

# 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).

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                   |      | Retained catch | Total catch | OFL  | ABC  |
|---------|--------------------|---------------------------|------|----------------|-------------|------|------|
|         |                    | ( $MMB_{\text{mating}}$ ) | TAC  |                |             |      |      |
| 2012/13 | 13.19 <sup>A</sup> | 29.05 <sup>A</sup>        | 3.56 | 3.62           | 3.9         | 7.96 | 7.17 |
| 2013/14 | 12.85 <sup>B</sup> | 27.12 <sup>B</sup>        | 3.90 | 3.99           | 4.56        | 7.07 | 6.36 |
| 2014/15 | 13.03 <sup>C</sup> | 27.25 <sup>C</sup>        | 4.49 | 4.54           | 5.44        | 6.82 | 6.14 |
| 2015/16 | 12.89 <sup>D</sup> | 27.68 <sup>D</sup>        | 4.52 | 4.61           | 5.34        | 6.73 | 6.06 |
| 2016/17 |                    | 24.00 <sup>D</sup>        |      |                |             | 6.64 | 5.97 |

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

| Year    | MSST              | Biomass<br>( $MMB_{\text{mat}}^{\text{ing}}$ ) | TAC  | Retained<br>catch | Total<br>catch | OFL   | ABC   |
|---------|-------------------|--|------|-------------------|----------------|-------|-------|
| 2012/13 | 29.1 <sup>A</sup> | 64.0 <sup>A</sup>                              | 7.85 | 7.98              | 8.59           | 17.55 | 15.8  |
| 2013/14 | 28.3 <sup>B</sup> | 59.9 <sup>B</sup>                              | 8.6  | 8.8               | 10.05          | 15.58 | 14.02 |
| 2014/15 | 28.7 <sup>C</sup> | 60.1 <sup>C</sup>                              | 9.99 | 10.01             | 11.99          | 15.04 | 13.53 |
| 2015/16 | 28.4 <sup>D</sup> | 61.0 <sup>D</sup>                              | 9.97 | 10.17             | 11.77          | 14.84 | 13.36 |
| 2016/17 |                   | 52.9 <sup>D</sup>                              |      |                   |                | 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 4 stock, with males measuring 105 mm CL or more considered mature. The  $B_{MSY}$  proxy is obtained by averaging estimated MMB over a specific reference time period, and current CPT/SSC guidance recommends using the full assessment time frame as the default reference period (Table 3).

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

| Year    | Tier | $B_{MSY}$ | Biomass<br>( $MMB_{\text{mat}}^{\text{ing}}$ ) | $B/B_{MSY}$ | $F_{OFL}$ | $\gamma$ | Basis for $B_{MSY}$ | Natural<br>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<br>( $MMB_{\text{mat}}^{\text{ing}}$ ) | $B/B_{MSY}$ | $F_{OFL}$ | $\gamma$ | Basis for $B_{MSY}$ | Natural<br>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

- 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

### 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 spermatophore 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) frameworked in the FMP, and (3) discretion of the State of Alaska. The State of Alaska is responsible for determining and establishing the GH/L/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 GH/L/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 GH/L 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 GH/L threshold in 2012. The current harvest strategy is illustrated in Figure ??).

## 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 2.

### 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 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.

## Mature Harvest Rate

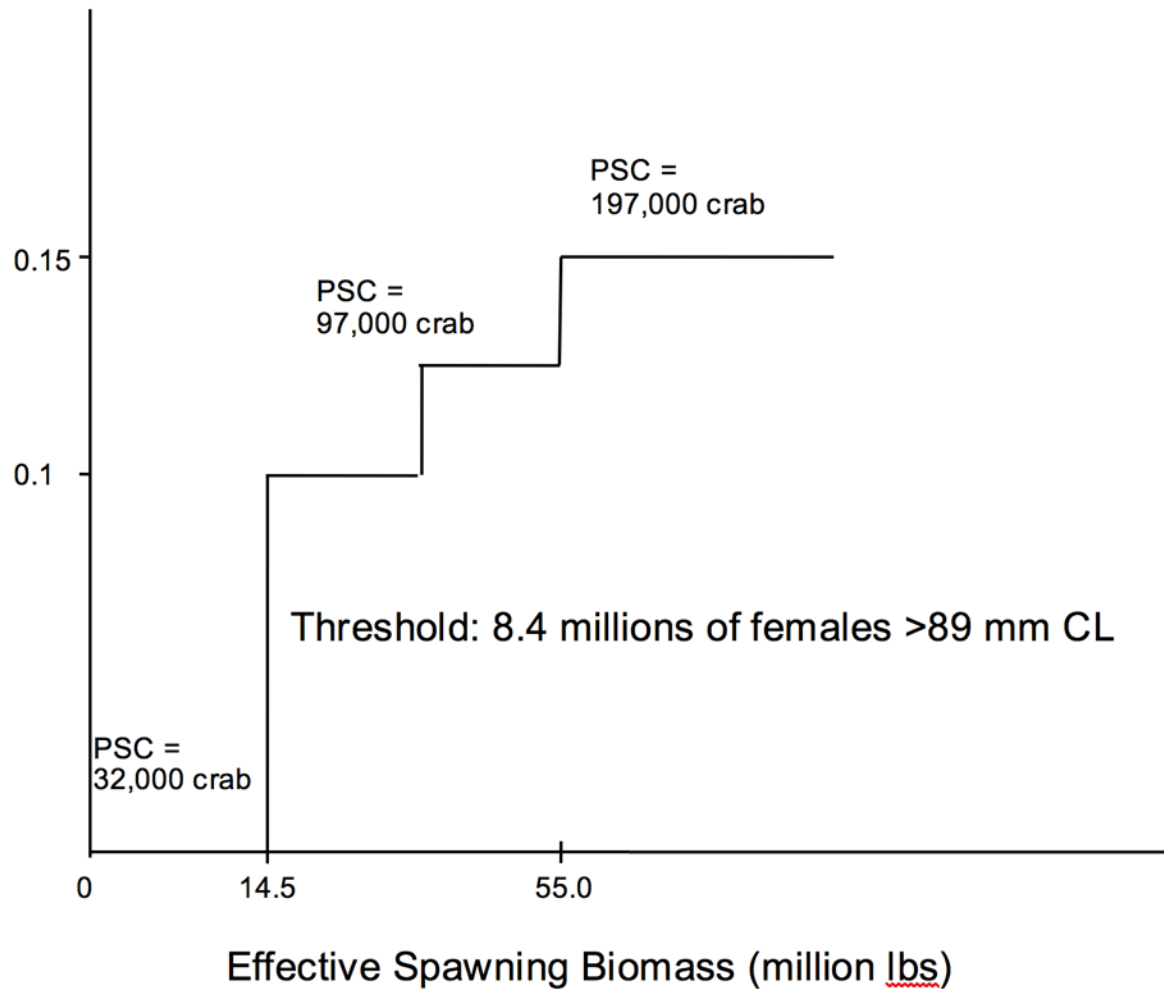


Figure 1: Current harvest rate strategy (line) for the Bristol Bay red king crab fishery and annual prohibited species catch (PSC) limits (numbers of crab) of Bristol Bay red king crab in the groundfish fisheries in zone 1 in the eastern Bering Sea. Harvest rates are based on current-year estimates of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

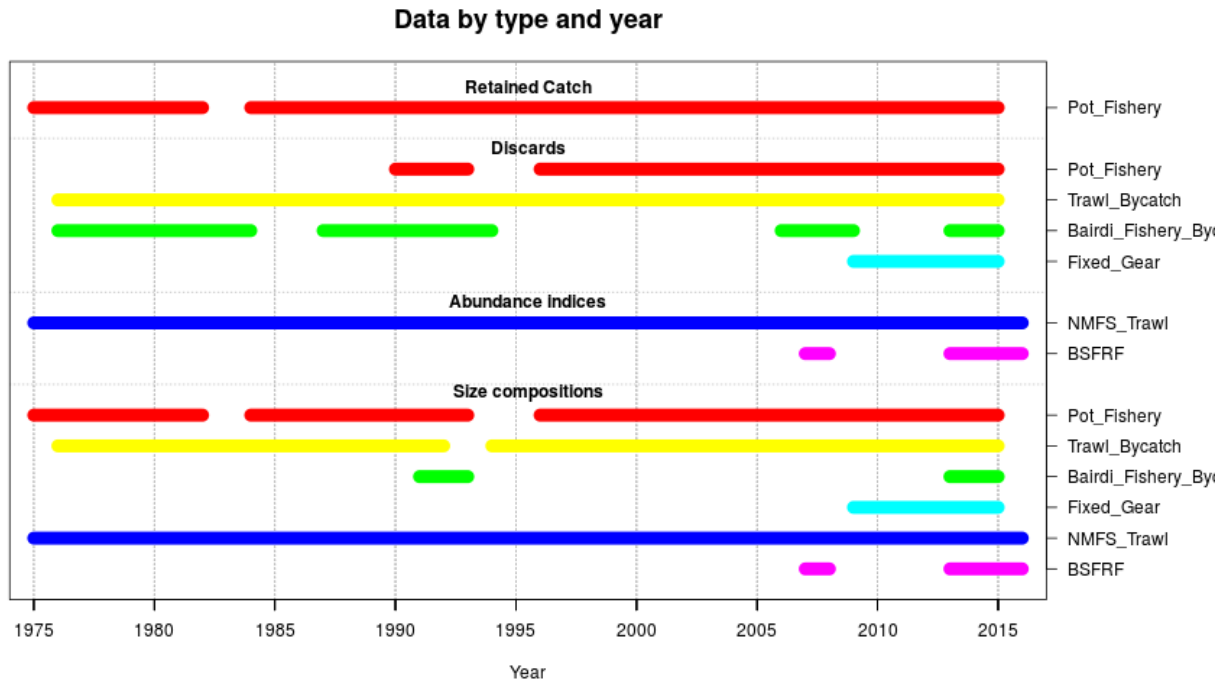


Figure 2: Data extent for the BBRKC assessment.

### 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 nm<sup>2</sup>. 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 omitted 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 |               |         | Total   | Pot    | Bycatch | Trawl | Tanner Fshry | Total   | Catch   |
|------|----------------|---------------|---------|---------|--------|---------|-------|--------------|---------|---------|
|      | U.S.           | Cost-Recovery | Foreign |         | Males  | Females |       | Bycatch      | Bycatch |         |
| 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.

| Year | Trawl survey |         | Retained<br>Catch | Pot bycatch |         | Trawl bycatch |         | Tanner bycatch |         |
|------|--------------|---------|-------------------|-------------|---------|---------------|---------|----------------|---------|
|      | Males        | Females |                   | 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 ( $\delta_y^R$ ), the initial numbers in each size category ( $n^0$ ), 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. **Free q**: is similar to the scenario above except that it estimates the BSFRF survey catchability parameter  $q$  rather than fixing it at  $q = 1.0$ .
3. **Variable 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  $\sigma_M$  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 10, 11, 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 9 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 6.

