name

Red king crab (RKC), *Paralithodes camtschaticus*, in Bristol Bay, Alaska.

Distribution

Red king crab inhabit intertidal waters to depths >200 m of the North Pacific Ocean from British Columbia, Canada, to the Bering Sea, and south to Hokkaido, Japan, and are found in several areas of the Aleutian Islands, eastern Bering Sea, and the Gulf of Alaska.

Stock Structure

The State of Alaska divides the Aleutian Islands and eastern Bering Sea into three management registration areas to manage RKC fisheries: Aleutian Islands, Bristol Bay, and Bering Sea (Alaska Department of Fish and Game (ADF&G) 2012). The Bristol Bay area includes all waters north of the latitude of Cape Sarichef (54°36' N lat.), east of 168°00' W long., and south of the latitude of Cape Newenham (58°39' N lat.) and the fishery for RKC in this area is managed separately from fisheries for RKC outside of this area; i.e., the red king crab in the Bristol Bay area are assumed to be a separate stock from red king crab outside of this area. This report summarizes the stock assessment results for the Bristol Bay RKC stock.

Life History

Red king crab have a complex life history. Fecundity is a function of female size, ranging from several tens of thousands to a few hundreds of thousands (Haynes 1968; Swiney et al. 2012). The eggs are extruded by females, fertilized in the spring, and held by females for about 11 months (Powell and Nickerson 1965). Fertilized eggs are hatched in the spring, most during April-June (Weber 1967). Primiparous females are bred a few weeks earlier in the season than multiparous females. Larval duration and juvenile crab growth depend on temperature (Stevens 1990; Stevens and Swiney 2007). Male and female RKC mature at 5–12 years old, depending on stock and temperature (Loher et al. 2001; Stevens 1990) and may live >20 years (Matsuura and Takeshita 1990). Males and females attain a maximum size of 227 and 195 mm carapace length (CL), respectively (Powell and Nickerson 1965). Female maturity is evaluated by the size at which females are observed to carry egg clutches. Male maturity can be defined by multiple criteria including spermataphore production and size, chelae vs. carapace allometry, and participation in mating in situ (reviewed by Webb 2014). For management purposes, females >89 mm CL and males >119 mm CL are assumed to be mature for Bristol Bay RKC. Juvenile RKC molt multiple times per year until age 3 or 4; thereafter, molting continues annually in females for life and in males until maturity. Male molting frequency declines after attaining functional maturity.

Fishery

The RKC stock in Bristol Bay, Alaska, supports one of the most valuable fisheries in the United States. A review of the history of the Bristol Bay RKC fishery is provided in Fitch et al. (2012) and Otto (1989). The Japanese fleet started the fishery in the early 1930s, stopped fishing from 1940 to 1952, and resumed the fishery from 1953 until 1974. The Russian fleet fished for RKC from 1959 to 1971. The Japanese fleet employed primarily tanglenets with a very small proportion of catch from trawls and pots. The Russian fleet used only tanglenets. United States trawlers started fishing Bristol Bay RKC in 1947, but the effort and catch declined in the 1950s. The domestic RKC fishery began to expand in the late 1960s and peaked in 1980 with a catch of 129.95 million lbs (58,943 t), worth an estimated $115.3 million ex-vessel value. The catch declined dramatically in the early 1980s and has remained at low levels during the last two decades (Table 1). After the early 1980s stock collapse, the Bristol Bay RKC fishery took place during a short period in the fall (usually lasting about a week) with the catch quota based on the stock assessment conducted the previous summer (Zheng and Kruse 2002). Beginning with the 2005/2006 season, new regulations associated with fishery rationalization resulted in an increase in the duration of the fishing season (October 15 to January 15). With the implementation of crab rationalization, historical guideline harvest levels (GHL) were changed to a total allowable catch (TAC). Before rationalization, the implementation errors were quite high for some years and total actual catch from 1980 to 2007 was about 6% less than the sum of GHL/TAC over that period.

Fisheries Management

King and Tanner crab stocks in the Bering Sea and Aleutian Islands are managed by the State of Alaska through a federal king and Tanner crab fishery management plan (FMP). Under the FMP, management measures are divided into three categories: (1) fixed in the FMP, (2) frame worked in the FMP, and (3) discretion of the State of Alaska. The State of Alaska is responsible for determining and establishing the GHL/TAC under the framework in the FMP. Harvest strategies for the Bristol Bay RKC fishery have changed over time. Two major management objectives for the fishery are to maintain a healthy stock that ensures reproductive viability and to provide for sustained levels of harvest over the long term (ADF&G 2012). In attempting to meet these objectives, the GHL/TAC is coupled with size-sex-season restrictions. Only males 6.5-in carapace width (equivalent to 135-mm carapace length, CL) may be harvested and no fishing is allowed during molting and mating periods (ADF&G 2012). Specification of TAC is based on a harvest rate strategy. Before 1990, harvest rates on legal males were based on population size, abundance of prerecruits to the fishery, and postrecruit abundance, and rates varied from less than 20% to 60% (Schmidt and Pengilly 1990). In 1990, the harvest strategy was modified, and a 20% mature male harvest rate was applied to the abundance of mature-sized (120-mm CL) males with a maximum 60% harvest rate cap of legal (135-mm CL) males (Pengilly and Schmidt 1995). In addition, a minimum threshold of 8.4 million mature-sized females (90-mm CL) was added to existing management measures to avoid recruitment overfishing (Pengilly and Schmidt 1995). Based on a new assessment model and research findings (Zheng et al. 1995a, 1995b, 1997a, 1997b), the Alaska Board of Fisheries adopted a new harvest strategy in 1996. That strategy had two mature male harvest rates: 10% when effective spawning biomass (ESB) is between 14.5 and 55.0 million lbs and 15% when ESB is at or above 55.0 million lbs (Zheng et al. 1996). The maximum harvest rate cap of legal males was changed from 60% to 50%. A threshold of 14.5 million lbs of ESB was also added. In 1997, a minimum threshold of 4.0 million lbs was established as the minimum GHL for opening the fishery and maintaining fishery manageability when the stock abundance is low. The Board modified the current harvest strategy by adding a mature harvest rate of 12.5% when the ESB is between 34.75 and 55.0 million lbs in 2003 and eliminated the minimum GHL threshold in 2012. The current harvest strategy is illustrated in Figure 1.

5).

D. Data

Summary of New Information

Data used in this assessment have been updated to include the most recently available fishery and survey numbers. The NMFS and BSFRF trawl survey data were updated to include the survey data in 2016.
Catch and biomass data were updated to 2016/17. Groundfish fisheries bycatch data during 2009-2016 were updated and separated into trawl fisheries and fixed gear. Bycatch of BBRKC in the directed Tanner crab pot fishery were also included.

Survey and fishery size composition data were also used updated and the extent is shown in Figure 1.

Major Data Sources

Fishery

Data on landings of Bristol Bay RKC by length and year and catch per unit effort from 1960 to 1973 were obtained from annual reports of the International North Pacific Fisheries Commission (Hoopes et al. 1972;

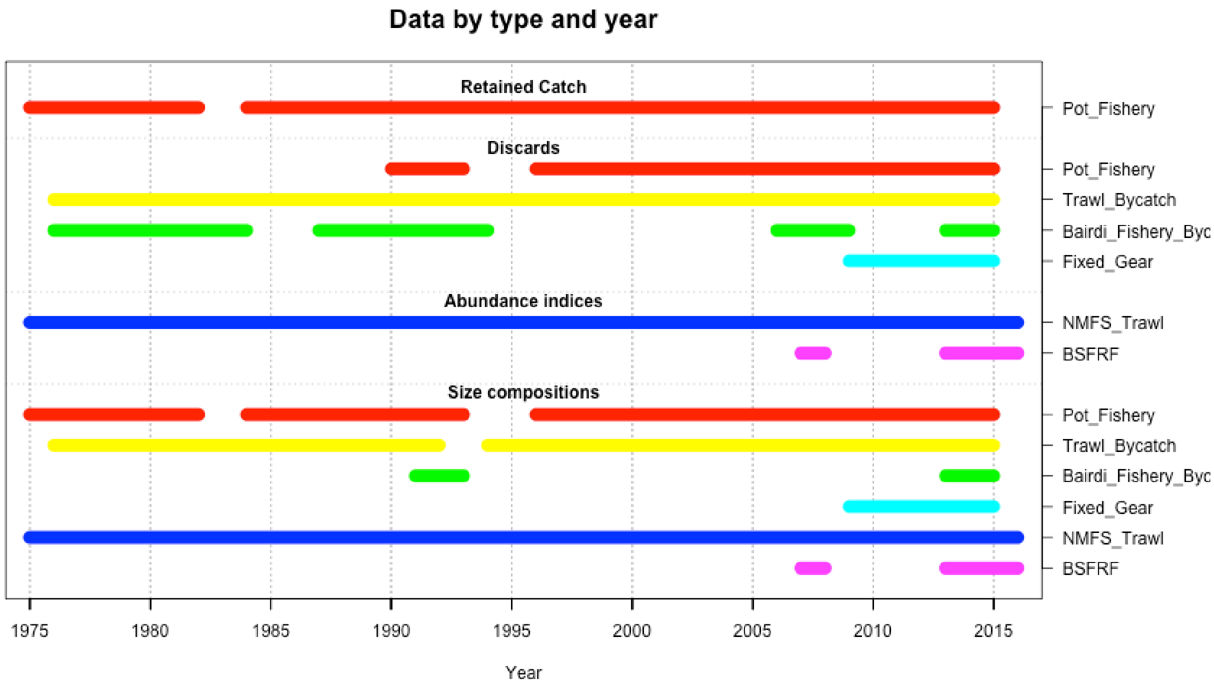

Figure 1: Data extent for the BBRKC assessment.

Jackson 1974; Phinney 1975) and from the ADF&G from 1974 to 2015. Bycatch data are available starting from 1990 and were obtained from the ADF&G observer database and reports (Gaeuman 2013). Sample sizes for catch by length and shell condition are summarized in Table 6. Relatively large samples were taken from the retained catch each year. Sample sizes for trawl bycatch were the annual sums of length frequency samples in the National Marine Fisheries Service (NMFS) database.

