Stock Assessment of eastern Bering Sea snow crab

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EXECUTIVE SUMMARY

1. Stock: species/area.

A size based model was developed for eastern Bering Sea snow crab (*Chionoecetes opilio*) to estimate population biomass and harvest levels.

2. Catches: trends and current levels

Catch trends historically followed survey abundance estimates of large males, as the survey estimates were the basis for calculating the GHL (Guideline Harvest Level for retained catch). A TAC is currently set (starting in 2009) by ADFG using the ADFG harvest strategy. Retained catches increased from about 3,040 t at the beginning of the directed fishery in 1973 to a peak of 149,110 t in 1991, declined thereafter, then increased to another peak of 110,410 t in 1998. Retained catch in the 1999/2000 fishery was reduced to 15,200 t due to the low abundance estimated by the 1999 survey. A harvest strategy (Zheng et al. 2002) was developed using a earlier generation simulation model that pre-dated the current stock assessment model. This early generation model has been used to set the GHL (TAC since 2009) since the 2000/01 fishery. Retained catch in the 2013/14 fishery decreased to 24,480 t from the 2012/13 fishery retained catch of 30,060 t. The total catch in the 2013/14 fishery was estimated at 28,200 t (30% mortality on directed discards) below the OFL of 78,100 t. Discard in the directed fishery was 12,090 t in 2013/14, an increase from 7,350 t (no mortality applied) in 2012/13.

Estimated discard mortality (mostly undersized males and old shell males) in the directed pot fishery has averaged about 31% (no mortality applied) of the retained catch biomass since 1992 when observers were first placed on crab vessels. Discards prior to 1992 were estimated based on fishery selectivities estimated for the period with observer data and the full selection fishing mortality estimated using the retained catch and retained fishery selectivities.

3. Stock Biomass:

Model estimates of total mature biomass of snow crab increased from the early 1980's to a peak in 1990 of about 1,005,600 t. The total mature biomass includes all sizes of mature females and morphometrically mature males. The stock was declared overfished in 1999 due to the survey estimate of total mature biomass (149,900 t) being below the minimum stock size threshold (MSST = 208,710 t). A rebuilding plan was implemented in 2000. Subsequently, the assessment model structure was changed and the currency for estimating B_{MSY} changed during the 10 year rebuilding period from total mature survey biomass to model estimated mature male biomass at mating (MMB). Using the current definitions for estimating B_{MSY}, MMB at mating was above B35% in 2010/11 and the stock was declared rebuilt in 2011. The total mature observed survey biomass in 2011 was 447,400 t which was also above the Bmsy(418,150 t) in place under the rebuilding plan implemented in 2000. The increase in total mature biomass was mainly due to a large increase in observed female mature biomass in 2011.

Observed survey mature male biomass decreased from 120,800 t in 2012 to 96,100 t in 2013, then increased to 156,900 t in 2014. Observed survey mature female biomass also decreased from 220,600 t in 2012 to 195,100 t in 2013, then increased to 212,500 t. The estimate of males greater than 101 mm decreased from 87.0 million in 2012 to 73.6 million in 2013, then increased to 138.5 million in 2014.

Base model estimates of mature male biomass at mating decreased from 129,700 t in 2011/12 to 109,100 t in 2012/13 then increased to 126,500 t in 2013/14 (89% of B35% (142,909 t)).

4. Recruitment

Recruitment was at or above average in 2004 and 2005 (lag 5 years) which has resulted in increasing biomass in the female mature stock and in 2014 in increasing male mature stock. Recruitment estimates in 2008 and 2009 were just above average.

5. Management

Historical status and catch specifications for snow crab (1000t).

Year	MSST	Biomass (MMB)	TAC	Retained Catch	Total Catch	OFL	ABC
2010/11	73.7	196.6[A]	24.6	24.7	26.7	44.4	
2011/12	77.3	165.2[B]	40.3	40.5	44.7	73.5	66.2[E]
2012/13	77.1	170.1[C]	30.1	30.1	32.4	67.8	61.0[E]
2013/14	71.5	126.5[D]	24.5	24.5	28.1	78.1	70.3[E]
2014/15		137.6[D]				69.0	62.1[E]

Historical status and catch specifications for snow crab (millions of lb.).

Year	MSST	Biomass (MMB)	TAC	Retained Catch	Total Catch	OFL	ABC
2010/11	162.5	433.4 [A]	54.2	54.5	58.9	97.9	
2011/12	170.4	364.2 [B]	88.8	89.3	98.5	162.0	145.8
2012/13	169.9	374.9 [C]	66.3	66.3	71.4	149.5	134.5
2013/14	157.7	279.0[D]	54.0	54.0	62.0	172.1	154.9
2014/15		303.5[D]				152.2	137.0

A – Calculated from the assessment reviewed by the Crab Plan Team in September 2011
B– Calculated from the assessment reviewed by the Crab Plan Team in September 2012
C – Calculated from the assessment reviewed by the Crab Plan Team in September 2013
D – Calculated from the assessment reviewed by the Crab Plan Team in September 2014
E – 10% Buffer recommended by SSC

6. Basis for the OFL

The OFL for 2014/15 for the Base model was 69,000 t fishing at F_{OFL} = 1.34, a decrease from the 2013/14 OFL of 78,100 t. The MMB at mating projected for 2014/15 when fishing at the F35% control rule (OFL) was 96.3% of B35%.

7. Probability Density Function of the OFL

   The ABC (P*=.49) was estimated from the PDF of the OFL with a cv = 0.08 on beginning biomass estimated from the hessian. The projection model used to estimate the PDF is description is included in this assessment in a later section.

8. Basis for ABC

The ACL was estimated at 68,810 t using a p*=0.49. The total catch estimated at 90% of OFL (the ACL recommended by the SSC for 2013/14) was 62,100 t. The MMB projected for 2014/15 when fishing at 90% of the OFL catch was 100.3% of B35%. B35% for the Base model was estimated at 142,909 t and F35% was estimated at 1.40. MMB at mating for 2013/14 was estimated at 126,500 t above the estimated MMST of 71,455 t.

A. Summary of Major Changes

Changes to the Data

2014 Bering Sea survey biomass and length frequency data added to the model. 2013/14 directed fishery retained and discard catch and length frequencies for retained and discard catch were added to the model. Groundfish discard length frequency and discard catch from 2013/14 were added to the model.

Changes to the Assessment Methodology

The base model in the current assessment differs from the September 2013 base model in fitting a two part linear function with a smooth transition to the 2011 growth data, recommended in the 2014 CIE review (Cadigan 2014) and by the CPT and SSC. Nine model scenarios are presented in this assessment: 1) The September 2013 model (Model 0, one linear function fit to growth data), 2) two linear functions with a fixed intersection fit to growth data (Model 1), 3) Two linear functions with a smooth transition fit to growth data (Model 2a, Cardgan 2014), 4) same as 3 with factor of 2 times on growth likelihood (Model 2b, Base model for this assessment), 5) same as 3 with factor of 3 times on growth likelihood (Model 2c), 6) same as 3 with 0.5 weight on fishing penalties likelihood (Model 2d, weights relative to base model), 7) same as 3 with 0.25 weight on fishing penalties likelihood (Model 2e) 8) same as 3 with 0.1 weight on fishing penalties likelihood (Model 2f), 9) same as 3 with 0.001 weight on penalties on fishing mortality likelihood (Model 2g).

Model 2b was selected as the base model for this assessment because it uses the smooth transition for growth and the weight of 2 on the likelihood fits growth data much better than weight of 1, while a higher weight (3) does not improve the fit to growth data while degrading other fits.

Changes to Assessment Results
See above

CPT May 2014 Recommendations for next assessment:

*For the September 2014 stock assessment, the CPT would like to see Model 0 (*September 2013 base model*), Model 1 (*two linear lines with fixed intersection) *and Model 0 with Cadigan-recommended growth parameterization. If the model converges, then they would also like to see the model with fishing penalties removed.*

The model uses empirically-derived proportion mature data from the chela height measurements from 1989-2007 (new shell males only). For females, the actual proportion mature is used. The CPT would like to see further analyses of the existing data and evaluate how these data are used in the model. This topic could be considered at a future model/data workshop.

The CPT requested that the data used in the models for the September 2014 assessment be updated with the data set provided by Bob Foy (catch, bycatch, and survey data) to ensure use of the most up-to-date data.

Authors response

Model scenarios include all CPT recommended models. Survey data used in all the model scenarios are the most up-to-date data. No new analysis on male chela height data are presented in this assessment due to time constraints, new analysis is planned for May 2015.

SSC Recommendations June 2014:

For the September assessment the SSC agrees with the CPT recommendations that Model 0 go forward along with a Model 1 scenario with an alternative parameterization of the growth model that is continuous and differentiable. The SSC has the following additional recommendations*:*

1) *Conduct additional sensitivity analyses on the penalties to constrain fishing mortality rate deviations and their impacts on biological reference points.*
2) *Investigate direct integration of the chela height data into the assessment model.*
3) *Explore time varying maturity options and potential environmental covariates as an explanation for the observed variability in male maturity-at-length.*

The SSC further requests detailed information on the new length-frequency information to be considered for use in the stock assessment model and details regarding the re-analysis of the landed-length composition data. Lastly, the SSC requests that the author provide a rationale for the various weightings used in the likelihood composition. Specifically, the SSC asks whether inverse variance weighting was used and how the effective sample size was determined for the length composition data.

Authors response

Model scenarios include all SSC recommended models, except no new analysis on male chela height data and time varying maturity are presented in this assessment. New analyses are planned for May 2015. Data weighting is not addressed in this assessment, this will be addressed in future assessments.

INTRODUCTION

Snow crab (*Chionoecetes opilio*) are distributed on the continental shelf of the Bering Sea, Chukchi Sea, and in the western Atlantic Ocean as far south as Maine. In the Bering Sea, snow crab are common at depths less than about 200 meters. The eastern Bering Sea population within U.S. waters is managed as a single stock; however, the distribution of the population may extend into Russian waters to an unknown degree.

FISHERY HISTORY

Snow crab were harvested in the Bering Sea by the Japanese from the 1960s until 1980 when the Magnuson Act prohibited foreign fishing. Retained catch in the domestic fishery increased in the late 1980’s to a high of about 149,110 t in 1991, declined to 29,820 t in 1996, increased to 110,410 t in 1998 then declined to 15,200 t in the 1999/2000 fishery (Table 1, Figure 1). Due to low abundance and a reduced harvest rate, retained catches from 2000/01 to 2006/07 ranged from a low of about 10,860 t to 16,780 t. In the 2013/14 fishery retained catch was 24,480 t and total catch was estimated at 28,200 t (0.3 mortality for pot fishery discard and 0.8 mortality for groundfish discard). Total catch in 2011/12 to 42,000 t and in 2012/13 32,400 t.

Discard from the directed pot fishery was estimated from observer data since 1992 and ranged from 11% to 64% (average 33%) of the retained catch of male crab biomass (Table 1). Female discard catch is very low and not a significant source of mortality. In 1991/92 trawl discard was about 1,950 t (no mortality applied), increased to about 3,550 t in 1994/95, then declined and ranged between 900 t and 1,500 t until 1998/99. Trawl bycatch in 2012/13 and 2013/14 was 220 t and 120 t respectively. Discard of snow crab in groundfish fisheries from highest to lowest is the yellowfin sole trawl fishery, flathead sole trawl fishery, Pacific cod bottom trawl fishery, rock sole trawl fishery and the Pacific cod hook and line and pot fisheries.

Size frequency data and catch per pot have been collected by observers on snow crab fishery vessels since 1992. Observer coverage was 10% on catcher vessels larger than 125 ft (since 2001), and 100% coverage on catcher processors (since 1992).

The average size of retained crabs has remained fairly constant over time ranging between 105 mm and 118 mm, and most recently about 110 mm to 111 mm. The percent new shell animals in the catch has varied between 69% (2002 fishery) to 98% (1999), and was 87% for the 2005/6 fishery and 93% in the 2007/8 fishery. In the 2007/8 fishery 94% of the new shell males >101mm CW were retained, while 78% of the old shell males >101mm CW were retained. Only 3% of crab were retained between 78mm and 101 mm CW. The average weight of retained crab has varied between 0.5 kg (1983-1984) and 0.73 kg (1979), and 0.59 kg in the recent fisheries.

Several modifications to pot gear have been introduced to reduce bycatch mortality. In the 1978/79 season, pots used in the snow crab fishery first contained escape panels to prevent ghost fishing. Escape panels consisted of an opening with one-half the perimeter of the tunnel eye laced with untreated cotton twine. The size of the cotton laced panel to prevent ghost fishing was increased in 1991 to at least 18 inches in length. No escape mechanisms for undersized crab were required until the 1997 season when at least one-third of one vertical surface had to contain not less than 5 inches stretched mesh webbing or have no less than four circular rings of no less than 3 3/4 inches inside diameter. In the 2001 season the escapement for undersize crab was increased to at least eight escape rings of no less than 4 inches placed within one mesh measurement from the bottom of the pot, with four escape rings on each side of the two sides of a four-sided pot, or one-half of one side of the pot must have a side panel composed of not less than 5 1/4 inch stretched mesh webbing.

Harvest rates

The harvest rate used to set the GHL (Guideline Harvest Level of retained crab only) previous to 2000 was 58% of the number of male crab over 101 mm carapace width estimated from the survey. The minimum legal size limit for snow crab is 78 mm, however, the snow crab market generally accepts animals greater than 101 mm. In 2000, due to the decline in abundance and the declaration of the stock as overfished, the harvest rate for calculation of the GHL was reduced to 20% of male crab over 101 mm. After 2000, a rebuilding strategy was developed based on simulations by Zheng (2002).

The realized retained catch typically exceeded the GHL historically, resulting in exploitation rates for the retained catch on males >101mm ranging from about 10% to 80% (Figure 3). The exploitation rate for total catch divided by mature male biomass ranged from 6% to 46% and was 18% in 2013/14.

Prior to adoption of Amendment 24, B_{MSY} (921.6 million lbs (418,150 t)) was defined as the average total mature biomass (males and females) estimated from the survey for the years 1983 to 1997 (NPFMC 1998). MSST was defined as 50% of the B_{MSY} value (MSST=460 million lbs of total mature biomass (209,074 t)). The harvest strategy since 2000/1 used a retained crab harvest rate on the mature male biomass of 0.10 on levels of total mature biomass greater than ½ MSST (230 million lbs), increasing linearly to 0.225 when biomass is equal to or greater than B_{MSY} (921.6 million lbs) (Zheng et al. 2002). The GHL was actually set as the number of retained crab allowed in the harvest, calculated by dividing the GHL in lbs by the average weight of a male crab > 101 mm. If the GHL in numbers was greater than 58% of the estimated number of new shell crabs greater than 101 mm plus 25% of the old shell crab greater than 101 mm, the GHL is capped at 58%. If natural mortality is 0.2, then this actually results in a realized exploitation rate cap for the retained catch of 66% at the time of the fishery, occurring approximately 7 months after the survey (if survey Q=1). The fishing mortality rate that results from this harvest strategy depends on the relationship between mature male size numbers and male numbers greater than 101 mm.

DATA

Data Sources

Catch data and size frequencies of retained crab from the directed snow crab pot fishery from 1978 to the 2013/14 season were used in this analysis. Observers were placed on directed crab fishery vessels starting in 1990. Size frequency data on the total catch (retained plus discarded) in the directed crab fishery were available from 1992 to 2013/14. Total discarded catch was estimated from observer data from 1992 to 2013/14 (Table 1). The discarded male catch was estimated for 1978 to 1991 in the model using the estimated fishery selectivities based on the observer data for the period 1992 to 2013/14. The discard catch estimate was multiplied by the assumed mortality of discards from the pot fishery. The mortality of discarded crab was 30% in the Base model. This estimate differs from the current rebuilding harvest strategy used since 2001 to the present by ADFG to set the TAC, which assumes a discard mortality of 25% (Zheng, et al. 2002). The discards prior to 1992 may be underestimated due to the lack of escape mechanisms for undersized crab in the pots before 1997.

The following table contains the various data components used in the model,

Data component	Years

Retained male crab pot fishery size frequency by shell condition	1978/79-2013/14
Discarded male and female crab pot fishery size frequency	1992/3-2013/14
Trawl fishery bycatch size frequencies by sex	1991-2013/2014
Survey size frequencies by sex and shell condition	1978-2014
Retained catch estimates	1978/79-2013/14
Discard catch estimates from snow crab pot fishery	1992/93-2013/14 from observer data
Trawl bycatch estimates	1973-2013/14
Total survey biomass estimates and coefficients of variation	1978-2014
2009 study area biomass estimates and coefficients of variation and length frequencies for BSFRF and NMFS tows	2009
2010 study area biomass estimates and coefficients of variation and length frequencies for BSFRF and NMFS tows	2010

Survey Biomass

Abundance is estimated from the annual eastern Bering Sea (EBS) bottom trawl survey conducted by NMFS (see Rugolo et al. 2003 for design and methods). Since 1989, the survey has sampled stations farther north than previous years (61.2^{o} N previous to 1989). In 1982 the survey net was changed resulting in a change in catchability. Juvenile crabs tend to occupy more inshore northern regions (up to about 63^{o} N) and mature crabs deeper areas to the south of the juveniles (Zheng et al. 2001).

All survey data in this assessment use measured net widths instead of a fixed 50 ft net width used in the September 2009 snow crab assessment (variable net width data were shown for comparison in the September 2009 assessment). Snow crab assessments prior to and including September 2009 used survey biomass estimates for all crab based on an assumed 50 ft net width. In 2009, Chilton et al. (2009) provided new survey estimates based on measured net width. The average measured net width for all tows in the 2009 survey was 17.08 meters which is about 112% of 50ft (15.24 meters) (Chilton et al. 2009). The 2009 mature male survey biomass was 162,890 t using the fixed 50 ft net width and 141,300 t using the measured net width for each tow. The difference between the survey male mature biomass estimates calculated with the fixed 50 ft width and the measured net width is small in the early part of the time series, and then is an average ratio of 0.86 (range 0.81 to 0.90) from 1998 to 2009.

