A Gmacs application to the 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 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 the 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).

Table 1: Status and catch specifications (1000 tons) (scenario **Gmacs base**).

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

6. **Basis for the OFL**: Estimated mature-male biomass (MMB) on 15 February is used as the measure of biomass for this Tier 3 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 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

A. Summary of Major Changes

Changes in Management of the Fishery

There were no new changes in management of the fishery.

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 data.

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.

Changes in Assessment Results

Results from the alternative models are qualitatively very similar to those conducted using the current assessment approach.

B. Responses to SSC and CPT Comments

CPT and SSC Comments on Assessments in General

Comment:

Response:

CPT and SSC Comments Specific to the BBRKC Stock Assessment

Comment: *The SSC and CPT (loosely) requested the following models for review at the spring 2017 meeting:*

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

Response:

Models 1, 2, and 3 are all included and evaluated in this document as the **Gmacs base** (the same type of blocked changes in time for natural mortality), **Free q** (estimate the catchability of BSFRF survey), and **Variable M** (look at a flexible time-varying natural mortality configuration) 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.

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 updated and the extent of all different data sources is shown in Figure 2.

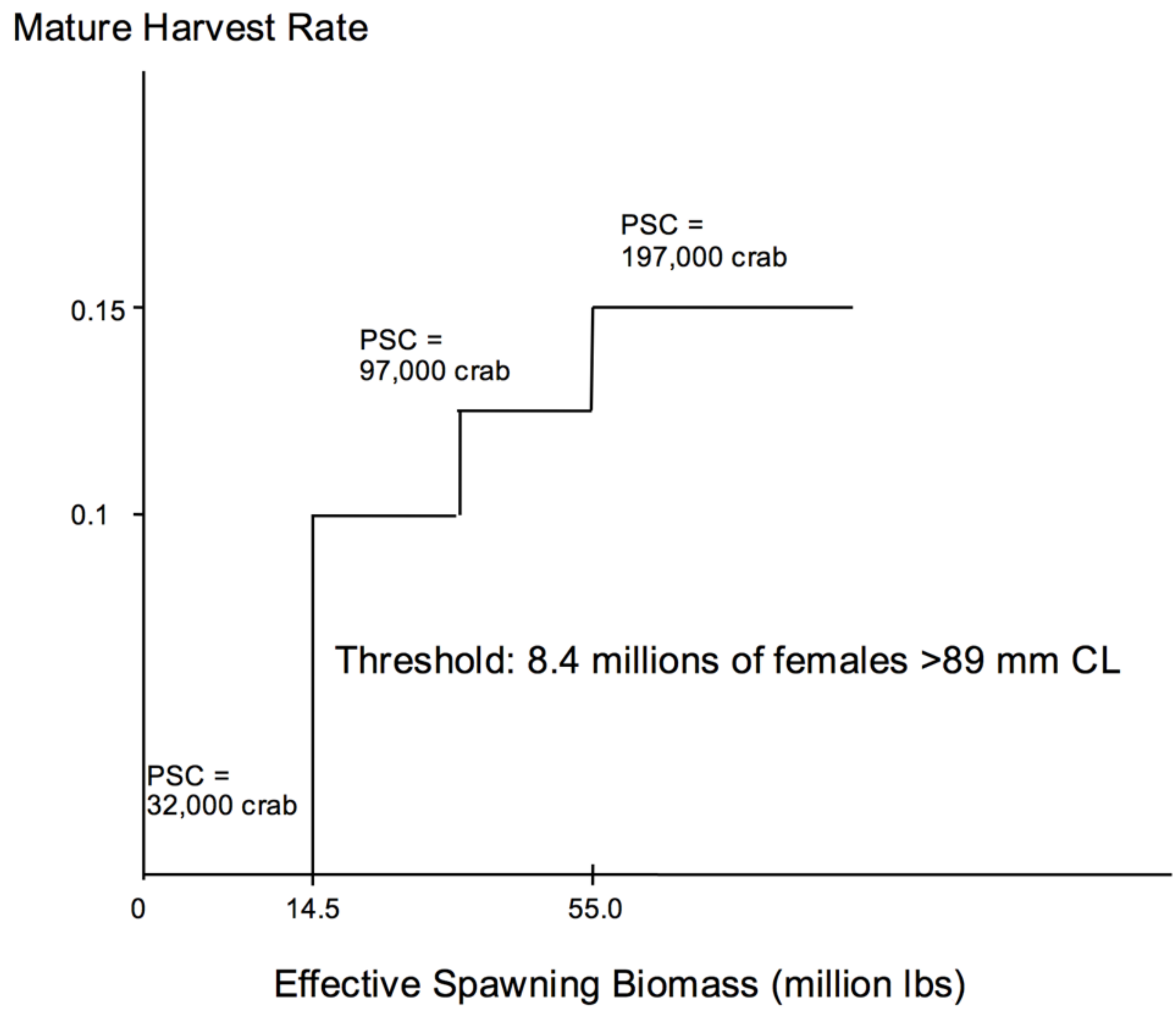

Figure 1: Current harvest rate strategy (line) for the Bristol Bay red king crab fishery and annual prohibited species catch (PSC) limits (numbers of crab) of Bristol Bay red king crab in the groundfish fisheries in zone 1 in the eastern Bering Sea. Harvest rates are based on current-year estimates of effective spawning biomass (ESB), whereas PSC limits apply to previous-year ESB. \labe{fig:HarvestPolicy}

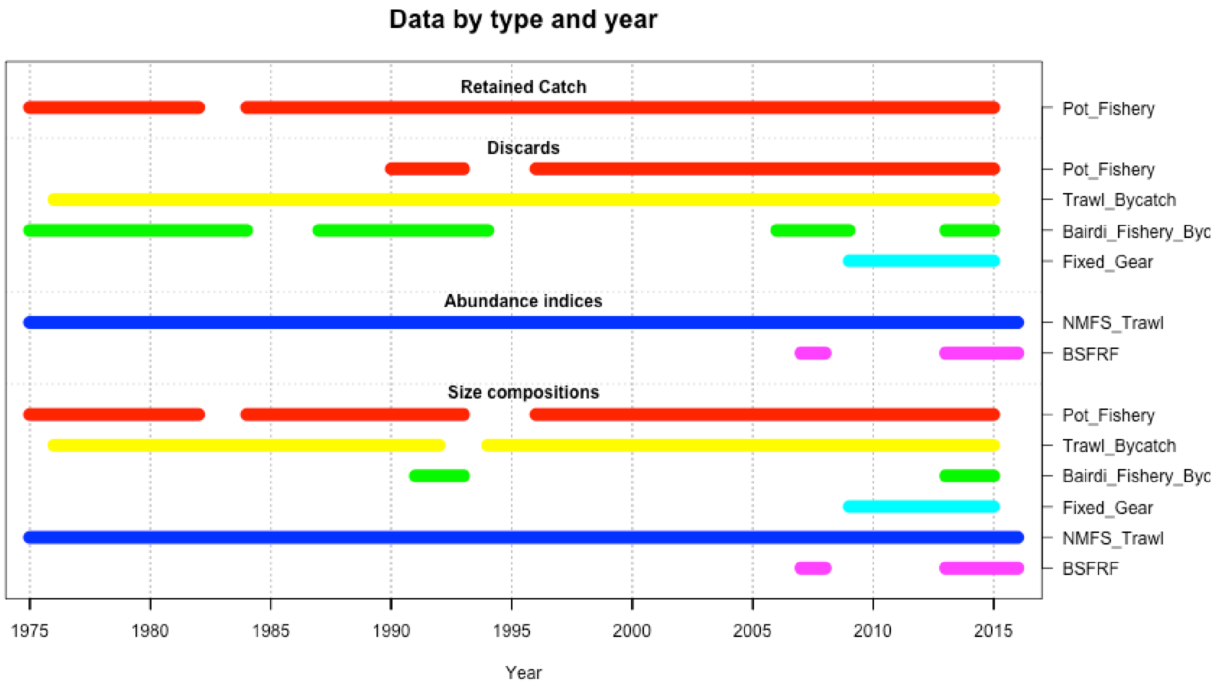

Figure 2: Data extent for the BBRKC assessment.

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; 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 7. 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 Fishery	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 retained catch (millions of crab) and catch per unit effort of the Bristol Bay red king crab fishery.

Year	Japanese Tanglenet		Russian Tanglenet		U.S. Pot/Trawl		Standardized
	Catch	Crab/tan	Catch	Crab/tan	Catch	Crab/Potlift	Crab/tan
1960	1.949	15.2	1.995	10.4	0.088		15.8
1961	3.031	11.8	3.441	8.9	0.062		12.9
1962	4.951	11.3	3.019	7.2	0.010		11.3
1963	5.476	8.5	3.019	5.6	0.101		8.6
1964	5.895	9.2	2.800	4.6	0.123		8.5
1965	4.216	9.3	2.226	3.6	0.223		7.7
1966	4.206	9.4	2.560	4.1	0.140	52	8.1
1967	3.764	8.3	1.592	2.4	0.397	37	6.3
1968	3.853	7.5	0.549	2.3	1.278	27	7.8
1969	2.073	7.2	0.369	1.5	1.749	18	5.6
1970	2.080	7.3	0.320	1.4	1.683	17	5.6
1971	0.886	6.7	0.265	1.3	2.405	20	5.8
1972	0.874	6.7			2.405	20	
1973	0.228				4.826	25	
1974	0.476				7.710	36	
1975					8.745	43	
1976					10.603	33	
1977					11.733	26	
1978					14.746	36	
1979					16.809	53	
1980					20.845	37	
1981					5.308	10	
1982					0.541	4	
1983					0.000		
1984					0.794	7	
1985					0.796	9	
1986					2.100	12	
1987					2.122	10	
1988					1.236	8	
1989					1.685	8	
1990					3.130	12	
1991					2.661	12	
1992					1.208	6	
1993					2.270	9	
1994					0.015		
1995					0.014		
1996					1.264	16	
1997					1.338	15	
1998					2.238	15	
1999					1.923	12	
2000					1.272	12	
2001					1.287	19	
2002					1.484	20	
2003					2.510	18	
2004					2.272	23	
2005					2.763	30	
2006					2.477	31	
2007					3.154	28	
2008					3.064	22	
2009					2.553	21	
2010					2.410	18	
2011					1.298	28	
2012					1.176	30	
2013					1.272	27	
2014					1.501	26	
2015					1.527	31	

Table 7: 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).

Model Description

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 closely matched the 2016/17 BBRKC stock assessment model using the configuration options presently available in GMACS. 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 Gmacs models include:

1. **Gmacs base**: includes removals by the directed BBRKC fishery, Tanner crab trawl and fixed gear fisheries (separated). The model uses the NMFS trawl and BSFRF surveys as abudance indces. The BSFRF survey catchability coefficient is fixed at $q = 1.0$ in this model run. The estimated parameters include the average recruitment ($\bar{R}$), the recruitment deviations (δ_y^R), 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, the tanner crab bycatch fishery, and the fixed-gear bycatch fishery ($\bar{F}^{\text{df}}$, $\bar{F}^{\text{tb}}$, $\bar{F}^{\text{tcb}}$, $\bar{F}^{\text{fgb}}$, $\delta_{t,y}^{\text{df}}$, $\delta_{t,y}^{\text{tb}}$, $\delta_{t,y}^{\text{tcb}}$, $\delta_{t,y}^{\text{fgb}}$).
2. **Free q**: is similar to the scenario above except that it estimates the BSFRF survey catchability coefficient q rather than fixing it at $q = 1.0$.
3. **Variable M**: is similar to the Gmacs base scenario 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 8 outlines the major features of each of the models.

Table 8: Outline of the major features of the five different Gmacs scenarios.

Scenario	Estimate BSFRF q	Random walk natural mortality
Gmacs base	No	No
Free q	Yes	No
Variable M	No	Yes

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).

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 2016/17 model. The **Gmacs base** scenario 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 10. Effective sample sizes are also shown on size-composition plots (Figures **??**, 13, 14, 15), 16), 17), 18), 19), and 20). The survey size composition effective sample sizes are shown in the model fit Figures 21), 22), 23), and 24).

Data weighting factors, SDNRs, and MARs are presented in Table 14.

b. Tables of estimates

Model parameter estimates for each of the Gmacs scenarios are summarized in Tables 11, and 12.

Negative log-likelihood values for each of the Gmacs scenarios are compared in Table 13.

c. Graphs of estimates.

Estimated selectivities are compared in Figures 6 and 7.

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

Fits to size compositions for trawl survey, pot survey, and commercial observer data are shown in Figures 12 - 24 for the all scenarios. Bubble plots of stage composition residuals are provided in the Appendix.

Fits to retained catch numbers and bycatch biomass are shown for all scenarios in Figure 25.

Estimated recruitment is compared in Figure 26. Estimated abundances by stage and mature male biomasses for all scenarios are shown in Figures 29 and 27. Estimated natural mortality each year (M_t) is presented in Figure 30.

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 2016/17 model (Figures 8 and 9). Looking at the model fits to the NMFS trawl survey biomass (Figure 8), the **Base** scenario is the most similar to the 2017 model, as are the other model configuratios. the **variable M** model was constructed for contrast and to evaluate an intentionally overparameterized model. Interestingly, the pattern conforms to the general pattern of the pre-specified M-varying blocks.

Estimated recruitment to the model is variable over time and generally consistent among model configuraitons (Figure 26). Estimated recruitment during recent years is low in all scenarios. Estimated mature male biomass on 15 February also varies a bit in recent years and is consistent over model configurations (Figure 27).

e. Retrospective and comparisons with past analyses.

[placeholder]

f. Uncertainty and sensitivity analyses.

Estimated standard deviations of parameters and selected management measures for the five Gmacs scenarios are summarized in Tables 11, and 12. Probabilities for mature male biomass and OFL in 2016 are shown in Section F.

g. Comparison of alternative model scenarios.

All model scenarios gave qualitatively similare results in terms of stock trends and values of mature male biomass (Figure 27). For management purposes a more complete analysis or some ensemble approach might be considered.

F. Calculation of the OFL and ABC

The overfishing level (OFL) is the fishery-related mortality biomass associated with fishing mortality F_{OFL}. The BBRKC stock is currently managed as Tier 3 (2016 SAFE), and only a Tier 3 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 [needs checking]

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

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 3 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 9. ABC is 80% of the OFL.

Table 9: Comparisons of management measures for the three Gmacs model scenarios. Biomass and OFL are in tons.

Component	Base	Free q	Time-varying M
MMB_{2016}	36688.663	29520.541	24601.478
B_{MSY}	30314.620	26825.830	25988.611
F_{OFL}	0.180	0.174	0.147
OFL_{2016}	1893.235	1537.558	997.107
ABC_{2016}	1514.588	1230.046	797.686

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

[placeholder]

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. A projection module is under development.