The various model fits to total male ( $> 89$  mm CL) trawl survey biomass are compared in Figures 7 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 9 and ??.

Fits to stage compositions for trawl survey, pot survey, and commercial observer data are shown in Figures 10, 11, 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 12.

Estimated recruitment is compared in Figure 13. Estimated abundances by stage and mature male biomasses for all scenarios (including the 2015 model) are shown in Figures 16 and 14. Estimated natural mortality each year ( $M_t$ ) is presented in Figure 17.

## 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 7 and ??). Looking at the model fits to the NMFS trawl survey biomass (Figure 7), 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 slightly 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 expected 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 7, ??, ??, 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 13). Estimated recruitment during recent years is generally low in all scenarios. Estimated mature male biomass on 15 February also fluctuates strongly over time (Figure 14).

#### 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 14), 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- 1900s 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 abrupt, 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  $\alpha$  and  $\beta$ ,  $F_{OFL}$  is determined by the control rule

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

$F_{OFL} < F_{MSY}$  with directed fishery  $F = 0$  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  $M = 0.18 \text{ yr}^{-1}$  in setting the  $F_{MSY}$  proxy value  $\gamma M$ . The parameters  $\alpha$  and  $\beta$  are assigned their default values  $\alpha = 0.10$  and  $\beta = 0.25$ . The  $F_{OFL}$ , OFL, 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

Alaska Department of Fish and Game (ADF&G). 2012. Commercial king and Tanner crab fishing regulations, 2012-2013. Alaska Department of Fish and Game, Division of Commercial Fisheries, Juneau. 170 pp.

- Balsiger, J.W. 1974. A computer simulation model for the eastern Bering Sea king crab. Ph.D. dissertation, Univ. Washington, Seattle, WA. 198 pp.
- Fitch, H., M. Deiman, J. Shaishnikoff, and K. Herring. 2012. Annual management report for the commercial shellfish fisheries of the Bering Sea, 2010/11. In Fitch, H. M. Schwenzfeier, B. Baechler, T. Hartill, M. Salmon, M. Deiman, E. Evans, E. Henry, L. Wald, J. Shaishnikoff, K. Herring, and J. Wilson. 2012. Annual management report for the commercial and subsistence fisheries of the Aleutian Islands, Bering Sea and the Westward Region's shellfish observer program, 2010/11. Alaska Department of Fish and Game, Fishery Management report No. 12-22, Anchorage.
- Fournier, D.A., J. Hampton, and J.R. Sibert. 1998. MULTIFAN-CL: a length-based, age-structured model for fisheries stock assessment, with application to South Pacific albacore, *Thunnus alalunga*. *Can.J.Fish.Aquat. Sci.*, 55:2105-2116.
- Fournier, D.A., H.J. Skaug, J. Ancheta, J. Ianelli, A. Magnusson, M.N. Maunder, A. Nielsen, and J. Sibert. 2012. AD Model Builder: using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. *Optim. Methods Softw.* 27:233-249.
- Gaeuman, W.G. 2013. Summary of the 2012/13 mandatory crab observer program database for the Bering Sea/Aleutian Islands commercial crab fisheries. Alaska Department of Fish and game, Fishery Data Series No. 13-54, Anchorage.
- Gray, G.W. 1963. Growth of mature female king crab *Paralithodes camtschaticus* (Tilesius). Alaska Dept. Fish and Game, Inf. Leaflet. 26. 4 pp.
- Griffin, K. L., M. F. Eaton, and R. S. Otto. 1983. An observer program to gather in-season and post-season on-the-grounds red king crab catch data in the southeastern Bering Sea. Contract 82-2, North Pacific Fishery Management Council, Anchorage, 39 pp.
- Haynes, E.B. 1968. Relation of fecundity and egg length to carapace length in the king crab, *Paralithodes camtschaticus*. *Proc. Nat. Shellfish Assoc.* 58: 60-62.
- Hoopes, D.T., J.F. Karinen, and M. J. Pelto. 1972. King and Tanner crab research. *Int. North Pac. Fish. Comm. Annu. Rep.* 1970:110-120.
- Ianelli, J.N., S. Barbeaux, G. Walters, and N. Williamson. 2003. Eastern Bering Sea walleye Pollock stock assessment. Pages 39-126 in Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands regions. North Pacific Fishery Management Council, Anchorage.
- Jackson, P.B. 1974. King and Tanner crab fishery of the United States in the Eastern Bering Sea, 1972. *Int. North Pac. Fish. Comm. Annu. Rep.* 1972:90-102.
- Loher, T., D.A. Armstrong, and B.G. Stevens. 2001. Growth of juvenile red king crab (*Paralithodes camtschaticus*) in Bristol Bay (Alaska) elucidated from field sampling and analysis of trawl-survey data. *Fish. Bull.* 99:572-587.
- Matsuura, S., and K. Takeshita. 1990. Longevity of red king crab, *Paralithodes camtschaticus*, revealed by long-term rearing study. Pages 247-266 in Proceedings of the International Symposium on King and Tanner Crabs. University Alaska Fairbanks, Alaska Sea Grant College Program Report 90-04, Fairbanks. 633 pp.
- McCaughran, D.A., and G.C. Powell. 1977. Growth model for Alaskan king crab (*Paralithodes camtschaticus*). *J. Fish. Res. Board Can.* 34:989-995.
- North Pacific Fishery Management Council (NPFMC). 2007. Environmental assessment for proposed amendment 24 to the fishery management plan for Bering Sea and Aleutian Islands king and Tanner crabs to revise overfishing definitions. A review draft.
- Otto, R.S. 1989. An overview of eastern Bering Sea king and Tanner crab fisheries. Pages 9-26 in Proceedings of the International Symposium on King and Tanner Crabs, Alaska Sea Grant College Program Report No. 90-04.



- Parma, A.M. 1993. Retrospective catch-at-age analysis of Pacific halibut: implications on assessment of harvesting policies. Pages 247-266 in G. Kruse, D.M. Eggers, R.J. Marasco, C. Pautzke, and T.J. Quinn II (eds.). Proceedings of the international symposium on management strategies for exploited fish populations. University of Alaska Fairbanks, Alaska Sea Grant Rep. 90-04.
- Paul, J.M., and A.J. Paul. 1990. Breeding success of sublegal size male red king crab *Paralithodes camtschaticus* (Tilesius, 1815) (Decapoda, Lithodidae). *J. Shellfish Res.* 9:29-32.
- Paul, J.M., A.J. Paul, R.S. Otto, and R.A. MacIntosh. 1991. Spermatophore presence in relation to carapace length for eastern Bering Sea blue king crab (*Paralithodes platypus*, Brandt, 1850) and red king crab (*P. camtschaticus*, Tilesius, 1815). *Journal of Shellfish research*, Vol. 10, No. 1, 157-163.
- Pengilly, D., S.F. Blau, and J.E. Blackburn. 2002. Size at maturity of Kodiak area female red king crab. Pages 213-224 in A.J. Paul, E.G. Dawe, R. Elner, G.S. Jamieson, G.H. Kruse, R.S. Otto, B. Sainte-Marie, T.C. Shirley, and D. Woodby (eds.). *Crabs in Cold Water Regions: Biology, Management, and Economics*. University of Alaska Sea Grant, AK-SG-02-01, Fairbanks.
- Pengilly, D., and D. Schmidt. 1995. Harvest strategy for Kodiak and Bristol Bay red king crab and St. Matthew Island and Pribilof Islands blue king crab. Alaska Dep. Fish and Game, Comm. Fish. Manage. and Dev. Div., Special Publication 7. Juneau, AK. 10 pp.
- Phinney, D.E. 1975. United States fishery for king and Tanner crabs in the eastern Bering Sea, 1973. *Int. North Pac. Fish. Comm. Annu. Rep.* 1973: 98-109.
- Powell, G.C. 1967. Growth of king crabs in the vicinity of Kodiak, Alaska. Alaska Dept. Fish and Game, Inf. Leaf. 92. 106 pp.
- Powell, G. C., and R.B. Nickerson. 1965. Aggregations among juvenile king crab (*Paralithodes camtschaticus*, Tilesius) Kodiak, Alaska. *Animal Behavior* 13: 374-380.
- Schmidt, D., and D. Pengilly. 1990. Alternative red king crab fishery management practices: modeling the effects of varying size-sex restrictions and harvest rates, p.551-566. In *Proc. Int. Symp. King & Tanner Crabs*, Alaska Sea Grant Rep. 90-04.
- Sparks, A.K., and J.F. Morado. 1985. A preliminary report on diseases of Alaska king crabs, p.333-340. In *Proc. Int. Symp. King & Tanner Crabs*, Alaska Sea Grant Rep. 85-12.
- Stevens, B.G. 1990. Temperature-dependent growth of juvenile red king crab (*Paralithodes camtschaticus*), and its effects on size-at-age and subsequent recruitment in the eastern Bering Sea. *Can. J. Fish. Aquat. Sci.* 47: 1307-1317.
- Stevens, B.G., and K. Swiney. 2007. Hatch timing, incubation period, and reproductive cycle for primiparous and multiparous red king crab, *Paralithodes camtschaticus*. *J. Crust. Bio.* 27(1): 37-48.
- Swiney, K. M., W.C. Long, G.L. Eckert, and G.H. Kruse. 2012. Red king crab, *Paralithodes camtschaticus*, size-fecundity relationship, and interannual and seasonal variability in fecundity. *Journal of Shellfish Research*, 31:4, 925-933.
- Webb, J. 2014. Reproductive ecology of commercially important Lithodid crabs. Pages 285-314 In B.G. Stevens (ed.): *King Crabs of the World: Biology and Fisheries Management*. CRC Press, Taylor & Francis Group, New York.
- Weber, D.D. 1967. Growth of the immature king crab *Paralithodes camtschaticus* (Tilesius). *Int. North Pac. Fish. Comm. Bull.* 21:21-53.
- Weber, D.D., and T. Miyahara. 1962. Growth of the adult male king crab, *Paralithodes camtschaticus* (Tilesius). *Fish. Bull. U.S.* 62:53-75.
- Weinberg, K.L., R.S. Otto, and D.A. Somerton. 2004. Capture probability of a survey trawl for red king crab (*Paralithodes camtschaticus*). *Fish. Bull.* 102:740-749.