The total mature biomass (all sizes of morphometrically mature males and females) estimated from the survey declined to a low of 82,100 t in 1985, increased to a high of 809,600 t in 1991 (includes northern stations after 1989), then declined to 140,900 t in 1999, when the stock was declared overfished (Table 3 and Figure 4). The mature biomass increased in 2000 and 2001, mainly due to a few large catches of mature females. The survey estimate of total mature biomass increased from 245,000 t in 2009 to 447,400 t in 2011, declined to 291,200 t in 2013, then increased to 369,400 t in 2014.

Survey mature male biomass decreased from 167,400 t in 2011 to 96,100 t in 2013, then increased to 156,900 t in 2014. The observed survey estimate of males greater than 101 mm decreased from150.7 million in 2011 to 73.6 million in 2013, then increased to 138.9 million in 2014 (Table 3). Survey mature female biomass decreased from 280,000 t in 2011to 195,100 t in 2013, then increased to 212,500 t in 2014.

The term mature for male snow crab in this assessment means morphometrically mature. Morphometric maturity for males refers to a marked change in chelae size (thereafter termed “large claw”), after which males are assumed to be effective at mating. Males are functionally mature at smaller sizes than when they become morphometrically mature, although the contribution of these “small-clawed” males to annual reproductive output is negligible. The minimum legal size limit for the snow crab fishery is 78 mm, however the size for males that are generally accepted by the fishery is >101mm. The historical quotas were based on the survey abundance of large males (>101mm).

Survey Size Composition

Carapace width is measured on snow crab and shell condition noted in the survey and the fishery. Snow crab cannot be aged at present (except by radiometric aging of the shell since last molt) however, shell condition has been used as a proxy for age. Based on protocols adopted in the NMFS EBS trawl survey, shell condition class and presumptive age are as follows: soft shell (SC1) (less than three months from molting), new shell (SC2) (three months to less than one year from molting), old shell (SC3) (two years to three years from molting), very old shell (SC4) (three years to four years form molting), and very very old shell (SC5) (four years or longer from molting). Radiometric aging of shells from terminal molt male crabs (after the last molt of their lifetime) elucidated the relationship between shell condition and presumptive age, which will be discussed in a later section (Nevissi et al 1995).

Survey abundance by size for males and females indicate a moderate level of recruitment moving through the stock and resulting in the recent increase in abundance. (Figures 6 - 8). In 2009 small crab (<50mm) increased in abundance relative to 2008. The 2010 length frequency data showed high abundance in the 40 to 50 mm range. The recruitment progressed into the mature female abundance in 2011 and also can be seen in male abundance in the 50-65mm range in 2011(Figure 8a). However, in 2012 and 2013, the progress of the recruitment is not evident. Observed survey mature biomass for both males and females declined in 2013, which has resulted in estimated recent recruitments to be lower than in previous assessments. High numbers of small crab in the late 1970’s survey data did not follow through the population to the mid-1980’s. The high numbers of small crab in the late 1980’s resulted in the high biomass levels of the early 1990’s and subsequent high catches. Moderate increase in numbers can also be seen in the mid 1990’s.

Spatial distribution of catch and survey abundance

The majority of the fishery catch occurs south of 58.5^{o} N., even in years when ice cover did not restrict the fishery moving farther north. In past years, most of the fishery catch occurred in the southern portion of the snow crab range possibly due to ice cover and proximity to port and practical constraints of meeting delivery schedules. The directed fishery catch in 2012/13 is shown in Figure 11b showing some catch from east of the Pribilof Islands, however, the majority of catch is west and north of the Pribilof Islands.

CPUE of survey catch by tow for 2012 to 2014 are shown in Figures 12 through 25h. Immature female and small male (<78mm) distributions in 2013 and 2014 are farther south than in previous years with higher tows just north of the Pribilof Islands (Figures 20, 22, 25c and 25e). Legal males (>77mm) and large males (>101mm) are distributed farther south and east of the Pribilof Islands than in previous years (Figures 19, 21, 25b and 25d). Mature females with less than or equal to half clutch of eggs were mostly in the northern part of the survey area above 58 ^{o} N (Figures 23 and 25h).

The difference between the summer survey distribution of large males and the fishery catch distribution indicates that survey catchability may be less than 1.0 and/or some movement occurs between the summer survey and the winter fishery. However, the exploitation rate on males south of 58.5^{o} N latitude may exceed the target rate, possibly resulting in localized depletion of males from the southern part of their range. Snow crab larvae probably drift north and east after hatching in spring. Snow crab appear to move south and west as they age, however, no tagging studies have been conducted to fully characterize the ontogenetic or annual migration patterns of this stock. High exploitation rates in the southern area may have resulted in a northward shift in snow crab distribution. The last few years of survey data indicate a shift to the south in distribution of snow crab, which reverses the trends seen in early 2000's.

Ernst, et al. (2005) found the centroids of survey summer distributions have moved to the north over time (Figures 26 and 27). In the early 1980's the centroids of mature female distribution were near 58.5 ^{o} N, in the 1990's the centroids were about 59.5 ^{o} N. The centroids of old shell male distribution was south of 58 ^{o} N in the early 1980's, moved north in the late 1980's and early 1990's then shifted back to the south in the late 1990's. The distribution of males>101 mm was about at 58 ^{o} N in the early 1980's, then was farther north (58.5 to 59 ^{o} N) in the late 1980's and early 1990's, went back south in 1996 and 1997 then has moved north with the centroid of the distribution in 2001 just north of 59 ^{o} N.. The centroids of the catch are generally south of 58 ^{o} N, except in 1987. The centroids of catch also moved north in the late 1980's and most of the 1990's. The centroids of the catch were about at 56.5 ^{o} N in 1997 and 1998, then moved north to above 58.5 ^{o} in 2002.

2009 and 2010 Study Area Data Additional survey data

Bering Sea Fisheries Research Foundation (BSFRF) conducted a survey of 108 tows in 27 survey stations (10,827 sq nm, hereafter referred to as the "study area") in the Bering Sea in summer 2009(Figure 28, see Somerton et al 2010 for more details). The abundance estimated by the BSFRF survey in the study area was 66.9 million male crab

>=100 mm compared to 36.7 million for the NMFS tows (Table 4). The NMFS abundance of females >=50mm (121.5 million) was greater than the BSFRF abundance estimate in the study area (113.6 million) (Table 4).

The abundance of male crab in the entire Bering Sea survey for 2009 was greatest in the 30 – 60mm size range (Figures 29 and 30). The abundance of crab in the 35 to 60mm size range for the BSFRF net in the study area was very low compared to the abundance of the same size range for the NMFS entire Bering Sea survey. The differences in abundance by size for the NMFS entire Bering Sea survey and the BSFRF study area are due to availability of crab in the study area as well as capture probability. While the abundance of larger male crab for the NMFS net in the study area is less than for the BSFRF, the abundance of females >45 mm is greater for the NMFS net than the BSFRF (Figure 29). This difference may be due to different towing locations for the two nets within the study area, or to higher catchability of females possibly due to aggregation behavior. The ratio of abundance of the NMFS net and BSFRF net in the study area are quite different for males and females (Figure 31). The ratio of abundance indicates a catchability for mature females (mainly 45 – 65 mm) that is greater than 1.0 for the NMFS net.

The largest tows for small (<78mm) male crab in the entire Bering Sea area were north of the study area near St. Matthew Island (Figure 12 and 20). Some higher tows for large males (>=100mm) and for mature females occurred in the study area as well as outside the study areas (Figures 5-18 and 22-24). These distributions indicate that availability of crab of different sizes and sex varies spatial throughout the Bering Sea. The numbers by length and mature biomass by sex for the BSFRF tows and the NMFS tows within the study area were added to the model as an additional survey.

The 2009 estimated snow crab abundance by length in the study area had very low numbers of both male and female crab in the 35 mm to 70 mm range than observed in the Bering sea wide survey(Figures 29 and 30). The ratio of abundance (NMFS/BSFRF) by length for 2009 was 0.2 at about 45 mm increasing gradually to 0.4 at 95mm then increasing steeply to 0.9 to 1.25 above 115 mm (Figure 31). The mean size of crab retained by the fishery is about 110 mm, with minimum size retained about 102mm. Ratios of abundance for female crab were above 1.0 from 45mm to 60mm then declined to 0.5 to 0.8 above 60mm to 80mm. There were very few female crab above 80mm in the population.

The 2010 study area covered a larger portion of the distribution of snow crab than the 2009 study area. The abundance by length for the 2010 study area is very different from the 2009 data, with higher abundance in 2010 of small crab (Figure 32). The expanded estimate (expanded to the study area) of male abundance from BSFRF data is higher than the Bering Sea wide abundance for length from 50mm to about 110mm. Female abundance shows a similar relationship (Figure 33). The ratio of male abundance by length (NMFS/BSFRF) in 2010 increased to 0.6 at 40mm then decreased to about 0.2 at 65-70mm then increased and ranged between 0.3 and 0.4 up to about 112mm (Figure 34). The ratios increased from 0.4 at 112 to about 0.7 at 122mm then to 1.55 at 132mm. The ratio of female abundance by length in 2010 was 0.6 at about 45mm and declined to 0.4 at about 67mm then declined below 0.1 above about 77mm.

Several processes influence net performance. Somerton et al. accounted for area swept, sediment type, depth and crab size. They did not correct for the probability of encountering crab. The 2010 study area data have a number of paired tows where BSFRF caught no crab (within a particular size bin) or where NMFS caught no crab. This creates problems with simply taking the ratio of catches since a number of ratios will be infinity (dividing by 0). This occurs because the paired tows although near in space were not fishing on the same density of crab. In addition, the BSFRF tow covered about 10% of the area of the NMFS tow, due to the narrower net width and the 5 minute tow duration compared to the 30 minute NMFS tow duration. In order to analyze this data, first the ratio of the NMFS density (numbers per nm^2) to the sum of the density of NMFS and BSFRF were calculated (Figure 35 males and Figure 38 females). These values range from 0 to 1.0. The simple mean of these values was estimated by length bin and then transformed to estimate mean catchability by length bin (Figure 39 males Figure 40 females). A value of 0.5 for the ratio of NMFS to sum of density is equivalent to a catchability of 1.0 and 0.33 is catchability of 0.5. The size of the catch for each observation is plotted in Figure 36 (same data as Figure 35).

The BSFRF study provides a rich data set to evaluate net performance. In this survey the sample is the paired tows and the goal would be to evaluate net performance over a wide range of densities, sediment types and depths. Somerton et al. (February 2011 Modeling Workshop) used catch to weight observations for estimation of the selectivity curve. This assumes that trawl performance is influenced by local density of crab (an untested assumption). No weighting of the observations assumes that there is no relationship between catch and the selectivity of crab. If selectivity changes depending on whether catches are high or low, then further study and analysis is needed. Further analysis needs to be done on whether data should be weighted in the initial estimation of the selectivity curve. The unweighted mean values by length bin are higher than the values estimated by Somerton et al.. Somerton weights again by survey abundance and adjusts for depth and sediment type in a separate step in the analysis to estimate a Bering Sea wide survey selectivity. Simulation studies are needed to determine the influence of weighting (whether bias is introduced) and whether the distributional assumptions and likelihood equations used in the analysis of the paired tow data are correct and unbiased.

The overall distribution of the ratio of NMFS density to the sum of the densities is skewed with about 140 - 0.0 values and 110 - 1.0 values (Figure 41). The percentage of observations where NMFS caught crab and no crab were caught by the BSFRF tow increases by size bin for male crab (Figures 41 through 46).

Catches of male crab decrease with size simply because they are lower in abundance in the population. At sizes of male crab greater than about 90 mm the fraction of observations where the ratio of NMFS density to the sum of densities was 1.0 and 1 crab was caught in the net was about 10% to 30%. In other, words the majority of the tows involved more than 1 crab caught.

The mean values of the ratio of NMFS density to the sum of densities for female crab transformed to catchability increase from less than 0.1 at 25mm to about 0.5 at 55mm then decrease slightly above 70mm (Figures 38 and 40).

Weight - Size

The weight (kg) – size (mm) relationship was estimated from survey data, where weight = a* size^{b}. Juvenile female a= 0.00000253, b=2.56472. Mature female a=0.000675 b=2.943352, and males, a= 0.00000023, b=3.12948 (Figure 47).

Maturity

Maturity for females was determined by visual examination during the survey and used to determine the fraction of females mature by size for each year. Female maturity was determined by the shape of the abdomen, by the presence of brooded eggs or egg remnants. The average fraction mature for female snow crab is shown in Figure 48b, although this curve is not used in the model.

Morphometric maturity for males is determined by chela height measurements, which are available starting from the 1989 survey (Otto 1998). The number of males with chela height measurements has varied between about 3,000 and 7,000 per year. In this report a mature male refers to a morphometrically mature male.

One maturity curve for males was estimated using the average fraction mature based on chela height data and applied to all years of survey data to estimate mature survey numbers (Figure 48c). The separation of mature and immature males by chela height at small widths may not be adequately refined given the current measurement to the nearest millimeter. Chela height measured to the nearest tenth of a millimeter (by Canadian researchers on North Atlantic snow crab) shows a clear break in chela height at small and large widths and shows fewer mature animals at small widths than the Bering Sea data measured to the nearest millimeter. Measurements taken in 2004-2005 on Bering Sea snow crab chela to the nearest tenth of a millimeter show a similar break in chela height to the Canadian data (Rugolo et al. 2005).

The probability of a new shell crab maturing was estimated in the model at a smooth function to move crab from immature to mature (Figure 48). The probability of maturing was estimated to match the observed fraction mature for all mature males and females observed in the survey data. The probability of maturing by size for female crab was about 50% at about 48 mm and increased to 100% at 60mm (Figure 49). The probability of maturing for male crab was about 15% to 20% at 60 mm to 90mm and increased sharply to 50% at about 98mm, and 100% at 108 mm.

Natural Mortality

Natural mortality is a critical variable in population dynamic modeling, and may have a large influence on derived optimal harvest rates. Natural mortality rates estimated in a population dynamics model may have high uncertainty and may be correlated with other parameters, and therefore are usually fixed. The ability to estimate natural mortality in a population dynamics model depends on how the true value varies over time as well as other factors (Fu and Quinn 2000, Schnute and Richards 1995).

Nevissi, et al. (1995) used radiometric techniques to estimate shell age from last molt (Table 7). The total sample size was 21 male crabs (a combination of Tanner and snow crab) from a collection of 105 male crabs from various hauls in the 1992 and 1993 NMFS Bering Sea survey. Fishing mortality rates before and during the time period when these crab were collected were relatively high, and therefore maximum age would represent Z (total mortality) rather than M. Representative samples for the 5 shell condition categories were collected that made up the 105 samples. The oldest looking crab within shell conditions 4 and 5 were selected from the total sample of SC4 and SC5 crabs to radiometrically age (Orensanz, pers comm.). Shell condition 5 crab (SC5 = very, very old shell) had a maximum age of 6.85 years (s.d. 0.58, 95% CI approximately 5.69 to 8.01 years). The average age of 6 crabs with SC4 (very old shell) and SC5, was 4.95 years. The range of ages was 2.70 to 6.85 years for those same crabs. Given the small sample size, this maximum age may not represent the 1.5% percentile of the population that is approximately equivalent to Hoenig's method (1983). Maximum life span defined for a virgin stock is reasonably expected to be longer than these observed maximum ages from exploited populations. Radiometric ages estimated by Nevissi, et al. (1995) may be underestimated by several years, due to the continued exchange of material in crab shells even after shells have hardened (Craig Kastelle, pers. comm., Alaska Fisheries Science Center, Seattle, WA).

Tag recovery evidence from eastern Canada reveal observed maximum ages in exploited populations of 17-19 years (Nevissi, et al. 1995, Sainte-Marie 2002). A maximum time at large of 11 years for tag returns of terminally molted mature male snow crab in the North Atlantic has been recorded since tagging started about 1993 (Fonseca, et al. 2008). Fonseca, et al. (2008) estimated a maximum age of 7.8 years post terminal molt using data on dactal wear.

We reasoned that in a virgin population of snow crab, longevity would be at least 20 years. Hence, we used 20 years as a proxy for longevity and assumed that this age would represent the upper 99th percentile of the distribution of ages in an unexploited population if observable. Under negative exponential depletion, the 99th percentile corresponding to age 20 of an unexploited population corresponds to a natural mortality rate of 0.23. Using Hoenig's (1983) method an M=0.23 corresponds to a maximum age of 18 years (Table 8). M=0.23 was used for all female crab in the model. Male natural mortality estimated in the model with a prior constraint of mean M=0.23 with a se = 0.054 estimated from using the 95% CI of +-1.7 years on maximum age estimates from dactal wear and tag return analysis in Fonseca, et al. (2008).

Molting probability

Female and male snow crab have a terminal molt to maturity. Many papers have dealt with the question of terminal molt for Atlantic Ocean mature male snow crab (e.g., Dawe, et al. 1991). A laboratory study of morphometrically mature male Tanner crab, which were also believed to have a terminal molt, found all crabs molted after two years (Paul and Paul 1995). Bering Sea male snow crab appear to have a terminal molt based on data on hormone levels (Tamone et al. 2005) and findings from molt stage analysis via setagenesis. The models presented here assume a terminal molt for both males and females.

Male Tanner and snow crabs that do not molt (old shell) may be important in reproduction. Paul et al. (1995) found that old shell mature male Tanner crab out-competed new shell crab of the same size in breeding in a laboratory study. Recently molted males did not breed even with no competition and may not breed until after about 100 days from molting (Paul et al. 1995). Sainte-Marie et al. (2002) states that only old shell males take part in mating for North Atlantic snow crab. If molting precludes males from breeding for a three month period, then males that are new shell at the time of the survey (June to July), would have molted during the preceding spring (March to April), and would not have participated in mating. The fishery targets new shell males, resulting in those animals that molted to maturity and to a size acceptable to the fishery of being removed from the population before the chance to mate. Animals that molt to maturity at a size smaller than what is acceptable to the fishery may be subjected to fishery mortality from being caught and discarded before they have a chance to mate. However, new shell males will be a mixture of crab less than 1 year from terminal molt and 1+ years from terminal molt due to the inaccuracy of shell condition as a measure of shell age.