K. Acknowledgements

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L. References

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Tables

Figures

Table 10: Observed and assumed sample sizes for observer data from the directed pot fishery, the NMFS trawl survey, and the BSFRF survey.

	Observed sample sizes			Assumed sample sizes		
Year	Observer pot	NMFS survey	BSFRF survey	Observer pot	NMFS survey	BSFRF survey
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 11: Model parameter estimates, selected derived quantities, and their standard deviations (SD) for the **Gmacs base** model.

Parameter	Estimate	SD
M deviation(δ^M_{1980})	1.485	0.031
$\log(\bar{R})$	16.002	0.065
$\log(q_{nmfs})$	0.921	0.021
$\log(F^{\mathrm{df}})$	-1.536	0.031
$\log(\bar{F}^{\mathrm{tgb}})$	-4.829	0.054
$\log(\bar{F}^{\mathrm{fgb}})$	-18.207	0.191
$\log(\bar{F}^{\mathrm{tcb}})$	-7.354	0.085
F_{OFL}	0.139	0.012
OFL	1112.900	166.760

Table 12: Model parameter estimates, selected derived quantities, and their standard deviations (SD) for the **Free q** model.

Parameter	Estimate	SD
M deviation(δ^M_{1980})	1.468	0.030
$\log(\bar{R})$	15.865	0.065
$\log(q_{NMFS})$	0.962	0.021
$\log(q_{BSFRF})$	0.834	0.072
$\log(\bar{F}^{\mathrm{df}})$	-1.429	0.032
$\log(\bar{F}^{\mathrm{tgb}})$	-4.810	0.050
$\log(\bar{F}^{\mathrm{fgb}})$	-6.045	0.045
$\log(\bar{F}^{\mathrm{tcb}})$	-7.228	0.087
F_{OFL}	0.174	0.009
OFL	1537.600	150.840

Table 13: Comparisons of negative log-likelihood values for the Gmacs model scenarios.

Component	Gmacs base	Free q	Variable M
Pot Retained Male Catch	29.61	42.12	29.18
Pot Discarded Male Catch	186.91	183.75	184.28
Pot Discarded Female Catch	-55.21	-55.21	-55.20
Trawl bycatch Discarded Aggregate Catch	-92.01	-92.00	-92.01
TC bycatch Discarded Female Catch	4990.56	-33.26	-33.27
TC bycatch Discarded Male Catch	4990.56	-33.26	-33.26
Fixed Bycatch Discarded Aggregate Catch	-9.70	-9.70	-9.70
NMFS Trawl Survey	20.23	-24.77	-29.60
BSFRF Survey	-2.95	-9.03	-8.13
Directed Pot LF	-1438.22	-1412.66	-1421.13
NMFS Trawl LF	-888.61	-889.94	-891.47
BSFRF LF	-1813.19	-1770.68	-1781.29
Recruitment deviations	174.42	180.73	165.32
F penalty	18.95	18.95	18.95
M penalty	30.47	63.64	13.84
Prior	162.19	166.19	169.28
Total	6304.02	-3675.13	-3774.22
Total estimated parameters	500.00	499.00	574.00

Table 14: Comparisons of data weights, SDNR values, and MAR values for the Gmacs model scenarios.

Component	Gmacs base	Free q	Variable M
Weight NMFS trawl survey	1.00	1.00	1.00
Weight BSFRF survey	1.00	1.00	1.00
Weight directed pot LF	1.00	1.00	1.00
Weight directed pot bycatch LF	1.00	1.00	1.00
Weight trawl bycatch LF	1.00	1.00	1.00
Weight tanner bycatch LF	1.00	1.00	1.00
Weight fixed bycatch LF	1.00	1.00	1.00
Weight NMFS trawl survey LF	1.00	1.00	1.00
Weight BSFRF survey LF	1.00	1.00	1.00
SDNR NMFS trawl survey	1.86	1.52	1.46
SDNR BSFRF survey	0.43	0.50	0.53
SDNR directed pot LF	13.10	0.00	0.00
SDNR directed pot bycatch LF	397.97	0.00	0.00
SDNR trawl bycatch LF	244.83	0.00	0.00
SDNR tanner bycatch LF	35.62	0.00	0.00
SDNR fixed bycatch LF	69.15	0.00	0.00
SDNR NMFS trawl survey LF	93.20	0.00	0.00
SDNR BSFRF survey LF	81.16	0.00	0.00
MAR NMFS trawl survey	1.16	1.04	0.98
MAR BSFRF survey	1.31	0.40	0.19
MAR directed pot LF	0.05	0.00	0.00
MAR directed pot bycatch LF	0.76	0.00	0.00
MAR trawl bycatch LF	0.61	0.00	0.00
MAR tanner bycatch LF	0.64	0.00	0.00
MAR fixed bycatch LF	0.73	0.00	0.00
MAR NMFS trawl survey LF	0.87	0.00	0.00
MAR BSFRF survey LF	1.11	0.00	0.00

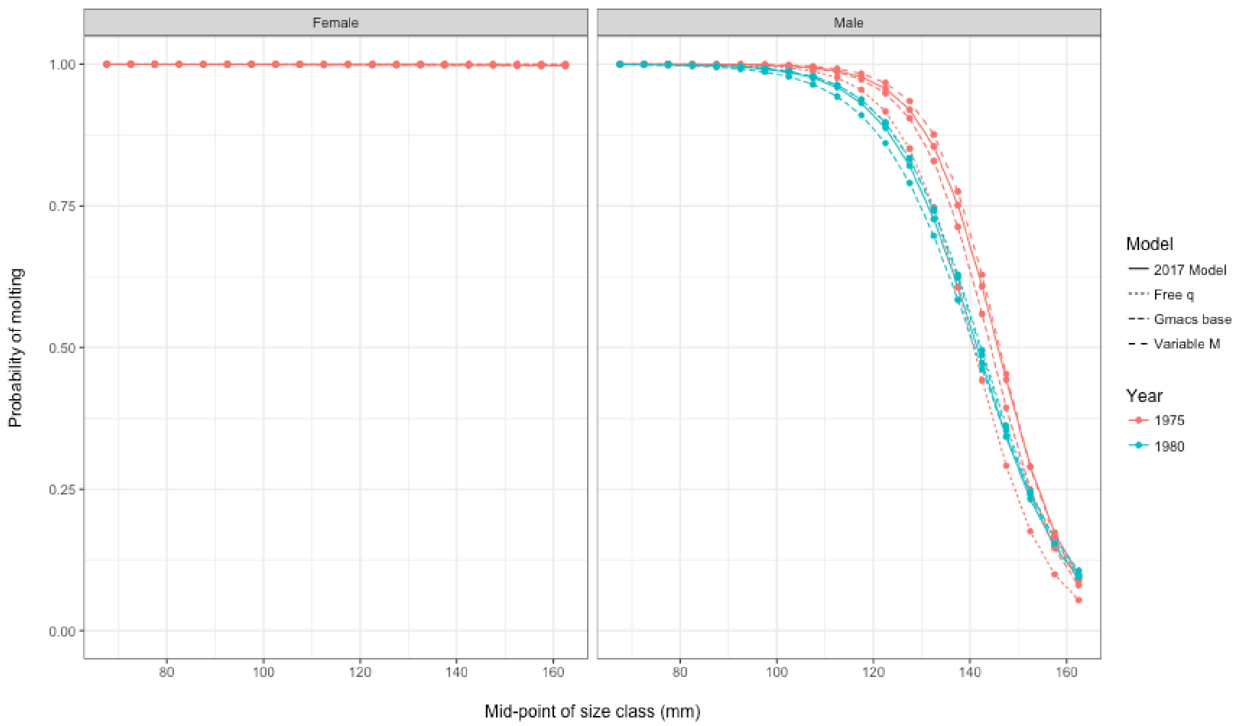

Figure 3: Comparisons of the estimated molting probabilities.

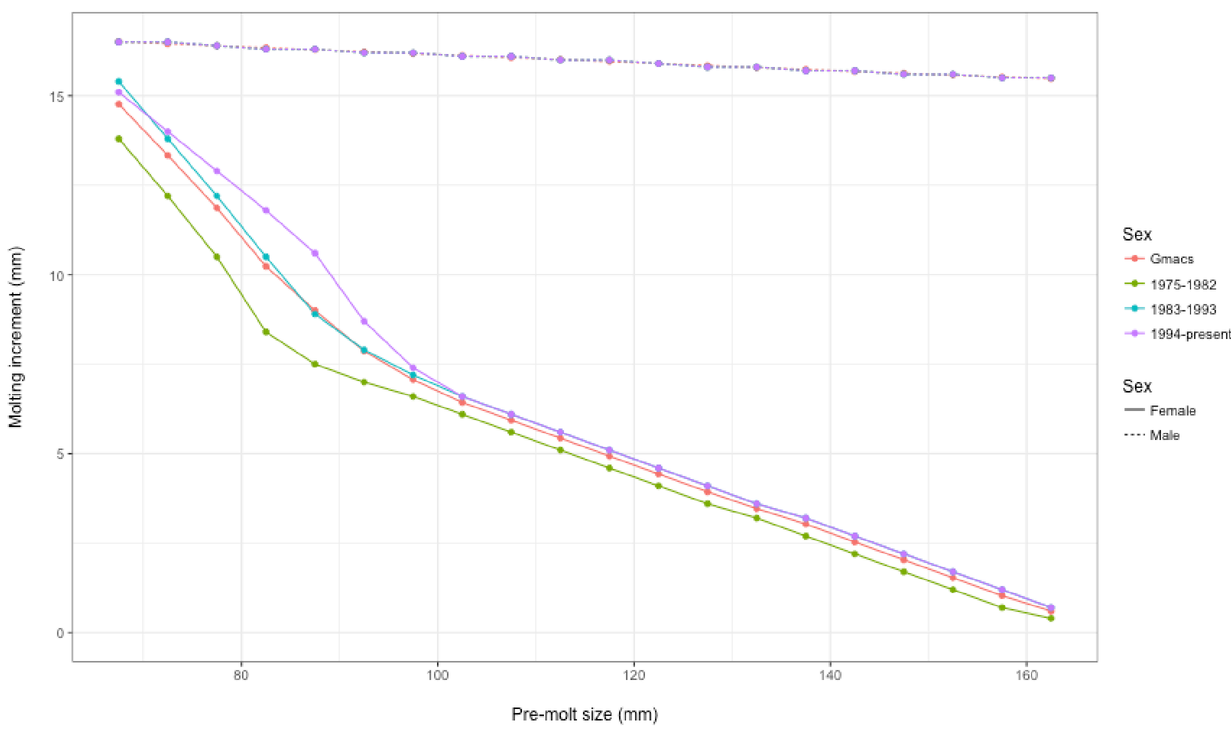

Figure 4: Comparisons of the molting increments.

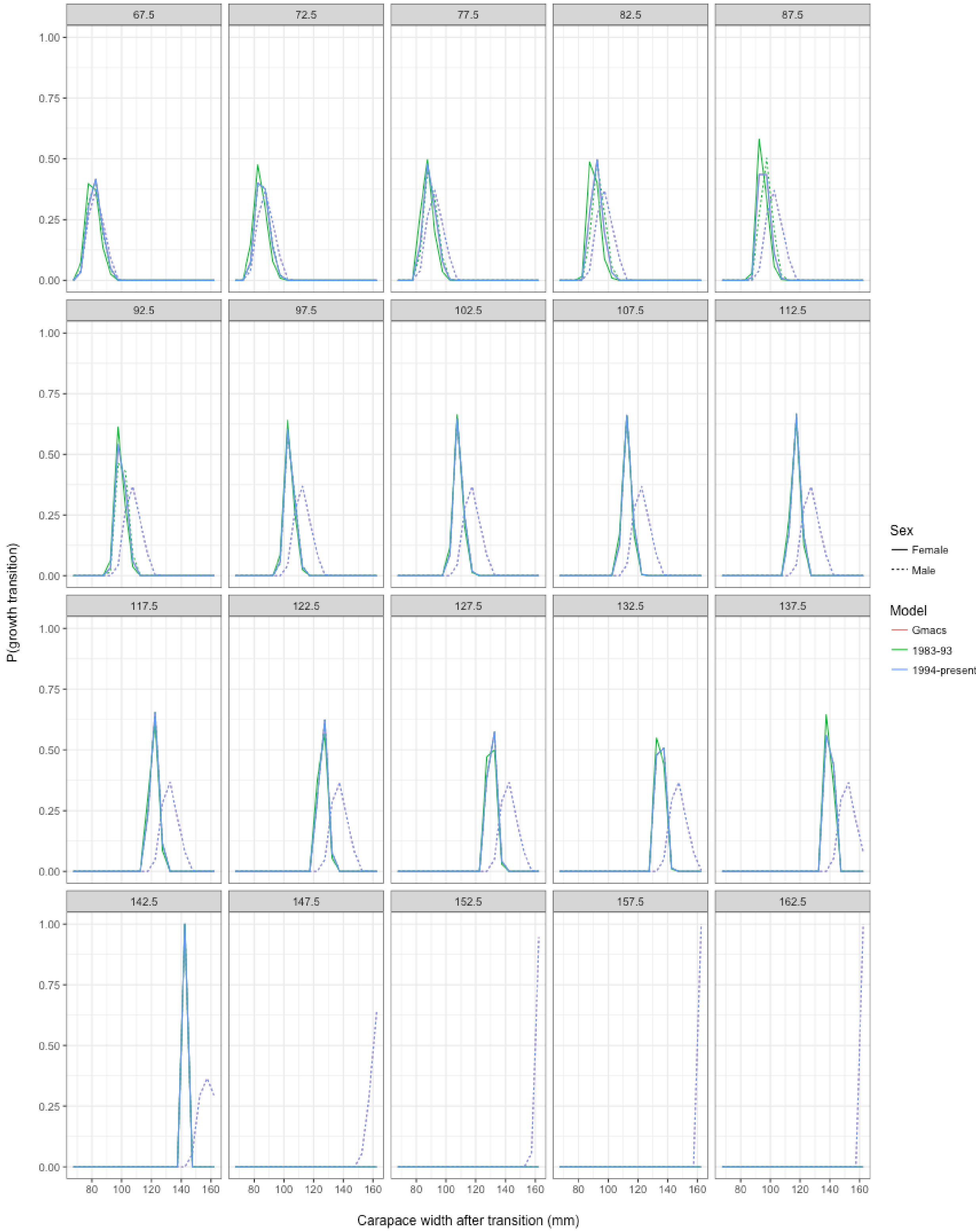

Figure 5: Probability of growth transition by stage. Each of the panels represent the stage before a transition. The x-axes represent the stage after a transition. The size transition matrix was provided as an input directly to Gmacs (as it was during the 2017 BBRKC assessment).