Zheng, J. 2005. A review of natural mortality estimation for crab stocks: data-limited for every stock? Pages 595-612 in G.H. Kruse, V.F. Gallucci, D.E. Hay, R.I. Perry, R.M. Peterman, T.C. Shirley, P.D. Spencer, B. Wilson, and D. Woodby (eds.). Fisheries Assessment and Management in Data-limited Situation. Alaska Sea Grant College Program, AK-SG-05-02, Fairbanks.

Zheng, J., and G.H. Kruse. 2002. Retrospective length-based analysis of Bristol Bay red king crabs: model evaluation and management implications. Pages 475-494 in A.J. Paul, E.G. Dawe, R. Elner, G.S. Jamieson, G.H. Kruse, R.S. Otto, B. Sainte-Marie, T.C. Shirley, and D. Woodby (eds.). Crabs in Cold Water Regions: Biology, Management, and Economics. University of Alaska Sea Grant, AK-SG-02-01, Fairbanks.

Zheng, J., M.C. Murphy, and G.H. Kruse. 1995a. A length-based population model and stock-recruitment relationships for red king crab, *Paralithodes camtschaticus*, in Bristol Bay, Alaska. Can. J. Fish. Aquat. Sci. 52:1229-1246.

Zheng, J., M.C. Murphy, and G.H. Kruse. 1995b. Updated length-based population model and stock-recruitment relationships for red king crab, *Paralithodes camtschaticus*, in Bristol Bay, Alaska. Alaska Fish. Res. Bull. 2:114-124.

Zheng, J., M.C. Murphy, and G.H. Kruse. 1996. Overview of population estimation methods and recommended harvest strategy for red king crabs in Bristol Bay. Alaska Department of Fish and Game, Reg. Inf. Rep. 5J96-04, Juneau, Alaska. 37 pp.

Zheng, J., M.C. Murphy, and G.H. Kruse. 1997a. Analysis of the harvest strategies for red king crab, *Paralithodes camtschaticus*, in Bristol Bay, Alaska. Can. J. Fish. Aquat. Sci. 54:1121-1134.

Zheng, J., M.C. Murphy, and G.H. Kruse. 1997b. Alternative rebuilding strategies for the red king crab *Paralithodes camtschaticus* fishery in Bristol Bay, Alaska. J. Shellfish Res. 16:205-217.

## 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.

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

Table 9: Comparisons of negative log-likelihood values for the Gmacs model scenarios.

| Component                               | Gmacs base | Free q   | Variable M |
|---|------------|----------|------------|
| Pot Retained Male Catch                 | 42.64      | 42.04    | 29.25      |
| Pot Discarded Male Catch                | 184.44     | 183.24   | 184.38     |
| Pot Discarded Female Catch              | -55.21     | -55.20   | -55.20     |
| Trawl bycatch Discarded Aggregate Catch | -92.00     | -91.99   | -92.01     |
| TC bycatch Discarded Male Catch         | -33.26     | -33.26   | -33.27     |
| TC bycatch Discarded Female Catch       | -33.26     | -33.26   | -33.26     |
| Fixed Bycatch Discarded Aggregate Catch | -9.70      | -9.70    | -9.70      |
| NMFS Trawl Survey                       | -24.70     | -24.87   | -29.90     |
| ADF&G Pot Survey                        | -7.93      | -9.03    | -8.02      |
| Directed Pot LF                         | -1412.84   | -1412.66 | -1420.95   |
| NMFS Trawl LF                           | -879.91    | -889.58  | -891.49    |
| ADF&G Pot LF                            | -1775.99   | -1770.71 | -1783.13   |
| Recruitment deviations                  | 183.08     | 180.96   | 165.72     |
| F penalty                               | 18.95      | 18.95    | 18.95      |
| M penalty                               | 63.72      | 63.63    | 13.87      |
| Prior                                   | 167.07     | 166.19   | 169.04     |
| Total                                   | -3664.90   | -3675.27 | -3775.72   |
| Total estimated parameters              | 498.00     | 499.00   | 574.00     |

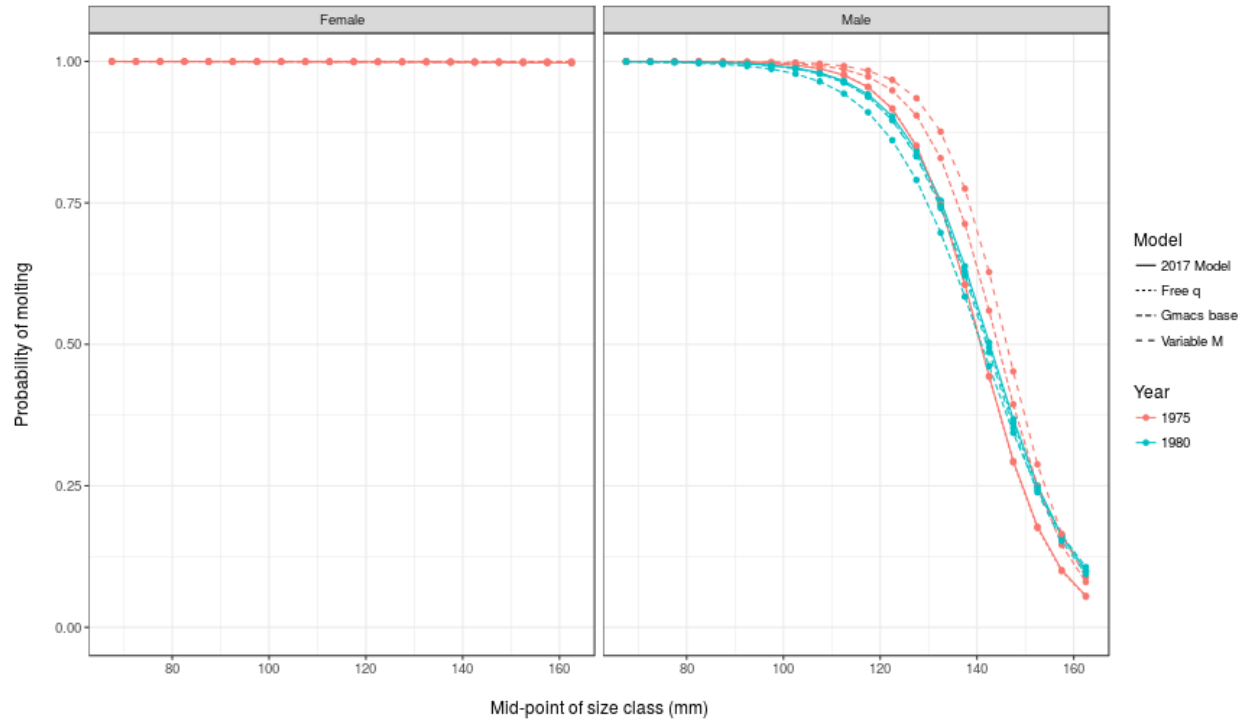


Figure 3: Comparisons of the estimated (and fixed to match the 2015 model selectivities in the Gmacs base scenario) stage-1 and stage-2 selectivities for each of the different model scenarios (the stage-3 selectivities are all fixed at 1). Estimated selectivities are shown for the directed pot fishery,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

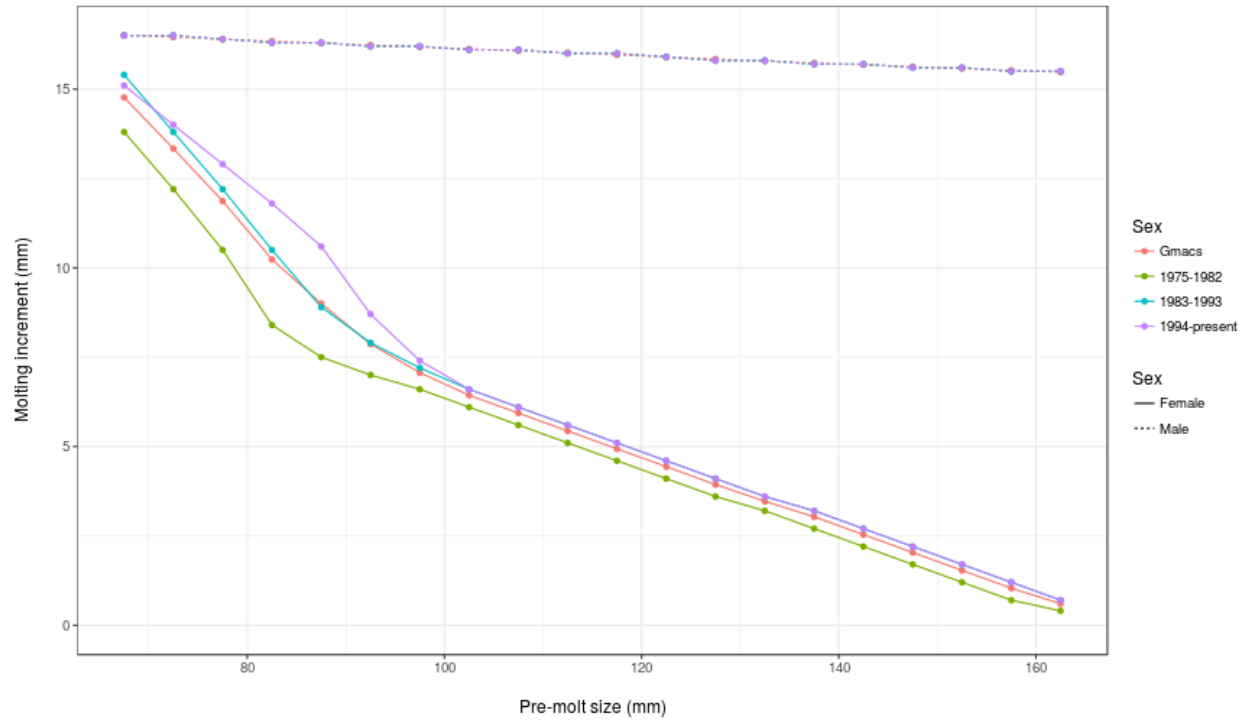


Figure 4: Comparisons of the estimated (and fixed to match the 2015 model selectivities in the Gmacs base scenario) stage-1 and stage-2 selectivities for each of the different model scenarios (the stage-3 selectivities are all fixed at 1). Estimated selectivities are shown for the directed pot fishery, 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.