Crabs in their first few years of life may molt more than once per year, however, the smallest crabs included in the model are probably 3 or 4 years old and would be expected to molt annually. The growth transition matrix was applied to animals that grow, resulting in new shell animals. Those animals that don’t grow become old shell animals. Animals that are classified as new shell in the survey are assumed to have molted during the last year. The assumption is that shell condition (new and old) is an accurate measure of whether animals have molted during the previous year. The relationship between shell condition and time from last molt needs to be investigated further.

Mating ratio and reproductive success

Full clutches of unfertilized eggs may be extruded and appear normal to visual examination, and may be retained for several weeks or months by snow crab. Resorption of eggs may occur if not all eggs are extruded resulting in less than a full clutch. Female snow crab at the time of the survey may have a full clutch of eggs that are unfertilized, resulting in overestimation of reproductive potential. Male snow crab are sperm conservers, using less than 4% of their sperm at each mating. Females also will mate with more than one male. The amount of stored sperm and clutch fullness varies with sex ratio (Sainte-Marie 2002). If mating with only one male is inadequate to fertilize a full clutch, then females will need to mate with more than one male, necessitating a sex ratio closer to 1:1 in the mature population, than if one male is assumed to be able to adequately fertilize multiple females.

The fraction barren females and clutch fullness observed in the survey increased in the early 1990's then decreased in the mid- 1990's then increased again in the late 1990's (Figures 49 and 50). The highest levels of barren females coincides with the peaks in catch and exploitation rates that occurred in 1992 and 1993 fishery seasons and the 1998 and 1999 fishery seasons. While the biomass of mature females was high in the early 1990's, the rate of production from the stock may have been reduced due to the spatial distribution of the catch and the resulting sex ratio in areas of highest reproductive potential. The percentage of barren females was low in 2006, increased in 2007, then declined in 2008 and 2009 to below 1 percent for new and old shell females and about 17% for very old females. Clutch fullness for new shell females declined slightly in 2009 relative to 2008, however, on average is about 70% compared to about 80% before 1997. Clutch fullness for old and very old shell females was high in 2006, declined in 2007, then was higher in 2009 (about 78% old shell and 60% very old).

The fraction of barren females in the 2003 and 2004 survey south of 58.5 ^{o} N latitude was generally higher than north of 58.5 ^{o} N latitude (Figures 51 and 52). In 2004 the fraction barren females south of 58.5 ^{o} N latitude was greater for all shell conditions. In 2003, the fraction barren was greater for new shell and very very old shell south of 58.5 ^{o} N latitude.

Laboratory analysis of female snow crab collected in waters colder than 1.5 ^{o} C from the Bering Sea have been determined to be biennial spawners in the Bering Sea. Future recruitment may be affected by the fraction of biennial spawning females in the population as well as the estimated fecundity of females, which may depend on water temperature.

An index of reproductive potential for crab stocks needs to be defined that includes spawning biomass, fecundity, fertilization rates and frequency of spawning. In most animals, spawning biomass is a sufficient index of reproductive potential because it addresses size related impacts on fecundity, and because the fertilization rates and frequency of spawning are relatively constant over time. This is not the case for snow crab.

The centroids of the cold pool (<2.0 ^{o} C) were estimated from the summer survey data for 1982 to 2006 (Figure 53). The centroid is the average latitude and average longitude. In the 1980's the cold pool was farther south(about 58 to 59 ^{o} N latitude) except for 1987 when the centroid shifted to north of 60 ^{o} N latitude. The cold pool moved north from about 58 ^{o} N latitude in 1999 to about 60.5 ^{o} N latitude in 2003. The cold pool was farthest south in 1989, 1999 and 1982 and farthest north in 1987, 1998, 2002 and 2003. In 2005 the cold pool was north, then in 2006 back to the south. The last three years (2007, 2008 and 2009) have all been cold years.

The clutch fullness and fraction of unmated females however, does not account for the fraction of females that may have unfertilized eggs. The fraction of barren females observed in the survey may not be an accurate measure of fertilization success because females may retain unfertilized eggs for months after extrusion. To examine this hypothesis, RACE personnel sampled mature females from the Bering Sea in winter and held them in tanks until their eggs hatched in March of the same year. All females then extruded a new clutch of eggs in the absence of males. All eggs were retained until the crabs were sacrificed near the end of August. Approximately 20% of the females had full clutches of unfertilized eggs. The unfertilized eggs could not be distinguished from fertilized eggs by visual inspection at the time they were sacrificed. Indices of fertilized females based on the visual inspection method of assessing clutch fullness and percent unmated females may overestimate fertilized females and not an accurate index of reproductive success.

McMullen and Yoshihara (1969) examined female red king crab around Kodiak Island in 1968 and found high percentages of females without eggs in areas of most intense fishing (up to 72%). Females that did not extrude eggs and mate were found to resorb their eggs in the ovaries over a period of several months. One trawl haul captured 651 post-molt females and nine male red king crab during the period April to May 1968. Seventy-six percent of the 651 females were not carrying eggs. Ten females were collected that were carrying eggs and had firm post-molt shells. The eggs were sampled 8 and 10 days after capture and were examined microscopically. All eggs examined were found to be infertile. This indicates that all ten females had extruded and held egg clutches without mating. Eggs of females sampled in October of 1968 appear to have been all fertile from a table of results in McMullen and Yoshihara(1969), however the results are not discussed in the text, so this is unclear. This may mean that extruded eggs that are unfertilized are lost between May and October.

ANALYTIC APPROACH

Model Structure

The model structure was developed following Fournier and Archibald's (1982) methods, with many similarities to Methot (1990). The model was implemented using automatic differentiation software developed as a set of libraries under C++ (ADModel Builder). ADModel Builder can estimate a large number of parameters in a non-linear model using automatic differentiation software extended from Greiwank and Corliss (1991) and developed into C++ class libraries. This software provides the derivative calculations needed for finding the objective function via a quasi-Newton function minimization routine (e.g., Press et al. 1992). The model implementation language (ADModel Builder) gives simple and rapid access to these routines and provides the ability to estimate the variance-covariance matrix for all parameters of interest.

The model estimates the abundance by length bin and sex in the first year (1978) as parameters rather than estimating the recruitments previous to 1978. This results in 44 estimated parameters.

Recruitment is determined from the estimated mean recruitment, the yearly recruitment deviations and a gamma function that describes the proportion of recruits by length bin,

$$N_{t,1} = pr_l \, e^{R_0^l + \tau_t}$$

where,

R_0^l Log Mean recruitment
pr_l Proportion of recruits for each length bin
τ_t Recruitment deviations by year.

Recruitment is estimated equal for males and females in the model.

Crab were distributed into 5mm CW bins based on a pre-molt to post-molt transition matrix. For immature crab, the number of crabs in length bin *l* in year *t-1* that remain immature in year *t* is given by,

$$N_{t,l}^{s} = (1-\phi_l^s) \sum_{l=l_1}^{l'} \psi_{l',l}^{s} \; e^{-Z_{l'}^{s}} N_{t-1,l'}^{s}$$

$\psi_{l',l}^{s}$ growth transition matrix by sex, pre-molt and post-molt length bins which defined the fraction of crab of sex *s* and pre-molt length bin *l*', that moved to length bin *l* after molting,
$N_{t,l}^{s}$ abundance of immature crab in year *t*, sex *s* and length bin *l*,
$N_{t-1,l'}^{s}$ abundance of immature crab in year *t-1*, sex s and length bin *l*',
$Z_{l'}^{s}$ total instantaneous mortality by sex *s* and length bin *l*',
ϕ_l^s fraction of immature crab that became mature for sex *s* and length bin *l*,
l' pre-molt length bin,
l post-molt length bin.

Growth

Very little information exists on growth for Bering Sea snow crab. A growth study was conducted in 2011 (Somerton 2013) that added new information that was used in the Base model of the current assessment. Tagging experiments were conducted on snow crab in 1980 with recoveries occurring in the Tanner crab (*Chionoecetes bairdi*) fishery in 1980 to 1982 (Mcbride 1982). All tagged crabs were males greater than 80mm CW and which were released in late May of 1980. Forty-nine tagged crabs were recovered in the Tanner crab fishery in the spring of 1981 of which only 5 had increased in carapace width. It is not known if the tags inhibited molting or resulted in mortality during molting, or the extent of tag retention. One crab was recovered after 15 days in the 1980 fishery, which apparently grew from 108 mm to 123 mm carapace width. One crab was recovered in 1982 after almost 2 years at sea that increased from 97 to 107 mm.

In the 2012 assessment and previous to 2012, growth data from 14 male crabs collected in March of 2003 that molted soon after being captured were used to estimate a linear function between premolt and postmolt width (Lou Rugolo unpublished data, Figure 54). The crabs were measured when shells were still soft because all died after molting, so measurements are probably underestimates of postmolt width (Rugolo, pers. com.). Growth appears to be greater than growth of some North Atlantic snow crab stocks (Sainte-Marie 1995). Growth from the 1980 tagging of snow crab was not used due to uncertainty about the effect of tagging on growth. Previous to the 2011 growth data collection that was used in the Base model and scenario 1, there were no growth measurements for Bering Sea snow crab females. North Atlantic growth data indicate growth is slightly less for females than males.

Somerton's (2013) estimates of growth for Bering sea snow crab combined several data sets as well as female and male data. The best model determined by Somerton(2013) included the following data :

1. Transit study; 14 crab
2. Cooperative seasonality study (Rugolo); 6 crab
3. Dutch harbor holding study; 9 crab
4. NMFS Kodiak holding study held less than 30 days; 6 crab

Total sample size was 35 crab. Somerton(2013) excluded data from the NMFS Kodiak holding study where crab were held more than 30 days and also for the ADF&G Kodiak holding study where crab were collected during the summer survey and held until molting the next spring because growth was significantly lower than the above four data sets.

Some data points were excluded from 1, 2 and 3 above (35 is the final sample size). Females molting to maturity were excluded from all data sets, since the molt increment is usually smaller. Crab missing more than two limbs were excluded due to other studies showing lower growth. Crab from Rugolo's seasonal study were excluded that were measured less than 3 days after molting due to difficulty in measuring soft crab accurately. Somerton fit each data set starting with (1) above and testing the next data set for significant difference. Two linear models were fit that joined at 36.1 mm (males and females combined, Figure 55),

For < =36.1mm

Postmolt = -4.0 + 1.46 * Premolt

>= 36.1 mm
Postmolt = 6.59 + 1.17 * Premolt

The postmolt size is 48.8 mm at premolt size of 36.1 mm.

The September 2013 model fit the growth data by sex reported by Somerton (2013) within the assessment model by adding a sum of squared deviations likelihood component. Sample sizes were 17 for males and 18 for females. One linear function for each sex was estimated resulting in four parameters (an intercept and slope by sex) (Figures 54b and 54c),

$$Width_{t+1,\, s} = a_s + b_s * width_{t,\, s}$$

where s is sex and t is width interval.

The two line growth model estimates two linear segments similar to Somerton (2013), except by sex with the intersection of the lines fixed at 36.1 mm (premolt) and 48.8 mm (postmolt). This results in four parameters total (two parameters estimated per sex). The parameters of the intersection point are not estimable in the assessment model due the equation being nondifferentiable.

Premolt < 36.1mm

$Postmolt_s = a1_s + Premolt_s * (48.8 - a1_s)/36.1$

Premolt > 36.1mm

$Postmolt_s = a2_s + Premolt_s * (48.8 - a2_s)/36.1$

Where $a1_s$ and $a2_s$ are estimated parameters by sex.

Likelihood equations were added for the sum of squares fit with the new growth data by sex,

$$0.5\sum(g_i - \hat{g}_i)^2$$

Where g_i is post-molt size from growth data (Somerton 2013) and $g\hat{}_i$ is predicted post-molt size.

The base model in the current assessment has growth modeled as two linear segments with a smooth transition recommended by the 2014 CIE review (Cadigan 2014),

$$f_i(x) = a_i + b_i\, x, \qquad i = 1,2\,,$$

$$a_2 = a_1 + (b_1 - b_2)\delta$$

$$f(x) = f_1(x)\left\{1 - \varphi\left(\frac{x-\delta}{s}\right)\right\} + f_2(x)\left\{\varphi\left(\frac{x-\delta}{s}\right)\right\}$$

Where φ is the cumulative distribution function for a standard normal random variable. δ constrains the breakpoint, and s is a scale parameter determining how smooth the transition is between equation segments. The cumd_norm function was used in ADMB for the cumulative normal distribution. Separate parameters were estimated for male and female crab, except one s parameter was estimated for both sexes. This results in 4 estimated parameters per sex plus the s parameter, for a total of 9 estimated parameters.

Crab were assigned to 5mm width bins using a two-parameter gamma distribution with mean equal to the growth increment by sex and length bin and a beta parameter (which determines the variance),

$$\psi^{s}_{l',l} = \int_{l-2.5}^{l+2.5} gamma(l / \alpha_{s,l'}, \beta_s)$$

where,

$\alpha_{s,l'}$ expected growth interval for sex s and size l' divided by the shape parameter β,

$\psi^{s}_{l',l}$ growth transition matrix for sex, s and length bin l' (pre-molt size), and post-molt size l.

The Gamma distribution was,

$$gamma(l / \alpha_{s,l}, \beta_s) = \frac{l^{\alpha_{s.l}-1} e^{-\frac{l}{\beta_s}}}{\beta^{\alpha_{s,l}} \Gamma(\alpha_{s,l})}$$

where l is the length bin, β for both males and females was set equal to 0.75, which was estimated from growth data on Bering Sea Tanner and King crab due to the small amount of growth data available for snow crab. The distribution was truncated at postmolt sizes greater 40mm above the premolt size due to problems in estimation of very small values in the growth transition matrix, and that crab would not be expected to have a larger molt increment than 40mm. There was no difference in the results of the model with the truncated growth matrix and without.

The probability of an immature crab becoming mature by size is applied to the post-molt size. Crab that mature and reach their terminal molt in year t then are mature new shell during their first year of maturity. The abundance of newly mature crab ($\Omega^{s}_{t,l}$) in year t is given by,

$$\Omega^{s}_{t,l} = \phi^{s}_{l} \sum_{L=l_1}^{l'} \psi^{s}_{l',l} \; e^{-Z^{s}_{l'}} N^{s}_{t-1,l'}$$

Crab that were mature SC2 in year *t-1* no longer molt and move to old shell mature crab (SC3+) in year *t* ($\Lambda^{s}_{t,l}$). Crab that are SC3+ in year *t-1* remained old shell mature for the rest of their lifespan. The total old shell mature abundance ($\Lambda^{s}_{t,l}$) in year *t* is the sum of old shell mature crab in year *t-1* plus previously new shell (SC2) mature crabs in year *t-1*,

$$\Lambda^{s}_{t,l} = e^{-Z^{s,old}_{l}} \Lambda^{s}_{t-1,l} + e^{-Z^{s,new}_{l}} \Omega^{s}_{t-1,l}$$

The fishery is prosecuted in early winter prior to growth in the spring. Crab that molted in year *t-1* remain as SC2 until after the spring molting season. Crab that molted to maturity in year *t-1* are SC2 through the fishery until the spring molting season after which they become old shell mature (SC3).

Mature male biomass (MMB) was calculated as the sum of all mature males at the time of mating multiplied by respective weight at length.

$$B_t = \sum_{L=1}^{lbins} (\Lambda^{males}_{tm,l} + \Omega^{males}_{tm,l}) \, W^{males}_{l}$$

tm	nominal time of mating after the fishery and before molting,
lbins	number of length bins in the model,
$\Lambda^{males}_{tm,l}$	abundance of mature old shell males at time of mating in length bin *l*,
$\Omega^{males}_{tm,l}$	abundance of mature new shell males at the time of mating in length bin *l*,
W_l	mean weight of a male crab in length bin *l*.

Catch of male snow crab was estimated as a pulse fishery 0.62 yr after the beginning of the assessment year (July 1),

$$catch = \sum_{l} (1 - e^{-(F * Sel_l + Ftrawl * TrawlSel_l)}) w_l N_l \, e^{-M * .62}$$

F	Full selection fishing mortality determined from the control rule using biomass including implementation error
$Sel_{,l}$	Fishery selectivity for length bin l for male crab
Ftrawl	Fishing mortality for trawl bycatch fixed at 0.01 (average F)
$TrawlSel_l$	Trawl bycatch fishery selectivity by length bin l
W_l	weight by length bin l
N_l	Numbers by length for length bin l
M	Natural Mortality

Selectivity

The selectivity curve total catch, female discard and groundfish bycatch were estimated as two-parameter ascending logistic curves (Figure 56 and 67).

$$S_l = \frac{1}{1+e^{-a\,(l-b\,)}}$$

The probability of retaining crabs by size with combined shell condition was estimated as an ascending logistic function. The selectivities for the retained catch were estimated by multiplying a two parameter logistic retention curve by the selectivities for the total catch.

$$S_{ret,l} = \frac{1}{1+e^{-a(l-b)}}\,\frac{1}{1+e^{-c_{ret}(l-d_{ret})}}$$

The selectivities for the survey were estimated with three-parameter (Q, L95% and L50%), ascending logistic functions (Survey selectivities in Figure 57).

$$\text{Selectivity}_l = \frac{Q}{1+e^{\left\{\frac{-\ln(19)(l-l_{50\%})}{(l_{95\%}-l_{50\%})}\right\}}}$$

Separate survey selectivities were estimated for the period 1978 to 1981, 1982 to 1988, and 1989 to the present. Survey selectivities were estimated separately for males and females in the 1989 to present period. The maximum selectivity(Q) for each time period was estimated in the model for the Base Model. The separate selectivities were used due to the change in catchability in 1982 from the survey net change, and the addition of more survey stations to the north of the survey area after 1988. Survey selectivities have been estimated for Bering Sea snow crab from underbag trawl experiments (Somerton and Otto 1999). A bag underneath the regular trawl was used to catch animals that escaped under the footrope of the regular trawl, and was assumed to have selectivity equal to 1.0 for all sizes. The selectivity was estimated to be 50% at about 74 mm, 0.73 at 102 mm, and reached about 0.88 at the maximum size in the model of 135 mm.