Catch by fishery

Estimated retained catch and bycatch are summarized in Table 5). Catch estimates from the directed fishery include the general, open-access fishery (prior to rationalization), or the individual fishery quota (IFQ) fishery (after rationalization), as well as the Community Development Quota (CDQ) fishery and the ADF&G cost-recovery harvest. Starting in 1973, the fishery generally occurred during the late summer and fall. Before 1973, a small portion of retained catch in some years was caught from April to June. Because most crab bycatch from the groundfish trawl fisheries occurred during the spring, the years in Table 5) are one year less than those from the NMFS trawl bycatch database to approximate the annual bycatch for reporting years defined as June 1 to May 31; e.g., year 2002 in Table 5 for trawl bycatch corresponds to what is reported for year 2003 in the NMFS database. Bycatch data for the cost-recovery fishery before 2006 were unavailable. In this report, pot fisheries are distinguished between the directed fishery and the Tanner crab fishery.

Catch size composition

Retained catch by length and shell condition and bycatch by length, shell condition, and sex were obtained for stock assessments. From 1960 to 1966, only retained catch length compositions from the Japanese fishery were available. Retained catch from the Russian and U.S. fisheries were assumed to have the same length compositions as the Japanese fishery during this period. From 1967 to 1969, the length compositions from the Russian fishery were assumed to be the same as those from the Japanese and U.S. fisheries. After 1969, foreign catch declined sharply and only length compositions from the U.S. fishery were used to distribute catch by length.

Surveys

NMFS annual trawl surveys of the eastern Bering Sea began in 1968. Two vessels, each towing an eastern otter trawl with an 83 ft headrope and a 112 ft footrope, conducted this multispecies, crab-groundfish survey during the summer. Stations were sampled in the center of a systematic 20 X 20 nm grid overlaid in an area of 140,000 nmˆ2. Since 1972, the trawl survey has covered the full stock distribution except in nearshore waters. The survey in Bristol Bay occurs primarily during late May and June. Tow-by-tow trawl survey data for Bristol Bay RKC during 1975-2016 were provided by NMFS.

Abundance estimates by sex, carapace length, and shell condition were derived from survey data using an area-swept approach. Until the late 1980s, NMFS used a post-stratification approach, but subsequently treated Bristol Bay as a single stratum; If multiple tows were made for a single station in a given year, the average of the abundances from all tows within that station was used as the estimate of abundance for that station. The new time series since 2015 discards all "hot spot" tows. We used the new area-swept estimates provided by NMFS in 2016.

In addition to standard surveys, NMFS also conducted some surveys after the standard surveys to better assess mature female abundance. In addition to the standard surveys conducted in early June (late May to early June in 1999 and 2000), a portion of the distribution of Bristol Bay RKC was re-surveyed in 1999, 2000, and 2006-2012. "Resurveys" performed in late July, about six weeks after the standard survey, included 31 stations (1999), 23 stations (2000), 31 stations (2006, 1 bad tow and 30 valid tows), 32 stations (2007-2009), 23 stations (2010) and 20 stations (2011 and 2012) with high female density. The resurveys were necessary because a high proportion of mature females had not yet molted or mated when sampled by the standard survey. Differences in area- swept estimates of abundance between the standard surveys and resurveys of these same stations are attributed to survey measurement errors or to seasonal changes in distribution between survey and resurvey. More large females were observed in the resurveys than during the standard surveys in 1999 and 2000 because most mature females had not molted prior to the standard surveys. As in 2006, area-swept estimates of males >89 mm CL, mature males, and legal males within the 32 resurvey stations in 2007 were not significantly different (P=0.74, 0.74 and 0.95; paired t-test of sample means) between the standard survey and resurvey tows. However, similar to 2006, area-swept estimates of mature females within the 32 resurvey stations in 2007 were significantly different (P=0.03; paired t-test) between the standard survey and resurvey tows. Resurvey stations were close to shore during 2010-2012, and mature and legal male abundance estimates were lower for the re-tow than the standard survey. Following the CPT recommendation, we used the standard survey data for male abundance estimates and only the resurvey data, plus the standard survey data outside the resurveyed stations, to assess female abundances during these resurvey years.

Other data sources and excluded data sources

Catch per unit effort (CPUE) is defined as the number of retained crab per tan (a unit fishing effort for tanglenets) for the Japanese and Russian tanglenet fisheries and the number of retained crab per potlift for the U.S. fishery. Soak time, while an important factor influencing CPUE, is difficult to standardize. Furthermore, complete historical soak time data from the U.S. fishery are unavailable. Based on the approach of Balsiger (1974), all fishing effort from Japan, Russia, and U.S. were standardized to the Japanese tanglenet from 1960 to 1971, and the CPUE was standardized as crab per tan. Except for the peak-to-crash years of late 1970s and early 1980s the correspondence between U.S. fishery CPUE and area-swept survey abundance is poor. Due to the difficulty in estimating commercial fishing catchability commercial CPUE data were ommitted used in the model.

Table 5: Bristol Bay red king crab annual catch and bycatch mortality biomass (t) from June 1 to May 31. A handling mortality rate of 20% for the directed pot, 25% for the Tanner fishery, and 80% for trawl was assumed to estimate bycatch mortality biomass.

Year	Retained Catch				Pot Bycatch	Trawl	Tanner Fshry	Total	
	U.S.	Cost-Recovery	Foreign	Total	Males	Females	Bycatch	Bycatch	Catch
1953	1331.3		4705.6	6036.9					6036.9
1954	1149.9		3720.4	4870.2					4870.2
1955	1029.2		3712.7	4741.9					4741.9
1956	973.4		3572.9	4546.4					4546.4
1957	339.7		3718.1	4057.8					4057.8
1958	3.2		3541.6	3544.8					3544.8
1959	0		6062.3	6062.3					6062.3
1960	272.2		12200.7	12472.9					12472.9
1961	193.7		20226.6	20420.3					20420.3
1962	30.8		24618.7	24649.6					24649.6
1963	296.2		24930.8	25227					25227
1964	373.3		26385.5	26758.8					26758.8
1965	648.2		18730.6	19378.8					19378.8
1966	452.2		19212.4	19664.6					19664.6
1967	1407		15257	16664.1					16664.1
1968	3939.9		12459.7	16399.6					16399.6
1969	4718.7		6524	11242.7					11242.7
1970	3882.3		5889.4	9771.7					9771.7
1971	5872.2		2782.3	8654.5					8654.5
1972	9863.4		2141	12004.3					12004.3
1973	12207.8		103.4	12311.2					12311.2
1974	19171.7		215.9	19387.6					19387.6
1975	23281.2		0	23281.2					23281.2
1976	28993.6		0	28993.6			682.8		29676.4
1977	31736.9		0	31736.9			1249.9		32986.8
1978	39743		0	39743			1320.6		41063.6
1979	48910		0	48910			1331.9		50241.9
1980	58943.6		0	58943.6			1036.5		59980.1
1981	15236.8		0	15236.8			219.4		15456.2
1982	1361.3		0	1361.3			574.9		1936.2
1983	0		0	0			420.4		420.4
1984	1897.1		0	1897.1			1094		2991.1
1985	1893.8		0	1893.8			390.1		2283.8
1986	5168.2		0	5168.2			200.6		5368.8
1987	5574.2		0	5574.2			186.4		5760.7
1988	3351.1		0	3351.1			597.8		3948.9
1989	4656		0	4656			174.1		4830.1
1990	9236.2	36.6	0	9272.8	526.9	651.5	247.6		10698.7
1991	7791.8	93.4	0	7885.1	407.8	75	316	1401.8	10085.7
1992	3648.2	33.6	0	3681.8	552	418.5	335.4	244.4	5232.2
1993	6635.4	24.1	0	6659.6	763.2	637.1	426.6	54.6	8541
1994	0	42.3	0	42.3	3.8	1.9	88.9	10.8	147.8
1995	0	36.4	0	36.4	3.3	1.6	194.2	0	235.5
1996	3812.7	49	0	3861.7	164.6	1	106.5	0	4133.9
1997	3971.9	70.2	0	4042.1	244.7	19.6	73.4	0	4379.8
1998	6693.8	85.4	0	6779.2	959.7	864.9	159.8	0	8763.7
1999	5293.5	84.3	0	5377.9	314.2	8.8	201.6	0	5902.4
2000	3698.8	39.1	0	3737.9	360.8	40.5	100.4	0	4239.5
2001	3811.5	54.6	0	3866.2	417.9	173.5	164.6	0	4622.1
2002	4340.9	43.6	0	4384.5	442.7	7.3	155.1	0	4989.6
2003	7120	15.3	0	7135.3	918.9	430.4	172.3	0	8656.9
2004	6915.2	91.4	0	7006.7	345.5	187	119.6	0	7658.8
2005	8305	94.7	0	8399.7	1359.5	498.3	155.2	0	10412.8
2006	7005.3	137.9	0	7143.2	563.8	37	116.7	3.8	7864.4
2007	9237.9	66.1	0	9303.9	1001.3	186.1	138.5	1.8	10631.6
2008	9216.1	0	0	9216.1	1165.5	148.4	159.5	4	10693.5
2009	7226.9	45.5	0	7272.5	888.1	85.2	103.7	1.6	8351.2
2010	6728.5	33	0	6761.5	797.5	122.6	85.3	0	7767
2011	3553.3	53.8	0	3607.1	395	24	68.8	0	4094.9
2012	3560.6	61.1	0	3621.7	205.2	12.3	61.2	0	3900.5
2013	3901.1	89.9	0	3991	310.6	99.8	136.2	28.5	4566
2014	4530	8.6	0	4538.6	584.7	86.2	221.9	42	5473.4
2015	4522.3	91.4	0	4613.7	266.1	222.9	149.4	84.2	5336.3

Table 6: Annual sample sizes (>64 mm CL) in numbers of crab for trawl surveys, retained catch and pot and trawl fishery bycatch of Bristol Bay red king crab.