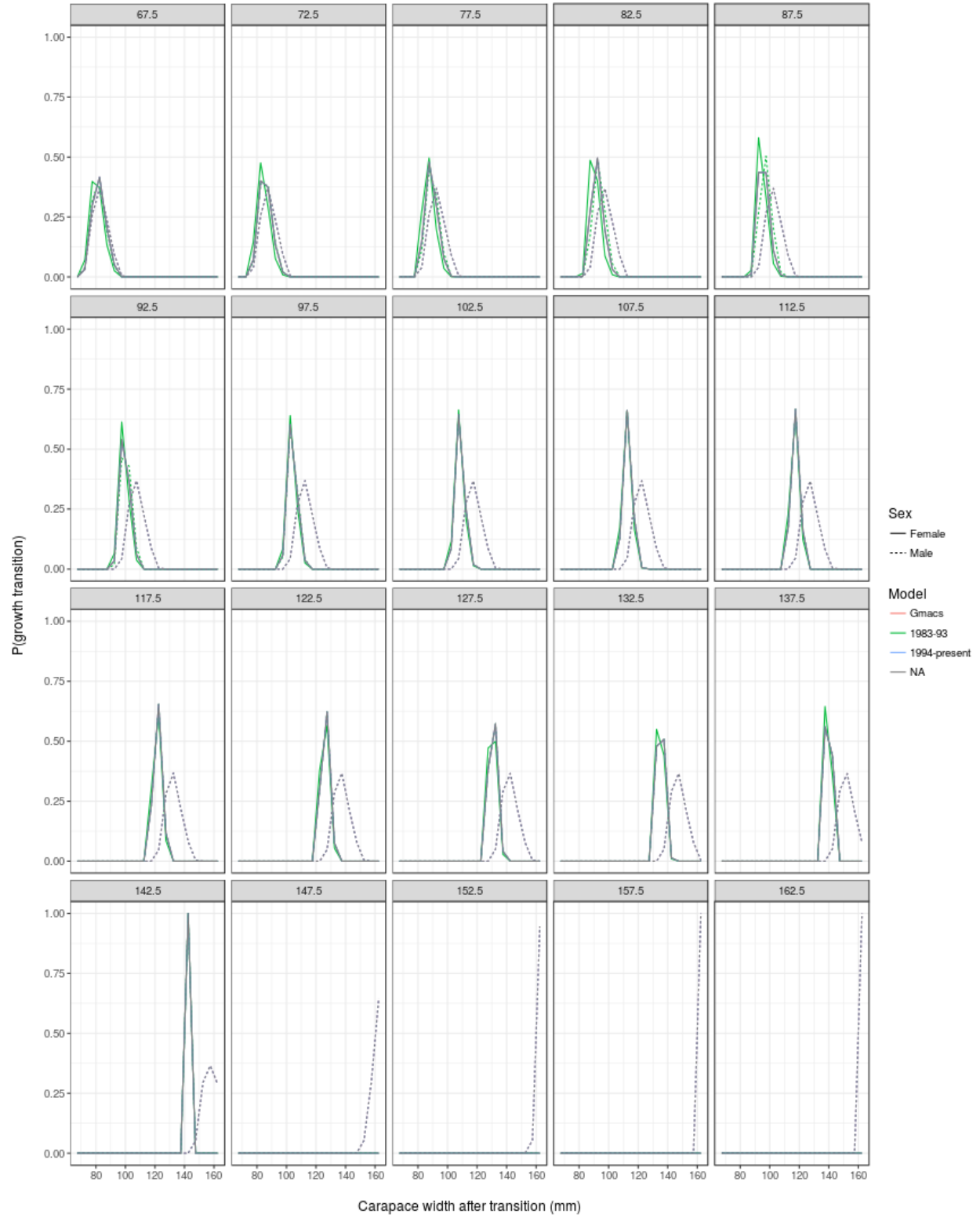


Figure 5: Probability of growth transition by stage. Each of the panels represent the stage before a transition. The x-axes represent the stage after a transition. The size transition matrix was provided as an input directly to Gmacs (as it was during the 2015 SMBKC assessment).



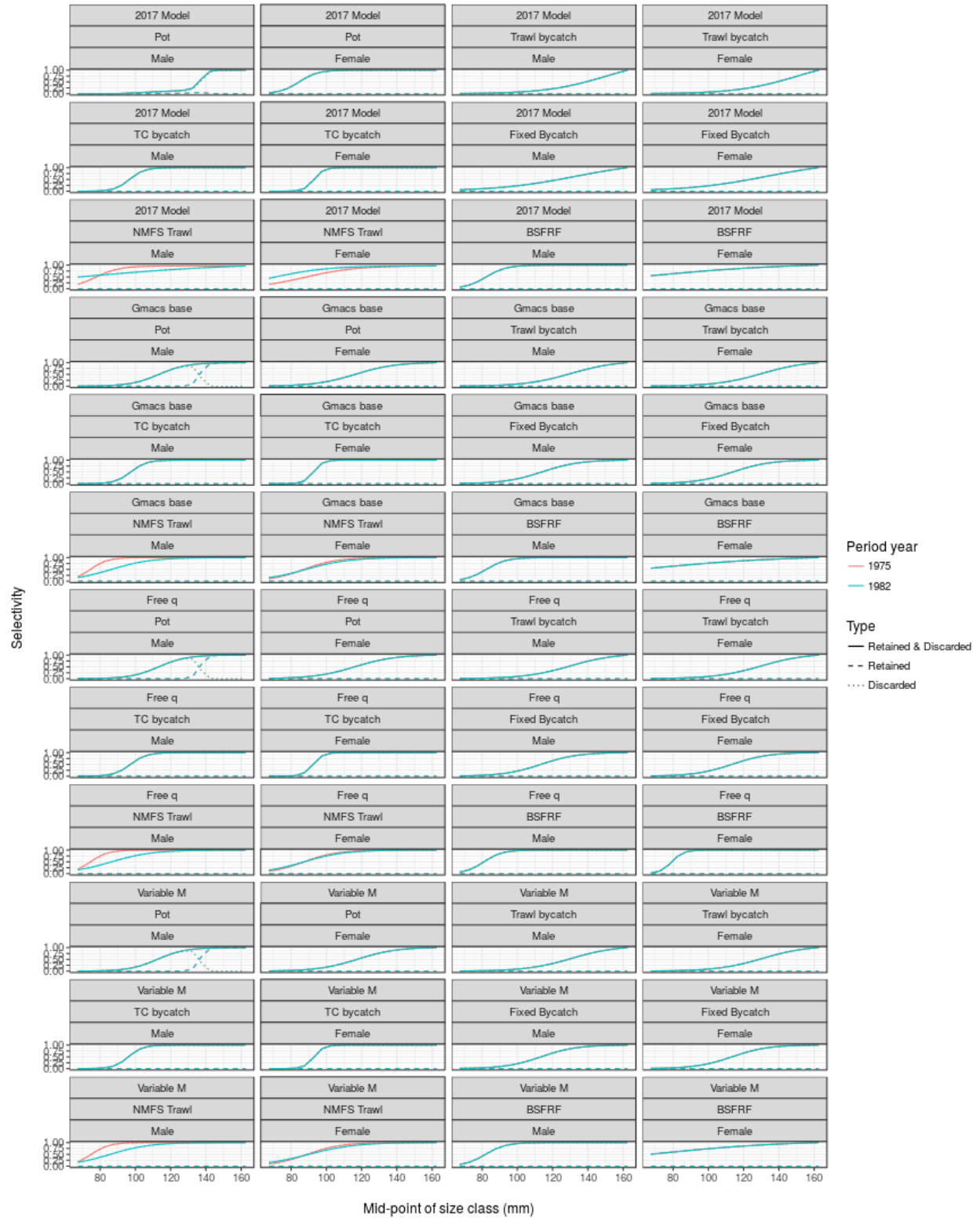


Figure 6: Comparisons of the estimated (and fixed to match the 2015 model selectivities in the Gmacs base scenario) stage-1 and stage-2 selectivities for each of the different model scenarios (the stage-3 selectivities are all fixed at 1). Estimated selectivities are shown for the directed pot fishery, 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.

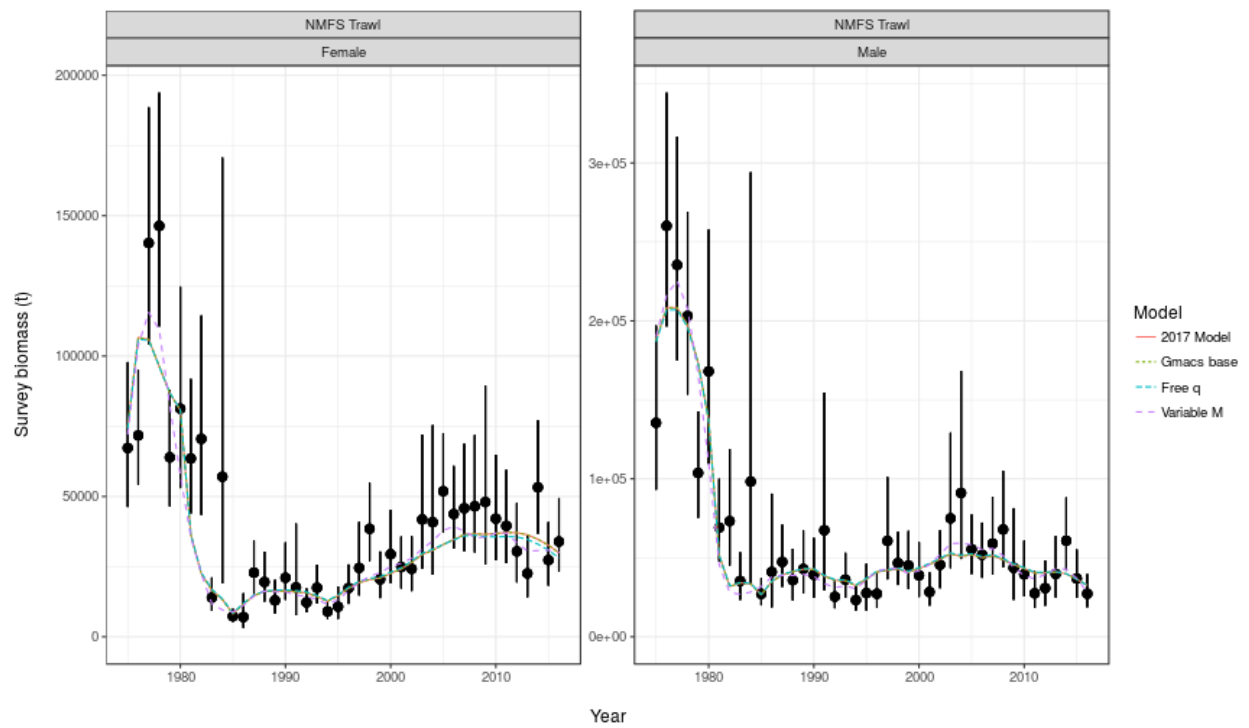


Figure 7: Comparisons of area-swept estimates of total male survey biomass (tons) and model predictions for the 2017 model and each of the Gmacs model scenarios. The error bars are plus and minus 2 standard deviations.