Likelihood Equations

Weighting values (λ) for each likelihood equation are shown in Table 11.

Catch biomass is assumed to have a normal distribution,

$$\lambda \sum_{t=1}^{T} \left[C_{t,\ fishery,obs} - C_{t,\ fishery.pred} \right]^2$$

There are separate likelihood components for the retained and total catch.

The robust multinomial likelihood is used for length frequencies from the survey and the catch (retained and total) for the fraction of animals by sex in each 5mm length interval. The number of samples measured in each year is used to weight the likelihood. However, since thousands of crab are measured each year, the sample size was set at 200.

$$Length\ Likelihood = -\sum_{t=1}^{T} \sum_{l=1}^{L} nsamp_t * p_{t,l} \log(\hat{p}_{t,l} + o) - Offset$$

$$Offset = \sum_{t=1}^{T} \sum_{l=1}^{L} nsamp_t * p_{t,l} \log(p_{t,l})$$

Where, T is the number of years, $p_{t,l}$ is the proportion in length bin *l*, an *o* is fixed at 0.001.

An additional length likelihood weight (2) is added to the first year survey length composition fit to facilitate the estimation of the initial abundance parameters. A smoothness constraint is also added to the numbers at length by sex in the first year,

$$\sum_{S=1}^{2} \sum_{l=1}^{L} (\mathit{first\ differences}(N_{1978,s,l}))^2$$

The survey biomass (including biomass in the 2009 and 2010 study areas) assumes a lognormal distribution with the inverse of the standard deviation of the log(biomass) in each year used as a weight,

The survey biomass assumes a lognormal distribution with the inverse of the standard deviation of the log(biomass) in each year used as a weight,

$$\lambda \sum_{t=1}^{ts} \left[\frac{\log(SB_t) - \log(S\hat{B}_t)}{sqrt(2) * s.d.(\log(SB_t))} \right]^2$$

$$s.d.(\log(SB_t)) = sqrt(\log((cv(SB_t))^2 + 1))$$

Recruitment deviations likelihood equation is,

$$\lambda \sum_{s=1}^{2} \sum_{t=1}^{T} \tau_{s,t}^2$$

Smooth constraint on probability of maturing by sex and length

$$\sum_{S=1}^{2} \sum_{l=1}^{L} (\mathit{first\ differences}(\mathit{first\ differences}(PM_{s,l}))^2$$

Where $PM_{s,l}$ is a vector of parameters that define the probability of molting.

Penalties on Fishing mortalities.

Penalty on average F for males (λ = 2 in last phases),

$$\lambda \sum_{t=1}^{T} (F_t - 1.15)^2$$

Fishing mortality deviations for males(λ = 0.1),

$$\lambda \sum_{s=1}^{2} \sum_{t=1}^{T} \varepsilon_{s,t}^2$$

Female bycatch fishing mortality penalty (λ = 1.0).

$$\lambda \sum_{t=1}^{T} (\varepsilon_{female,t})^2$$

Trawl bycatch fishing mortality penalty (λ = 1.0).

$$\lambda \sum_{t=1}^{T} (\varepsilon_{trawl,t})^2$$

Male natural mortality, when estimated in the model uses a penalty which assumes a normal distribution. A 95% CI of +/- 1.7 yrs translates to a 95% CI in M of about +-0.025 using an exponential model, which is a CV= 0.054.

$$0.5(\frac{M-0.23}{0.0125})^2$$

No penalty was used when immature M was estimate.

Likelihood equations were added for the sum of squares fit for the Base model with the new growth data by sex and a linear model by sex, where post-molt CW = a + b Premolt CW.
(λ = 2.0 Base model)

$$\lambda \ 0.5\sum(g_i - \hat{g}_i)^2$$

Where g_i is post-molt size from growth data (Somerton 2013) and $g^{\wedge}_i$ is predicted post-molt size from a linear model with intercept and slope parameters.

There were a total of 320 parameters estimated in the Base model (Table 10) for the 37 years of data (1978-2014). The 105 fishing mortality parameters (one set for the male catch, one set for the female discard catch, and one set for the trawl fishery bycatch) estimated in the model were constrained so that the estimated catch fit the observed catch closely. There were 37 recruitment parameters estimated in the model, one for the mean recruitment, 36 for each year from 1979 to 2014 (male and female recruitment were fixed to be equal). There were 8 fishery selectivity parameters that did not change over time. Survey selectivity was estimated for three different periods resulting in 9 parameters for males and 9 parameters for females. There were 6 survey selectivity parameters estimated for the study area for BSFRF female logistic availability curves for 2009 and 2010. 22 parameters for each year (2009 and 2010) for male crab were estimated for the smooth availability curve for the BSFRF net. Two parameters for natural mortality and 9 growth parameters were also estimated in the Base model. The September 2013 model and the two line growth model estimated 4 growth parameters.

Molting probabilities for mature males and females were fixed at 0, i.e., growth ceases at maturity which is consistent with the terminal molt paradigm (Rugolo et al. 2005 and Tamone et al. 2005). Molting probabilities were fixed at 1.0 for immature females and males. The intercept and slope of the linear growth function of postmolt relative to premolt size were estimated in the model (3 parameters, Table 10). A gamma distribution was used in the growth transition matrix with the beta parameters fixed at 0.75 for male and females.

The model separates crabs into mature, immature, new shell and old shell, and male and female for the population dynamics. The model estimate of survey mature biomass is fit to the observed survey mature biomass time series by sex. The model fits the size frequencies of the survey by immature and mature separately for each sex. The probability of immature crab maturing was estimated in the model using 22 parameters for each sex with a second difference smooth constraint (44 total parameters). The model fits the size frequencies for the pot fishery catch by new and old shell and by sex.

Crabs 25 mm CW (carapace width) and larger were included in the model, divided into 22 size bins of 5 mm each, from 25-29 mm to a plus group at 130-135mm. In this report the term size as well as length will be considered synonymous with CW. Recruits were distributed in the first few size bins using a two parameter gamma distribution with the alpha parameter of the distribution fixed at 11.5 and the beta parameter fixed at 4.0. Seventy parameters were estimated for the initial population size composition of new and old shell males and females in 1978. No spawner-recruit relationship was used in the population dynamics part of the model. Recruitments for each year were estimated in the model to fit the data.

The NMFS trawl survey occurs in summer each year, generally in June-July. In the model, the time of the survey is considered to be the start of the year (July), rather than January. The modern directed snow crab pot fishery has occurred generally in the winter months (January to February) over a short period of time. In contrast, in the early years the fishery occurred over a longer time period. The mean time of the fishery was estimated from the weighted distribution of catch by day for each year. The fishing mortality was applied all at once at the mean time for that year. Natural mortality is applied to the population from the time the survey occurs until the fishery occurs, then catch is removed. After the fishery occurs, growth and recruitment take place (in spring), with the remainder of the natural mortality through the end of the year as defined above.

Discard mortality

Discard mortality was 30% for all model scenarios as recommended by the CPT and the SSC 2013. The fishery for snow crabs occurs in winter when low temperatures and wind may result in freezing of crabs on deck before they are returned to the sea. Short term mortality may occur due to exposure, which has been demonstrated in laboratory experiments by Zhou and Kruse (1998) and Shirley (1998), where 100% mortality occurred under temperature and wind conditions that may occur in the fishery. Even if damage did not result in short term mortality, immature crabs that are discarded may experience mortality during molting some time later in their life.

Model Scenarios

The model structure of the Base model in this assessment is the same as the base model in the September 2013 assessment except for the formulation of the growth function.

The base model in the current assessment fits a two part linear function with a smooth transition recommended in the 2014 CIE review (Cadigan 2014). Nine model scenarios are presented in this assessment: 1) The September 2013 model (Model 0, one linear function fit to growth data), 2) two linear functions with a fixed intersection fit to growth data (Model 1), 3) Two linear functions with a smooth transition fit to growth data (Model 2a, Cardgan 2014), 4) same as 3 with factor of 2 times on growth likelihood (Model 2b, Base model for this assessment), 5) same as 3 with factor of 3 times on growth likelihood (Model 2c), 6) same as 3 with 0.5 weight on fishing penalties likelihood (Model 2d, weights relative to base model), 7) same as 3 with 0.25 weight on fishing penalties likelihood (Model 2e) 8) same as 3 with 0.1 weight on fishing penalties likelihood (Model 2f), 9) same as 3 with 0.001 weight on penalties on fishing mortality likelihood (Model 2g).

Model 2b was selected as the base model for this assessment because it uses the smooth transition for growth and the weight of 2 on the likelihood fits growth data much better than weight of 1, while a higher weight (3) does not provide much better fit to growth data.

The CPT and SSC in 2010 and 2011 recommended the use of the BSFRF 2009 and 2010 survey data as an additional survey in the assessment model to inform estimates of survey selectivity.

The current models and the September 2013 assessment estimated natural mortality for immature crab (male and female as 1 parameter), mature male crab and growth parameters for male and female crab. Survey selectivities for the BSFRF and NMFS data in the study area are also estimated separately for males and females.

Following the recommendation of the CPT and SSC in 2011, abundance estimates by length as well as survey biomass for the study area for the BSFRF tows and the NMFS tows were included in the September 2011, 2012 stock assessment models and the current assessment as an additional survey. Likelihood equations were added to the model for fits to the length frequency by sex for the BSFRF tows in the study area and the NMFS tows in the study area. A likelihood equation was also added for fit to the mature biomass by sex in the study area for the BSFRF tows and NMFS tows separately.

The formulation used in this assessment (and since the September 2011) was recommended by the February 2011 Crab Modeling Workshop,

$$\tilde{C}_l^s = N_l \, Q_{BSFRF}^s A_l S_l Q_{NMFS}^n$$

$\tilde{C}_l^s =$ numbers by length for NMFS in study area

A_l = a smooth function of availability in the study area for the BSFRF net

S_l = 2 parameter logistic function for the entire Bering Sea for the NMFS net

Q^{s}_{BSFRF} = Q for study area (s) for the BSFRF net

Q^{n}_{NMFS} = Q for the entire Bering Sea NMFS net

N_l = population abundance by length

All Bering Sea male survey selectivity was estimated as a 3 parameter logistic function,

$$\mathrm{Selectivity}_l = \frac{Q}{1+e^{\left\{\frac{-\ln(19)(l-l_{50\%})}{(l_{95\%}-l_{50\%})}\right\}}}$$

The BSFRF availability was estimated as a smooth function (22 parameters, 1 parameter for each length bin(22),

$$A_l = \exp(p_l); \qquad p_l \le 0.$$

A second difference constraint was added to the likelihood with a weight of 5.0,

$$5.0 \sum_{l=1}^{L} (\mathit{first\ differences}(\mathit{first\ differences}(p_l)))^2 \quad .$$

The maximum survey selectivity (Q) estimated for the entire Bering Sea area in Somerton et al. 2010 was estimated at 0.76 at 140 mm. The maximum size bin in the model is 130-135, which for the Somerton curve has a maximum selectivity of 0.75.

Projection Model Structure

The projection model was used to estimate the OFL, ABC and future biomass values. Variability in recruitment, as well as implementation error, was simulated with temporal autocorrelation. Recruitment was generated from a Beverton-Holt stock-recruitment model,

$$R_t = \frac{0.8\,h\,R_0\,B_t}{0.2\ spr_{F=0}\ R_0(1-h)+(h-0.2)B_t}\ e^{\varepsilon_t - \sigma_R^2/2}$$

$spr_{F=0}$ mature male biomass per recruit fishing at F=0. $B_0 = spr_{F=0}\ R_0$,

B_t mature male biomass at time t,

h steepness of the stock-recruitment curve defined as the fraction of R_0 at 20% of B_0,

R_0 recruitment when fishing at F=0,

σ_R^2 variance for recruitment deviations, estimated at 0.74 from the assessment model.

The temporal autocorrelation error (ε_t) was estimated as,

$$\varepsilon_t = \rho_R \varepsilon_{t-1} + \sqrt{1+\rho_R^2}\ \ \eta_t \qquad where\ \eta_t \sim N(0;\sigma_R^2) \tag{2}$$

ρ_R temporal autocorrelation coefficient for recruitment, set at 0.6.

Recruitment variability and autocorrelation were estimated using recruitment estimates from the stock assessment model. Steepness (h) and R_0 were estimated by setting Bmsy and Fmsy equal to B35% and F35% using a Beverton and Holt spawner recruit curve.

Implementation error was modeled as a lognormal autocorrelated error on the mature male biomass used to determine the fishing mortality rate in the harvest control rule,

$$B_t^{'} = B_t\ e^{\phi_t - \sigma_I^2/2};\ \ \phi_t = \rho_I \phi_{t-1} + \sqrt{1+\rho_I^2}\ \ \varphi_t \qquad where\ \varphi_t \sim N(0;\sigma_I^2)$$

$B_t^{'}$ mature male biomass in year t with implementation error input to the harvest control rule,

B_t mature male biomass in year t,

ρ_I temporal autocorrelation for implementation error, set at 0.6 (estimated from the recruitment time series),

σ_I standard deviation of φ which determines the magnitude of the implementation error.

Implementation error was set at a fixed value (e.g., 0.2) plus the s.d. on log scale from the assessment model for mature male biomass. Implementation error in mature male biomass resulted in fishing mortality values applied to the population that were either higher or lower than the values without implementation error. The autocorrelation was assumed to be the same value as that estimated for recruitment. Implementation autocorrelation was used to more closely approximate the process of estimating a biomass time series from within a stock assessment model. The variability in biomass of the simulated population resulted from the variability in recruitment and variability in full selection F arising from implementation error on biomass. The population dynamics equations were identical to those presented for the assessment model in the model structure section of this assessment.

RESULTS

The Base model estimated immature M at 0.367 and mature male M at 0.270 (Table 13).

The model estimated total mature biomass increased from about 384,400 t in 1978 to the peak biomass of 1,006,800 t in 1990 for the Base model (Table 6). Table 6a contains model predicted survey biomass and numbers. Model estimated total mature biomass declined after 1997 to about 372,400 t in 2003. Total mature biomass increased from 484,300 t in 2013 to 556,000 t in 2014 (Table 6 and Figure 4). The model results are informed by the population dynamics structure, including natural mortality, the growth and selectivity parameters and the fishery catches. The low observed survey abundance in the mid-1980's were followed by an abrupt increase in the survey abundance of crab in 1987, which followed through the population and resulted in the highest catches recorded in the early 1990's.

Average model estimated discard catch mortality for 1978 to 2012 was about 9.1% of the retained catch (with 30% mortality applied). The average observed discards from 1992 to 2012 was 8.4% of the retained catch (30% mortality applied) (Tables 1 and 2, and Figure 58). Estimates of observed discard mortality ranged from 2.5% of the retained catch to 19.2% of the retained catch (30% discard mortality). The percent observed discard has increased from 7.3% in 2012/13 to 14.8% in 2013/4 possibly due to recruitment.

Parameter estimates are listed in Table 10. The model fit to the total directed male catch, groundfish bycatch, male discard catch and female discard catch are shown in Figures 58, 59, 60, and 61 respectively.

Mature male and female biomass show similar trends (Table 3 and Table 6, Figures 62 and 64). Model estimates of mature male biomass increased from about 168,000 t to 178,000 t in the period 2002 to 2006, to 250,700 t in 2009, declined to 166,100 t in 2012, then increased to 236,100 t in 2014. Observed survey mature male biomass declined from 120,800 t in 2012 and 96,100 t in 2013, then increased to 156,900 t in 2014. Mature female biomass observed from the survey increased from 86,400 t in 2008 to 280,000 t in 2011 then declined to 195,100 t in 2012, then increased to 212,500 t in 2014. Model estimates of mature female biomass have an increasing trend from 187,300 t in 2009 to 287,100 t in 2014.

Fishery selectivities and retention curves were estimated using ascending logistic curves (Figures 56 and 66). Selectivities for trawl bycatch were estimated as ascending logistic curves (Figure 67). Plots of model fits to the survey size frequency data are presented in Figures 68 and 70 by sex for shell conditions combined with residual plots in Figures 69 and 71. A summary of the fit across all years for male and female length frequency data indicates a very good fit overall (Figure 72). The model is not fit to crab by shell condition due to the inaccuracy of shell condition as a measure of shell age. Tagging results presented earlier indicate that the number of animals that are more than one year from molting may be underestimated by using shell condition as a proxy for shell age. However, an accurate measure of shell age is needed to improve the estimation of the composition of the catch that is extracted from the stock.

Differences between the observed and predicted survey length frequencies could be a result of spatial differences in growth due to temperature, or size at maturity. These would need to be investigated using a spatial model. Changing growth or maturity over time simply to fit the length frequency data was not recommended by the 2008 CIE reviewers. There also could be changes in survey catchability by area or between years that could contribute to any lack of fit to the observed survey length frequency data.

The September 2013 assessment survey Q for the 1989 to present period was estimated at 0.55 for male crab (Turnock and Rugolo 2013). The Base model estimate for survey Q was 0.61. The maximum survey selectivity estimated using the 2009 study area by Somerton (2010) was 0.76 at 140 mm for male crab (Figure 90). The survey selectivity curves estimated for the base model are shown in Figure 57. Immature M was estimated at 0.366 (2013 assessment 0.386) and mature male M 0.270 (2013 assessment 0.261). Mature female M was fixed at 0.23.