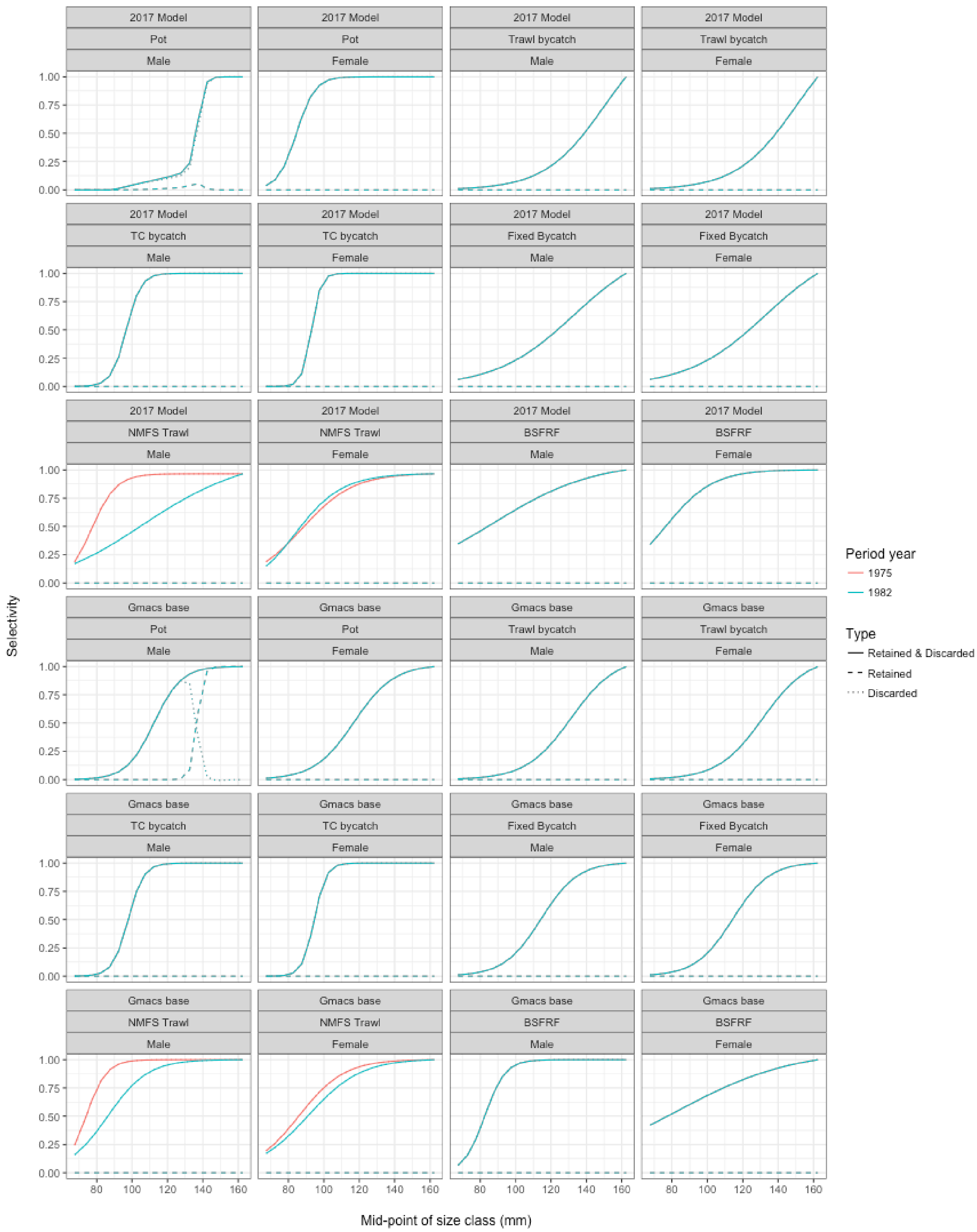

Figure 6: Comparisons of the estimated selectivities for each of the different model scenarios. Estimated selectivities are shown for the directed pot fishery, the trawl bycatch fishery, the tanner crab bycatch fishery, the fixed bycatch fishery, the NMFS trawl survey, and the BSFRF survey. Two selectivity periods are estimated in the NMFS trawl survey, from 1975-1981 and 1982-2016.

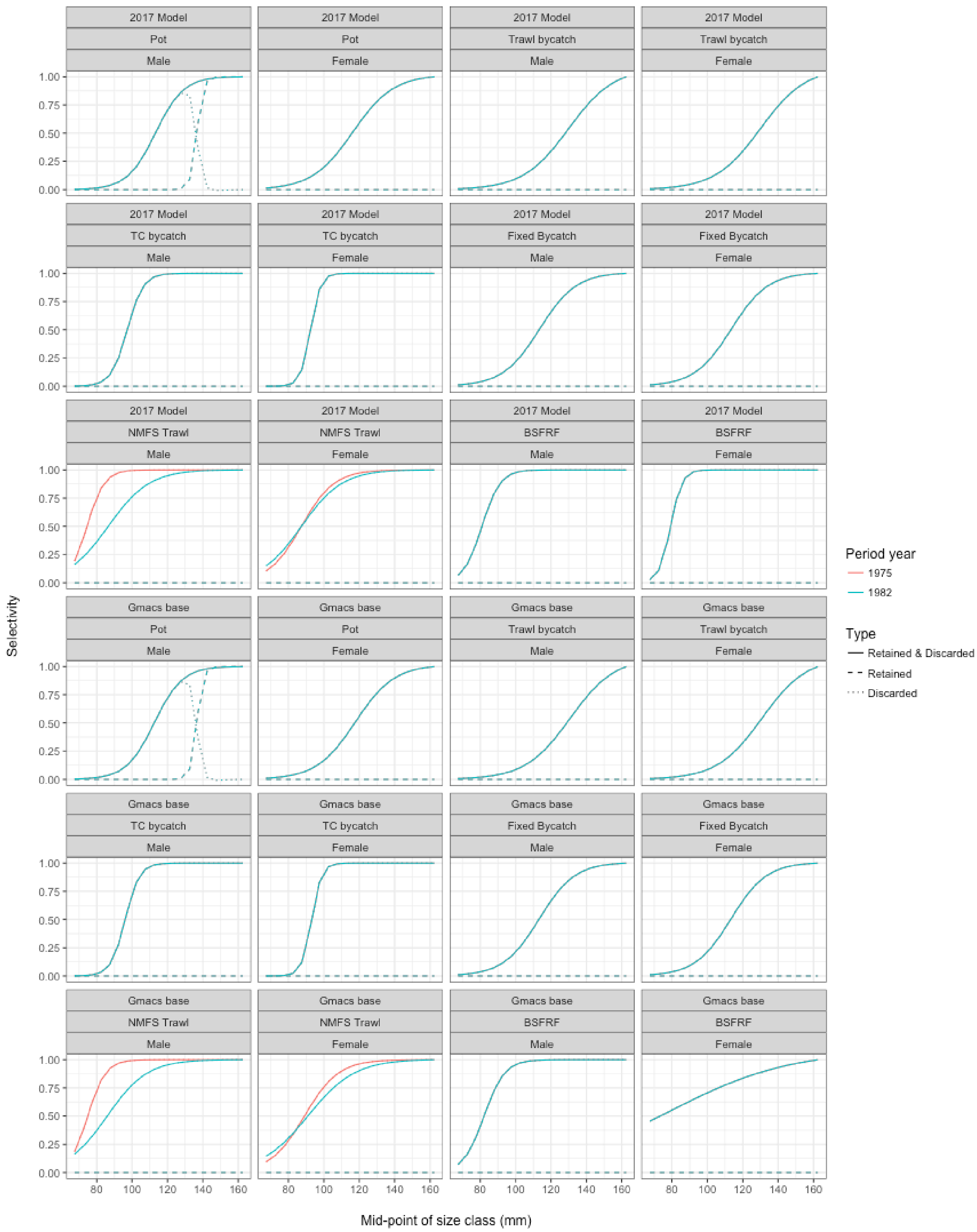

Figure 7: Comparisons of the estimated selectivities for each of the different model scenarios. Estimated selectivities are shown for the directed pot fishery, the trawl bycatch fishery, the tanner crab bycatch fishery, the fixed bycatch fishery, the NMFS trawl survey, and the BSFRF survey. Two selectivity periods are estimated in the NMFS trawl survey, from 1975-1981 and 1982-2016.

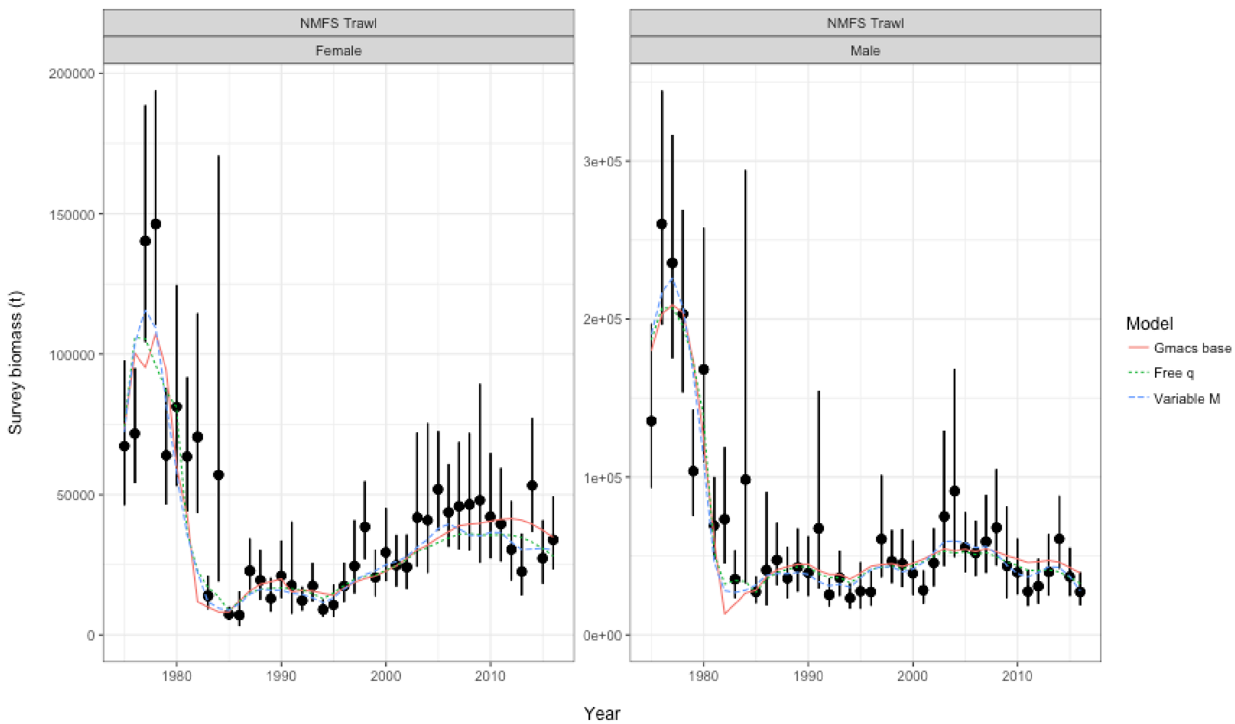

Figure 8: Comparisons of area-swept biomass estimates for males and females (tons) and model predictions for the NMFS trawl survey showing the 2017 model and each of the Gmacs model scenarios. The error bars represent plus and minus 2 standard deviations.

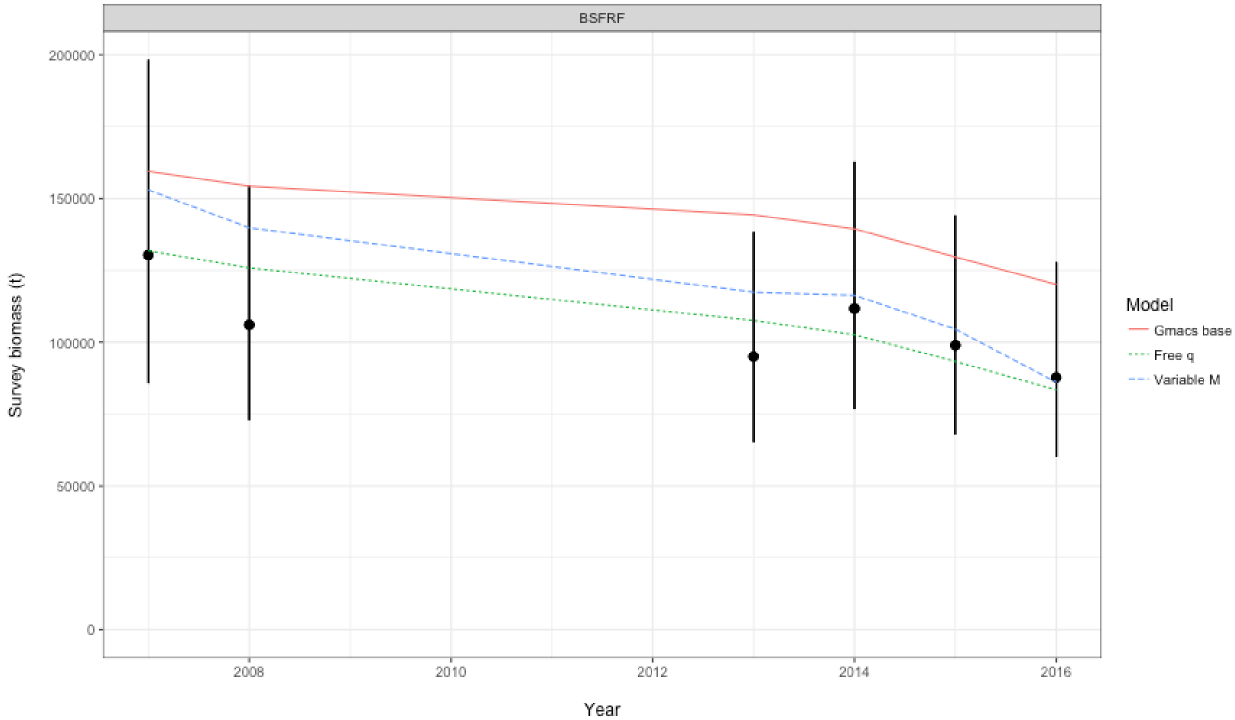

Figure 9: Comparisons of area-swept biomass estimates (tons) for the BSFRF survey showing the 2017 model and each of the Gmacs model scenarios. The error bars represent plus and minus 2 standard deviations derived using the original survey CVs.