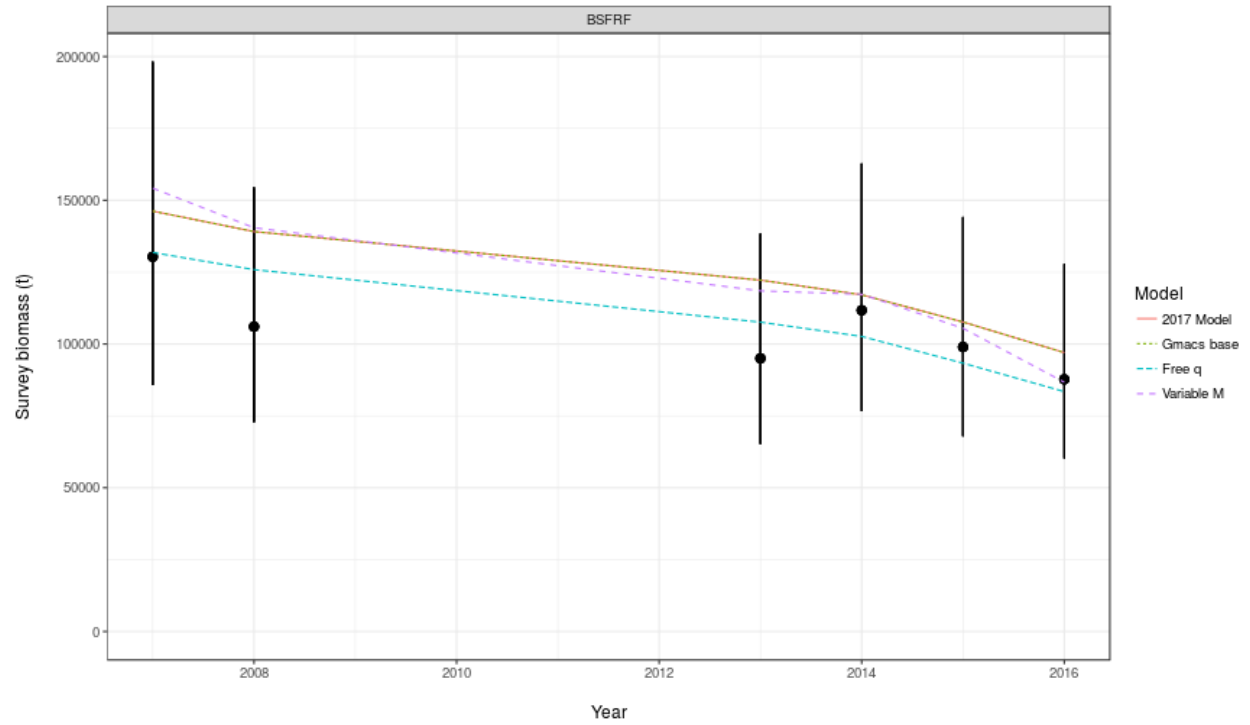


Figure 8: Comparisons of area-swept biomass estimates for the BSFRF data for the 2017 model and each of the Gmacs model scenarios. The solid black error bars are plus and minus 2 standard deviations derived using the original survey CVs.

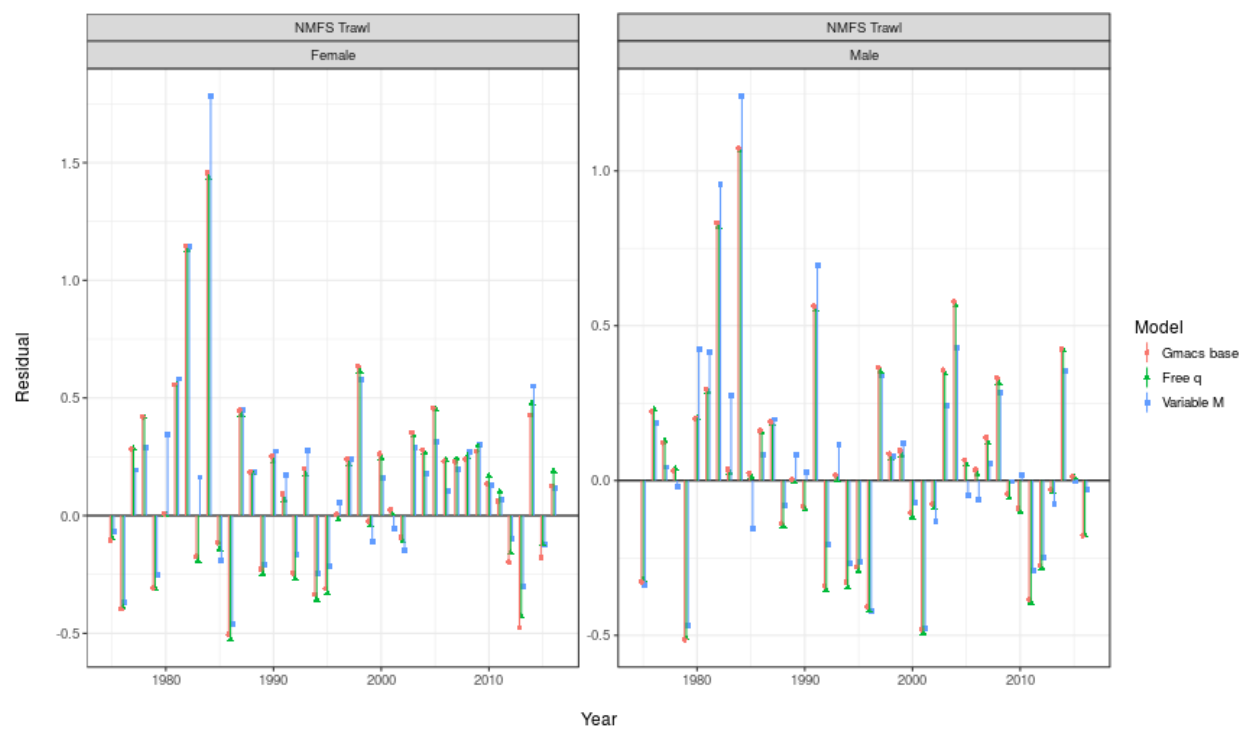


Figure 9: Standardized residuals for area-swept estimates of total male survey biomass for each of the Gmacs model scenarios.

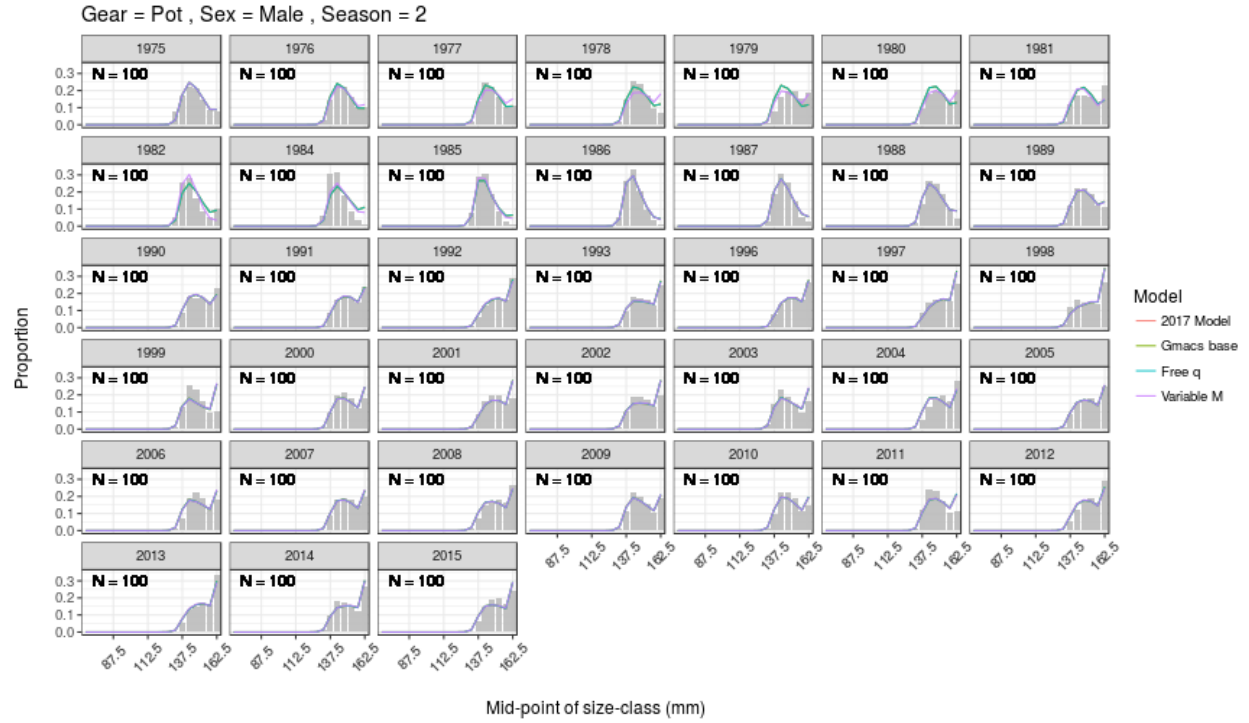
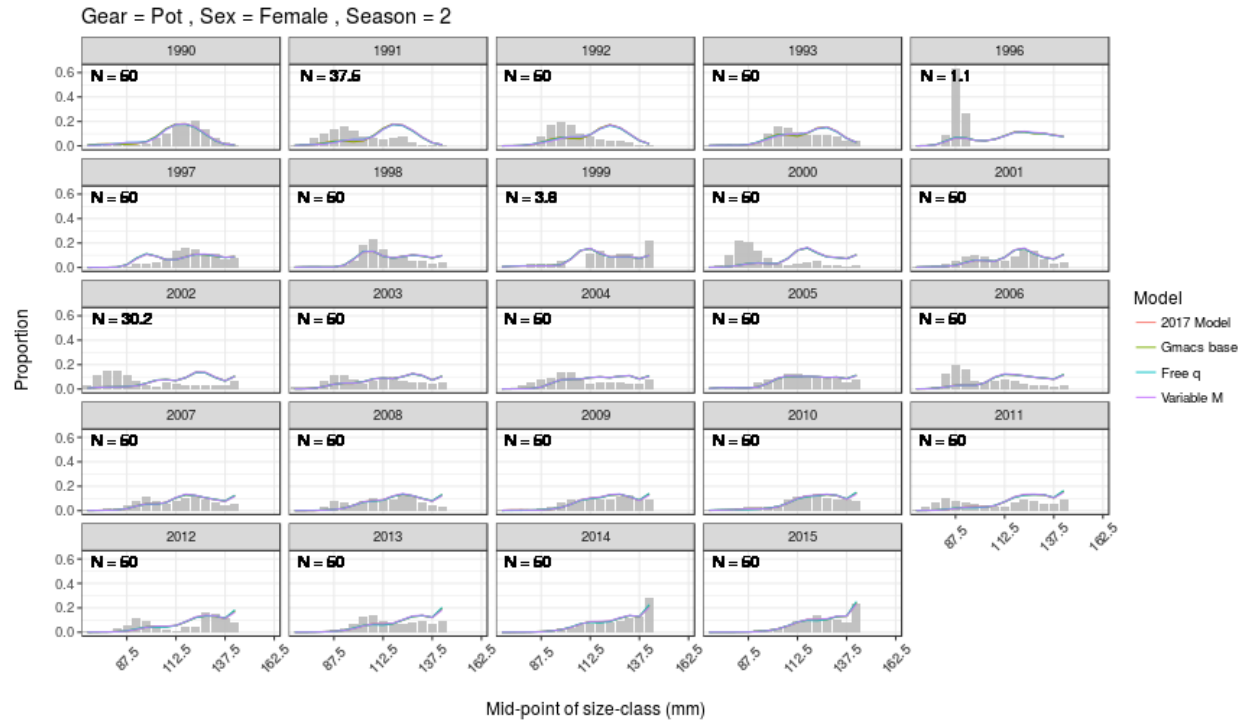