The estimated number of males > 101mm generally follows the observed survey abundance estimates (Figure 73). Observed survey Males >101mm declined from 150.7 million crab in 2011 to 73.2 million in 2013 then increased to 138.5 million in 2014 (Table 3). Model estimates of large males show a decreasing trend from 233.0 million in 2009 to 109.9 million in 2012, then an increase to 183.0 million in 2014.

Several periods of above average recruitment were estimated by the model in 1979-1981, 1983, 1987-1988, 1998-99, and 2004-2005 (fertilization year, Figure 74). Recruits are 25mm to about 40 mm and may be about 4 years from hatching, 5 years from fertilization (Figure 75, although age is approximated). Lower than average recruitments were estimated from 1989 to 1997, 2000 to 2003, 2006-2007. The 1998-1999 and 2004 and 2005 year classes appear to be near or above average recruitment and have resulted in an increase in biomass in recent years. Recruitment through the male stock can be seen in the abundance by length (Figure 8a).

The size at 50% selected for the pot fishery for total catch (retained plus discarded) was 106.2 mm for males (shell condition combined, Figure 56). The size at 50% selected for the retained catch was about 106 mm. The fishery generally targets and retains new shell animals > 101mm with clean hard shells and all legs intact. The fits to the fishery size frequencies are in Figures 76 through 81. Fits to the trawl fishery bycatch size frequency data are in Figures 82 through 84.

Fishing mortality rates ranged from 0.15 to 2.6 (Figure 85 and Table 6). Fishing mortality rates ranged from 0.57 to 2.59, for the 1986/87 to 1998/99 fishery seasons. For the period after the snow crab stock was declared overfished (1999/2000 to 20010/11), full selection fishing mortality ranged from 0.18 to 0.58. Fishing mortality rate increased from 0.32 in 2010/11 to 0.94 in 2012/13 then declined to 0.73 in 2013/14.

Base Model estimates of mature male biomass at mating decreased from 189,300 t in 2009/10 to 109,200 t in 2012/13 then increased to 126,500 t in 2013/14 (89% of B35% (142,909 t), Table 6 and Figure 86). Estimates of MMB at mating in recent years are lower for the Base model than the 2013 assessment due to higher survey Q and changes in B35% and F35% from different growth estimates (Figure 103). Estimates of MMB at mating were lower for lower weights on fishing mortality penalties (Figure 87).

Likelihood values for all 9 model scenarios are shown in Table 13. Total likelihood values are not comparable between scenarios due to different numbers of parameters, weights on likelihood components (growth and fishing mortality penalties) and model structure (growth equations). Model 2b fits survey length data better than lower or higher weights on growth likelihood (models 2a and 2c). Survey biomass fit is best for model 2a relative to 2b and 2c. Length data are fit better with lower weight on fishing mortality penalties. Fit to survey biomass decreases with decreasing weight on fishing mortality penalties.

When weights on fishing mortality penalties are reduced, estimates of discard mortality and fishing mortality in early years increase to levels that are not plausible (Figures 107 and 108). In years where there are not data on discards the model is fitting retained catch to estimate Fs and uses the selectivity curves for total and retained crab to estimate catches. The model can still fit the retained catch with an F of 20 (where selectivity is close to 1.0) however, estimates much higher discard (where selectivities are less than 1).

The estimated growth for the base model (2b, weight 2 on growth likelihood) and the models with weight 1 (2a) and weight 3 (2c) on the growth likelihood are shown in Figures 54b to 54e. The estimated growth transition matrix for males and females are shown in Figures 105 and 106.

Survey selectivity curves estimated for the Base model are shown in Figures 90 to 97. Base Model fits to the length frequency in the 2009 and 2010 study areas are shown in Figure 98. Base Model fits to the mature biomass in the 2009 and 2010 study areas are shown in Figures 99 and 100.

The history of fishing mortality and MMB at mating with the F35% control rule for the Base model estimates the 2013/14 F to be below the overfishing level and MMB at mating at 89% of B35% (Figure 101).

Fishing mortality estimates and estimated male discard in the directed fishery were higher with lower weights on the fishing mortality penalties (Figures 107 and 108). With a weight of 0.001 relative to the base model F was about 19.9 in 1982 and 1983 and discard catch very high.

B35% decreased and F35% increased with decreasing weight on F penalties (Table 14).

Survey Q increased, mature male biomass decreased and OFL declined with decreasing weight on F penalties.

Harvest Strategy and Projected Catch

Rebuilding Harvest Strategy

A rebuilding harvest strategy was developed and adopted in December 2000 in Amendment 14 and first applied in the 2000/01 fishing season (NPFMC 2000). Harvest strategy simulations are reported by Zheng et al. (2002) based on a model with structure and parameter values different than the model presented here. The harvest strategy by Zheng et al. (2002) was developed for use with survey biomass estimates. Prior to the passage of Amendment 24, Bmsy was defined as the average total mature survey biomass for 1983 to 1997. MSST was defined as ½ Bmsy. The harvest strategy consists of a threshold for opening the fishery (104,508 t (230.4 million lbs) of total mature biomass (TMB), 0.25*Bmsy), a minimum GHL of 6,804 t (15 million lbs) for opening the fishery, and rules for computing the GHL. This strategy without the minimum constraint is currently used by ADFG for setting the TAC.

This exploitation rate is based on total survey mature biomass (TMB) which decreases below maximum E when TMB < average 1983-97 TMB calculated from the survey.

$$E = \begin{cases} \text{Bycatch only, Directed } E = 0, & \text{if } \dfrac{TMB}{averageTMB} < 0.25 \\[2ex] \dfrac{0.225 * \left[\dfrac{TMB}{averageTMB} - \alpha \right]}{(1-\alpha)} & \text{if } 0.25 < \dfrac{TMB}{averageTMB} < 1 \\[2ex] 0.225 & \text{if } TMB \geq averageTMB \end{cases} \qquad (13)$$

Where, α = -0.35 and averageTMB = 418,030 t (921.6 million lbs).

The maximum target for the retained catch is determined by using E as a multiplier on survey mature male biomass (MMB),

Retained Catch = E * MMB.

There is a 58% maximum harvest rate on exploited legal male abundance. Exploited legal male abundance is defined as the estimated abundance of all new shell males >=102 mm CW plus a percentage of the estimated abundance of old shell males >= 102 mm CW. The percentage to be used is determined using fishery selectivities for old shell males.

Overfishing Control Rule

Amendment 24 to the FMP introduced revised the definitions for overfishing. The information provided in this assessment is sufficient to estimate overfishing based on Tier 3b. The overfishing control rule for tier 3b is based on spawning biomass per recruit reference points (NPFMC 2007) (Figure 101).

$$F = \begin{cases} Bycatch\ only, Directed\ F = 0,\ if\ \dfrac{B_t}{B_{REF}} \le \beta \\[2em] \dfrac{F_{REF}\left[\dfrac{B_t}{B_{REF}} - \alpha\right]}{(1-\alpha)} \qquad if\ \beta < \dfrac{B_t}{B_{REF}} < 1 \\[2em] F_{REF} \qquad if\ B_t \ge B_{REF} \end{cases} \tag{12}$$

B_t mature male biomass at time of mating in year t,

B_{REF} mature male biomass at time of mating resulting from fishing at F_{REF},

F_{REF} F_{MSY} or the fishing mortality that reduces mature male biomass at the time of mating-per-recruit to x% of its unfished level,

α fraction of B_{REF} where the harvest control rule intersects the x-axis if extended below β,

β fraction of B_{REF} below which directed fishing mortality is 0.

B35% was estimated using average recruitment from1978 to 2013 and mature male biomass per recruit fishing at F35%.

The natural log of recruits/MMB at mating (5 yr lag for recruitment) indicates productivity of the Bering sea snow crab stock is currently not different from earlier levels (Figure 102).

Biomass and catch projections based on $F_{REF} = F_{35\%}$ and $B_{REF} = B_{35\%}$ were used to estimate the catch OFL and the ABC (Tables 9a and 9b). The OFL was estimated as the median of the distribution of OFLs from the stochastic projection model described earlier. The OFL for the Base model in 2014/15 was estimated at 77,400 t total catch (67,500 t retained catch). The previous year's OFL (2013/14) was 78,100 t of total catch (69,100 t retained catch). The average catch from 1978/79 to 1998/99 was 70,348 t, and was 19,975 t during the rebuilding period 1999/2000 to 2010/11.

The ABC was estimated at 77,270 t, based on a probability of overfishing of 49% from the projection model with a cv= 0.08 on 2013/14 biomass estimated from the Hessian matrix by the ADMB software and the median of the projected distribution of catch fishing at F35% as the estimate of OFL (Table 9a and Table 14). The SSC in 2013 recommended an ACL of 90% of the OFL (70,290 t) for the 2013/14 fishing season. 90% of the 2014/15 Base Model OFL is 69,700 t of total catch.

F35% in the September 2013 assessment was estimated at 1.58 and B35% at 154,170 t. F35% for the Base model was 1.40 and B35% 142,909 t. The MMB at mating projected for 2013/14 when fishing at the F35% control rule (OFL) was 100.2% of B35% from the base model in the September 2013 assessment. The MMB at mating projected for 2014/15 when fishing at the F35% control rule (OFL) was 96.3% of B35%. Reference points for scenarios and key parameters for the 9 scenarios are shown in Table 14.

The total catch, including all bycatch of both sexes, using the control rule is estimated by the following equation,

$$catch = \sum_{s} \sum_{l} (1 - e^{-(F*Sel_{s,l} + F_{trawl}*Sel_{Trawl,l})}) w_{s,l} N_{s,l} \, e^{-M_s*.62}$$

Where $N_{S,l}$ is the current year numbers at length(l) and sex at the time of the survey estimated from the population dynamics model, M_s is natural mortality by sex, 0.625 is the time elapsed (in years) from when the survey occurs to the fishery, F is the value estimated from the harvest control rule using the current year mature male biomass projected forward to the time of mating time (Feb. 15), and $w_{s,l}$ is weight at length by sex. $Sel_{s,l}$ are the fishery selectivities by length and sex for the total catch (retained plus discard) estimated from the population dynamics model (Figure 56).

Projections were run for the Base model fishing at the F35% control rule and fishing at a catch of 90% of the OFL (the SSC recommended ACL method in 2011/12 to 2013/14). Steepness of the Beverton and Holt spawner recruit curve used in projections was estimated at 0.74 and R_0 at 1.69 billion crab, by equating F35% with Fmsy and B35% with Bmsy.

Median MMB at mating was projected to increase in 2014/15 based on projections from the September 2013 assessment (Turnock and Rugolo 2013). Projections using the Base model, estimate MMB at mating to increase over the next 5 years from 96.3% of B35% in 2014/15 to 125.9% in 2019/20 (Tables 9a and 9b). Fishing at 90% of the OFL also results in increasing MMB over the next several years from about 100% of B35% in 2014/15 to 135% of B35% in 2019/20.

Conservation concerns

- Estimation of natural mortality in the model at values higher than estimates based on current knowledge of snow crab age could be risk prone. Aging methods need to be developed to improve estimation of natural mortality.
- Exploitation rates in the southern portion of the range of snow crab may have been higher than target rates, possibly contributing to the shift in distribution to less productive waters in the north.

Data Gaps and Research Needs

Research is needed to improve our knowledge of snow crab life history and population dynamics to reduce uncertainty in the estimation of current stock size, stock status and optimum harvest rates.

Tagging programs need to be initiated to estimate longevity and migrations. Studies and analyses are needed to estimate natural mortality.

A method of verifying shell age is needed for all crab species. A study was conducted using lipofuscin to age crabs, however verification of the method is needed. Radiometric aging of shells of mature crabs is costly and time consuming. Aging methods will provide information to assess the accuracy of assumed ages from assigned shell conditions (i.e. new, old, very old, etc), which have not been verified, except with the 21 radiometric ages reported here from Orensanz (unpub data).

Techniques for determining which males are effective at mating and how many females they can successfully mate with in a mating season are needed to estimate population dynamics and optimum harvest rates. At the present time it is assumed that when males reach morphometric maturity they stop growing and they are effective at mating. Field studies are needed to determine how morphometric maturity corresponds to male effectiveness in mating. In addition the uncertainty associated with the determination of morphometric maturity (the measurement of chelae height and the discriminate analysis to separate crabs into mature and immature) needs to be analyzed and incorporated into the determination of the maturity by length for male snow crab.

Female opilio in waters less than 1.5 ^{o} C and colder have been determined to be biennial spawners in the Bering Sea. Future recruitment may be affected by the fraction of biennial spawning females in the population as well as the estimated fecundity of females, which may depend on water temperature.

A female reproductive index needs to be developed that incorporates males, mating ratios, fecundity, sperm reserves, biennial spawning and spatial aspects.

Analysis needs to be conducted to determine a method of accounting for the spatial distribution of the catch and abundance in computing quotas.

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Table 1. Catch (1,000 t) for the snow crab pot fishery and groundfish trawl bycatch. Retained catch for 1973 to 1981 contain Japanese directed fishing. Observed discarded catch is the total estimate of discards before applying mortality. Discards from 1992 to 2011/12 were estimated from observer data. Total catch discard mortality applied.

Year fishery occurred	Retained catch (1000 t)	Observed Discard male catch (no mort. applied) (1000 t)	Observed Retained + discard male catch(no mort. Applied) (1000 t)	Year of trawl bycatch	Observed trawl bycatch(no mort. Applied) (1000 t)	Total catch (1000 t) 0.3 mort.applied directed fishery 0.8 mort. Applied GF	GHL(1980-2007) or TAC (2008 to present)(retained catch only) (1000 t)	OFL (2008/9 first year of total catch OFL) (1000 t)
1973/74	3.04			1973	13.63			
1974/75	2.28			1974	18.87			
1975/76	3.74			1975	7.3			
1976/77	4.56			1976	3.16			
1977/78	7.39			1977	2.14			
1978/79	23.72			1978	2.46			
1979/80	34.04			1979	1.98			
1980/81	30.37			1980	1.44		17.9-41.3	
1981/82	13.32			1981	0.6		7.3-10.0	
1982/83	11.85			1982	0.24		7.17	
1983/84	12.17			1983	0.31		22.23	
1984/85	29.95			1984	0.33		44.46	
1985/86	44.46			1985	0.29		25.86	
1986/87	46.24			1986	1.23		25.59	
1987/88	61.41			1987	0		50.23	
1988/89	67.81			1988	0.44		59.89	
1989/90	73.42			1989	0.51		63.43	
1990/91	149.11			1990	0.39		142.92	
1991/92	143.06	43.65	186.71	1991	1.95	157.7	151.09	
1992/93	104.71	56.65	161.37	1992	1.84	123.2	94.01	
1993/94	67.96	17.66	85.62	1993	1.81	74.7	48	
1994/95	34.14	13.36	47.5	1994	3.55	41.0	25.27	
1995/96	29.82	19.1	48.92	1995	1.35	36.6	23	
1996/97	54.24	24.68	78.92	1996	0.93	62.4	53.09	
1997/98	110.41	19.05	129.46	1997	1.5	117.3	102.5	
1998/99	88.02	15.5	103.52	1998	1.02	93.5	84.48	
1999/00	15.2	1.72	16.92	1999	0.61	16.2	12.93	
2000/01	11.46	2.06	13.52	2000	0.53	12.5	12.39	
2001/02	14.85	6.27	21.12	2001	0.39	17.0	13.97	
2002/03	12.84	4.51	17.35	2002	0.23	14.4	11.62	
2003/04	10.86	1.9	12.77	2003	0.76	12.0	9.44	
2004/05	11.29	1.69	12.98	2004	0.96	12.6	9.48	
2005/06	16.78	4.52	21.3	2005	0.37	18.4	16.74	
2006/07	16.5	5.9	22.39	2006	0.84	18.9	16.42	
2007/08	28.6	8.42	37.02	2007	0.44	31.5	28.58	
2008/09	26.56	6.86	33.42	2008	0.3	28.9	26.59	35.07
2009/10	21.82	4.09	25.91	2009/10	0.66	23.6	21.8	33.1
2010/11	24.67	2.05	26.72	2010/11	0.18	25.4	24.62	44.4
2011/12	40.3	5.21	45.51	2011/12	0.17	42.0	40.3	73.5
2012/13	30.06	7.35	37.41	2012/13	0.22	32.4	30.06	67.8
2013/14	24.48	12.09	36.57	2013/14	0.12	28.2	24.48	78.1

Table 2. Base model estimates of catch (1,000 t) for Bering Sea snow crab. Model estimates of pot fishery discards include 30% mortality and groundfish discard 80% mortality.