	Trawl survey		Retained	Pot bycatch		Trawl bycatch		Tanner bycatch	
Year	Males	Females	Catch	Males	Females	Males	Females	Males	Females
1975	2,943	2,139	29,570						
1976	4,724	2,956	26,450			2,327	676		
1977	3,636	4,178	32,596			14,014	689		
1978	4,132	3,948	27,529			8,983	1,456		
1979	5,807	4,663	27,900			7,228	2,821		
1980	2,412	1,387	34,747			47,463	39,689		
1981	3,478	4,097	18,029			42,172	49,634		
1982	2,063	2,051	11,466			84,240	47,229		
1983	1,524	944	0			204,464	104,910		
1984	2,679	1,942	4,404			357,981	147,134		
1985	792	415	4,582			169,767	30,693		
1986	1,962	367	5,773			1,199	284		
1987	1,168	1,018	4,230			723	927		
1988	1,834	546	9,833			437	275		
1989	1,257	550	32,858			3,147	194		
1990	858	603	7,218	873	699	761	1,570		
1991	1,378	491	36,820	1,801	375	208	396	885	2,198
1992	513	360	23,552	3,248	2,389	214	107	280	685
1993	1,009	534	32,777	5,803	5,942			232	265
1994	443	266	0	0	0	330	247		
1995	2,154	1,718	0	0	0	103	35		
1996	835	816	8,896	230	11	1,025	968		
1997	1,282	707	15,747	4,102	906	1,202	483		
1998	1,097	1,150	16,131	11,079	9,130	1,627	915		
1999	764	540	17,666	1,048	36	2,154	858		
2000	731	1,225	14,091	8,970	1,486	994	671		
2001	611	743	12,854	9,102	4,567	4,393	2,521		
2002	1,032	896	15,932	9,943	302	3,372	1,464		
2003	1,669	1,311	16,212	17,998	10,327	1,568	1,057		
2004	2,871	1,599	20,038	8,258	4,112	1,689	1,506		
2005	1,283	1,682	21,938	55,019	26,775	1,815	1,872		
2006	1,171	2,672	18,027	32,252	3,980	1,481	1,983		
2007	1,219	2,499	22,387	59,769	12,661	1,011	1,097		
2008	1,221	3,352	14,567	49,315	8,488	1,867	1,039		
2009	830	1,857	16,708	52,359	6,041	1,482	870		
2010	705	1,633	20,137	36,654	6,868	734	846		
2011	525	994	10,706	20,629	1,920	600	1,069		
2012	580	707	8,956	7,206	561	1,577	1,752		
2013	633	560	10,197	13,828	6,048	4,681	4,198	218	596
2014	1,106	1,255	9,618	13,040	1,950	1,966	2,580	256	381
2015	600	677	11,746	8,037	5,889	1,126	3,704	726	2163
2016	374	803							

E. Analytic Approach

History of Modeling Approaches for this Stock

To reduce annual measurement errors associated with abundance estimates derived from the area-swept method, ADF&G developed a length-based analysis (LBA) in 1994 that incorporates multiple years of data and multiple data sources in the estimation procedure (Zheng et al. 1995a). Annual abundance estimates of the Bristol Bay RKC stock from the LBA have been used to manage the directed crab fishery and to set crab bycatch limits in the groundfish fisheries since 1995. An alternative LBA (research model) was developed in 2004 to include small size groups for federal overfishing limits. The crab abundance declined sharply during the early 1980s. The LBA estimated natural mortality for different periods of years, whereas the research model estimated additional mortality beyond a basic constant natural mortality during 1976-1993. In this report, we present only the research model that was fit to the data from 1975 to 2016.

This assessment represents the implementation of a third modeling framework based on Gmacs (Anon. 2015).

Assessment Methodology

The original LBA model was described in detail by Zheng et al. (1995a, 1995b) and Zheng and Kruse (2002). The model combines multiple sources of survey, catch, and bycatch data using a maximum likelihood approach to estimate abundance, recruitment, selectivities, catches, and bycatch of the commercial pot fisheries and groundfish trawl fisheries. A full model description is provided in Appendix A.

- The base natural mortality is constant over shell condition and length and was estimated assuming a maximum age of 25 and applying the 12005).
- Survey and fisheries selectivities are a function of length and were constant over shell condition. Selectivities are also a function of sex except for trawl bycatch selectivities, which are the same for both sexes. Two different survey selectivities were estimated: (1) 1975-1981 and (2) 1982-2016, based on modifications to the trawl gear used in the assessment survey.
- Growth is a function of length and is assumed to not change over time for males. For females, growth-per-molt increments as a function of length were estimated for three periods (1975-1982, 1983-1993, and 1994-2016) based on sizes at maturity. Once mature, female red king crab grow with a much smaller growth increment per molt.
- Molting probabilities are an inverse logistic function of length for males. Females molt annually.
- Annual fishing seasons for the directed fishery are short.
- The prior of survey catchability (Q) was estimated to be 0.896, based on a trawl experiment by Weinberg et al. (2004) with a standard deviation of 0.025 for some scenarios. Q is assumed to be constant over time and is estimated in the model.
- Males mature at sizes 120 mm CL. For convenience, female abundance was summarized at sizes 90 mm CL as an index of mature females.
- Measurement errors were assumed to be normally distributed for length compositions and were log-normally distributed for biomasses.

The aim when developing this model was to provide a fit to the data that best matched the 2017 BBRKC stock assessment model. A detailed description of the Gmacs model and its implementation is presented in Appendix A.

Model Selection and Evaluation

The following elements required for crab stock assessments follow. ### Alternative model configurations Three different Gmacs model scenarios were considered, in this document results from these models and the 2017 model are compared. The models include:

1. **Gmacs base**: directed BBRKC fishery, Tanner crab trawl and fixed gear fisheries (separated), NMFS trawl and BSFRF surveys. The catchability coefficient (q) for the BSFRF survey was estimated as well as the average recruitment ($\bar{R}$), the recruitment deviations (δ_y^R), the initial numbers in each size category ($\boldsymbol{n}^0$), sex-specific natural mortality deviations in year t_m, ($\delta_{t_m}^M$), and the fishing mortalities for the directed pot fishery, the trawl bycatch fishery, and the fixed-gear bycatch fishery ($\bar{F}^{\text{df}}$, $\bar{F}^{\text{tcb}}$, $\bar{F}^{\text{fgb}}$, $\bar{F}^{\text{tgb}}$, $\delta_{t,y}^{\text{df}}$, $\delta_{t,y}^{\text{tcb}}$, $\delta_{t,y}^{\text{fgb}}$, $\delta_{t,y}^{\text{tgb}}$).
2. **Gmacs M**: is the same as above except that natural mortality (M) is fixed at 0.18 yr^{-1} during all years.
3. **Gmacs M**: is similar to the scenario above except that it allows M to change as a random walk with a log-normal distribution penalty with σ_M set to 0.25.

Table 7 outlines the major features of each of the models.

Table 7: Outline of the major features of the five different Gmacs scenarios.

Scenario	Selectivity estimated	Estimate M_{1998}	
Gmacs base	Yes	No	Yes
Gmacs M	Yes	No	No
Gmacs M_{rw}	Yes	No	No

Evaluation

Progression of results is based on comparison of previous assessment modeling approaches; the extent that these models strike an appropriate balance between realism and simplicity was not evaluated. Convergence status/criteria was based on the ADMB default convergence criteria (minimum gradients and positive definite Hessian matrix).

Sample sizes for length composition data observed sample sizes are summarized in Table xx. Estimated implied sample sizes and effective sample sizes are available via Francis weight computations (Francis 2011). Residual patterns are evaluated graphically.

Results

Results for all Gmacs scenarios are provided with comparisons to the 2016 model. We recommend the **Gmacs base** scenario for management purposes since it provides the best fit to the data and is most consistent with previous model specifications.

a. Effective sample sizes and weighting factors

Observed and estimated effective sample sizes are compared in Table 8. Effective sample sizes are also shown on size-composition plots (Figures 9, **??**, and **??**).

Data weighting factors, SDNRs, and MARs are presented in Table **??**. The SDNR for the trawl survey is acceptable at 1.44 in the **Gmacs match** scenario, and improves to 1.41 in the **Gmacs base** scenario. In the **Gmacs M** model the SDNR of the trawl survey is slightly worse at 1.59, and is much worse in the exploratory **Gmacs force** scenario at 2.16. The SDNRs for the pot surveys show much the same pattern between each of the scenarios, but are much higher values (ranging from 3.95 to 5.19). 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 0.78 to 1.30 (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 0.64 to 0.79. 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**, and **Gmacs Force** scenarios). Instead, the Francis size composition weights were used (Francis 2011).

b. Tables of estimates

Model parameter estimates for each of the Gmacs scenarios are summarized in Tables **??**, **??**, **??**, **??**, and **??**. These parameter estimates are compared in Table **??**. Negative log-likelihood values and management measures for each of the Gmacs scenarios are compared in Tables **??** and **??**.

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 **??**).

c. Graphs of estimates.

Estimated (and fixed) selectivities are compared in Figure 5.

The various model fits to total male ($>$ 89 mm CL) trawl survey biomass are compared in Figures 6 and **??**. The fits to pot survey CPUE are compared in Figures **??** and **??**. Standardized residuals of total male trawl survey biomass and pot survey CPUE are plotted in Figures 8 and **??**.

Fits to stage compositions for trawl survey, pot survey, and commercial observer data are shown in Figures 9, **??**, and **??** 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 M**, **Gmacs Francis**, and **Gmacs force** scenarios in Figures **??**, **??**, **??**, and **??**, respectively.

Fits to retained catch numbers and bycatch biomass are shown for all Gmacs scenarios in Figure 10.

Estimated recruitment is compared in Figure 11. Estimated abundances by stage and mature male biomasses for all scenarios (including the 2015 model) are shown in Figures 14 and 12. Estimated natural mortality each year (M_t) is presented in Figure 15.

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 6 and **??**). Looking at the model fits to the NMFS trawl survey biomass (Figure 6), 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 **??**). The three Gmacs scenarios that do not attempt to estimate natural mortality in 1998/99 (**Gmacs M**, **Gmacs Francis**, 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 6, **??**, **??**, and **??**). 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 11). Estimated recruitment during recent years is generally low in all scenarios. Estimated mature male biomass on 15 February also fluctuates strongly over time (Figure 12).

e. Retrospective and historic analyses.

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 **??**, **??**, **??**, **??**, and **??**. 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 12), 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. 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. Despite these concerns, more work is needed in the future to explore more parsimonious alternatives that provide better fits to the data.