Figure 10: Observed and model estimated size-frequencies of BBRKC by year retained in the directed pot fishery for the 2016 model and each of the Gmacs model scenarios. Note that there is no model estimated size- frequency for the 2016 model during the 2016 year.



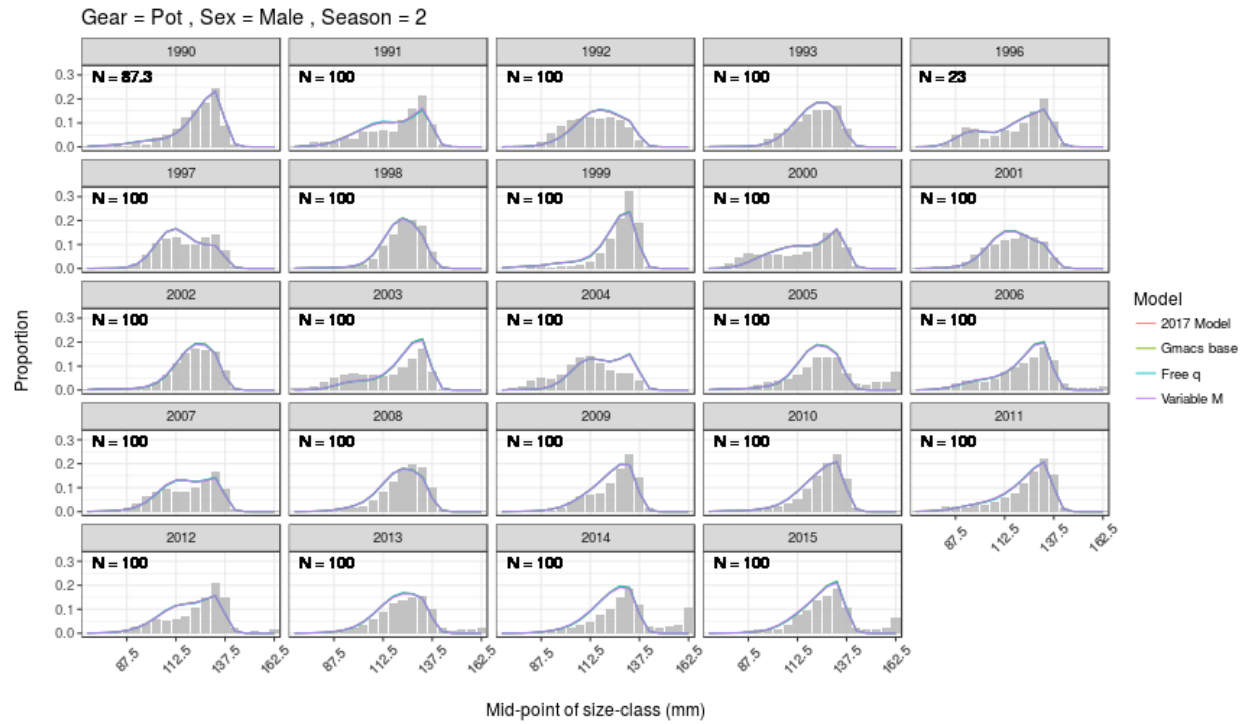


Figure 11: Observed and model estimated size-frequencies of discarded male BBRKC by year in the directed fishery for the 2017 model and each of the Gmacs model scenarios. Note that there is no model estimated size-frequency for the 2015 model during the 2016 year.

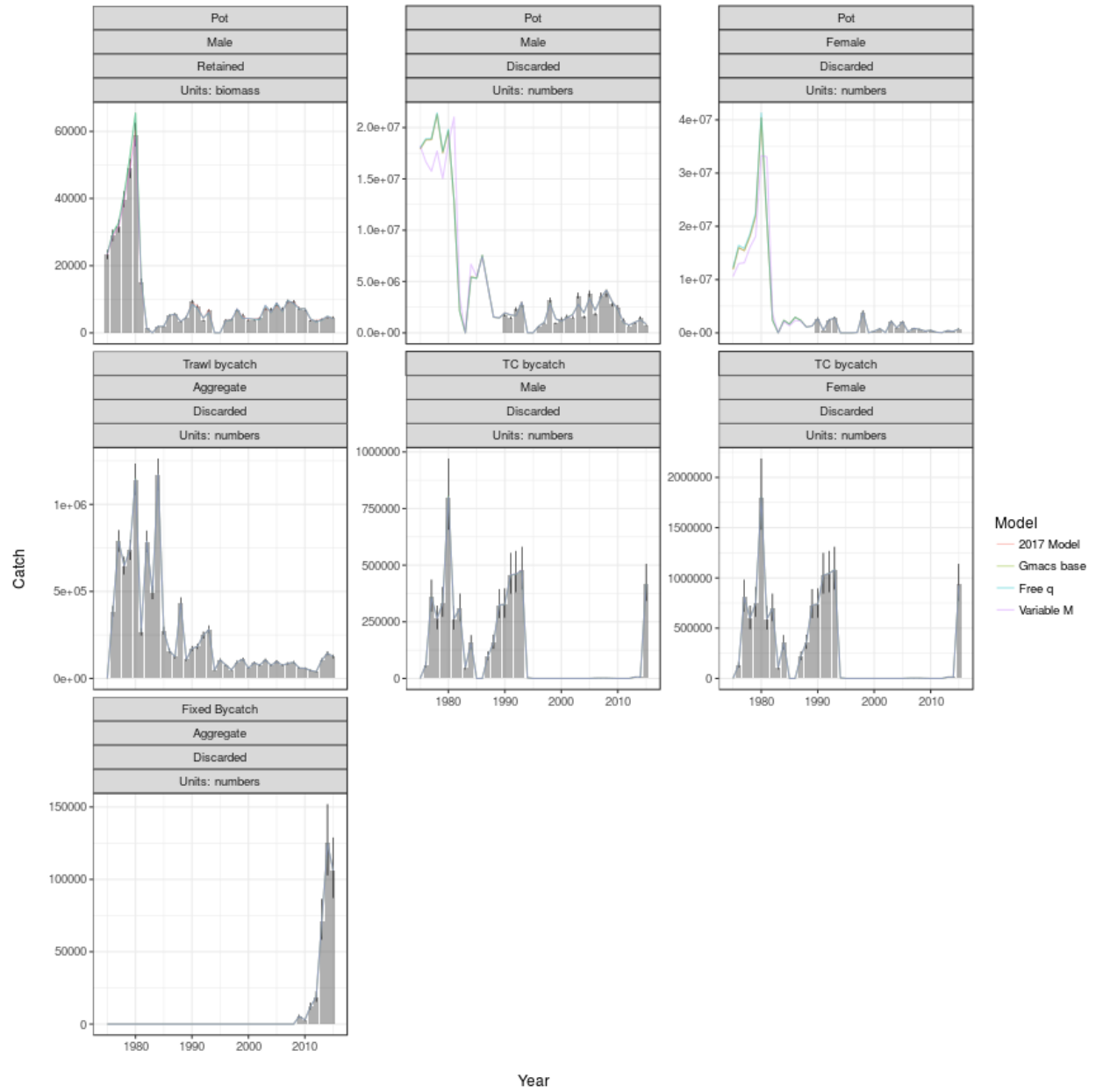


Figure 12: Comparison of observed and model predicted retained catch and bycatches in each of the Gmacs models. Note that difference in units between each of the panels, some panels are expressed in numbers of crab, some as biomass (tons).