Year	Model estimate of male retained (1000 t)	Model estimate of male discard(30% mort) (1000 t)	Model estimate Discard female catch (1000 t)	Model estimate groundfish bycatch(0.8 mort., 1000 t)	Model estimate total directed male catch (1000 t)	Model estimate total catch (1000 t)
1978/79	23.8	1.7	0	3.8	25.5	29.3
1979/80	34.1	1.9	0	3	36	39.1
1980/81	30.5	4.3	0	2.1	34.7	36.9
1981/82	13.4	4.5	0	0.7	17.9	18.6
1982/83	11.9	2.2	0	0.2	14.1	14.4
1983/84	12.2	0.9	0	0.4	13.1	13.5
1984/85	30	1.5	0	0.4	31.6	32
1985/86	44.5	2.1	0	0.4	46.6	47
1986/87	46.3	2.7	0.1	1.8	49	50.9
1987/88	61.5	6.8	0.1	0.2	68.3	68.6
1988/89	67.9	10.3	0.1	0.6	78.2	78.9
1989/90	73.6	10.4	0.1	0.7	83.9	84.7
1990/91	149.4	18.7	0.1	0.6	168.1	168.8
1991/92	143.3	20.5	0.1	1.9	163.8	165.8
1992/93	105	16.8	0.2	1.7	121.7	123.7
1993/94	67.9	6	0.1	1.7	73.9	75.8
1994/95	34.2	3.9	0.1	3.5	38.2	41.8
1995/96	29.9	5.9	0.1	1.2	35.7	37
1996/97	54.6	6.4	0.1	0.8	60.9	61.9
1997/98	114.5	6.9	0	1.4	121.4	122.8
1998/99	88.3	4.9	0	0.9	93.2	94.1
1999/00	15.1	0.8	0	0.5	15.9	16.4
2000/01	11.5	0.6	0	0.3	12.1	12.5
2001/02	15	1.1	0	0.2	16.1	16.3
2002/03	12.9	1.1	0	0.2	14.1	14.3
2003/04	10.9	0.7	0	0.5	11.6	12.1
2004/05	11.3	0.6	0	0.8	11.9	12.6
2005/06	16.9	0.9	0	0.2	17.8	18.1
2006/07	16.6	1.4	0	0.6	18	18.6
2007/08	28.6	2.7	0	0.3	31.4	31.7
2008/09	26.6	2	0	0.2	28.6	28.9
2009/10	21.8	1.1	0	0.5	22.9	23.5
2010/11	24.6	1.1	0	0.2	25.7	26
2011/12	40.5	1.9	0.3	0.2	42.4	42.8
2012/13	30.1	2.9	0	0.2	32.9	33.2
2013/14	25	3.6	0.1	0.2	28.6	28.8

Table 3. Observed survey female, male and total spawning biomass(1000t) and numbers of males > 101mm (millions of crab).

Year	Observed survey female mature biomass	CV female mature biomass	Observed survey male mature biomass	CV male mature biomass	Observed survey total mature biomass	Observed number of males > 101mm (millions)
1978/79	153.0	0.2	193.1	0.12	346.2	163.4
1979/80	323.7	0.2	240.3	0.12	564.1	169.1
1980/81	364.9	0.2	193.8	0.12	558.7	133.9
1981/82	195.9	0.2	107.7	0.12	303.6	40.7
1982/83	213.3	0.2	173.1	0.12	386.4	60.9
1983/84	125.4	0.2	146.0	0.12	271.5	65.2
1984/85	70.4	0.4	161.2	0.24	231.5	139.9
1985/86	12.5	0.4	69.6	0.24	82.1	71.5
1986/87	47.7	0.4	87.3	0.24	135.1	77.1
1987/88	294.7	0.2	192.1	0.12	486.8	130.5
1988/89	276.9	0.125	251.6	0.12	528.5	170.2
1989/90	427.3	0.32	299.1	0.095	726.4	162.4
1990/91	312.1	0.185	442.4	0.105	754.5	389.6
1991/92	379.2	0.19	430.5	0.145	809.6	418.8
1992/93	242.4	0.2	238.5	0.12	480.9	232.5
1993/94	237.3	0.2	178.3	0.12	415.6	124.4
1994/95	216.8	0.16	163.6	0.15	380.4	71.2
1995/96	257.0	0.115	209.5	0.105	466.5	63.0
1996/97	161.7	0.145	281.7	0.09	443.4	154.8
1997/98	157.5	0.195	319.9	0.09	477.4	280.2
1998/99	124.3	0.255	201.1	0.12	325.4	208.4
1999/00	51.4	0.195	89.5	0.10	140.9	82.1
2000/01	152.4	0.435	88.9	0.14	241.3	65.7
2001/02	131.4	0.28	129.2	0.185	260.6	67.6
2002/03	50.5	0.295	90.2	0.195	140.8	63.1
2003/04	74.2	0.285	73.0	0.20	147.3	52.3
2004/05	84.5	0.28	75.8	0.16	160.3	56.0
2005/06	158.2	0.17	119.5	0.16	277.7	61.5
2006/07	109.6	0.17	134.5	0.18	244.2	118.7
2007/08	121.4	0.26	147.3	0.15	268.7	124.1
2008/09	86.4	0.22	121.6	0.10	208.0	97.7
2009/10	103.8	0.22	141.3	0.12	245.0	125.9
2010/11	145.1	0.156	157.3	0.142	302.4	137.6
2011/12	280.0	0.178	167.4	0.120	447.4	150.7
2012/13	220.6	0.198	120.8	0.143	341.4	87.0
2013/14	195.1	0.185	96.1	0.125	291.2	73.6
2014/15	212.5	0.207	156.9	0.192	369.4	138.5

Table 4. Abundance estimates of females and males by size groups for the BSFRF net in the 2009 and 2010 study areas, the NMFS net in the study area, and the NMFS survey of the entire Bering Sea. Mature abundance uses the maturity curve.

		Females			Males	
	>25mm	>50mm	mature	>25mm	Mature	>100
2009 BSFRF Study	585.3	113.6	129.4	422.9	200.9	66.9
2009 NMFS Study	150.2	121.5	120.5	119.2	76.9	36.7
2009 NMFS Bering Sea	1773.5	828.7	1,143.9	1,225.0	463.8	147.2
2010 BSFRF Study	6372.1	2328.9	3459.4	3344.8	877.7	186.9
2010 NMFS Study	2509.2	919.0	1102.6	1318.9	402.8	68.8

Table 5. Observed male and female mature biomass for the 2009 and 2010 study areas.

Mature Biomass (1000 t) 2009 and 2010 Study areas.

	BSFRF		NMFS	
	Female	Male	Female	Male
2009 Obs	12.2	68.4	11.9	32.3
2009 Pred	12.6	54.4	10.3	41.0
2010 Obs	279.0	193.3	91.5	77.7
2010 Pred	203.9	176.3	163.3	132.7

Table 6. Base model estimates of population biomass (1000t), population numbers, male, female and total mature biomass(1000t) and number of males greater than 101 mm in millions. Recruits enter the population at the beginning of the survey year after molting occurs. * Numbers by length estimated in the first year, so recruitment estimates start in second year.

Year	Biomass (1000t 25mm+)	numbers (million crabs 25mm+)	Female mature biomass(1000t)	Male mature biomass(1 000t)	Total mature biomass (1000t)	Number of males >101mm (millions)	Recruit-ment (millions, 25 mm to 50 mm)	Male mature biomas s at mating time(Fe b of survey year+1) (1000t)	Full selec tion fishin g morta lity	Exp.rat e of total male catch on mature male biomas s
1978/79	605.2	11521.6	189.2	197.2	386.4	143.3	1608.8	141.7	0.45	0.15
1979/80	685.1	11418.7	254.2	177.5	431.7	120.8	1421.9	112.3	0.81	0.24
1980/81	762.4	11062.1	372.5	133.3	505.8	63.8	968.4	78.5	2.21	0.31
1981/82	793.8	10036.6	393.9	124.1	517.9	34.8	319.2	90.2	1.57	0.17
1982/83	803.4	8070.4	374.8	180.2	555	93.1	1301.8	140.4	0.4	0.09
1983/84	828.1	8670	330.2	273.9	604.1	226.1	2068.6	218.9	0.15	0.06
1984/85	873.8	10577.9	309.6	321.1	630.7	298.6	2669	240.6	0.28	0.12
1985/86	944.8	13054	331.2	311	642.3	289.5	4743.8	217.2	0.46	0.18
1986/87	1130.3	18924.3	383.2	275.8	659	227.7	763.4	184.4	0.65	0.21
1987/88	1223.6	15084.6	498.4	270.8	769.2	184.8	4501.8	166	1.33	0.3
1988/89	1403.6	20019.2	515.3	303.9	819.2	189	178.8	188.3	1.53	0.3
1989/90	1434.3	14785.6	570.8	372.3	943.1	246.5	580.7	241.1	1.14	0.27
1990/91	1378.8	12044.8	545.5	460.2	1005.6	355.9	713.8	239.5	2.01	0.43
1991/92	1171.5	10239.1	469.2	417.5	886.7	302.9	6601.7	206.5	2.59	0.46
1992/93	1222.7	20659.9	405.7	344.7	750.4	233.4	1429.3	184.8	2.29	0.42
1993/94	1251.1	17511.6	528.5	302.7	831.3	204.7	978.2	185.4	1.33	0.29
1994/95	1257.9	14688.5	585.5	264	849.5	126.5	250.9	185.2	0.95	0.17
1995/96	1230.5	11388.2	542.4	298.6	841	134.6	135	221.5	0.75	0.14
1996/97	1168.2	8825.6	462.7	426.1	888.8	313.8	193.3	305.8	0.57	0.17
1997/98	1019.6	7044.5	379.8	506.8	886.6	469.7	867.6	312	0.84	0.28
1998/99	793.8	6972.4	310.9	387.4	698.2	340	1012.5	236.1	0.9	0.28
1999/00	642.1	7154.4	276.2	259.4	535.6	198.9	319.1	203.1	0.21	0.07
2000/01	579.9	5955.7	265.4	211	476.4	155	298.6	165.9	0.21	0.07
2001/02	527.5	5070.5	241.8	179.1	420.9	121.9	672.9	135.6	0.36	0.11
2002/03	496.8	5163.5	210.3	168.5	378.8	116.1	1340.4	129	0.33	0.1
2003/04	512.9	6524.2	193.4	176.8	370.2	141.1	1997.3	138	0.22	0.08
2004/05	581.5	8764.7	206	177.8	383.7	150.9	654	138	0.21	0.08
2005/06	620.6	7647.1	248.6	170.1	418.7	134	845	126.2	0.37	0.12
2006/07	647.7	7302.3	258.1	174.2	432.3	124	172	129.9	0.4	0.12

Table 6 Cont.. Base model estimates of population biomass (1000t), population numbers, male, female and total mature biomass(1000t) and number of males greater than 101 mm in millions. Recruits enter the population at the beginning of the survey year after molting occurs. * Numbers by length estimated in the first year, so recruitment estimates start in second year.

Year	Biomass (1000t 25mm+)	numbers (million crabs 25mm+)	Female mature biomass(1000t)	Male mature biomass(1 000t)	Total mature biomass (1000t)	Number of males >101mm (millions)	Recruit-ment (millions, 25 mm to 50 mm)	Male mature biomas s at mating time(Fe b of survey year+1) (1000t)	Full selec tion fishin g morta lity	Exp.rat e of total male catch on mature male biomas s
2007/08	639.7	5725.7	248.7	206.2	454.9	155.7	192.5	145.3	0.59	0.18
2008/09	592.2	4645.7	220.9	239.4	460.3	204.5	1367.2	175.4	0.39	0.14
2009/10	574.7	6220.8	187.3	250.7	438.1	233	2353.1	189.3	0.26	0.11
2010/11	627.1	9251.2	192.8	231.9	424.7	218.6	808.9	170.7	0.32	0.13
2011/12	655.5	8265.3	247.2	202.9	450.1	178.7	1197	129.7	0.75	0.25
2012/13	674.1	8399.2	267.8	166.1	433.9	109.9	1609.6	109.1	0.99	0.23
2013/14	732.5	9348.5	270.8	179.5	450.3	110	1527	126.5	0.79	0.19
2014/15	804.1	9851.7	287.1	236.1	523.2	183	NA	NA	NA	NA

Table 6a. Base model predicted survey values for female, male and total mature biomass and numbers of males > 101mm (millions of crab).

	Predicted Female survey mature Biomass:	Predicted Male survey mature Biomass:	Predicted total survey mature Biomass:	model Predicted survey males>101 (millions)
1978	147.2	196.7	343.9	143.3
1979	191.1	176.3	367.4	120.8
1980	284.8	131.3	416.1	63.8
1981	304.3	121.6	425.8	34.8
1982	169.1	113.1	282.1	60.7
1983	149.5	174.3	323.8	147.2
1984	139.8	205.2	345.1	194.5
1985	149.1	198.4	347.4	188.6
1986	172.3	174.5	346.8	148.3
1987	223.5	169.5	393.0	120.4
1988	233.3	190.1	423.4	123.1
1989	309.1	226.4	535.5	151.4
1990	295.7	280.5	576.2	218.7
1991	254.4	254.6	509.0	186.1
1992	220.0	210.1	430.1	143.4
1993	286.0	183.8	469.9	125.8
1994	317.3	159.8	477.1	77.7
1995	294.1	181.2	475.3	82.7
1996	250.9	259.9	510.8	192.8
1997	206.0	309.9	515.9	288.6
1998	168.6	236.8	405.4	208.9
1999	149.7	158.4	308.1	122.2
2000	143.8	128.6	272.4	95.2
2001	131.1	109.1	240.2	74.9
2002	114.0	102.7	216.8	71.3
2003	104.8	107.9	212.8	86.7
2004	111.6	108.4	220.0	92.7
2005	134.6	103.5	238.1	82.3
2006	139.9	106.0	245.9	76.2
2007	134.8	125.7	260.5	95.6
2008	119.8	146.2	266.0	125.6
2009	101.6	153.3	254.9	143.2
2010	104.4	141.7	246.2	134.3
2011	133.8	123.6	257.5	109.8
2012	145.1	100.9	246.0	67.5
2013	146.7	109.2	255.9	67.6
2014	155.6	143.9	299.4	112.4

Table 7. Radiometric ages for male crabs for shell conditions 1 through 5. Data from Orensanz (unpub).

			Radiometric age		
Shell Condition	description	sample size	Mean	minimum	maximum
1	soft	6	0.15	0.05	0.25
2	new	6	0.69	0.33	1.07
3	old	3	1.02	0.92	1.1
4	very old	3	5.31	4.43	6.6
5	very very old	3	4.59	2.7	6.85

Table 8. Natural mortality estimates for Hoenig (1983), the 5% rule and the 1% rule, given the oldest observed age.

	Natural Mortality		
oldest observed age	Hoenig (1983) empirical	5% rule	1% Rule
10	0.42	0.3	0.46
15	0.28	0.2	0.30
17	0.25	0.18	0.27
20	0.21	0.15	0.23

Tables 9a-b. Projections using a multiplier on the F35% control rule for 2014/15 to 2024/25 fishery seasons. Median total catch (ABC_{tot} 1000 t), median retained catch (C_{dir} 1000 t), Percent mature male biomass at time of mating relative to B35. Values in parentheses are 90% CI. F is full selection fishing mortality. Base model $B_{35\%}$ = 142,909 t. $F_{35\%}$ = 1.40.

a) 100%OFL Base Model, 100% $F_{35\%}$ B35% = 142,909 t F35%=1.40

Year	**ABC_{tot} (1000t)**	**C_{dir} (1000t)**	**Percent MMB/ $B_{35\%}$**	**Full Selection Fishing Mortality**
2014/15	69(57.2,81.8)	60.3(50,71.3)	96.3(87.9,109.6)	1.34
2015/16	68.2(45.3,87)	60.5(40.7,76.3)	98.8(84.5,116.1)	1.32
2016/17	58.2(39.4,74.8)	49.7(34.6,64.2)	99(83,118.9)	1.32
2017/18	62.6(40.8,79.5)	52.6(35.4,67)	106.8(86.8,134)	1.34
2018/19	70.9(46.7,94.2)	60.2(41.6,77)	116.6(87.3,169.2)	1.33
2019/20	78.7(45.7,142.8)	67.4(40.6,117.8)	125.9(81.8,224.5)	1.33
2020/21	84.7(35.2,210.5)	73.7(30.6,179.5)	127.8(74.5,276.2)	1.32
2021/22	82(25.1,213.7)	71.1(21.9,189.7)	126.7(67.8,288.2)	1.29
2022/23	74.1(21.9,207.5)	64(19.2,181.9)	120.3(63.6,294.4)	1.29
2023/24	66.9(19.8,205.1)	57.2(16.7,178.3)	117.5(63.8,292)	1.27
2024/25	68.3(18.8,198.7)	57.3(15.9,171.2)	118.5(61.4,297.9)	1.28

b) 90% Catch at FOFL Base Model, B35% = 142,909 t. $F_{35\%}$ = 1.40.

Year	**ABC_{tot} (1000t)**	**C_{dir} (1000t)**	**Percent MMB/ $B_{35\%}$**	**Full Selection Fishing Mortality**
2014/15	62.1(51.3,71.5)	54.4(45.1,62.7)	100.3(91.3,115.6)	1.15
2015/16	64.8(42.6,81.8)	58(38.5,72.6)	105.5(90.9,123.1)	1.12
2016/17	56.2(37.5,70.9)	48.8(33.4,61.5)	105.7(89.1,126.3)	1.12
2017/18	58.8(38.9,75.3)	50.6(34.1,63.8)	113.8(93.6,142.2)	1.12
2018/19	66.3(44.9,87.9)	57.3(40.1,73.4)	124.8(94.4,178.8)	1.11
2019/20	73.8(44.6,131.9)	64(40,111.6)	135.2(88.5,239.9)	1.11
2020/21	79.9(34.6,191.3)	70.1(30.6,170.4)	138(80,297.7)	1.1
2021/22	77.6(24.7,200.4)	68.6(21.8,178.7)	137.4(72,316.3)	1.08
2022/23	72.5(21.7,195)	63.1(18.7,173.1)	131.1(67.8,325.3)	1.08
2023/24	64.9(19.5,195.1)	56.1(16.8,171.1)	127.8(68.1,321.1)	1.06
2024/25	66.5(18.4,187.1)	56.8(15.9,165)	129(66.4,327.6)	1.07

Table 10 cont. Base Model Parameters values for the base model, excluding recruitments, probability of maturing and fishing mortality parameters.