In summary, we recommend the **Gmacs base** scenario for management purposes since it provides the best fit to the data and is most consistent with previous model specifications. Our initial preference was for **Gmacs M** since we had difficulty justifying an abrubt, single-year anomaly in natural mortality. However, the fact that the residual pattern is worse and until further work can be completed on alternative model specifications (e.g., better accounting of spatial processes affecting the data), the **Gmacs base** model was considered reasonable and should 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 1984-2016, 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 **??**. ABC is 80% of the OFL.

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. Ecosystem considerations

J. Projections and Future Outlook

With the recent long-term low levels of recruitment, the expectation of average or above average levels for stock improvements seems unlikely.

K. Acknowledgements

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L. References

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Tables

Table 8: 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

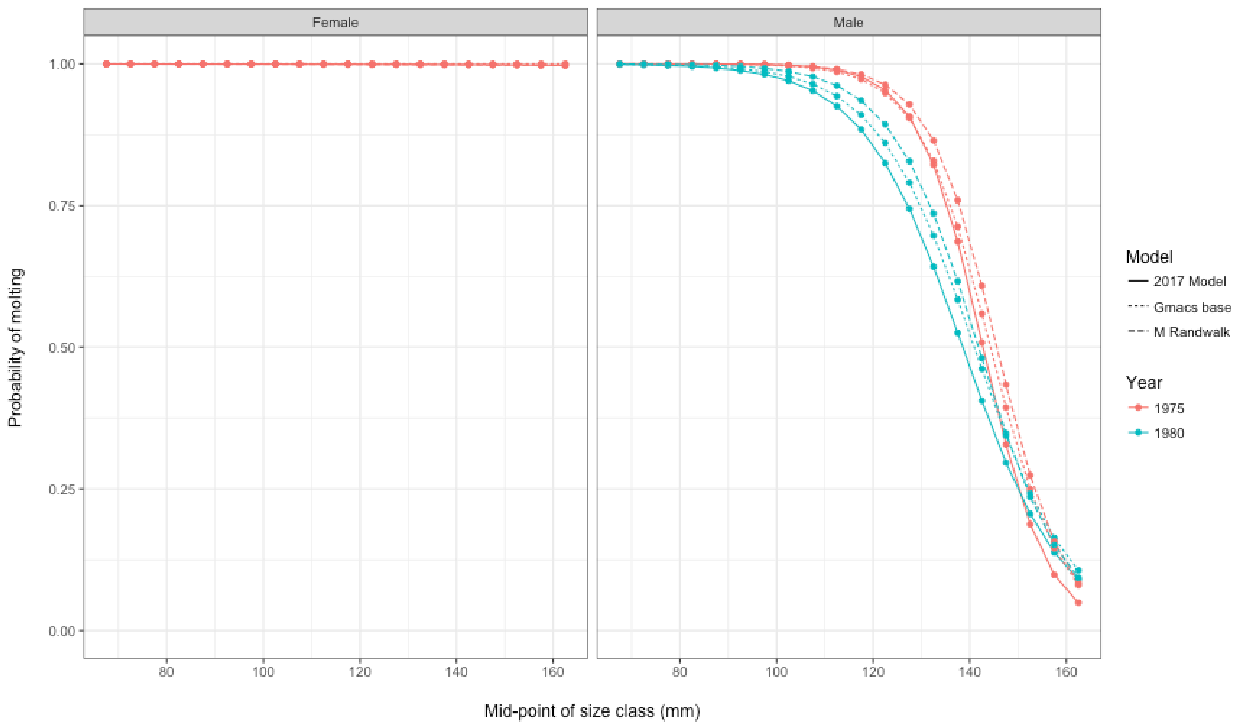

Figure 2: Comparisons of the estimated (and fixed to match the 2015 model selectivities in the Gmacs base scenario) stage-1 and stage-2 selectivities for each of the different model scenarios (the stage-3 selectivities are all fixed at 1). Estimated selectivities are shown for the directed pot fishery,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

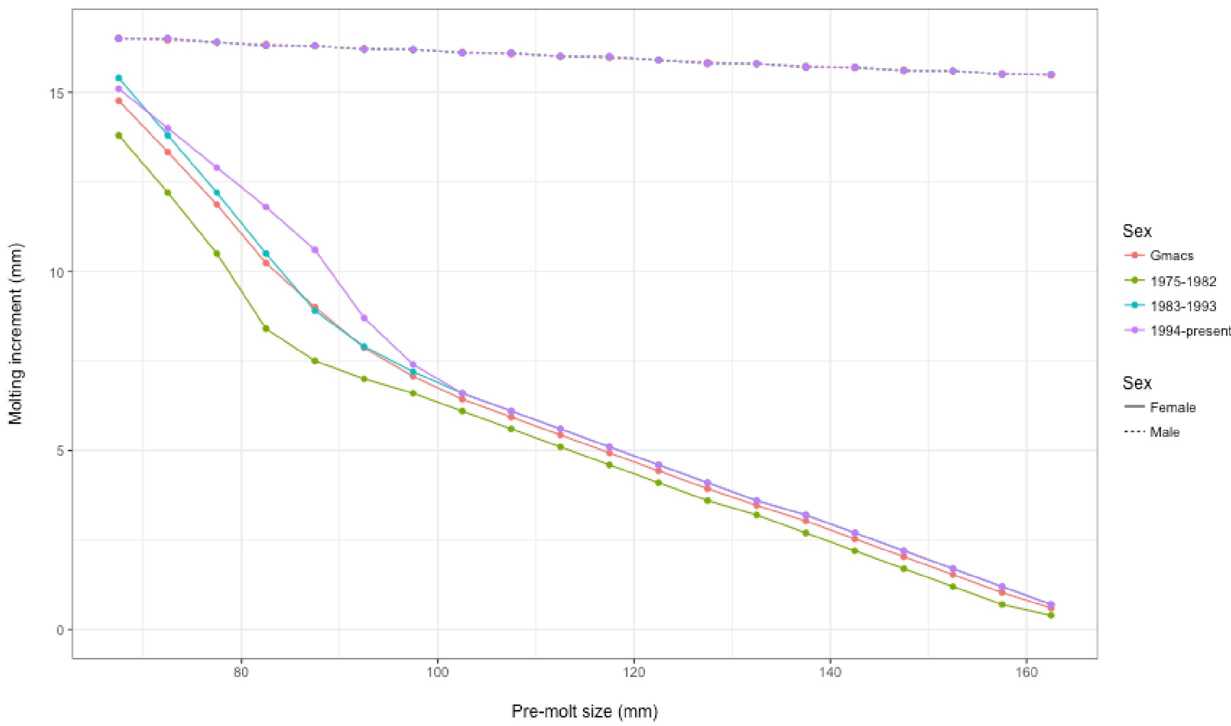

Figure 3: Comparisons of the estimated (and fixed to match the 2015 model selectivities in the Gmacs base scenario) stage-1 and stage-2 selectivities for each of the different model scenarios (the stage-3 selectivities are all fixed at 1). Estimated selectivities are shown for the directed pot fishery,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

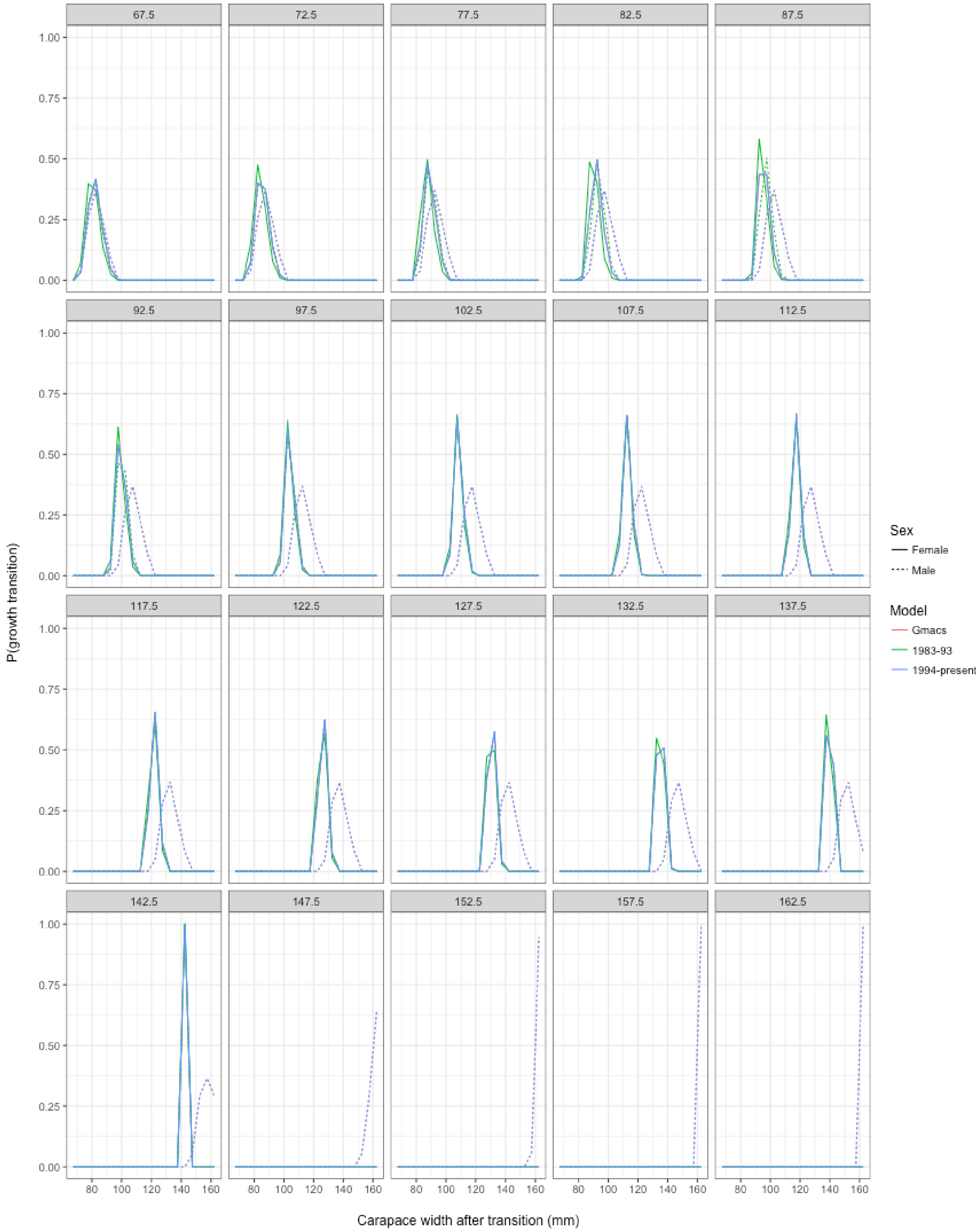

Figure 4: Probability of growth transition by stage. Each of the panels represent the stage before a transition. The x-axes represent the stage after a transition. The size transition matrix was provided as an input directly to Gmacs (as it was during the 2015 SMBKC assessment).