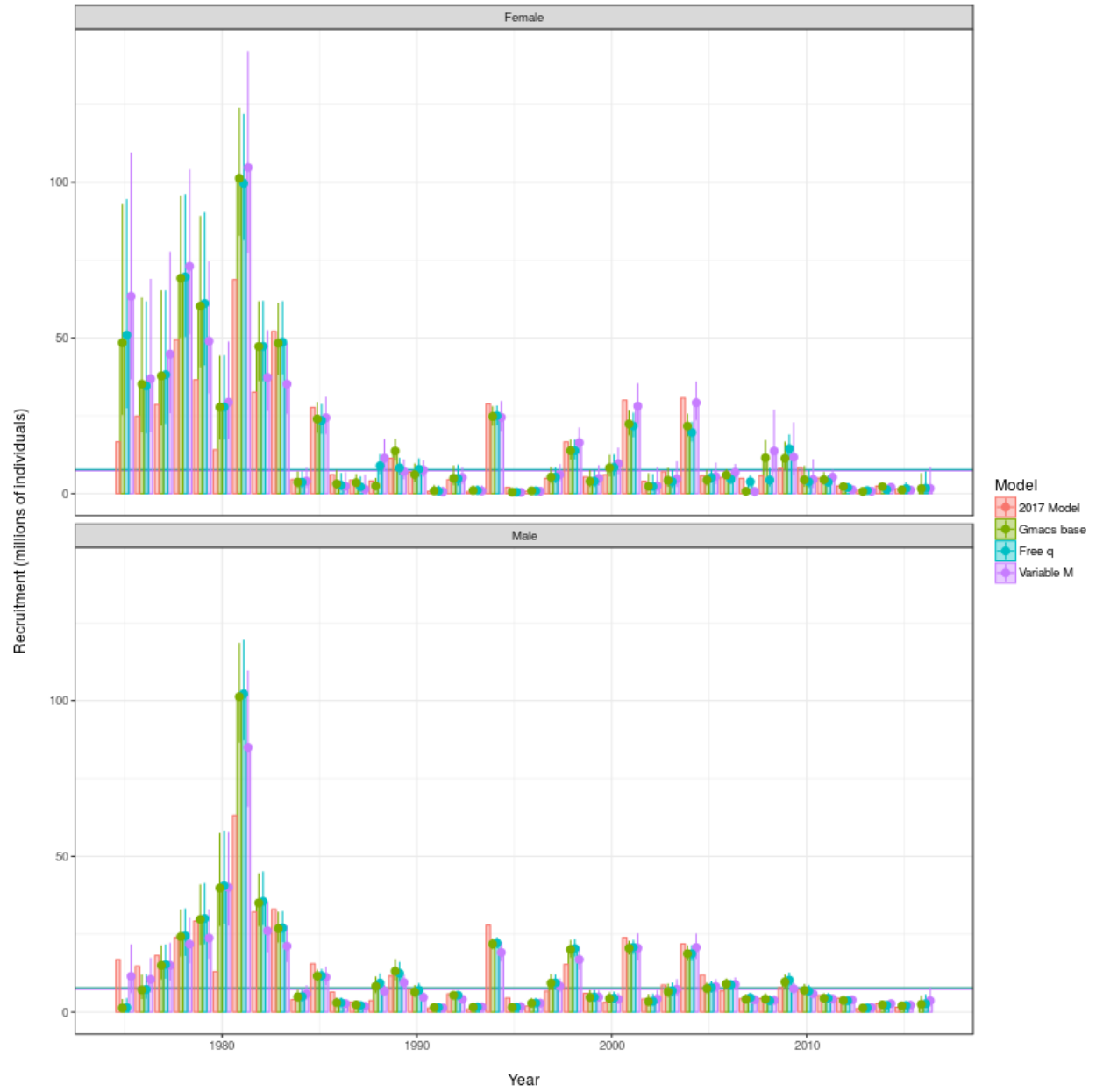


Figure 13: Comparisons of estimated recruitment time series during 1979-2016 in each of the scenarios. The solid horizontal lines in the background represent the estimate of the average recruitment parameter ( $\bar{R}$ ) in each model scenario.



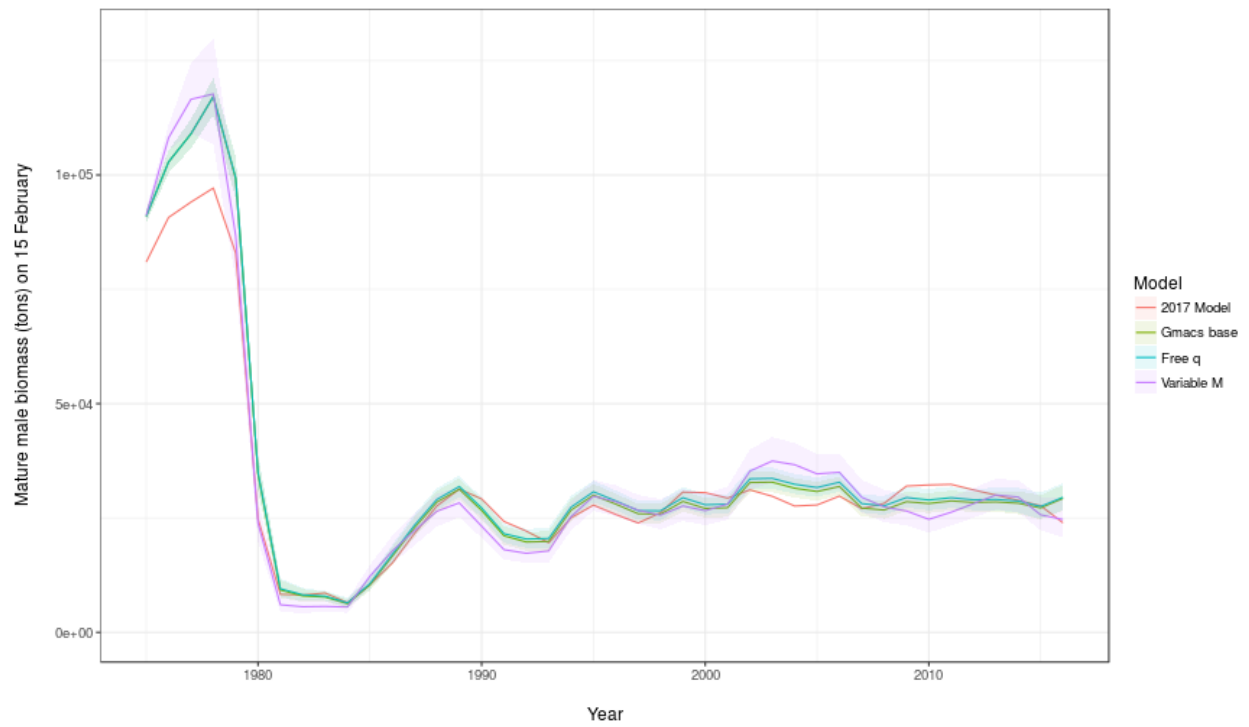


Figure 14: Comparisons of estimated mature male biomass (MMB) time series on 15 February during 1978-2016 for each of the model scenarios.

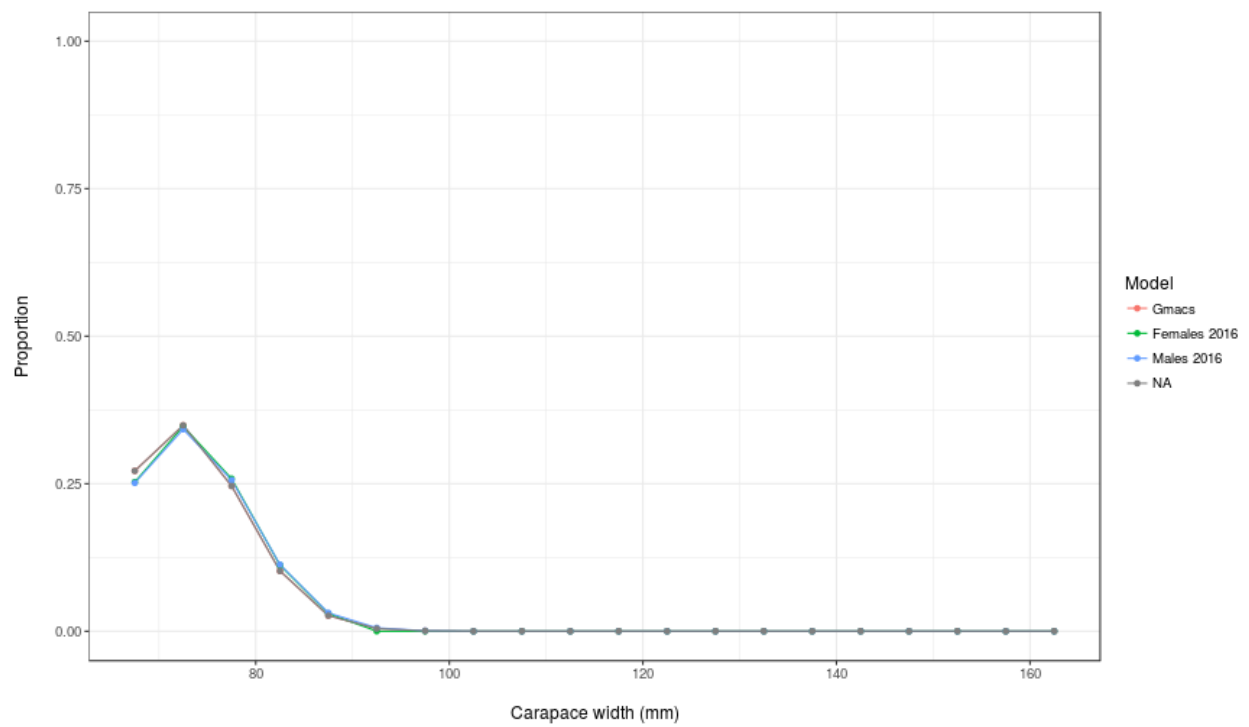


Figure 15: Distribution of carapace width (mm) at recruitment.