Parameter	Value	S.D. for estimated parameters	Estimated(Y/N)	Bounded (bounds)
Natural Mortality immature females and males	0.37	0.02	Y	0.05,0.46
Natural Mortality mature females	0.23		N	
Natural Mortality mature males	0.27	0.01	Y	0.05,0.46
Female intercept (a1) growth	-4.69	2.88	Y	0,10
Female slope(b1) growth	1.51	0.12	Y	
Female slope(b2) growth	1.07	0.02	Y	1,1.3
female delta	31.01	2.49	Y	
Male intercept(a1) growth	-29.82	10.86	Y	
Male slope (b1) growth	1.17	0.01	Y	
Male slope (b2) growth	2.54	0.47	Y	
male delta	25.58	1.13	Y	
female and male s (scale parameter smooth)	5.56	1.34	Y	
Alpha for gamma distribution of recruits	11.50		N	
Beta for gamma distribution of recruits	4.00		N	
Beta for gamma distribution female growth	0.75		N	
Beta for gamma distribution male growth	0.75		N	
Fishery selectivity total males slope	0.18	0.00	Y	0.1,0.5
Fishery selectivity total males length at 50%	106.23	0.12	Y	55,148
Fishery selectivity retention curve males slope	0.41	0.02	Y	0.05,0.5
Fishery selectivity retention curve males length at 50%	96.00	0.16	Y	85,120
Fishery discard selectivity female slope	0.32	0.01	Y	0.1,0.7
Fishery discard selectivity female length at 50%	66.70		N	
Trawl Fishery selectivity slope	0.10	0.00	Y	0.01,.3
Trawl Fishery selectivity length at 50%	95.91	1.49	Y	30,120
Survey Q 1978-1981 male	1.00	0.00	Y	0.2,1.0
Survey 1978-1981 length at 95% of Q male	60.15	2.88	Y	30,150
Survey 1978-1981 length at 50% of Q male	42.11	1.42	Y	0,150
Survey Q 1978-1981 Female	0.89	0.05	Y	0.04,2.0
Survey 1978-1981 length at 95% of Q female	60.15		Set equal to Male	
Survey 1978-1981 length at 50% of Q female	42.11		Set equal to Male	
Survey Q 1982-1988 male	0.65	0.05	Y	0.2,1.0
Survey 1982-1988 length at 95% of Q male	70.91	5.47	Y	50,160
Survey 1982-1988 length at 50% of Q male	43.29	2.10	Y	0,80
Survey Q 1982-1988 female	0.58		Y	0.04,2.0
Survey 1982-1988 length at 95% of Q female	70.91		Set equal to Male	50,160
Survey 1982-1988 length at 50% of Q female	43.29		Set equal to Male	0,80

Parameter	Value	S.D. for estimated parameters	Estimated(Y/N)	Bounded (bounds)
Survey Q 1989-present male	0.61	0.03	Y	0.2,1.0
Survey 1989-present, length at 95% of Q male	57.48	2.98	Y	40,200
Survey 1989-present length at 50% of Q male	38.34	1.11	Y	20,90
Female Survey Q 1989-present	0.55	0.03	Y	0.04,2.0
Female Survey 1989-present, length at 95% of Q	46.15	1.34	Y	40,150
Female Survey 1989-present length at 50% of Q	34.55	0.64	Y	0,90
Male BSFRF 2009 Study area Q (availability)	0.38	0.10	Y	0.1,1.0
Female BSFRF 2009 Study area Q (availability)	0.14		Y	0.01,1.0
Female BSFRF 2009 Study area length at 95% of Q	60.00	0.00	Y	50,120
Female BSFRF 2009 Study are length at 50% of Q	51.79	0.57	Y	-50.0,60.0
male BSFRF 2010 Study area Q (availability)	1.00	0.00	Y	0.2,1.0
Female BSFRF 2010 Study area Q (availability)	1.07	0.12	Y	0.5,2.0
Female BSFRF 2010 Study area length at 95% of Q	25		N	
Female BSFRF 2010 Study are length at 50% of Q	25		N	

Table 11. Weighting factors for likelihood equations.

Likelihood component	Weighting factor	Equivalent CV, SD or sample size
Retained catch	10	SD=0.22
Retained catch length comp	1	Sample size 200
Total catch	10	SD=0.22
Total catch length comp	1	Sample size 200
Female pot catch	10	SD=0.22
Female pot fishery length comp	0.2	Sample size 200
Trawl catch	10	SD=0.22
Trawl catch length comp	0.25	Sample size 200
Survey biomass	survey cv by year	See cv table
Survey length comp	1	Sample size 200
Recruitment deviations	1	CV=0.7
Fishing mortality average	1	SD=0.70
Fishing mortality deviations	0.1	CV=2.2
Initial length comp smoothness	1	SD=0.7

Table 12. Base Model estimated recruitments (male) and mature male biomass at mating with standard deviations. Recruits enter the population at the beginning of the survey year.

Survey year	Recruit (male,millions)	S.D.	MMB at mating (1000 tons)	S.D.
1978/79			141.67	11.40
1979/80	1,608.80	361.50	112.30	7.34
1980/81	1,421.90	326.54	78.46	5.50
1981/82	968.43	251.85	90.24	5.85
1982/83	319.16	140.67	140.45	9.71
1983/84	1,301.80	247.80	218.91	15.43
1984/85	2,068.60	360.59	240.62	18.01
1985/86	2,669.00	435.21	217.25	17.27
1986/87	4,743.80	574.48	184.40	14.64
1987/88	763.38	272.79	166.02	12.18
1988/89	4,501.80	460.56	188.28	12.27
1989/90	178.79	75.56	241.15	13.53
1990/91	580.74	105.34	239.52	12.76
1991/92	713.79	156.77	206.50	11.10
1992/93	6,601.70	669.06	184.80	10.62
1993/94	1,429.30	280.96	185.41	10.99
1994/95	978.25	158.46	185.22	11.82
1995/96	250.92	79.94	221.50	14.44
1996/97	135.00	48.64	305.78	18.59
1997/98	193.27	68.65	312.00	19.27
1998/99	867.64	154.68	236.06	16.82
1999/00	1,012.40	176.37	203.12	14.20
2000/01	319.14	89.37	165.92	11.90
2001/02	298.61	86.85	135.57	10.37
2002/03	672.86	134.56	128.98	9.82
2003/04	1,340.40	221.41	137.95	9.85
2004/05	1,997.30	266.46	138.01	9.49
2005/06	654.00	163.44	126.24	8.93
2006/07	845.03	141.51	129.90	9.08
2007/08	172.01	58.45	145.29	10.31
2008/09	192.50	52.57	175.40	11.57
2009/10	1,367.20	184.57	189.34	11.08
2010/11	2,353.00	363.01	170.73	9.51
2011/12	808.89	229.65	129.75	8.55
2012/13	1,197.10	274.26	109.11	9.27
2013/14	1,609.60	354.66	126.55	12.63
2014/15	1,527.00	446.73		

Table 13. Likelihood values for base model and other 9 model scenarios.

Likelihood Component	Model 0	Model 1	Model 2a	Model 2b Base Model	Model 2c	Model 2d	Model 2e	Model 2f	Model 2g
Scenario	13-Sep	Two line growth	grwt 1	grwt 2	grwt 3	0.5 fpen	.25 fpen	.1 fpen	.001 fpen
Discard mortality	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Recruitment	34.24	33.26	34.45	33.85	33.98	34.06	34.47	34.93	35.99
Initial numbers old shell males small length bins	2.20	2.22	2.17	2.22	2.23	2.32	2.29	2.33	2.55
ret fishery length	352.48	347.03	351.76	355.11	356.75	350.81	347.81	343.76	325.45
total fish length	778.00	778.78	775.80	777.80	779.67	775.99	774.87	772.88	769.94
female fish length	213.85	219.54	218.82	214.58	214.28	215.05	213.83	213.72	213.67
survey length	3773.97	3787.75	3785.73	3778.39	3792.45	3786.20	3771.44	3770.69	3773.23
trawl length	269.85	272.42	288.74	272.80	273.86	270.81	268.46	267.14	265.91
2009 BSFRF length	-83.50	-83.31	-85.49	-83.20	-83.36	-83.27	-83.49	-83.67	-84.16
2009 NMFS study area length	-70.97	-70.81	-71.53	-70.60	-70.35	-70.55	-70.50	-70.41	-70.30
M prior	5.84	11.38	17.64	10.59	10.44	10.42	9.97	9.57	9.10
maturity smooth	51.98	65.23	57.00	56.03	58.62	54.99	52.50	50.82	47.37
growth males	43.75	32.06	28.43	43.29	44.89	43.96	43.98	45.92	50.10
growth females	52.42	20.28	32.09	47.79	49.90	47.45	50.34	51.05	52.87
2009 BSFRF biomass	0.17	0.14	0.16	0.17	0.18	0.19	0.20	0.22	0.25
2009 NMFS study area biomass	0.08	0.05	0.07	0.08	0.08	0.09	0.11	0.13	0.16
retained catch	3.76	3.80	3.84	3.65	3.81	3.70	3.78	3.84	3.96
discard catch	139.92	148.72	131.35	135.85	144.40	136.16	137.75	135.89	129.81
trawl catch	9.46	9.67	9.76	9.82	9.81	7.92	7.07	4.69	0.93
female discard catch	5.93	5.76	5.99	5.83	5.76	4.85	3.30	2.75	2.47
survey biomass	183.11	181.97	173.87	181.52	181.94	181.19	183.50	183.65	187.62
F penalty	80.06	80.66	77.22	80.17	80.04	49.12	32.16	20.25	2.31
2010 BSFRF Biomass	2.29	1.85	2.62	2.18	2.27	2.28	2.35	2.53	2.84
2010 NMFS Biomass	1.24	0.84	0.90	1.29	1.21	1.41	1.58	1.80	2.18
initial numbers fit	506.67	559.26	503.58	507.99	508.32	525.33	508.07	507.83	509.78
2010 BSFRF length	-54.05	-52.84	-50.60	-55.49	-53.84	-55.64	-56.04	-56.26	-57.02
2010 NMFS length	-66.92	-63.75	-63.46	-65.85	-64.31	-65.83	-65.75	-65.58	-65.48
male survey selectivity smooth constraint	3.79	4.03	4.34	3.70	3.83	3.66	3.62	3.56	3.44
init nos smooth constraint	39.66	34.19	38.30	39.45	39.63	35.58	40.06	40.29	42.40
Total	6279.29	6330.20	6273.55	6289.02	6326.49	6268.26	6217.74	6194.32	6157.38

Table 13. Differences in Likelihood values for 9 model scenarios relative to Base model (negative values are better fits than Base Model).

Likelihood Component	Model 0	Model 1	Model 2a	Model 2b Base Model	Model 2c	Model 2d	Model 2e	Model 2f	Model 2g
Scenario	13-Sep	Two line growth	grwt 1	grwt 2	grwt 3	0.5 fpen	.25 fpen	.1 fpen	.001 fpen
Discard mortality	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Recruitment	0.39	-0.59	0.60	0.00	0.13	0.21	0.62	1.08	2.13
Initial numbers old shell males small length bins	-0.02	0.00	-0.05	0.00	0.01	0.10	0.07	0.11	0.33
ret fishery length	-2.63	-8.09	-3.35	0.00	1.63	-4.30	-7.31	-11.36	-29.66
total fish length	0.20	0.99	-2.00	0.00	1.87	-1.81	-2.93	-4.92	-7.86
female fish length	-0.73	4.96	4.24	0.00	-0.30	0.47	-0.75	-0.86	-0.91
survey length	-4.42	9.36	7.34	0.00	14.06	7.81	-6.95	-7.70	-5.16
trawl length	-2.94	-0.38	15.94	0.00	1.06	-1.99	-4.34	-5.66	-6.89
2009 BSFRF length	-0.30	-0.10	-2.29	0.00	-0.16	-0.06	-0.29	-0.47	-0.95
2009 NMFS study area length	-0.36	-0.20	-0.93	0.00	0.25	0.05	0.11	0.19	0.31
M prior	-4.75	0.78	7.04	0.00	-0.15	-0.17	-0.62	-1.02	-1.50
maturity smooth	-4.06	9.20	0.97	0.00	2.59	-1.04	-3.53	-5.21	-8.66
growth males	0.46	-11.23	-14.86	0.00	1.60	0.67	0.69	2.63	6.81
growth females	4.63	-27.51	-15.70	0.00	2.11	-0.34	2.55	3.26	5.08
2009 BSFRF biomass	-0.01	-0.03	-0.01	0.00	0.00	0.01	0.02	0.04	0.08
2009 NMFS study area biomass	-0.01	-0.03	-0.02	0.00	0.00	0.01	0.02	0.04	0.08
retained catch	0.11	0.14	0.19	0.00	0.15	0.04	0.13	0.19	0.31
discard catch	4.07	12.87	-4.51	0.00	8.55	0.30	1.89	0.04	-6.04
trawl catch	-0.36	-0.15	-0.06	0.00	-0.01	-1.90	-2.76	-5.13	-8.89
female discard catch	0.10	-0.07	0.16	0.00	-0.07	-0.98	-2.53	-3.08	-3.37
survey biomass	1.59	0.46	-7.65	0.00	0.42	-0.33	1.98	2.13	6.10
F penalty	-0.10	0.50	-2.95	0.00	-0.12	-31.05	-48.01	-59.91	-77.86
2010 BSFRF Biomass	0.12	-0.32	0.44	0.00	0.09	0.10	0.17	0.36	0.67
2010 NMFS Biomass	-0.04	-0.44	-0.39	0.00	-0.08	0.13	0.30	0.51	0.90
initial numbers fit	-1.32	51.27	-4.41	0.00	0.33	17.34	0.08	-0.16	1.80
2010 BSFRF length	1.43	2.64	4.89	0.00	1.65	-0.15	-0.55	-0.78	-1.54
2010 NMFS length	-1.07	2.10	2.39	0.00	1.54	0.02	0.10	0.27	0.37
male survey selectivity smooth constraint	0.09	0.33	0.64	0.00	0.13	-0.04	-0.09	-0.14	-0.26
init nos smooth constraint	0.21	-5.26	-1.15	0.00	0.18	-3.87	0.61	0.84	2.95
Total	-9.73	41.18	-15.48	0.00	37.47	-20.76	-71.28	-94.71	-131.64

Table 14. Reference values for 9 model scenarios.

Model	0	1	2a	2b	2c	2d	2e	2f	2g
	Sept 2013 model	Two line model	Model gr wt 1	Base Model Gr wt 2	Model gr wt 3	0.5 F penalty	0.25 F penalty	0.1 F penalty	0.001 F penalty
B35%	141.9	148.9	141.3	142.9	143.7	141.3	139.7	137.3	134.1
F35%	1.5	1.6	1.5	1.4	1.4	1.5	1.5	1.6	2.0
OFL 2014/15	67.1	81.2	83.6	69.0	70.6	66.9	63.6	59.3	52.7
ABC(p*=.49) 2014/15	66.9	80.9	83.3	68.8	70.3	66.6	63.4	59.1	52.6
ABC(90%OFL) 2014/15	60.4	73.1	75.2	62.1	63.5	60.2	57.2	53.4	47.4
Percent MMB/B35% 2013/14	94.7	99.9	99.9	96.3	97.3	95.4	93.4	91.7	87.8
Survey Q 1989-present	0.61	0.57	0.59	0.61	0.61	0.63	0.64	0.65	0.68
M mature males	0.27	0.27	0.28	0.27	0.27	0.27	0.27	0.27	0.27

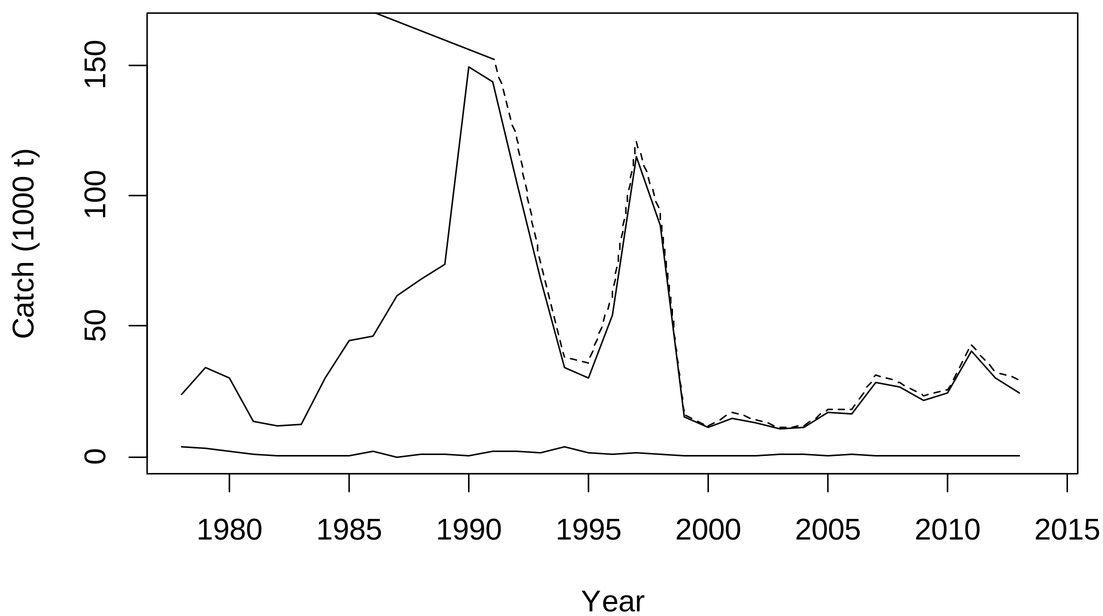

Figure 1. Catch (1000 t) from the directed snow crab pot fishery and groundfish trawl bycatch. Total catch (dashed line) is retained catch(solid line) plus discarded catch after 30% discard mortality was applied. Trawl bycatch (lower solid line) is male and female bycatch from groundfish trawl fisheries with 80% mortality applied.

Figure 2. Exploitation rate estimated as the preseason GHL divided by the survey estimate of large male biomass (>101 mm) at the time the survey occurs (dotted line). The solid line is the retained catch divided by the survey estimate of large male biomass at the time the fishery occurs. Year is the survey year.