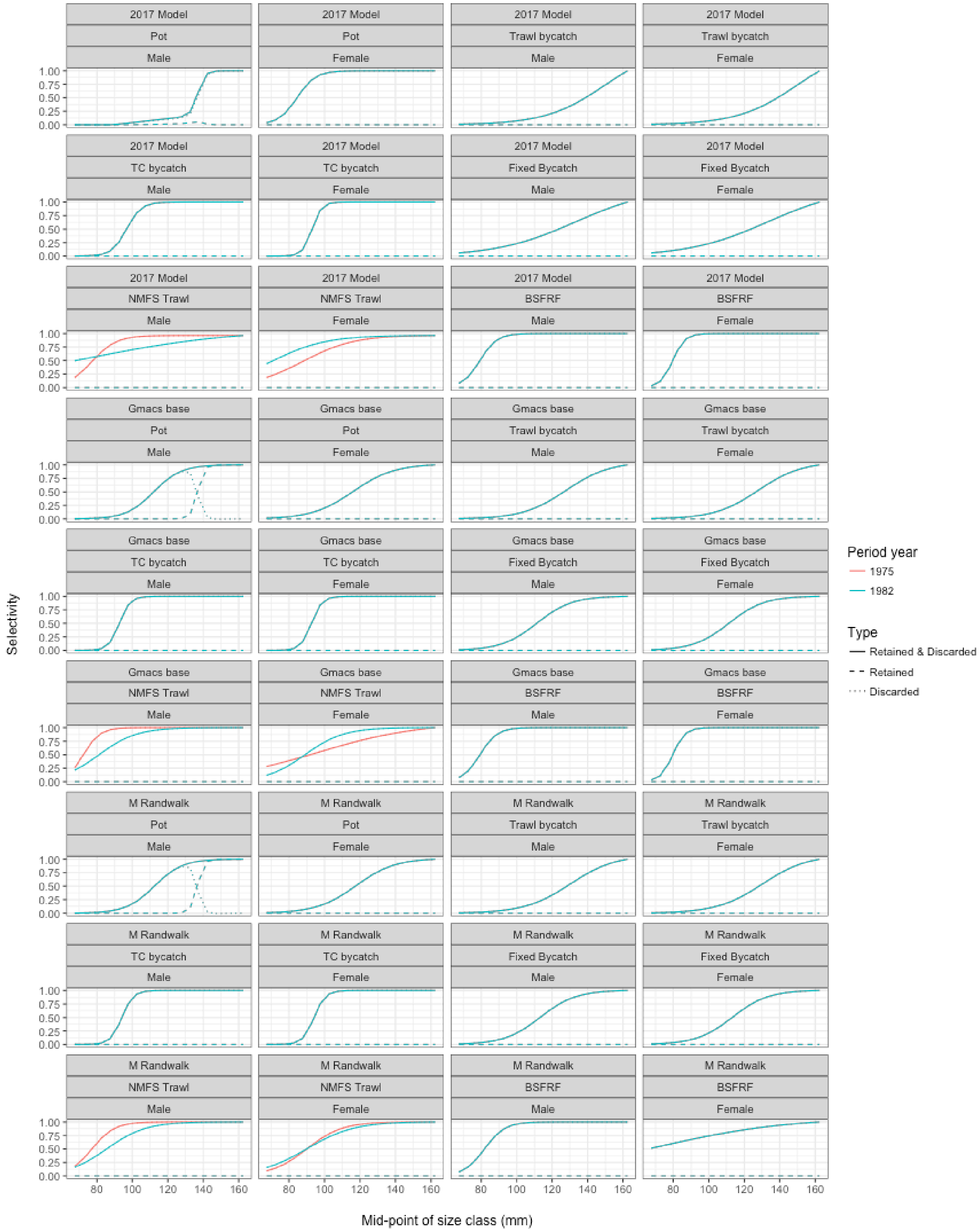

Figure 5: Comparisons of the estimated (and fixed to match the 2015 model selectivities in the Gmacs base scenario) stage-1 and stage-2 selectivities for each of the different model scenarios (the stage-3 selectivities are all fixed at 1). Estimated selectivities are shown for the directed pot fishery, 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.

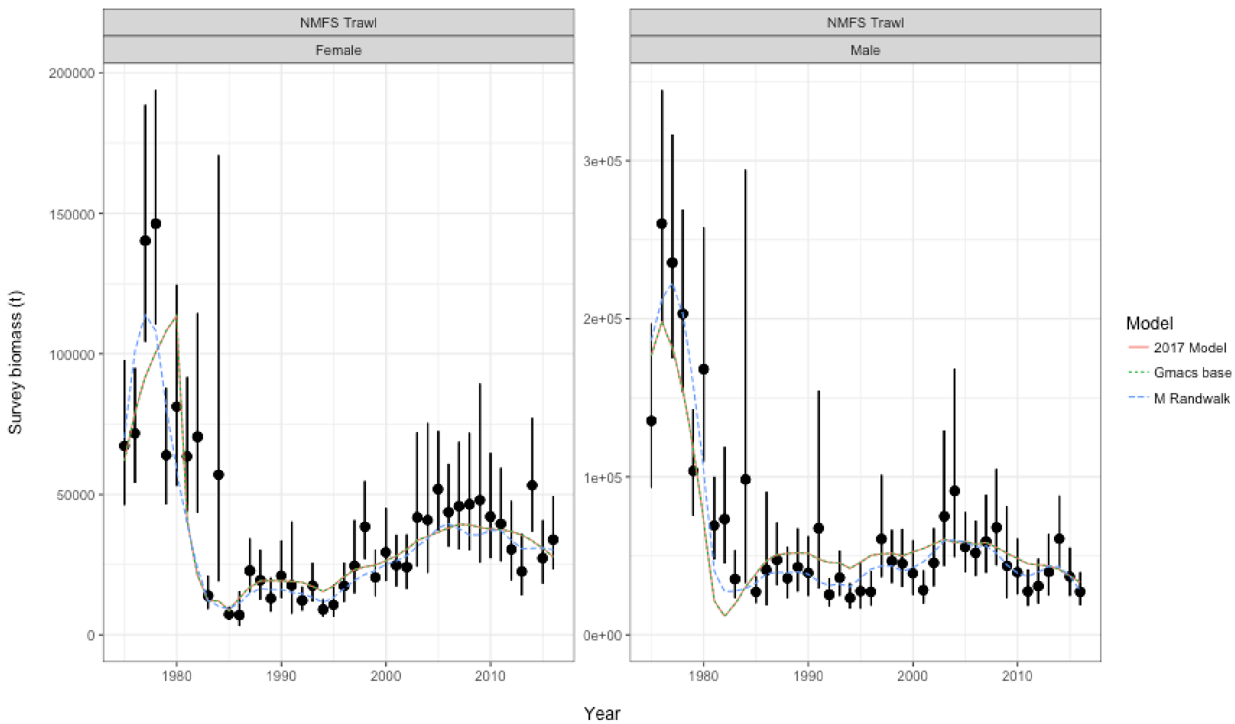

Figure 6: Comparisons of area-swept estimates of total male survey biomass (tons) and model predictions for the 2017 model and each of the Gmacs model scenarios. The error bars are plus and minus 2 standard deviations.

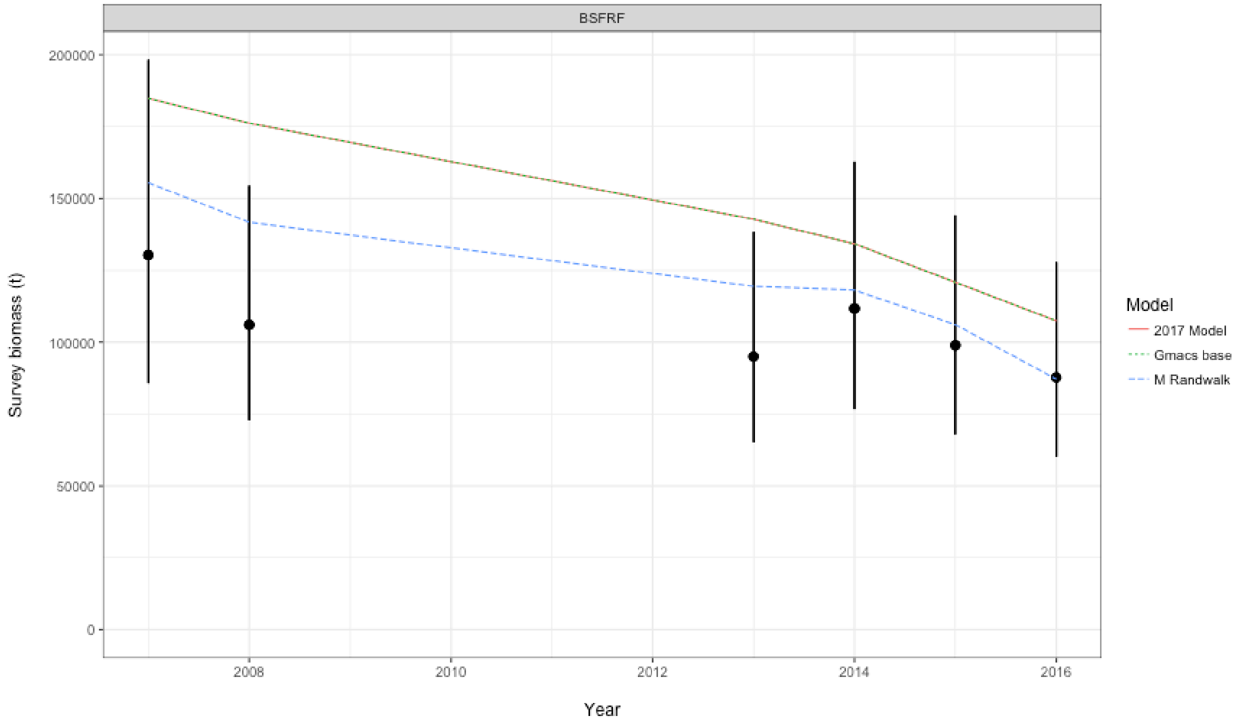

Figure 7: Comparisons of area-swept biomass estimates for the BSFRF data for the 2017 model and each of the Gmacs model scenarios. The solid black error bars are plus and minus 2 standard deviations derived using the original survey CVs.