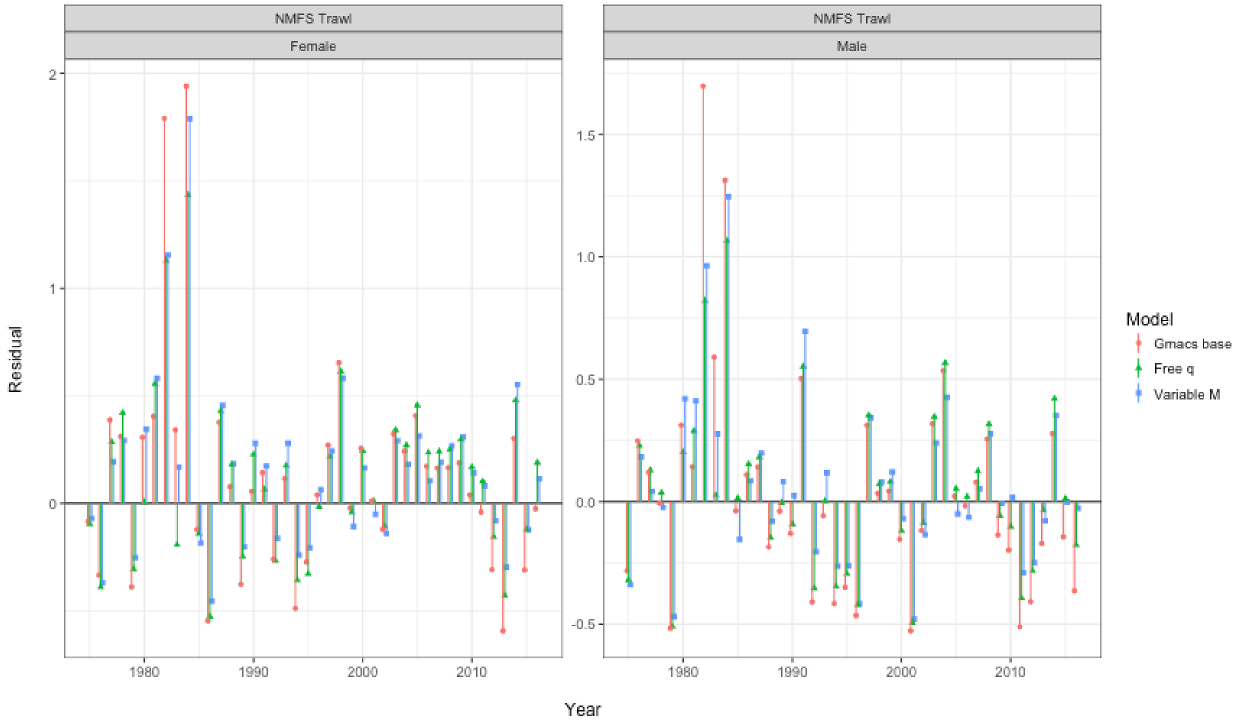

Figure 10: Standardized residuals for area-swept biomass estimates for males and females (tons) for the NMFS trawl survey showing each of the Gmacs model scenarios.

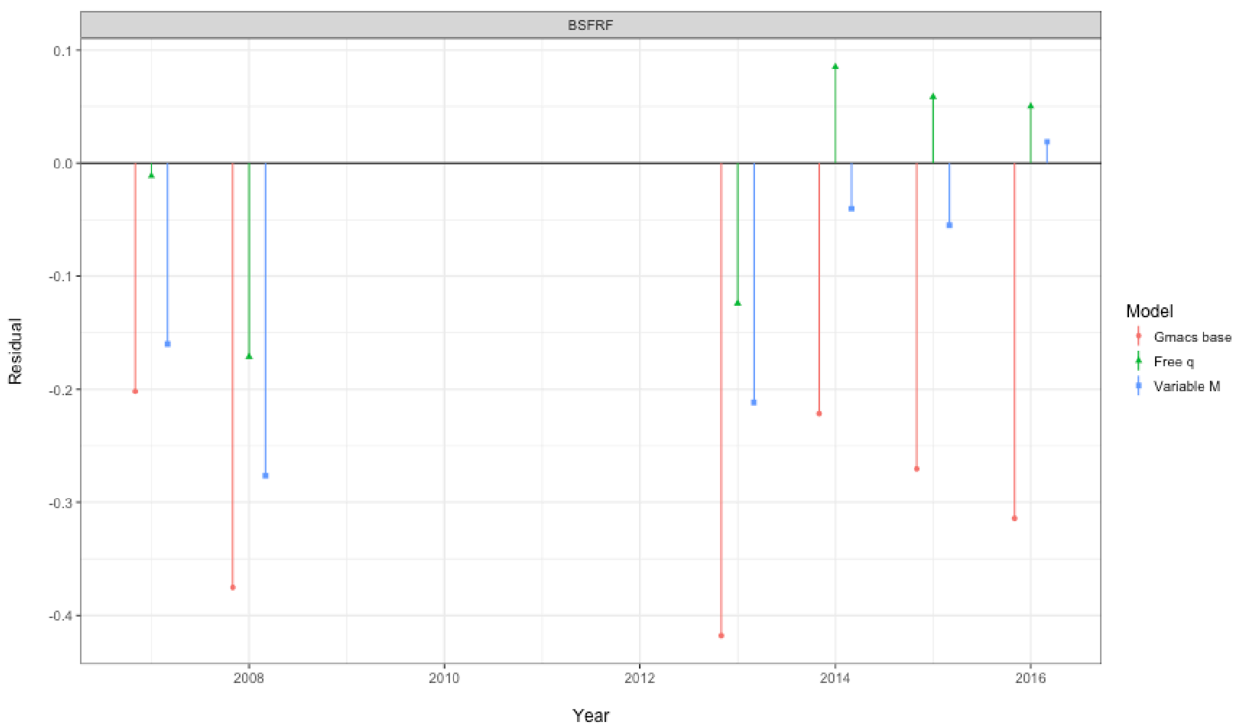

Figure 11: Standardized residuals for area-swept biomass estimates for males and females (tons) for the BSFRF trawl survey showing each of the Gmacs model scenarios.

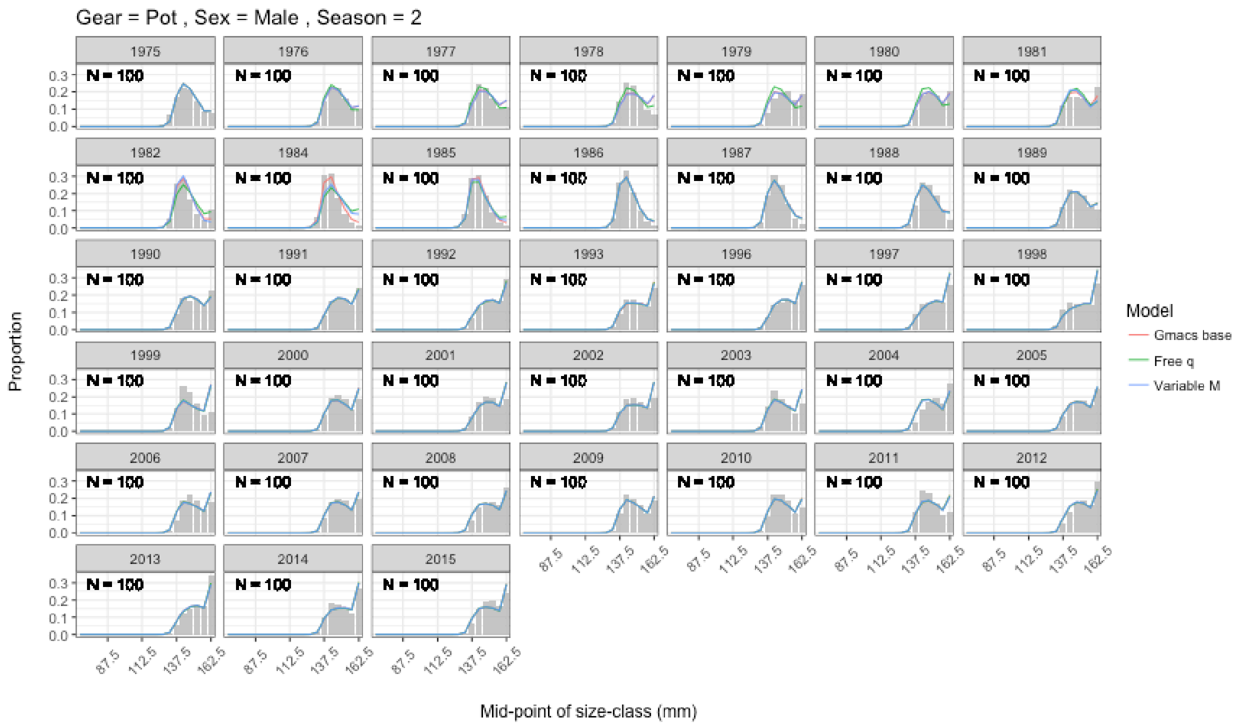

Figure 12: Observed and model estimated size-frequencies of male BBRKC by year retained in the directed pot fishery for the 2017 model and each of the Gmacs model scenarios.

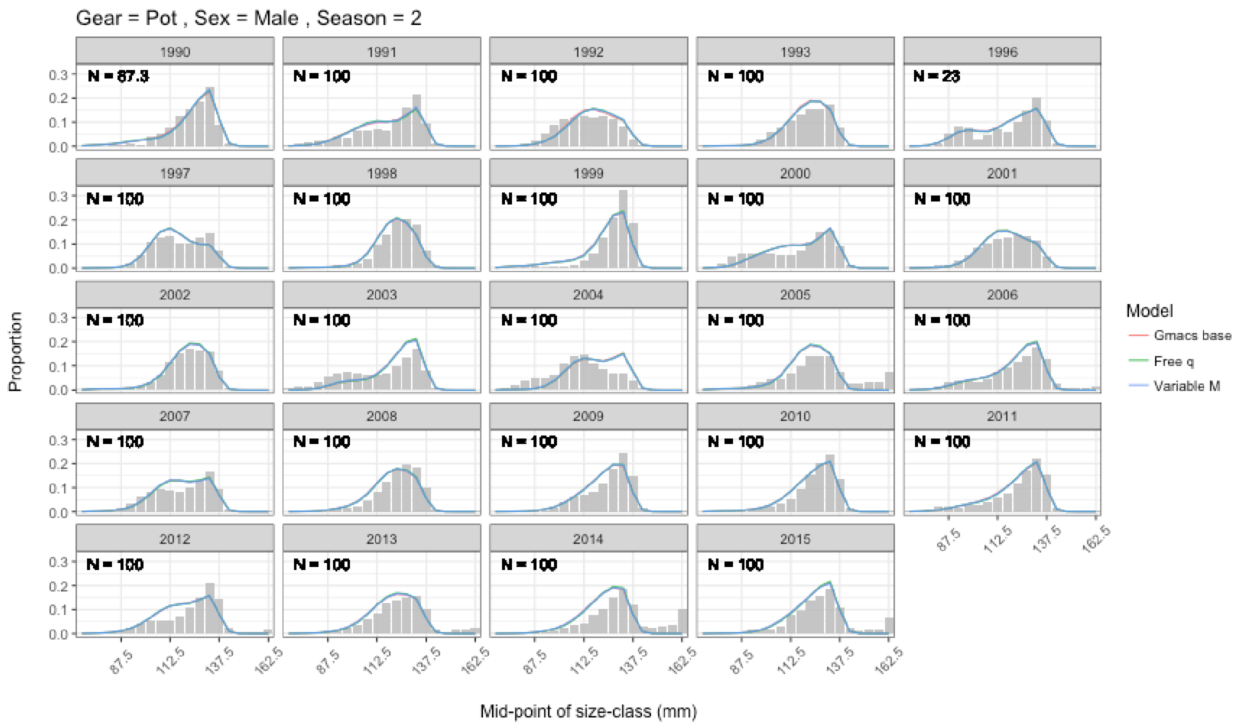

Figure 13: Observed and model estimated size-frequencies of discarded male BBRKC by year in the directed pot fishery for the 2017 model and each of the Gmacs model scenarios.

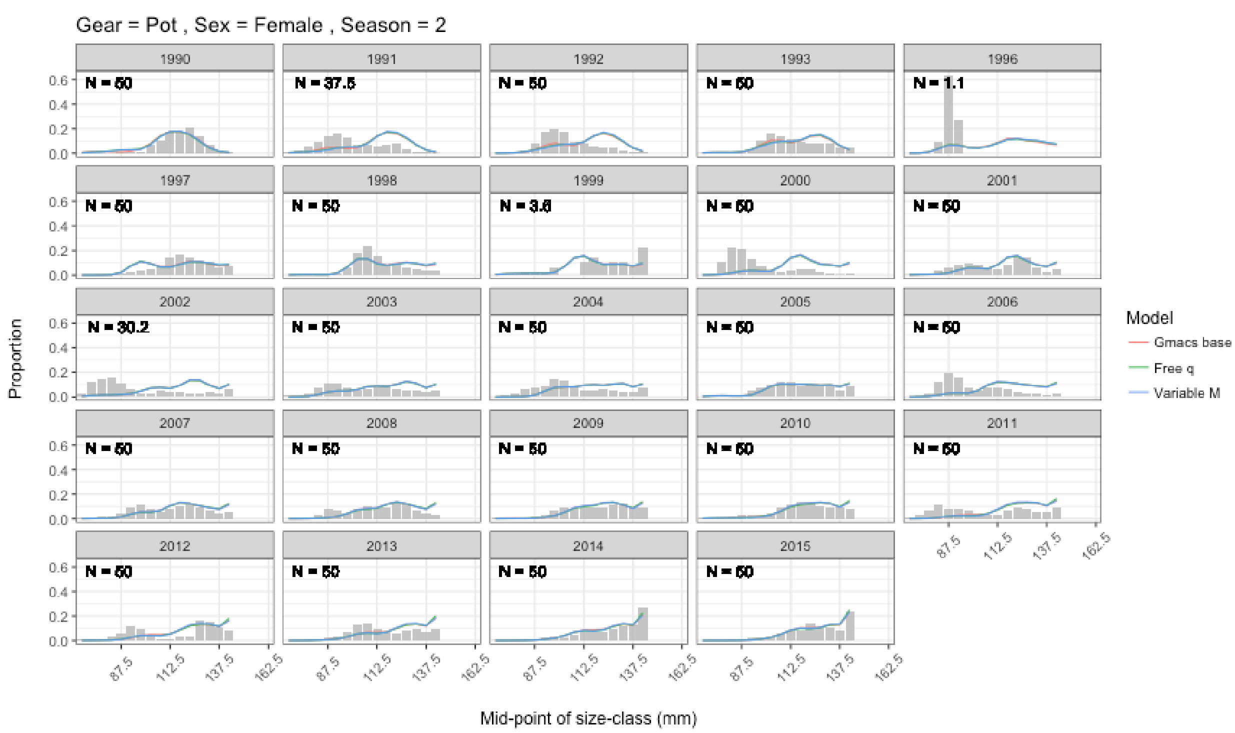

Figure 14: Observed and model estimated size-frequencies of discarded female BBRKC by year in the directed pot fishery for the 2017 model and each of the Gmacs model scenarios.