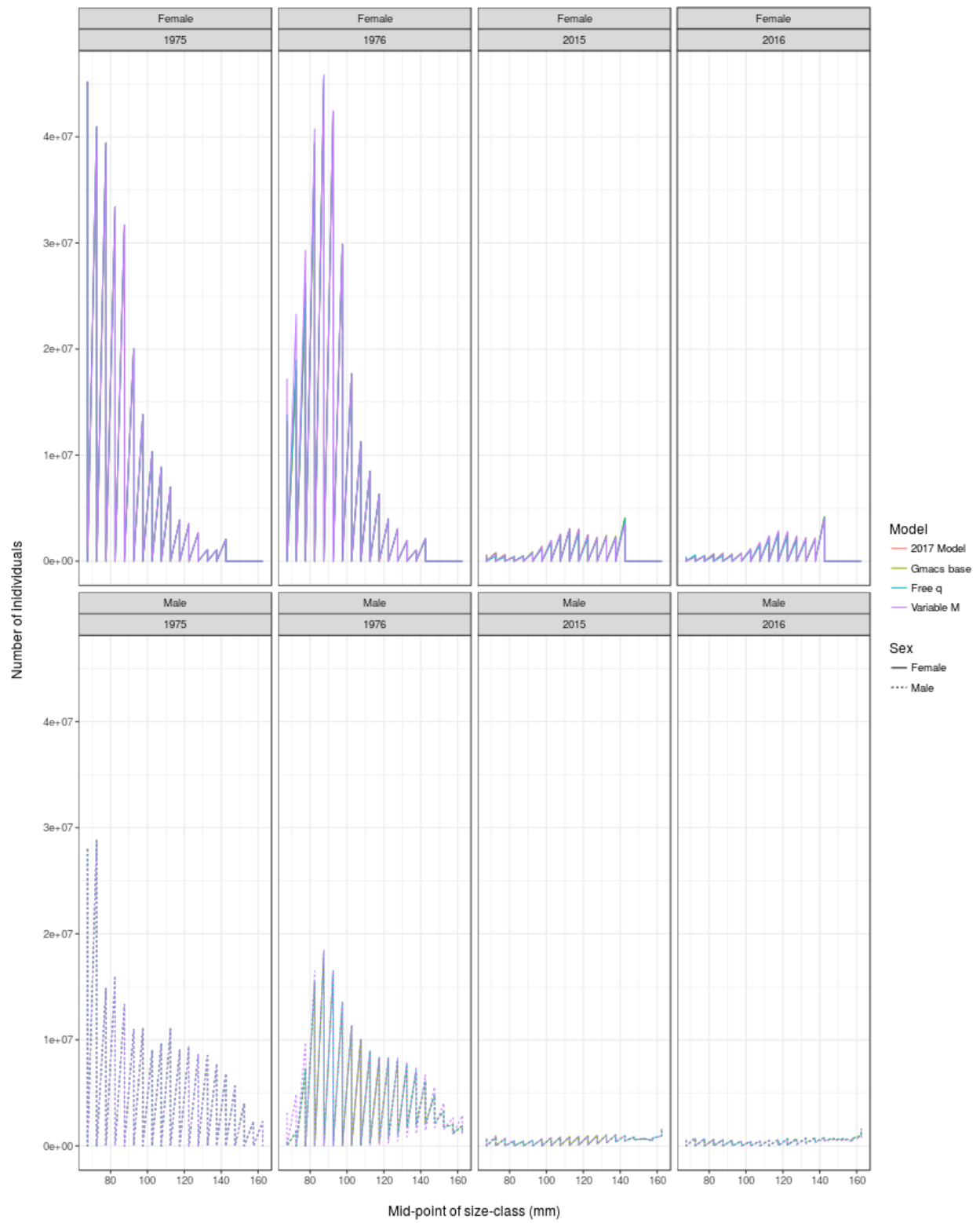


Figure 16: Numbers by stage each year (at the beginning of the model year, i.e. 1 July, season 1) in each of the models including the 2015 model.

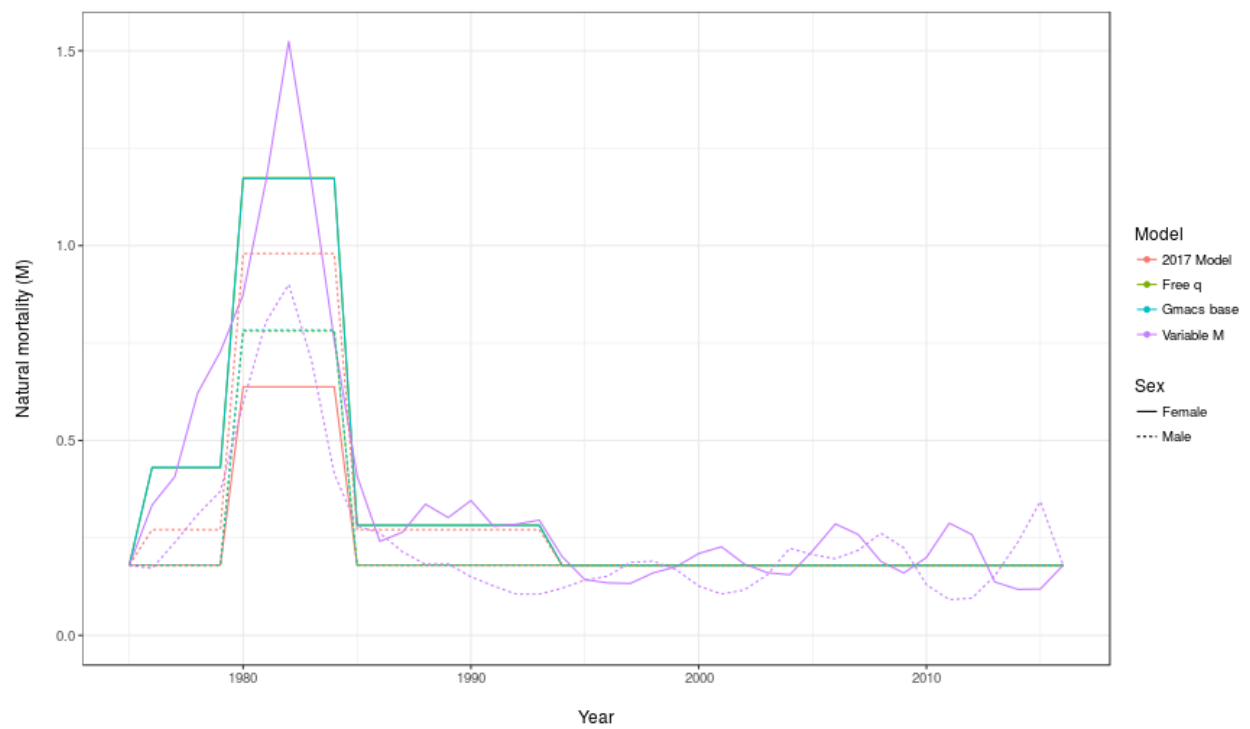


Figure 17: Time-varying natural mortality ( $M_t$ ). Estimated pulse period occurs in 1979/80 (i.e.  $M_{1980}$ ).

# Appendix A: BBRKC Model Description

## 1. Introduction

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

For management of the Britol Bay red king crab (BBRKC) 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  $n_{season}$  seasons ( $t$ ) and a proportion of the natural mortality ( $\tau_t$ ) 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 BBRKC fishing year (1 July)
- $\tau_1 = 0.01$
- Surveys

### 2. Season 2

- $\tau_2$  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 ( $\tau_t$ ) applied during each season in the model is provided in Table 10. The beginning of the year (1 July) to the date that MMB is measured (15 February) is 63% of the year. Therefore 63% of the natural mortality must be applied before the MMB is calculated. Because the timing of the fishery is different each year  $\tau_2$  is different each year and thus  $\tau_3$  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

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

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

$$\phi_t = [1, 0, 0]^\top, \quad (3)$$

and the recruitment is

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

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

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

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

$$\mathbf{G} = \begin{bmatrix} 1 - \pi_{12} - \pi_{13} & \pi_{12} & \pi_{13} \\ 0 & 1 - \pi_{23} & \pi_{23} \\ 0 & 0 & 1 \end{bmatrix}, \quad (6)$$

with  $\pi_{jk}$  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

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

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

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

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

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

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

$$\mathbf{Z}_{t,y} = \mathbf{Z}_{l,t,y} = \mathbf{M}_{t,y} + \mathbf{F}_{t,y}. \quad (10)$$

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

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

The basic population dynamics underlying Gmacs can thus be described as

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

### 3. Model Data

Data inputs used in model estimation are listed in Table 11.

### 4. Model Parameters

Table 12 lists fixed (externally determined) parameters used in model computations.

Estimated parameters are listed in Table 13 and include an estimated natural mortality deviation parameter in 1998/99 ( $\delta_{1998}^M$ ) assuming an anomalous mortality event in that year, as hypothesized by Zheng and Kruse (2002), with natural mortality otherwise fixed at  $0.18 \text{ yr}^{-1}$ .

### 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 9). A lognormal distribution is assumed to characterize the catch data and is modelled as

$$\sigma_{t,y}^{\text{catch}} = \sqrt{\log \left( 1 + \left( CV_{t,y}^{\text{catch}} \right)^2 \right)} \quad (13)$$

$$\delta_{t,y}^{\text{catch}} = \mathcal{N} \left( 0, \left( \sigma_{t,y}^{\text{catch}} \right)^2 \right) \quad (14)$$

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

$$\sigma_{t,y}^{\text{I}} = \frac{1}{\lambda} \sqrt{\log \left( 1 + \left( CV_{t,y}^{\text{I}} \right)^2 \right)} \quad (15)$$

$$\delta_{t,y}^{\text{I}} = \log \left( I^{\text{obs}} / I^{\text{pred}} \right) / \sigma_{t,y}^{\text{I}} + 0.5 \sigma_{t,y}^{\text{I}} \quad (16)$$

and the likelihood is

$$\sum \log \left( \delta_{t,y}^{\text{I}} \right) + \sum 0.5 \left( \sigma_{t,y}^{\text{I}} \right)^2 \quad (17)$$

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 reasonable 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 adequate. 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 10: Proportion of the natural mortality ( $\tau_t$ ) 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 11: Data inputs used in model estimation.

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

Table 12: Fixed model parameters for all scenarios.

| Parameter                                   | Symbol     | Value                       | Source/rationale  |
|---|------------|-----------------------------|---|
| BSFRF survey catchability                   | $q$        | 1.0                         | Default   |
| Natural mortality                           | $M$        | 0.18 yr <sup>-1</sup>       | NPFMC (2007)  |
| Stage-1 and stage-2<br>mean weights         | $w_1, w_2$ | 0.7, 1.2 kg                 | Length-weight equation (B. Foy, NMFS)<br>applied to stage midpoints   |
| Stage-3 mean weight                         | $w_{3,y}$  | Depends on year<br>Table ?? | Fishery reported average retained weight<br>from fish tickets, or its average, and<br>mean weights of legal males |
| Recruitment SD                              | $\sigma_R$ | 1.2                         | High value  |
| Natural mortality SD                        | $\sigma_M$ | 10.0                        | High value (basically free parameter)   |
| Directed fishery<br>handling mortality      |            | 0.2                         | 2010 Crab SAFE  |
| Groundfish trawl<br>handling mortality      |            | 0.8                         | 2010 Crab SAFE  |
| Groundfish fixed-gear<br>handling mortality |            | 0.5                         | 2010 Crab SAFE  |

Table 13: 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     |
| 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 $\delta_{1998}^M$          | -3  | 0.0           | 3  | Normal(0, $\sigma_M^2$ ) | 4     |
| Recruitment deviations $\delta_y^R$                                | -7  | 0.0           | 7  | Normal(0, $\sigma_R^2$ ) | 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     |