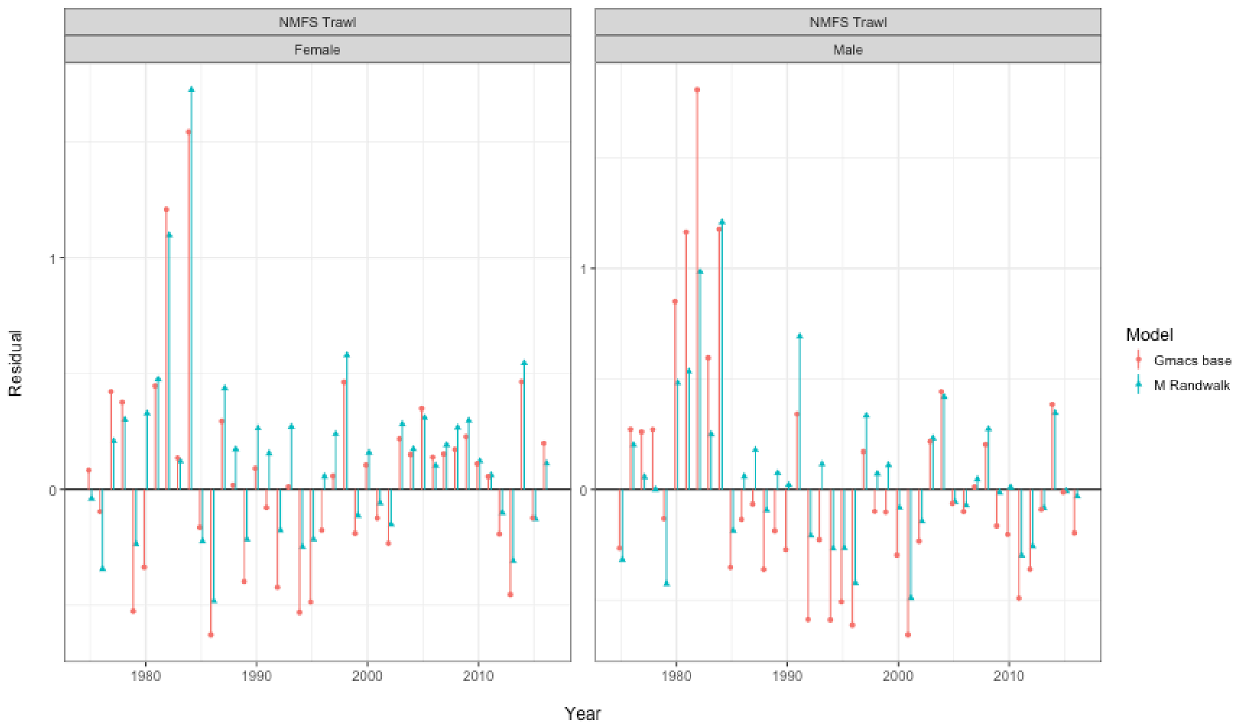

Figure 8: Standardized residuals for area-swept estimates of total male survey biomass for each of the Gmacs model scenarios.

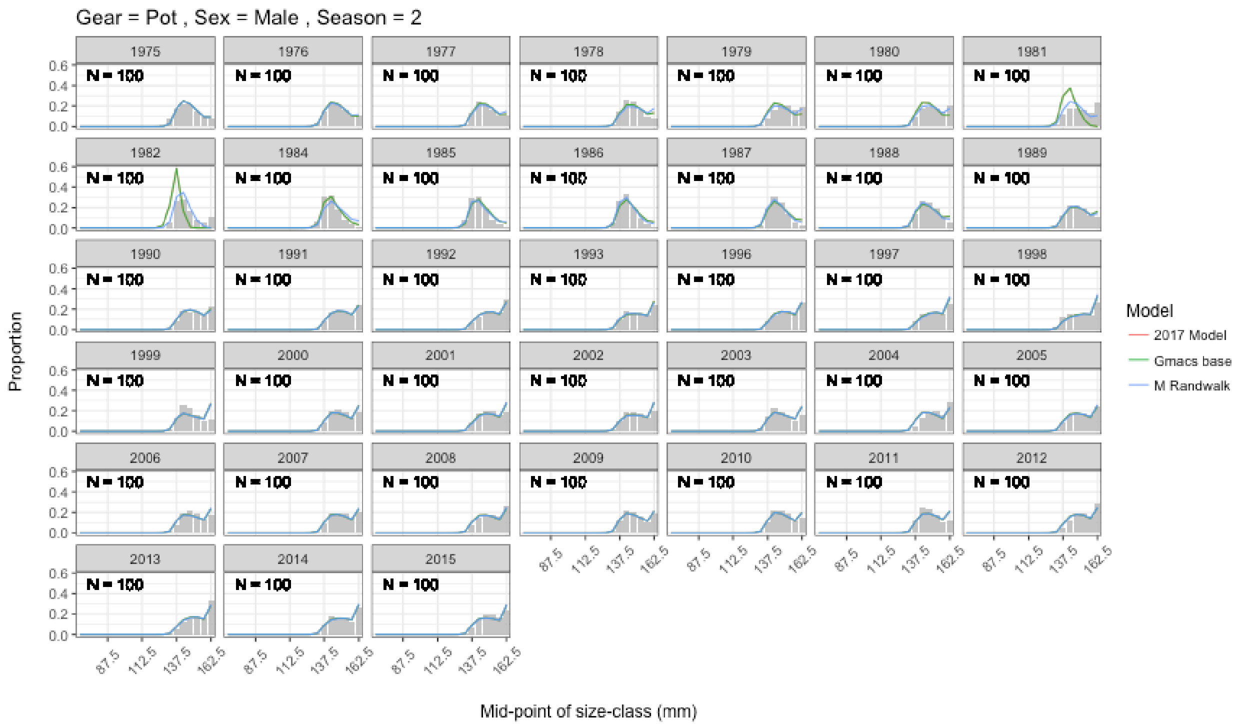

Figure 9: Observed and model estimated size-frequencies of BBRKC by year retained in the directed pot fishery for the 2016 model and each of the Gmacs model scenarios. Note that there is no model estimated size- frequency for the 2016 model during the 2016 year.

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{r sc_pot_discarded, fig.cap = "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.\\label{fig:sc_pot_discarded}"} plot_size_comps(M, 2)
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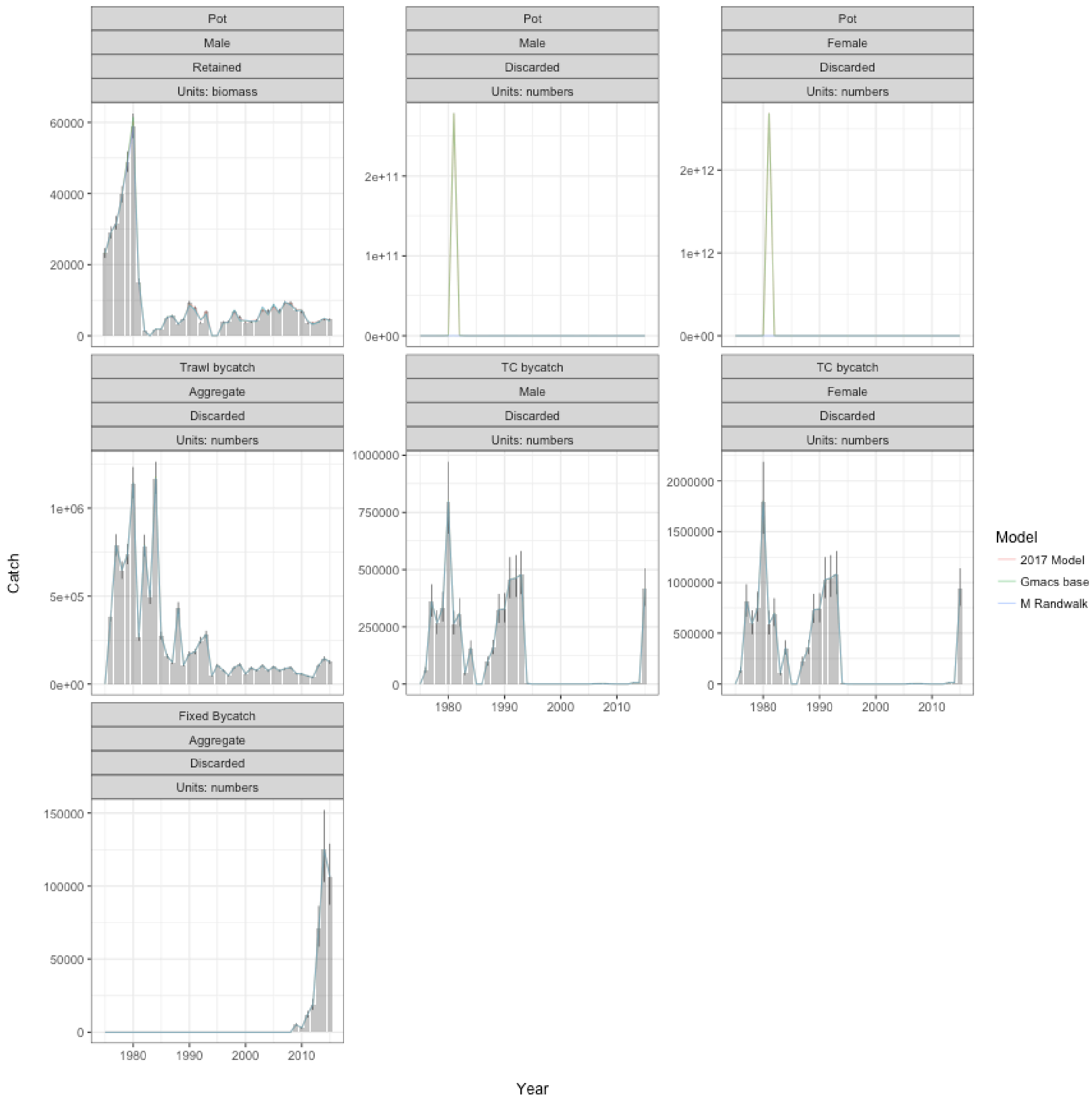

Figure 10: Comparison of observed and model predicted retained catch and bycatches in each of the Gmacs models. Note that difference in units between each of the panels, some panels are expressed in numbers of crab, some as biomass (tons).