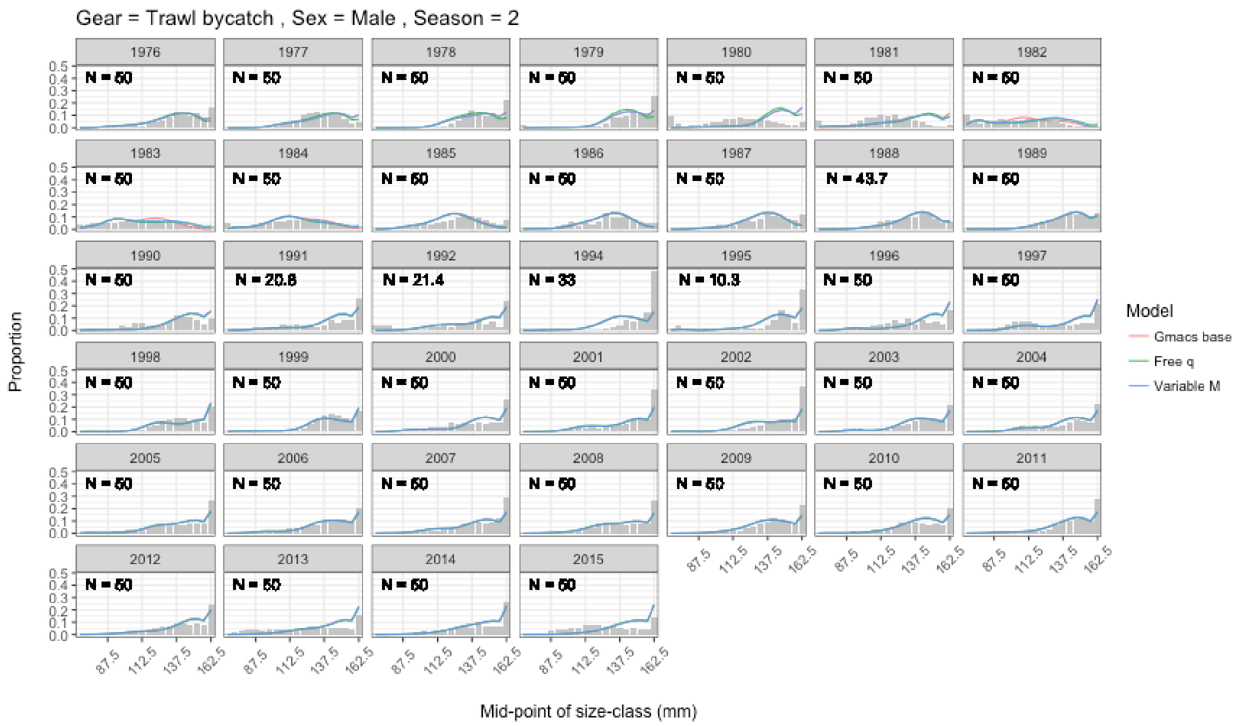

Figure 15: Observed and model estimated size-frequencies of discarded male BBRKC by year in the trawl bycatch fishery for the 2017 model and each of the Gmacs model scenarios.

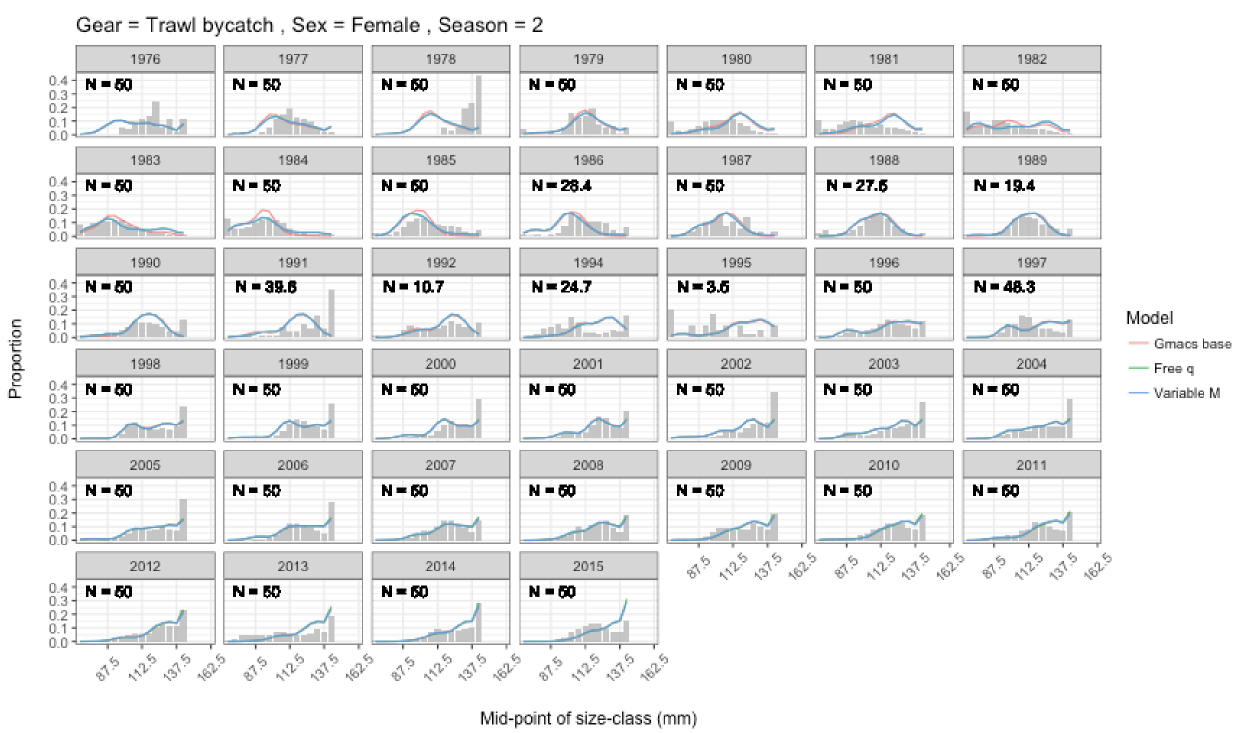

Figure 16: Observed and model estimated size-frequencies of discarded female BBRKC by year in the trawl bycatch fishery for the 2017 model and each of the Gmacs model scenarios.

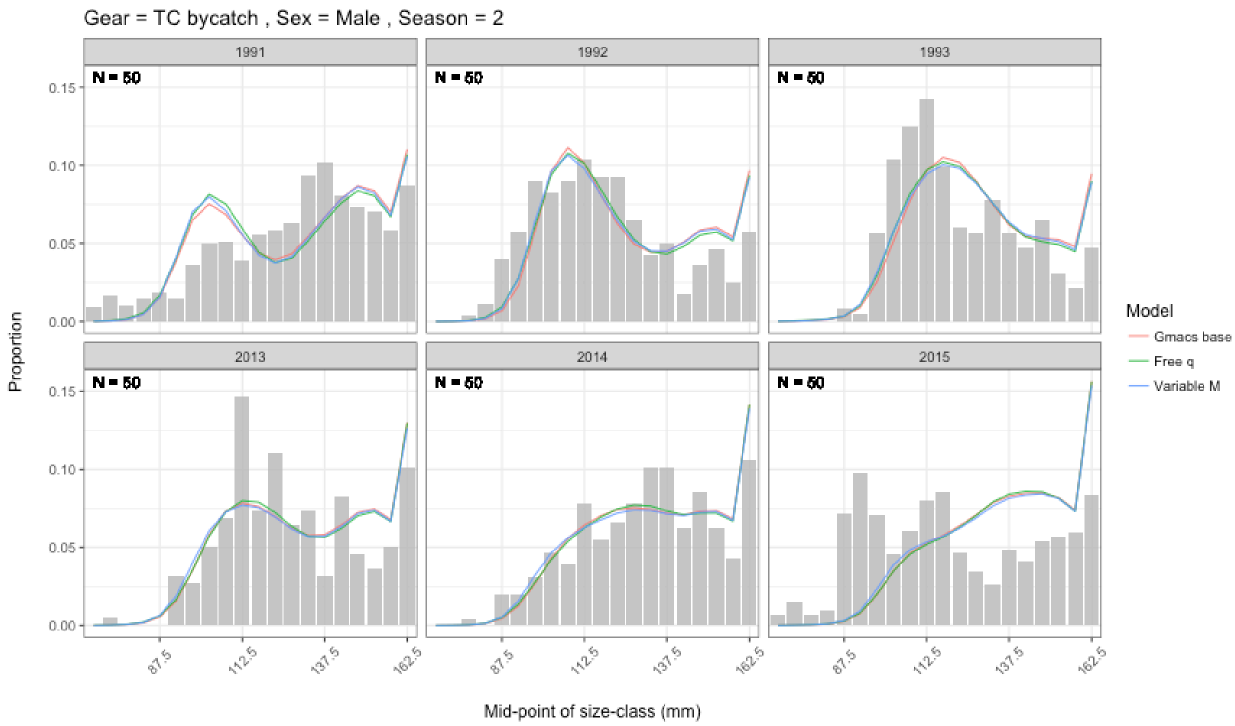

Figure 17: Observed and model estimated size-frequencies of discarded male BBRKC by year in the tanner crab bycatch fishery for the 2017 model and each of the Gmacs model scenarios.

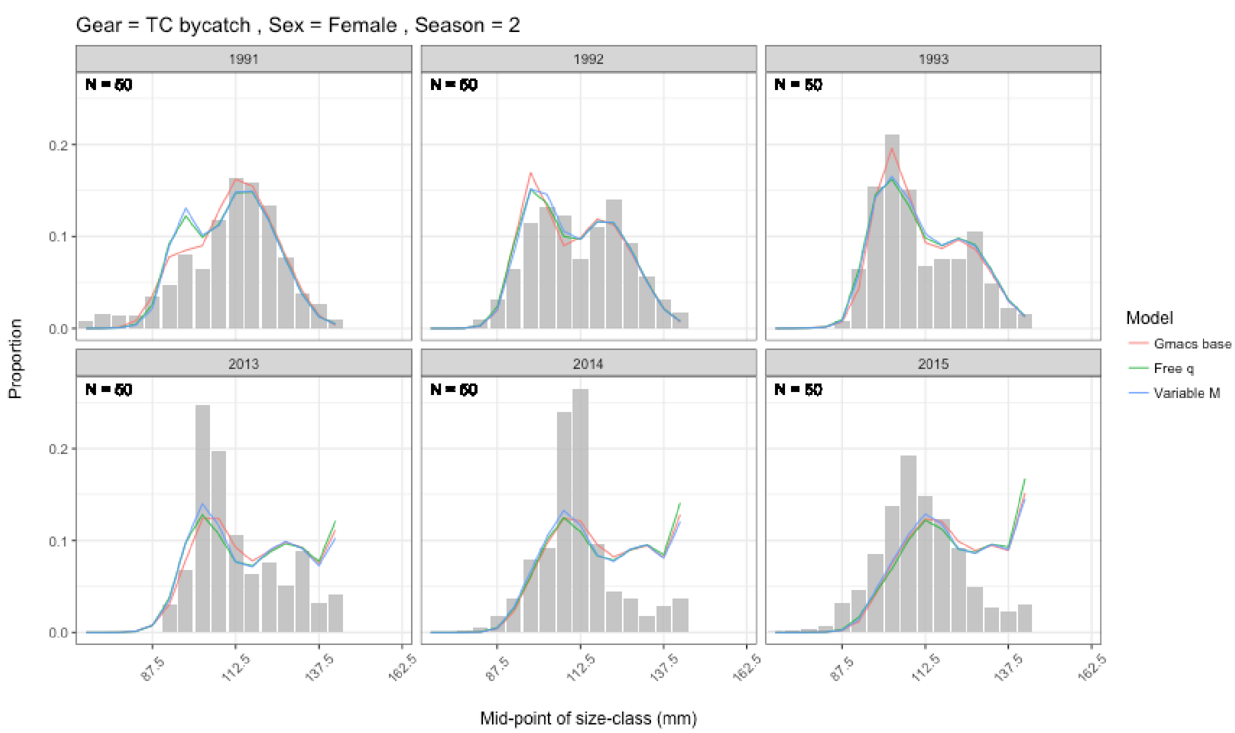

Figure 18: Observed and model estimated size-frequencies of discarded female BBRKC by year in the tanner crab bycatch fishery for the 2017 model and each of the Gmacs model scenarios.

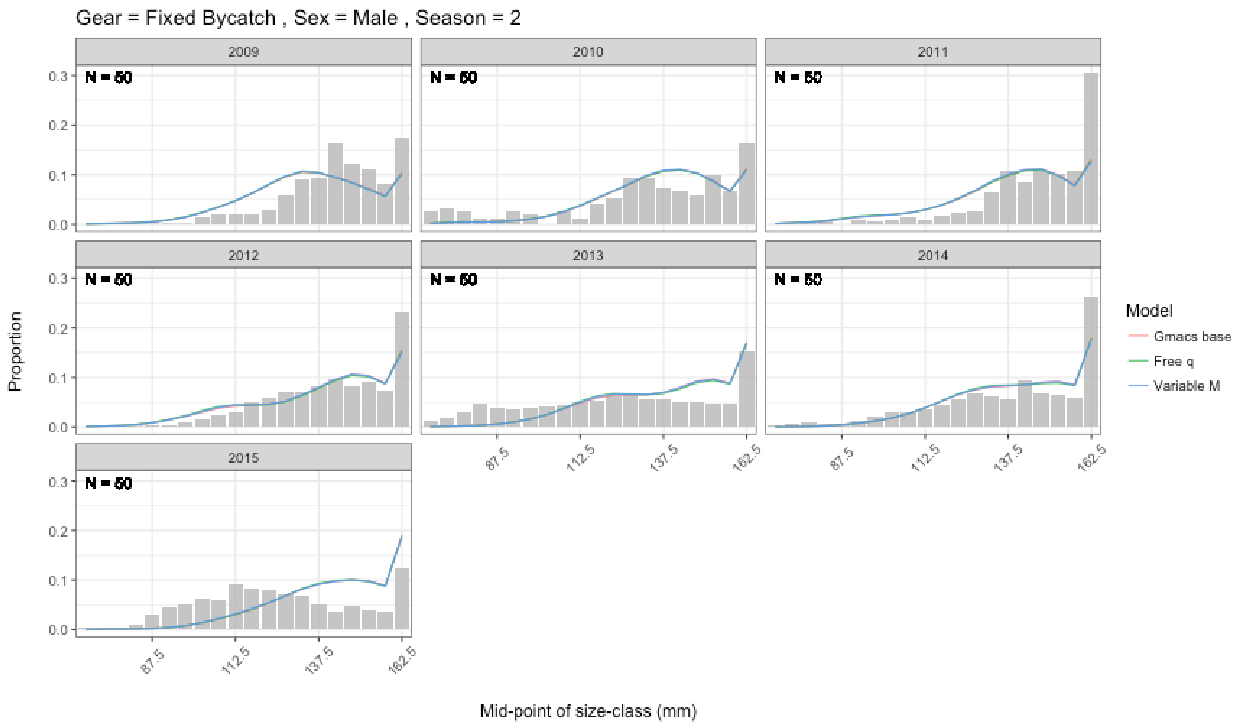

Figure 19: Observed and model estimated size-frequencies of discarded male BBRKC by year in the fixed bycatch fishery for the 2017 model and each of the Gmacs model scenarios.

Figure 20: Observed and model estimated size-frequencies of discarded female BBRKC by year in the fixed bycatch fishery for the 2017 model and each of the Gmacs model scenarios.

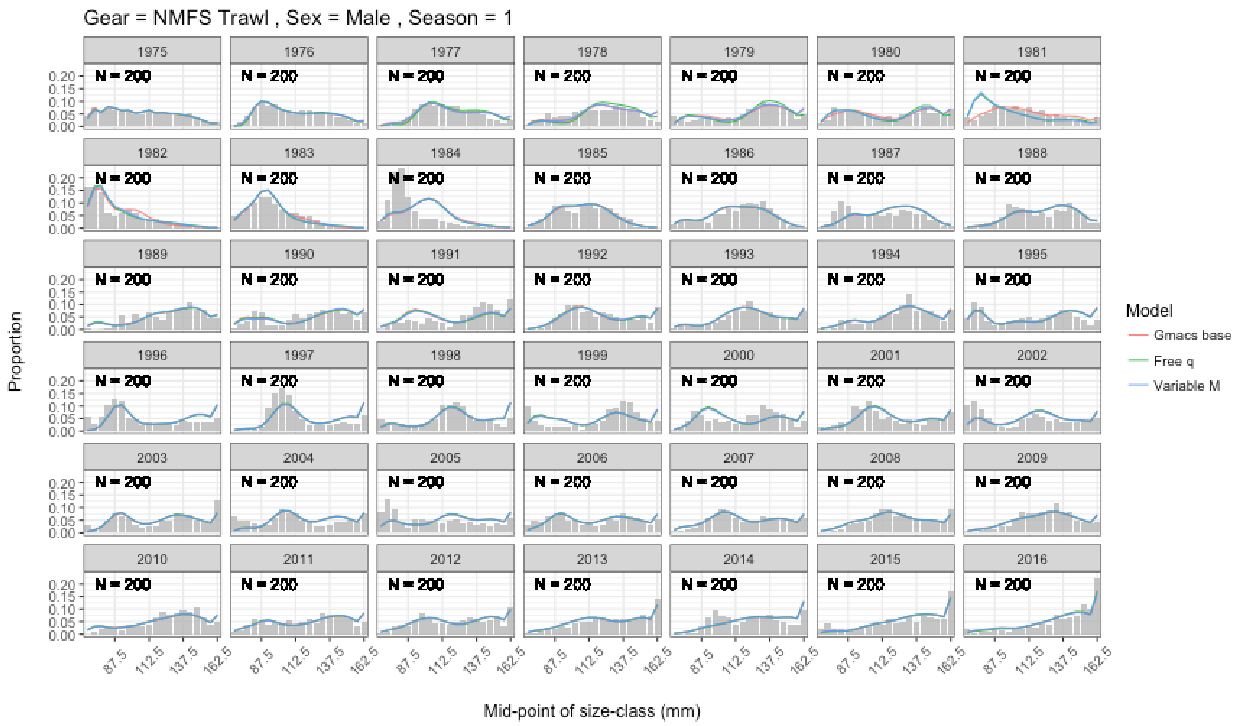

Figure 21: Observed and model estimated size-frequencies of discarded male BBRKC by year in the NMFS trawl survey for the 2017 model and each of the Gmacs model scenarios.

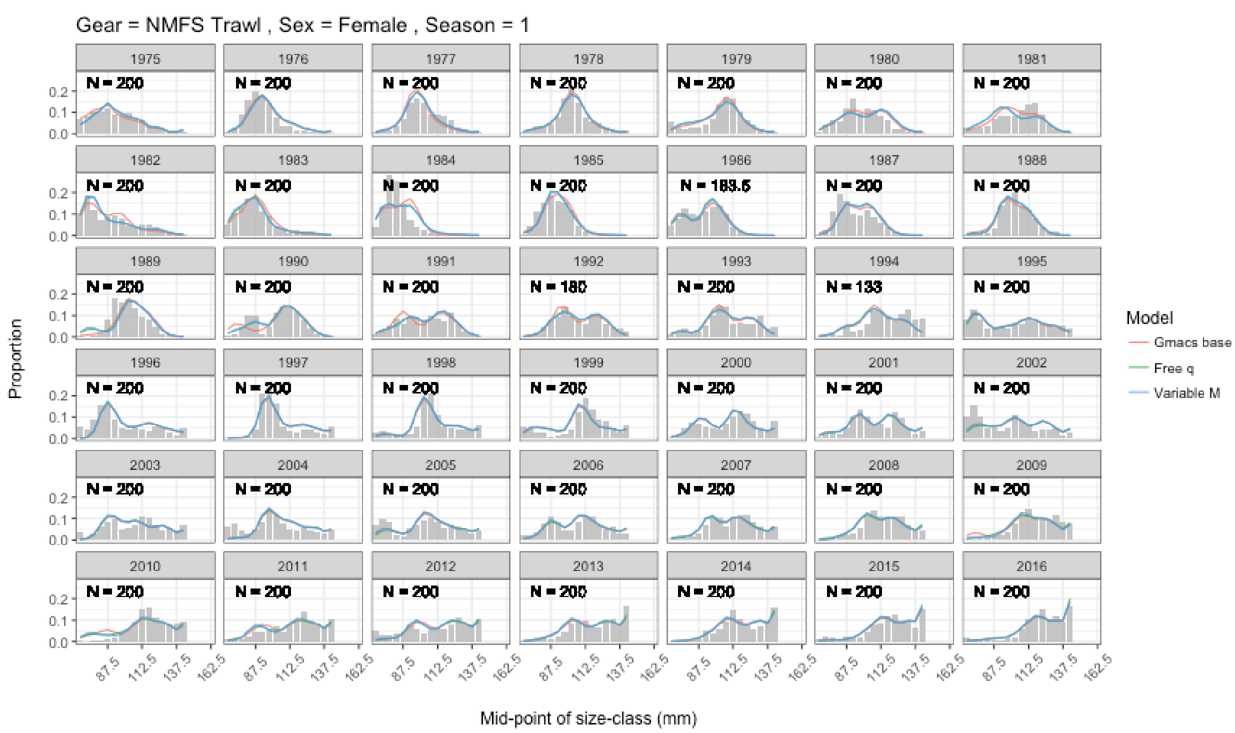

Figure 22: Observed and model estimated size-frequencies of discarded female BBRKC by year in the NMFS trawl survey for the 2017 model and each of the Gmacs model scenarios.

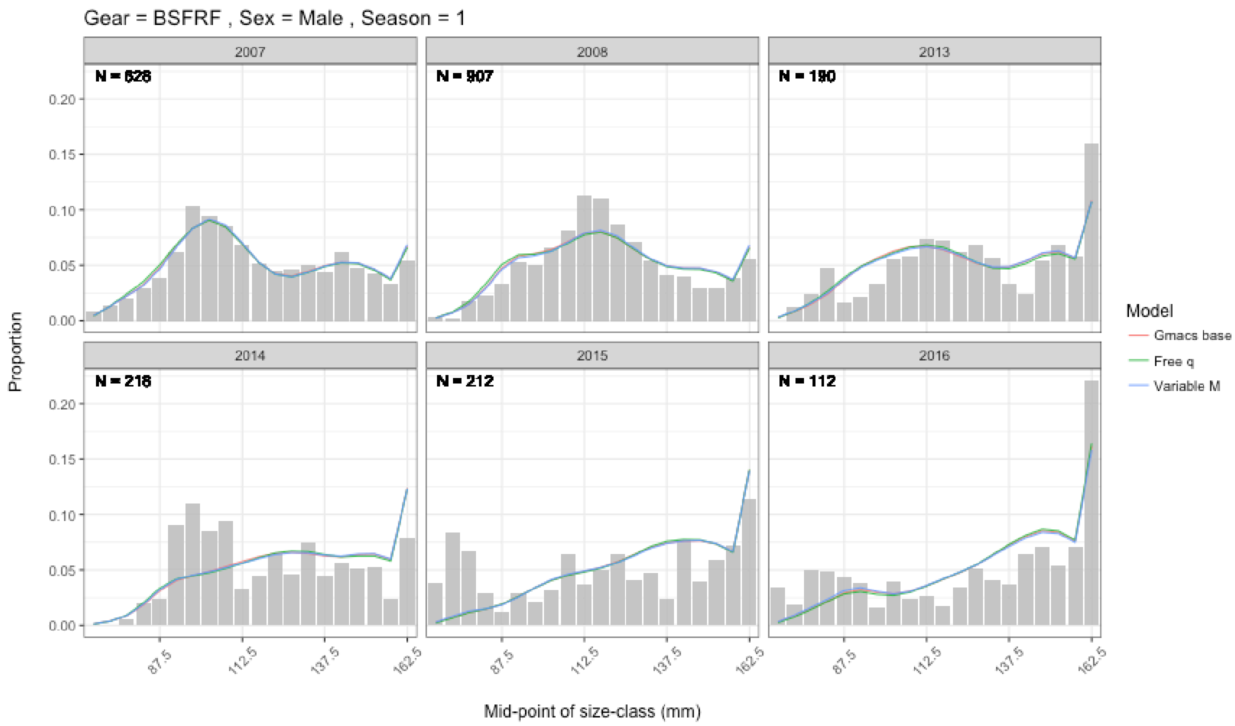

Figure 23: Observed and model estimated size-frequencies of discarded male BBRKC by year in the BSFRF survey for the 2017 model and each of the Gmacs model scenarios.

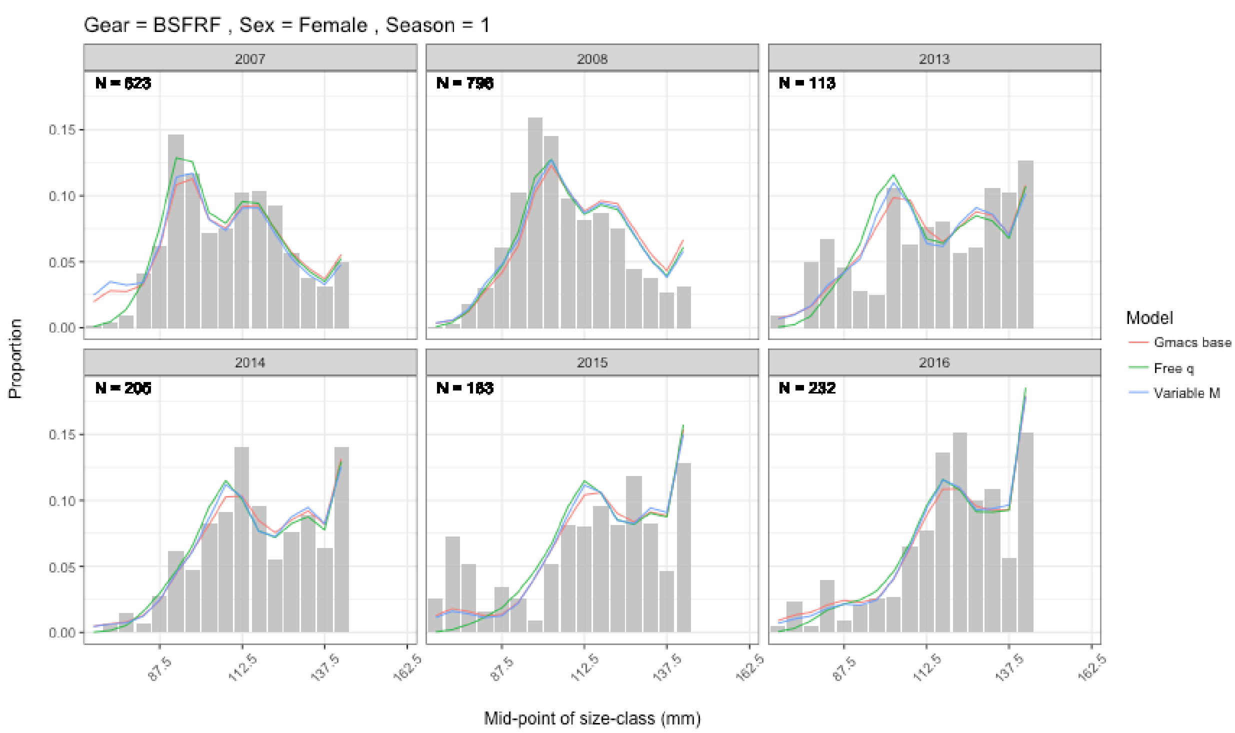

Figure 24: Observed and model estimated size-frequencies of discarded female BBRKC by year in the BSFRF survey for the 2017 model and each of the Gmacs model scenarios.