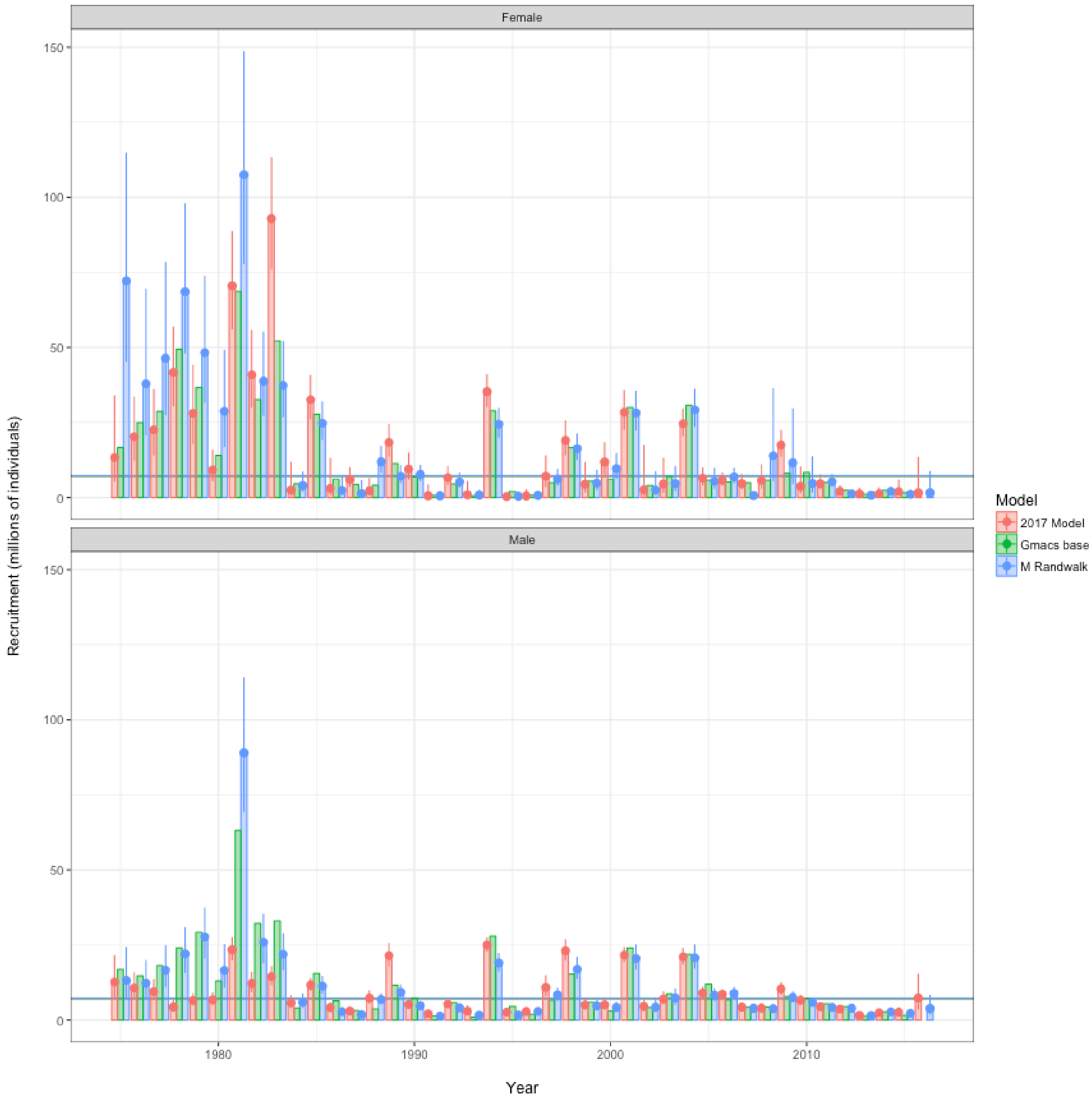

Figure 11: Comparisons of estimated recruitment time series during 1979-2016 in each of the scenarios. The solid horizontal lines in the background represent the estimate of the average recruitment parameter ($\bar{R}$) in each model scenario.

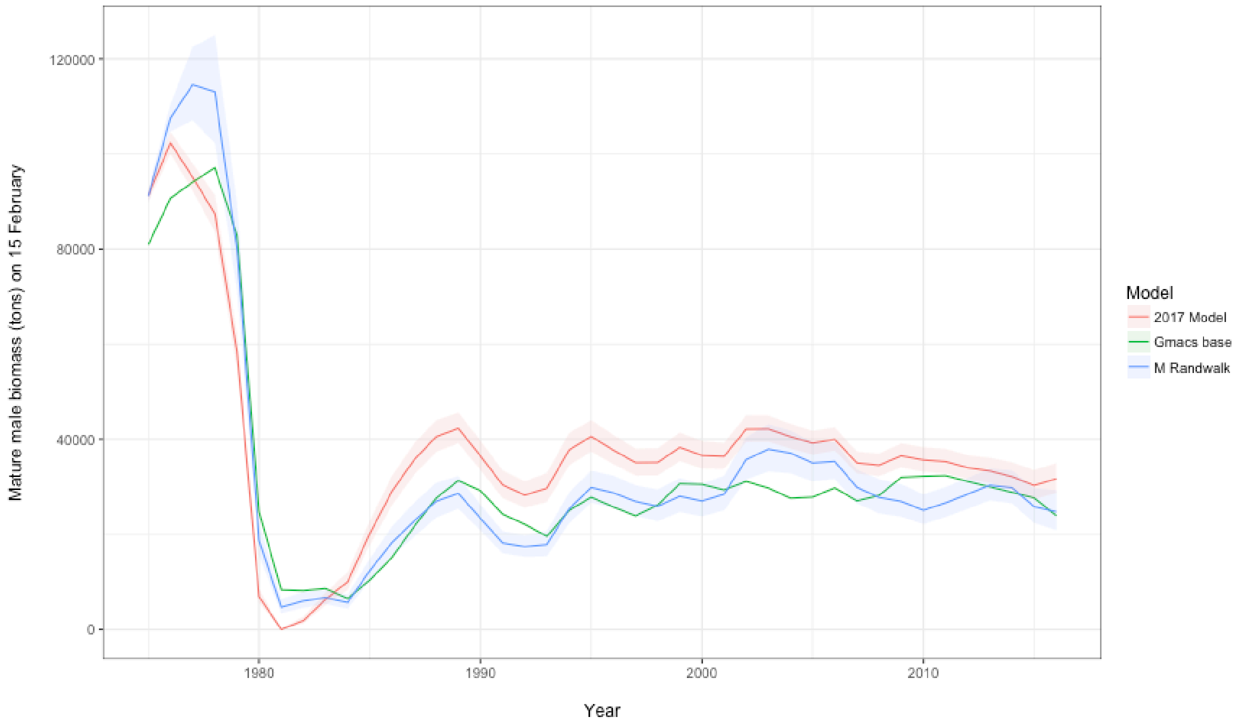

Figure 12: Comparisons of estimated mature male biomass (MMB) time series on 15 February during 1978-2016 for each of the model scenarios.

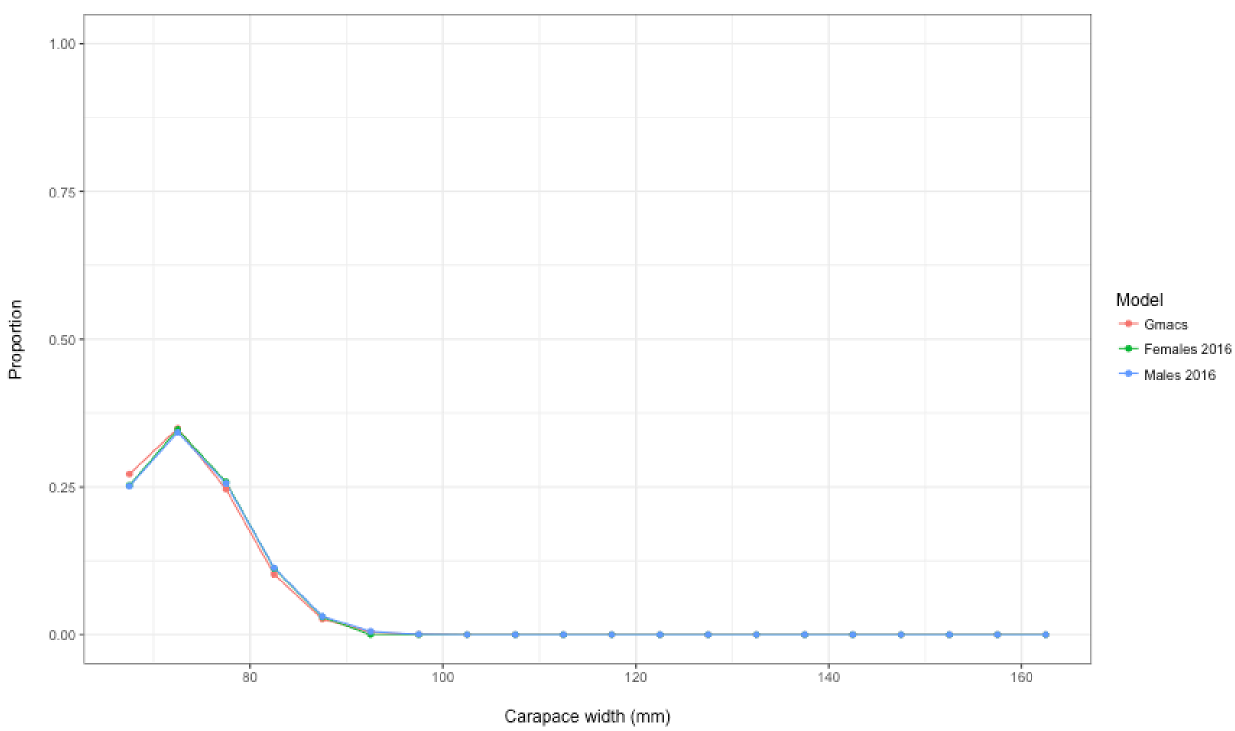

Figure 13: Distribution of carapace width (mm) at recruitment.