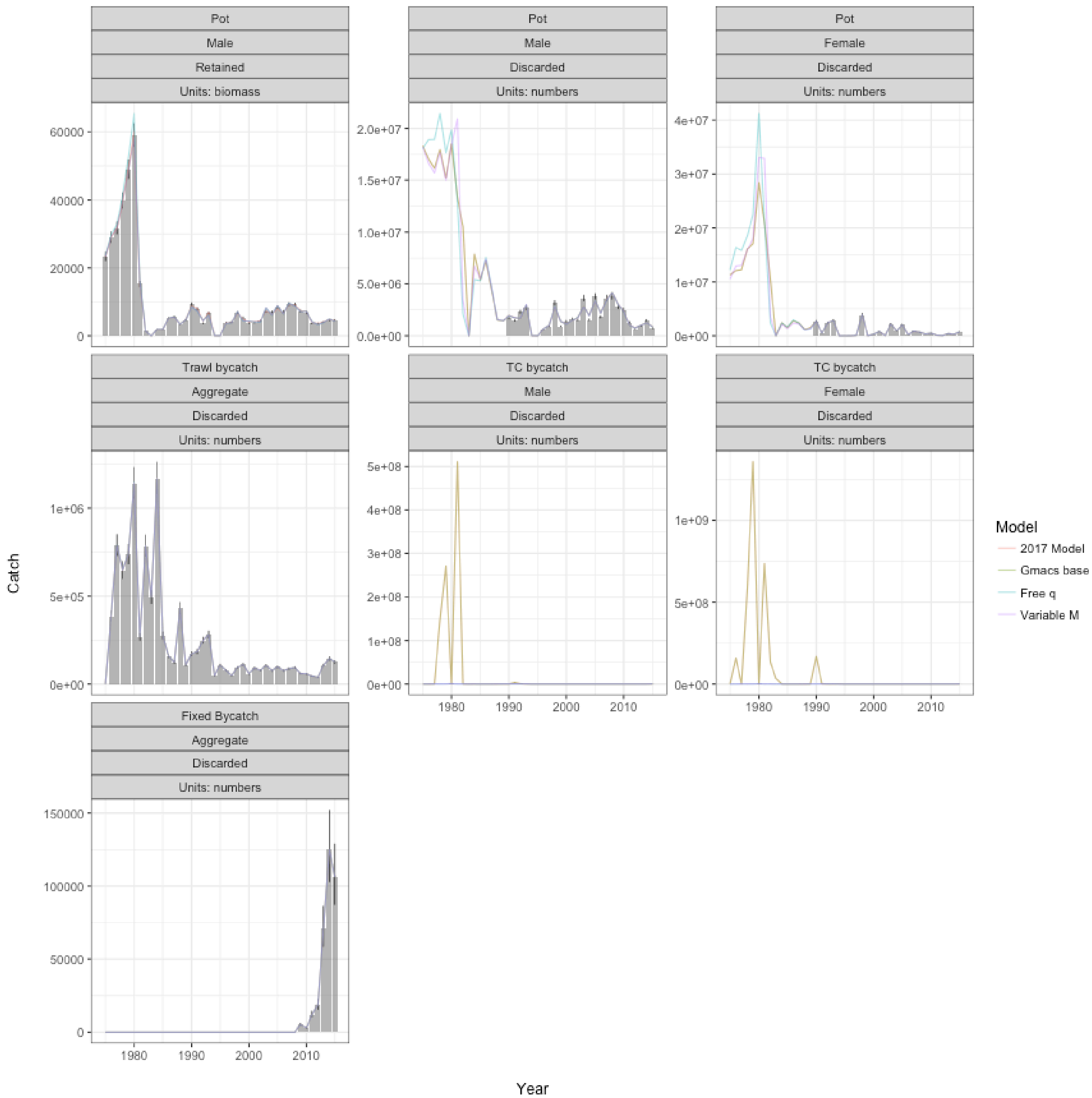

Figure 25: Comparison of observed and model predicted retained catch and bycatches in each of the Gmacs models. Note that difference in units between each of the panels, some panels are expressed in numbers of crab, some as biomass (tons).

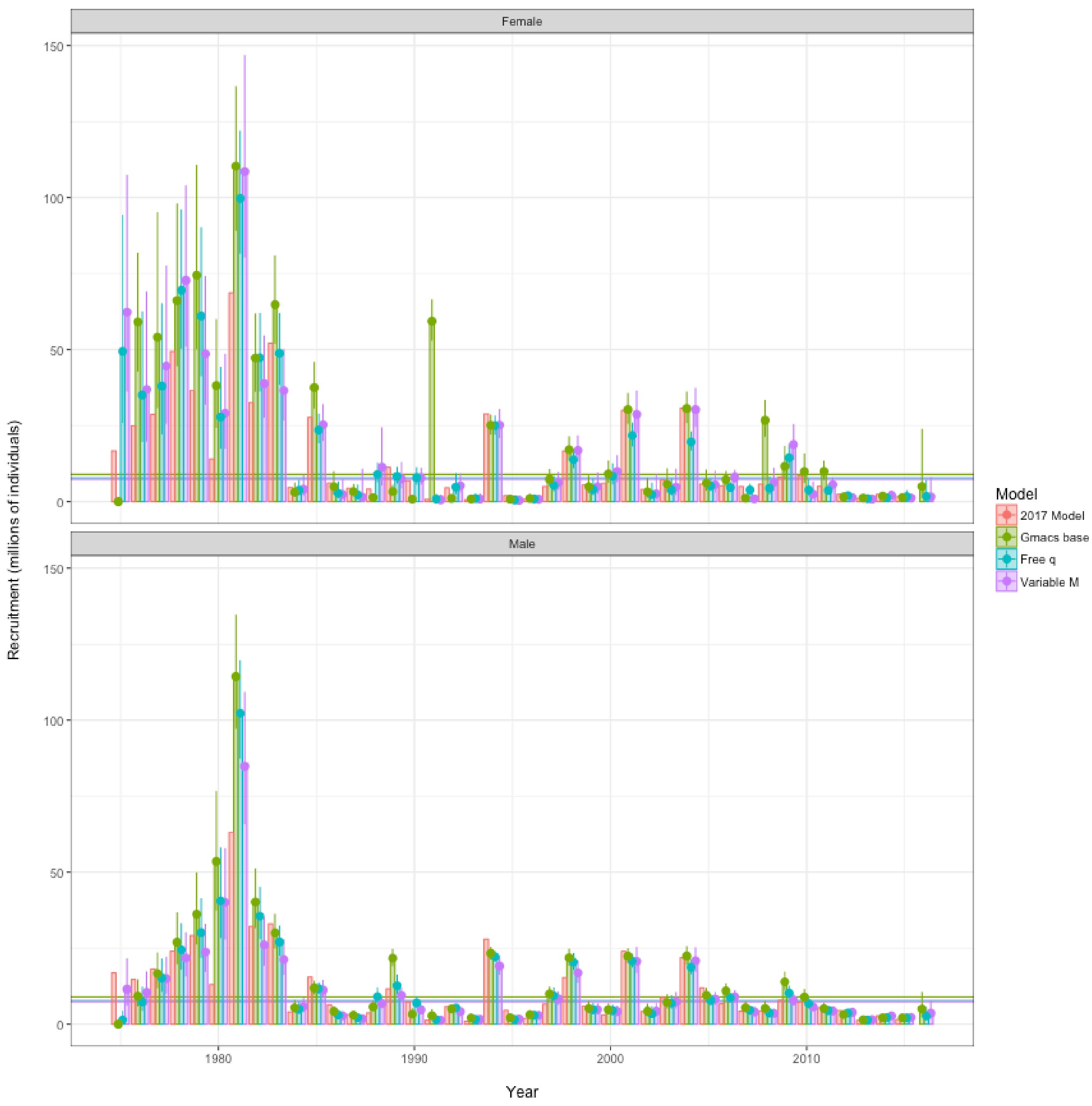

Figure 26: Comparisons of estimated recruitment time series during 1975-2016 in each of the scenarios. The solid horizontal lines in the background represent the estimate of the average recruitment parameter ($\bar{R}$) in each model scenario.

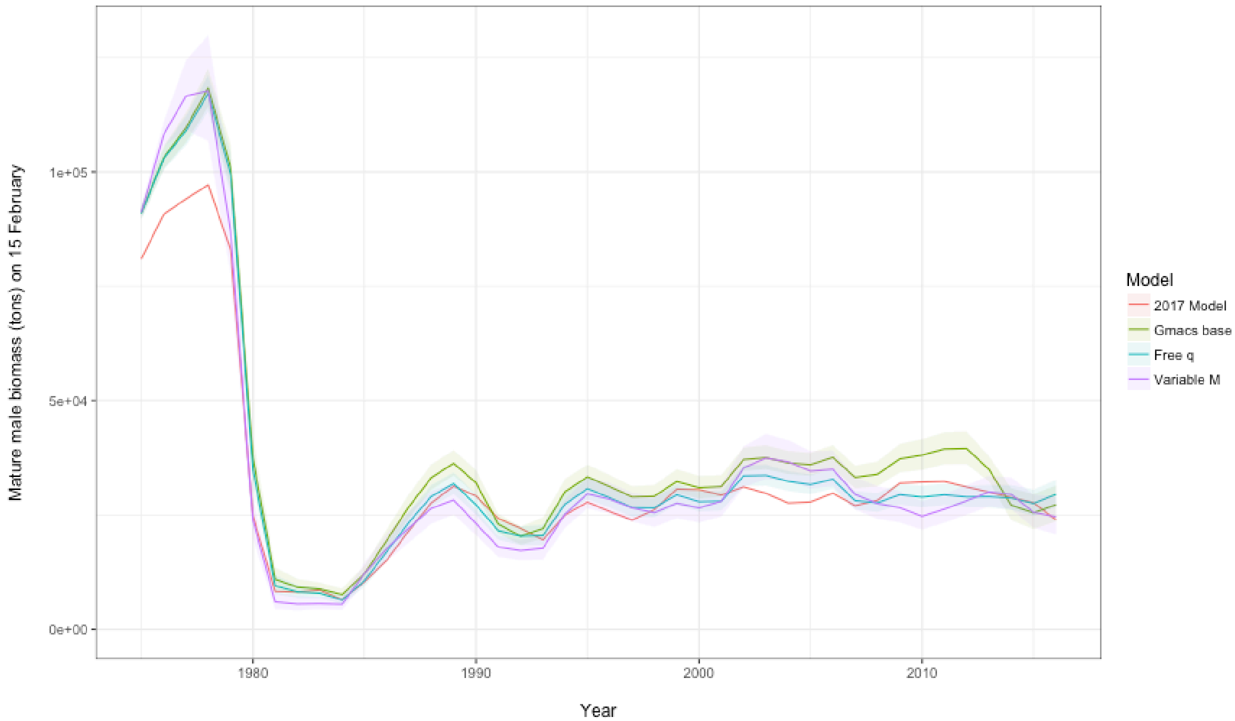

Figure 27: Comparisons of estimated mature male biomass (MMB) time series on 15 February during 1975-2016 for each of the model scenarios.

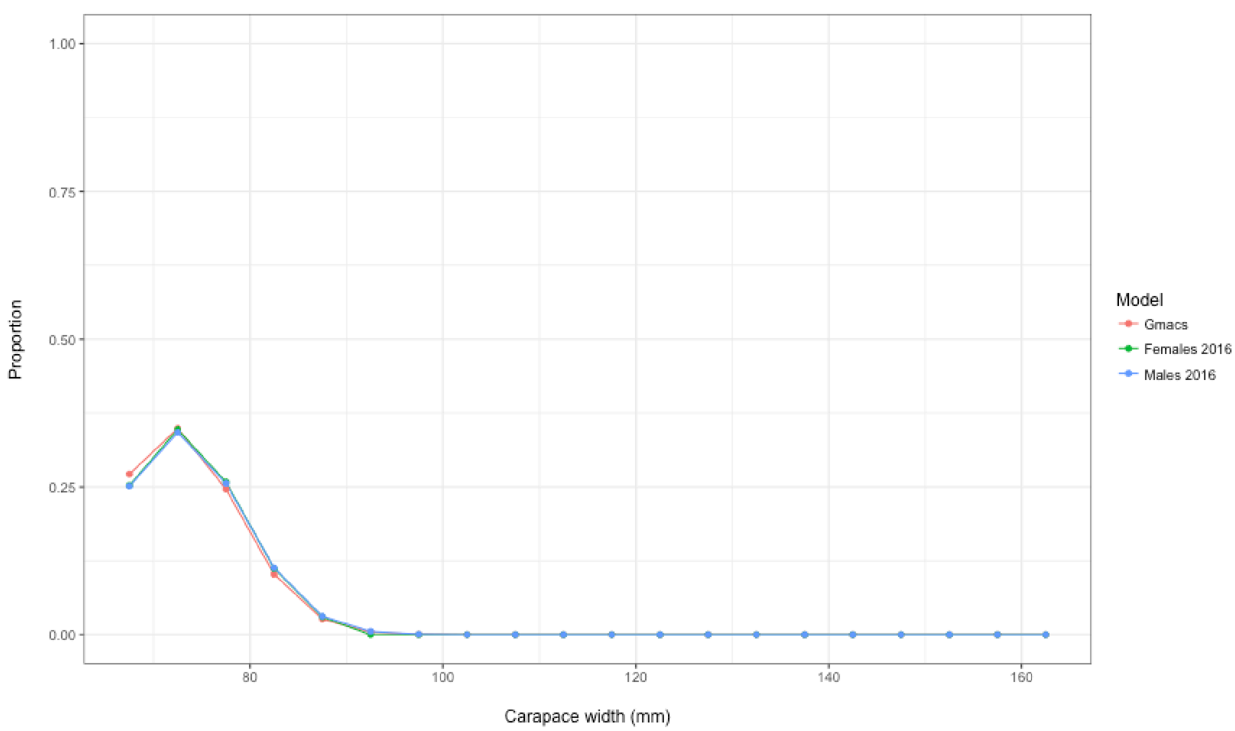

Figure 28: Distribution of carapace width (mm) at recruitment.

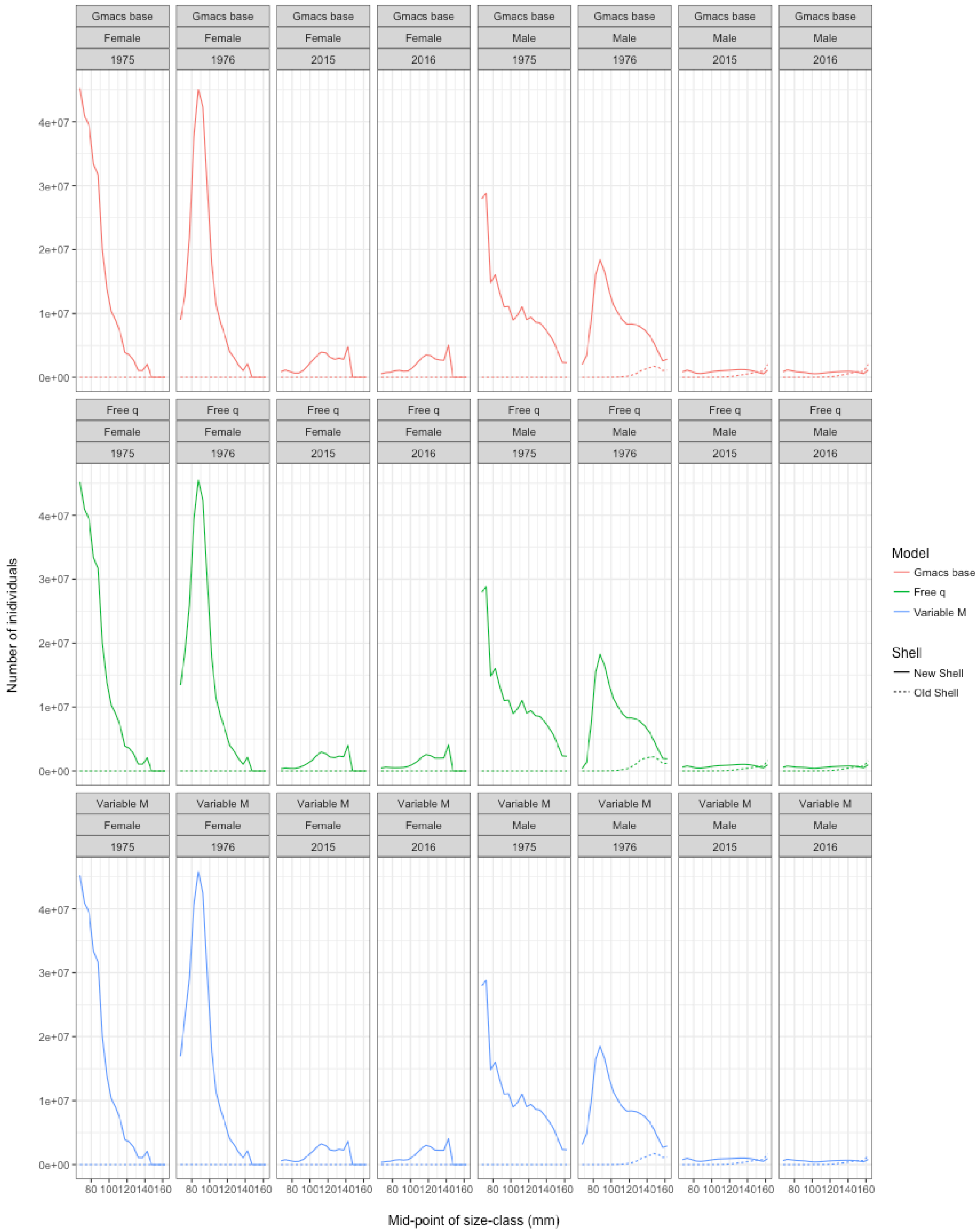

Figure 29: Numbers by stage each year (at the beginning of the model year, i.e. 1 July, season 1) in each of the models including the 2017 model.

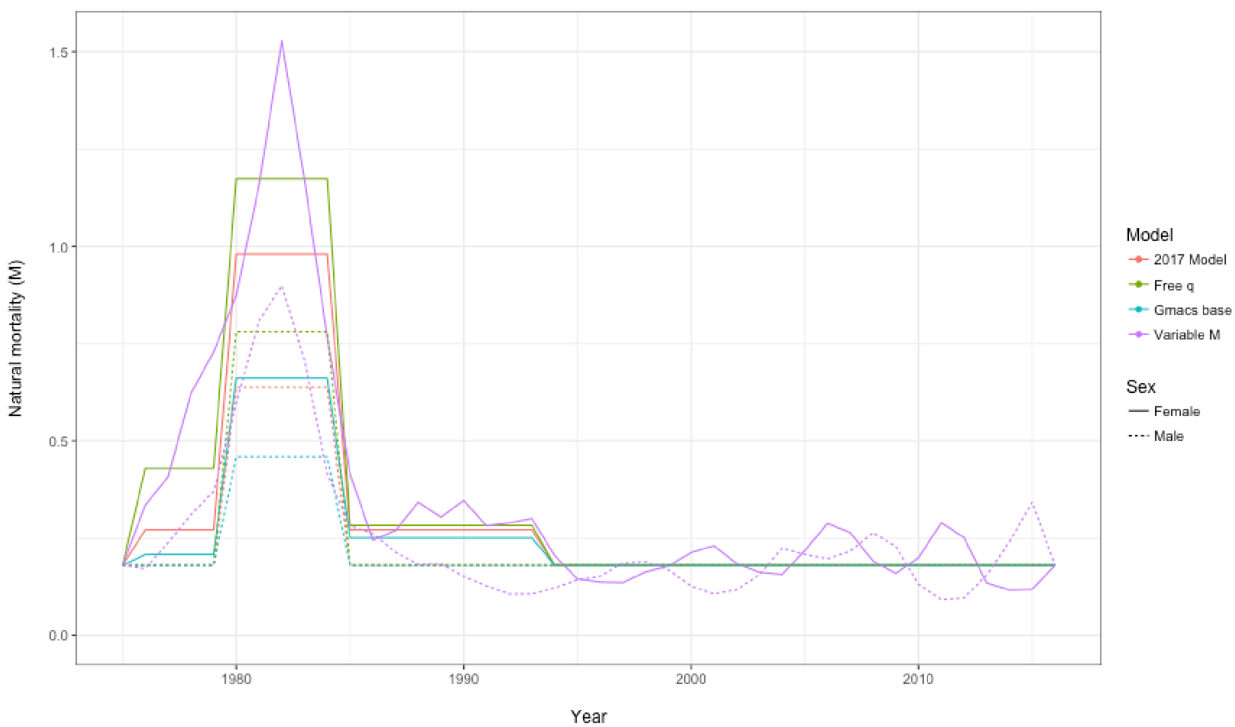

Figure 30: Time-varying natural mortality (M_t).

Appendix A: BBRKC Model Description

1. Introduction

The Gmacs model has been specified to account for newshell and oldshell, male and female crab. These are partitioned into 20 stages (size-classes) determined by carapace length (CL) measurements from 65-70 mm through to 160-165 mm.

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 4 seasons (t) and a proportion of the natural mortality (τ_t) is applied in each of these seasons where $\sum_{t=1}^{t=4} \tau_t = 1$. Each model year consists of the following processes:

1. Season 1
   - Beginning of the BBRKC fishing year (1 July)
   - $\tau_1 = 0.01$
   - Surveys
2. Season 2
   - τ_2 ranges from 0.2329 to 0.3507 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)
   - Fishing mortality applied
3. Season 3
   - $\tau_3 = 1 - (\tau_1 + \tau_2 + \tau_4)$
   - Calculate MMB (15 February)
4. Season 4
   - $\tau_4 = 0.306$
   - 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 15. 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_3 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

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

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 BBRKC formulation of Gmacs specifies recruitment to several stages during season $t = 4$, thus the recruitment size distribution is

$$\phi_l = \Gamma(\alpha, \beta), \tag{3}$$

and the recruitment is

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

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

$$\delta^R_y \sim \mathcal{N}\left(0, \sigma^2_R\right). \tag{5}$$

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

$$\boldsymbol{G} = \left[\begin{array}{ccc} 1 - \pi_{12} - \pi_{13} & \pi_{12} & \pi_{1\ldots} \\ 0 & 1 - \pi_{23} & \pi_{2\ldots} \\ & \ddots & \\ 0 & & \pi_{\ldots\ldots} \\ 0 & 0 & 1 \end{array} \right], \tag{6}$$

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

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

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

$$F_{t,y} = F^{\text{df}}_{t,y} + F^{\text{tb}}_{t,y} + F^{\text{tcb}}_{t,y} + F^{\text{fgb}}_{t,y} \tag{8}$$

where $F^{\text{df}}_{t,y}$ is the fishing mortality associated with the directed fishery, $F^{\text{tb}}_{t,y}$ is the fishing mortality associated with the trawl bycatch fishery, $F^{\text{tc}}_{t,y}$ is the fishing mortality associated with the tanner crab bycatch fishery, and $F^{\text{fgb}}_{t,y}$ is the fishing mortality associated with the fixed gear bycatch fishery. Each of these are derived as

$$\begin{aligned} F^{\text{df}}_{t,y} &= \bar{F}^{\text{df}} + \delta^{\text{df}}_{t,y} \quad \text{where} \quad \delta^{\text{df}}_{t,y} \sim \mathcal{N}\left(0, \sigma^2_{\text{df}}\right), \\ F^{\text{tb}}_{t,y} &= \bar{F}^{\text{tb}} + \delta^{\text{tb}}_{t,y} \quad \text{where} \quad \delta^{\text{tb}}_{t,y} \sim \mathcal{N}\left(0, \sigma^2_{\text{tb}}\right), \\ F^{\text{tcb}}_{t,y} &= \bar{F}^{\text{tcb}} + \delta^{\text{tcb}}_{t,y} \quad \text{where} \quad \delta^{\text{tcb}}_{t,y} \sim \mathcal{N}\left(0, \sigma^2_{\text{tcb}}\right), \\ F^{\text{fgb}}_{t,y} &= \bar{F}^{\text{fgb}} + \delta^{\text{fgb}}_{t,y} \quad \text{where} \quad \delta^{\text{fgb}}_{t,y} \sim \mathcal{N}\left(0, \sigma^2_{\text{fgb}}\right), \end{aligned} \tag{9}$$

where $\delta^{\text{df}}_{t,y}$, $\delta^{\text{tb}}_{t,y}$, $\delta^{\text{tcb}}_{t,y}$, and $\delta^{\text{fgb}}_{t,y}$ are the fishing mortality deviations for each of the fisheries, each season t during each year y, $\bar{F}^{\text{df}}$, $\bar{F}^{\text{tb}}$, $\bar{F}^{\text{tcb}}$, and $\bar{F}^{\text{fgb}}$ 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

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

The basic population dynamics underlying Gmacs can thus be described as

$$
\begin{aligned}
\boldsymbol{n}_{t+1,y} &= \boldsymbol{S}_{t,y}\boldsymbol{n}_{t,y}, && \text{if } t < 4 \\
\boldsymbol{n}_{t,y+1} &= \boldsymbol{G}\boldsymbol{S}_{t,y}\boldsymbol{n}_{t,y} + \boldsymbol{r}_{t,y} && \text{if } t = 4.
\end{aligned} \tag{12}
$$

3. Model Data

Data inputs used in model estimation are listed in Table 16.

4. Model Parameters

Table 17 lists fixed (externally determined) parameters used in model computations.

Estimated parameters are listed in Table 18 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 13). A lognormal distribution is assumed to characterize the catch data and is modelled as

$$
\sigma^{\text{catch}}_{t,y} = \sqrt{\log\left(1 + \left(CV^{\text{catch}}_{t,y}\right)^2\right)} \tag{13}
$$

$$
\delta^{\text{catch}}_{t,y} = \mathcal{N}\left(0, \left(\sigma^{\text{catch}}_{t,y}\right)^2\right) \tag{14}
$$

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

$$
\sigma^{\text{I}}_{t,y} = \frac{1}{\lambda}\sqrt{\log\left(1 + \left(CV^{\text{I}}_{t,y}\right)^2\right)} \tag{15}
$$

$$
\delta^{\text{I}}_{t,y} = \log\left(I^{\text{obs}}/I^{\text{pred}}\right)/\sigma^{\text{I}}_{t,y} + 0.5\sigma^{\text{I}}_{t,y} \tag{16}
$$

and the likelihood is

$$
\sum \log\left(\delta^{\text{I}}_{t,y}\right) + \sum 0.5\left(\sigma^{\text{I}}_{t,y}\right)^2 \tag{17}
$$

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 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.

Table 15: 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
1975	0.01	0.23	0.45	0.31
1976	0.01	0.28	0.40	0.31
1977	0.01	0.32	0.36	0.31
1978	0.01	0.25	0.43	0.31
1979	0.01	0.25	0.43	0.31
1980	0.01	0.25	0.43	0.31
1981	0.01	0.25	0.43	0.31
1982	0.01	0.24	0.45	0.31
1983	0.01	0.24	0.44	0.31
1984	0.01	0.27	0.41	0.31
1985	0.01	0.24	0.44	0.31
1986	0.01	0.25	0.43	0.31
1987	0.01	0.25	0.43	0.31
1988	0.01	0.24	0.44	0.31
1989	0.01	0.25	0.43	0.31
1990	0.01	0.35	0.33	0.31
1991	0.01	0.34	0.34	0.31
1992	0.01	0.34	0.34	0.31
1993	0.01	0.35	0.34	0.31
1994	0.01	0.34	0.34	0.31
1995	0.01	0.34	0.34	0.31
1996	0.01	0.34	0.34	0.31
1997	0.01	0.34	0.34	0.31
1998	0.01	0.34	0.34	0.31
1999	0.01	0.30	0.38	0.31
2000	0.01	0.30	0.38	0.31
2001	0.01	0.30	0.38	0.31
2002	0.01	0.30	0.38	0.31
2003	0.01	0.30	0.38	0.31
2004	0.01	0.30	0.38	0.31
2005	0.01	0.30	0.38	0.31
2006	0.01	0.30	0.38	0.31
2007	0.01	0.30	0.38	0.31
2008	0.01	0.30	0.38	0.31
2009	0.01	0.30	0.38	0.31
2010	0.01	0.30	0.38	0.31
2011	0.01	0.30	0.38	0.31
2012	0.01	0.30	0.38	0.31
2013	0.01	0.30	0.38	0.31
2014	0.01	0.30	0.38	0.31
2015	0.01	0.30	0.38	0.31
2016	0.01	0.30	0.38	0.31

Table 16: Data inputs used in model estimation.

Data	Years	Source
Directed pot-fishery retained-catch	1975/76 - 2015/16	Fish tickets and NMFS groundfish observers
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
BSFRF survey biomass abundance index and CV	2007, 2008, and 2013-2016	BSFRF survey biomass

Table 17: Fixed model parameters for all scenarios.

Parameter	Symbol	Value	Source/rationale
BSFRF survey catchability	q	1.0	Default
Natural mortality	M	0.18 yr^{-1}	NPFMC (2007)
Weight at length mean weights	w_l	-	Length-weight equation (B. Foy, NMFS) applied to stage midpoints
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

Table 18: 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 $\log(\bar{R})$	-10	14.0	20	Uniform(-10,20)	1
BSFRF trawl survey catchability q	0	4.0	5	Uniform(0,5)	1
Directed fishery male selectivity 50% 1975-2016	0	100	1	Uniform(0,1)	3
Directed fishery male selectivity 95% 1975-2016	0	120	1	Uniform(0,1)	3
Directed fishery female selectivity 50% 1975-2016	0	84	1	Uniform(0,1)	3
Directed fishery female selectivity 95% 1975-2016	0	95	1	Uniform(0,1)	3
Trawl bycatch fishery selectivity 50%	0	100	1	Uniform(0,1)	4
Trawl bycatch fishery selectivity 95%	0	120	1	Uniform(0,1)	4
NMFS trawl survey selectivity 50%	0	100	1	Uniform(0,1)	4
NMFS trawl survey selectivity 95%	0	120	1	Uniform(0,1)	4
BSFRF trawl survey selectivity 50%	0	100	1	Uniform(0,1)	4
BSFRF trawl survey selectivity 95%	0	120	1	Uniform(0,1)	4
Natural mortality deviation during 1998 δ^M_{1998}	-3	0.0	3	Normal(0, σ^2_M)	4
Recruitment deviations δ^R_y	-7	0.0	7	Normal(0, σ^2_R)	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