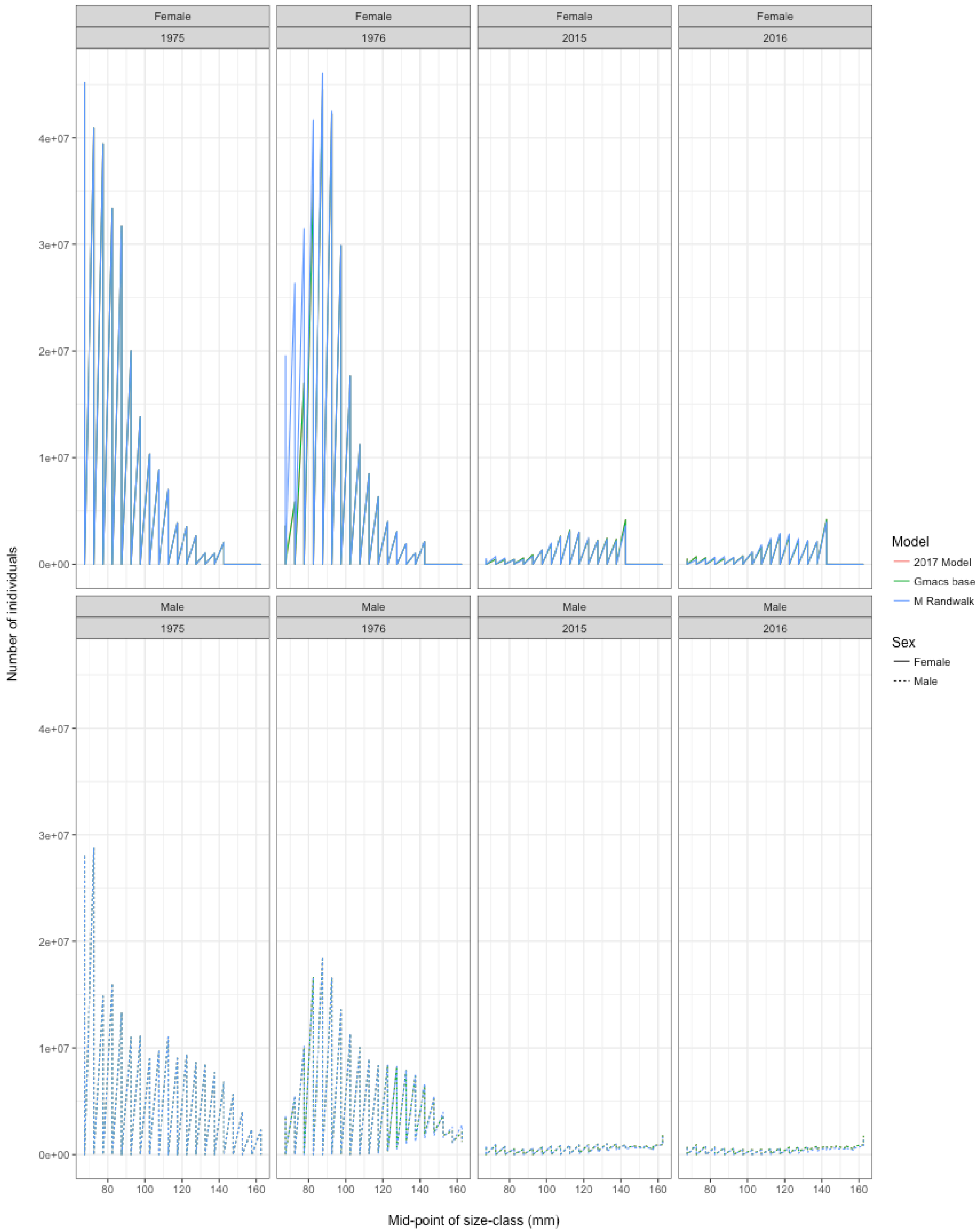

Figure 14: Numbers by stage each year (at the beginning of the model year, i.e. 1 July, season 1) in each of the models including the 2015 model.

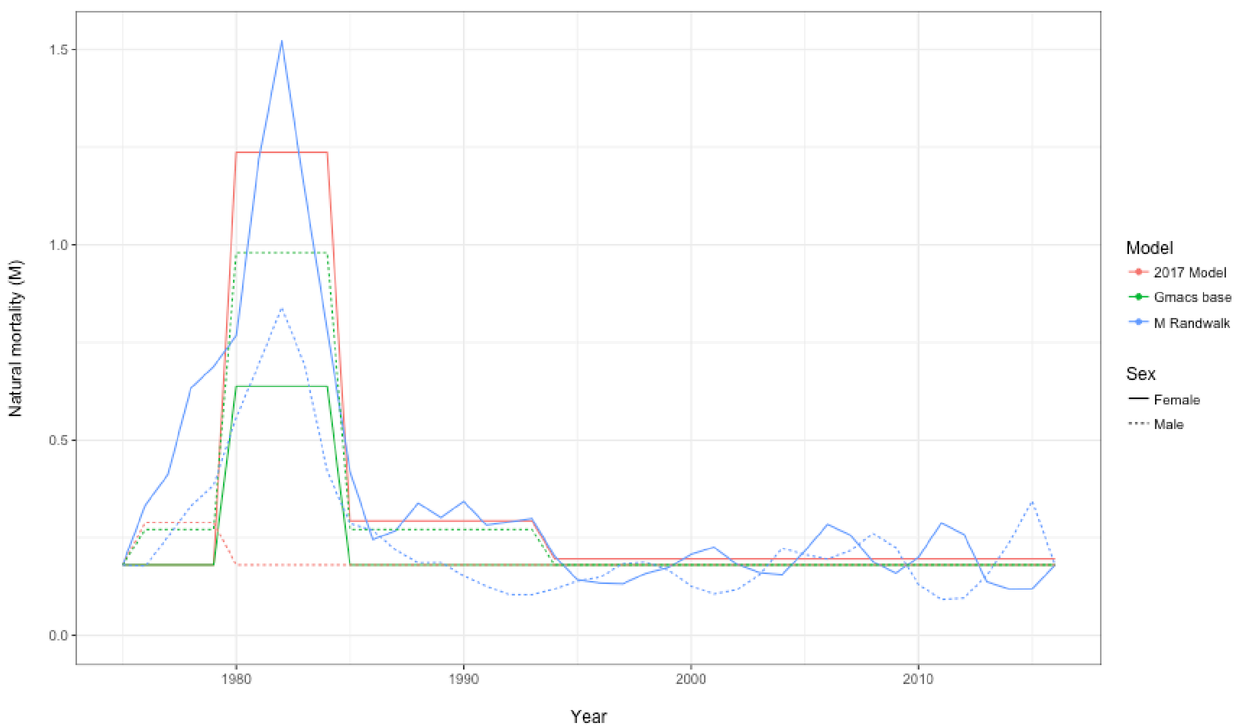

Figure 15: Time-varying natural mortality (M_t). Estimated pulse period occurs in 1979/80 (i.e. M_{1980}).

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 `r M[[2]]$nseason` 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 5)
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 **??**. 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

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

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 $\delta^{\mathrm{df}}_{t,y}$, $\delta^{\mathrm{tb}}_{t,y}$, and $\delta^{\mathrm{fb}}_{t,y}$ are the fishing mortality deviations for each of the fisheries, each season t during each year y, $\bar{F}^{\mathrm{df}}$, $\bar{F}^{\mathrm{tb}}$, and $\bar{F}^{\mathrm{fb}}$ 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 9.

Table 9: 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)

4. Model Parameters

Table 10 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.

Table 10: 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 **??**	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

Estimated parameters are listed in Table 11 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 **??**). A lognormal distribution is assumed to characterize the catch data and is modelled as

$$\sigma^{\text{catch}}_{t,y} = \sqrt{\log\left(1 + \left(CV^{\text{catch}}_{t,y}\right)^2\right)} \tag{14}$$

$$\delta^{\text{catch}}_{t,y} = \mathcal{N}\left(0, \left(\sigma^{\text{catch}}_{t,y}\right)^2\right) \tag{15}$$

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

$$\sigma^{\text{I}}_{t,y} = \frac{1}{\lambda}\sqrt{\log\left(1 + \left(CV^{\text{I}}_{t,y}\right)^2\right)} \tag{16}$$

$$\delta^{\text{I}}_{t,y} = \log\left(I^{\text{obs}}/I^{\text{pred}}\right)/\sigma^{\text{I}}_{t,y} + 0.5\sigma^{\text{I}}_{t,y} \tag{17}$$

and the likelihood is

$$\sum \log\left(\delta^{\text{I}}_{t,y}\right) + \sum 0.5\left(\sigma^{\text{I}}_{t,y}\right)^2 \tag{18}$$

Gmacs calculates standard deviation of the normalised residual (SDNR) values and median of the absolute residual (MAR) values for all abundance indices and size compositions to help the user come up with resonable likelihood weights. For an abundance data set to be well fitted, the SDNR should not be much

Table 11: 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^M_{1998}	-3	0.0	3	Normal(0, σ_M^2)	4
Recruitment deviations δ^R_y	-7	0.0	7	Normal(0, σ_R^2)	3
Average directed fishery fishing mortality $\bar{F}^{\text{df}}$	-	0.2	-	-	1
Average trawl bycatch fishing mortality $\bar{F}^{\text{tb}}$	-	0.001	-	-	1
Average fixed gear bycatch fishing mortality $\bar{F}^{\text{fb}}$	-	0.001	-	-	1

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 abundance index and size composition weights until adequate SDNR (and/or MAR) values are achieved, given the Francis weights.

6. Estimation

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