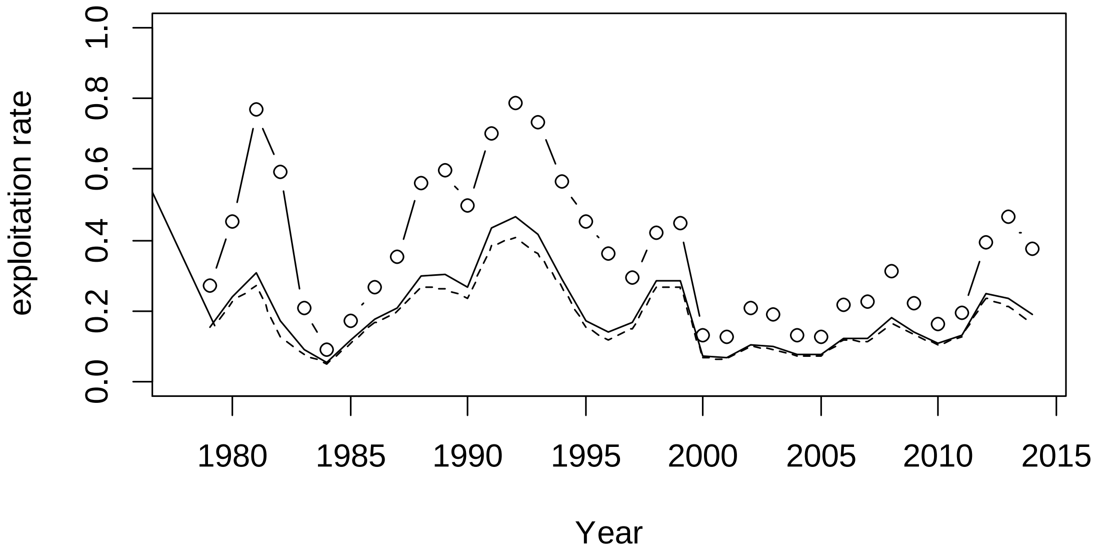

Figure 3. Base Model. Exploitation fraction estimated as the catch biomass (total or retained) divided by the mature male biomass from the model at the time of the fishery (solid line is total and dotted line is retained). The exploitation rate for total catch divided by the male biomass greater than 101 mm is the solid line with dots. Year is the year of the fishery.

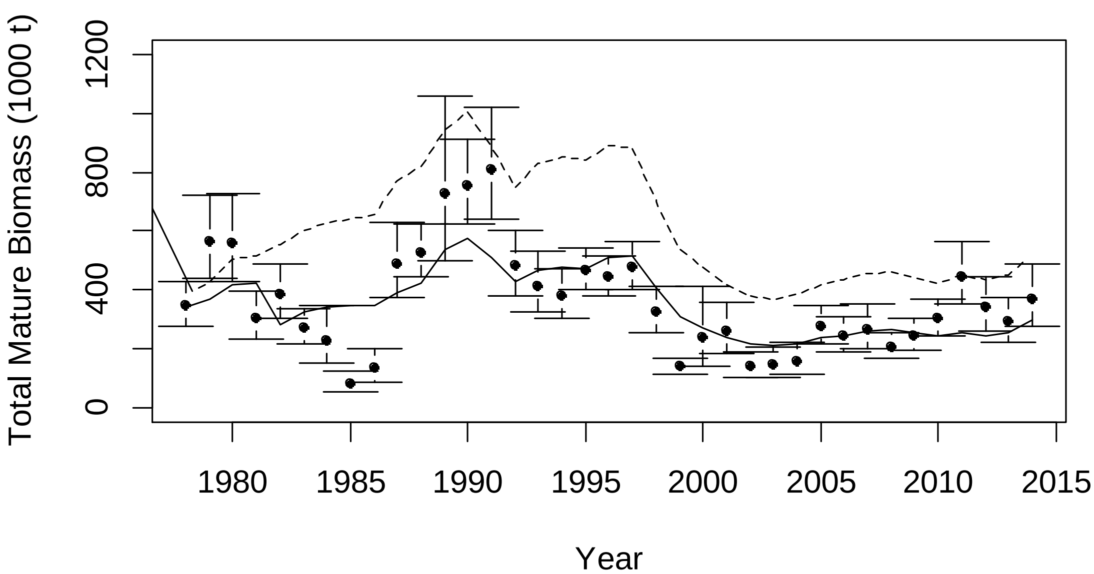

Figure 4. Population total mature biomass (millions of pounds, solid line), model

estimate of survey mature biomass (dotted line) and observed survey mature biomass with approximate lognormal 95% confidence intervals.

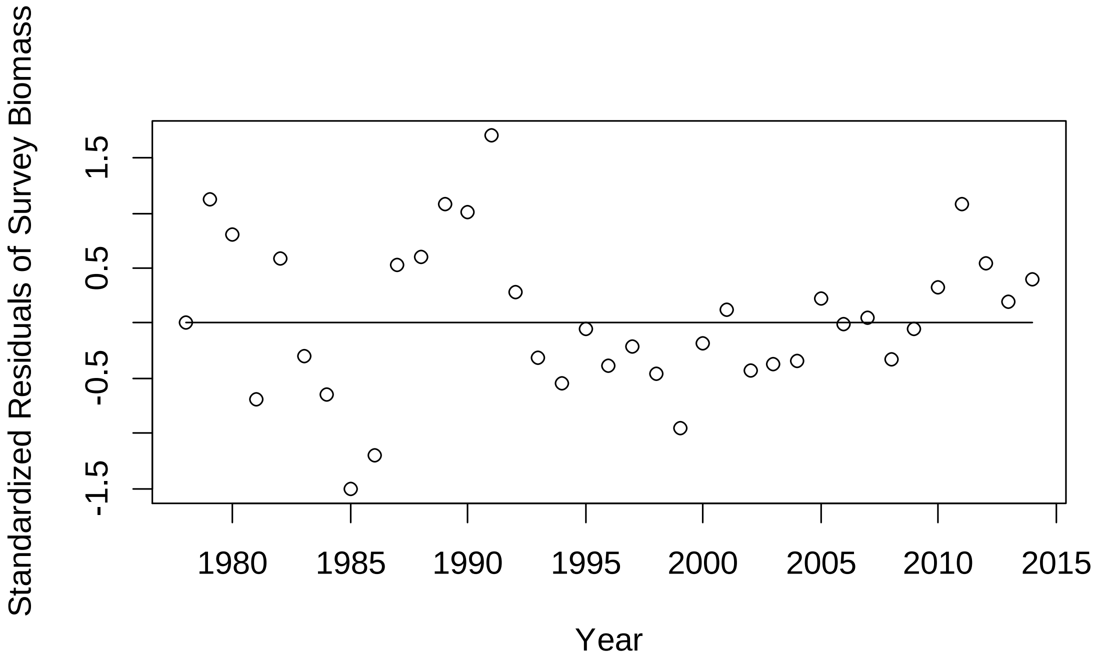

Figure 5. Standardized residuals for model fit to total mature biomass from Figure 4.

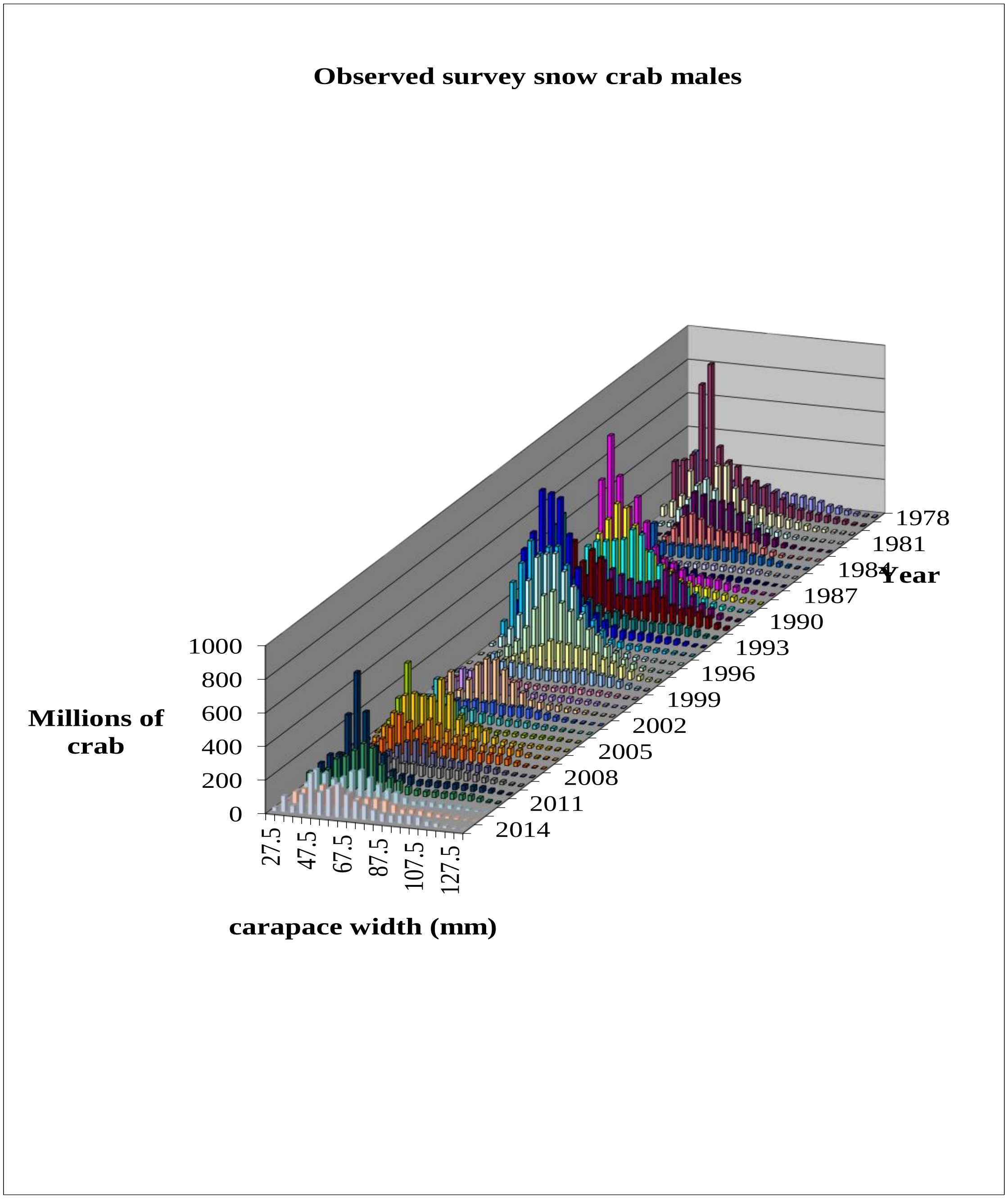

Figure 6. Observed survey numbers (millions of crab) by carapace width and year for male snow crab.

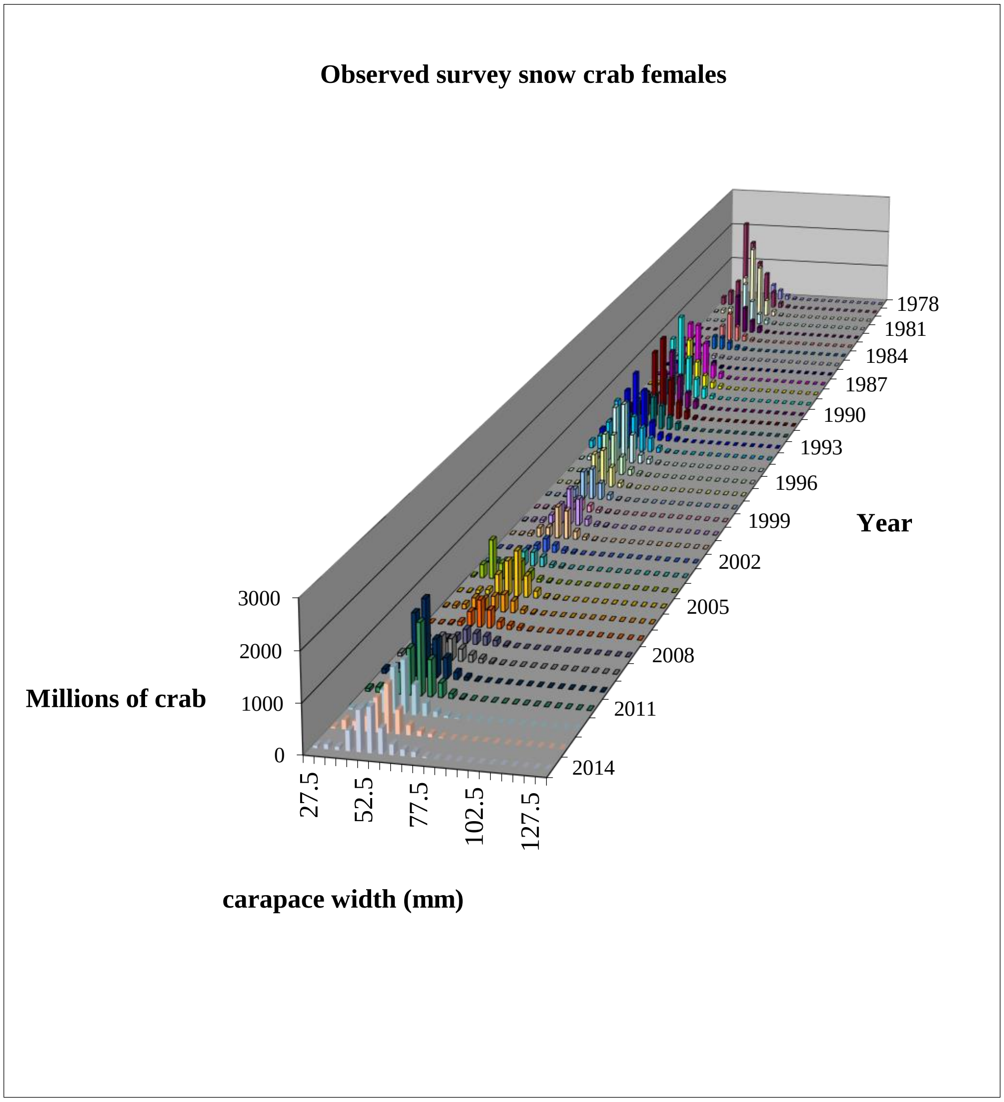

Figure 7. Observed survey numbers (millions of crab) by carapace width and year for female snow crab.

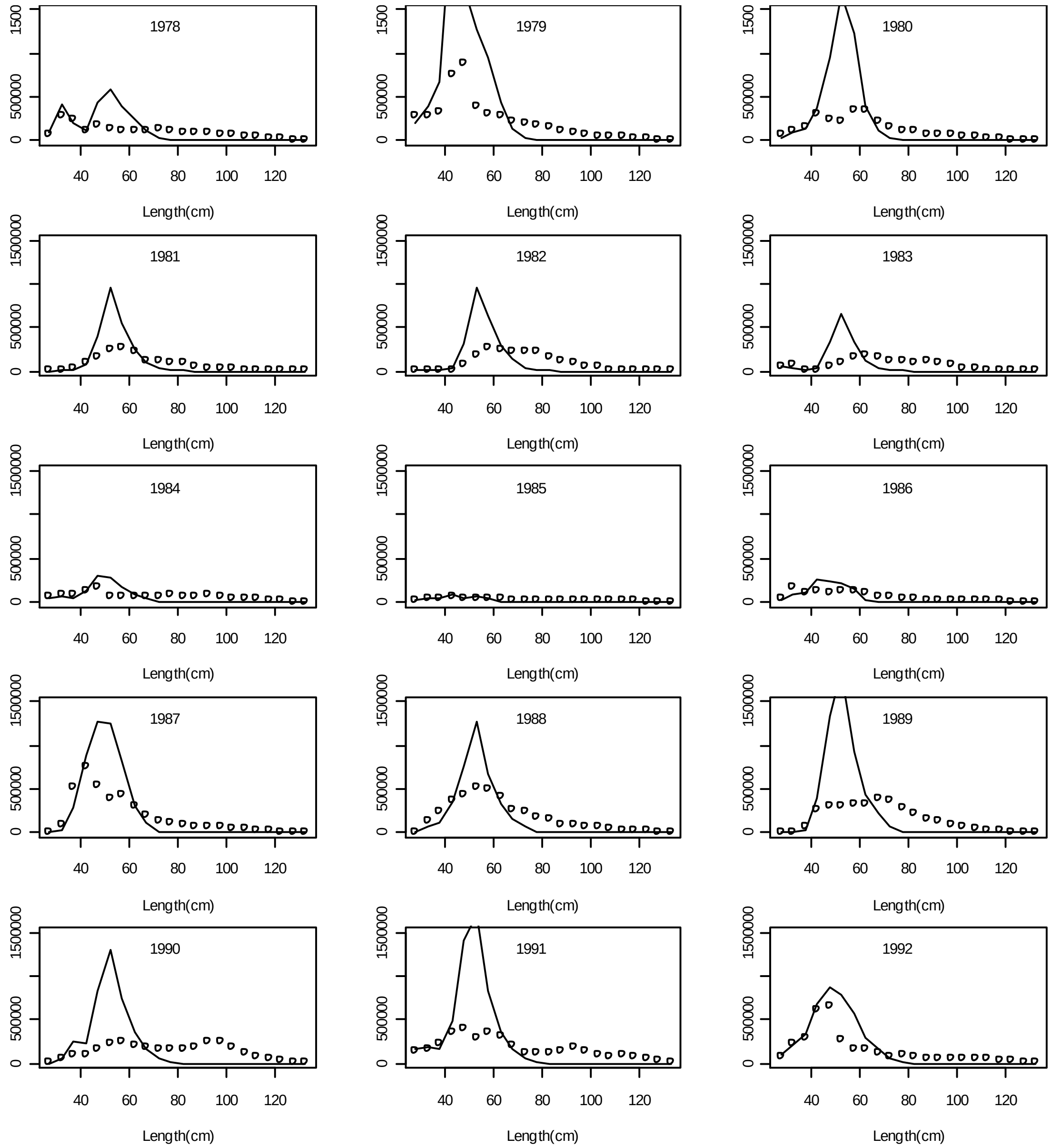

Figure 8. Observed survey numbers 1978 to 1992 by length, males circles, females solid line.

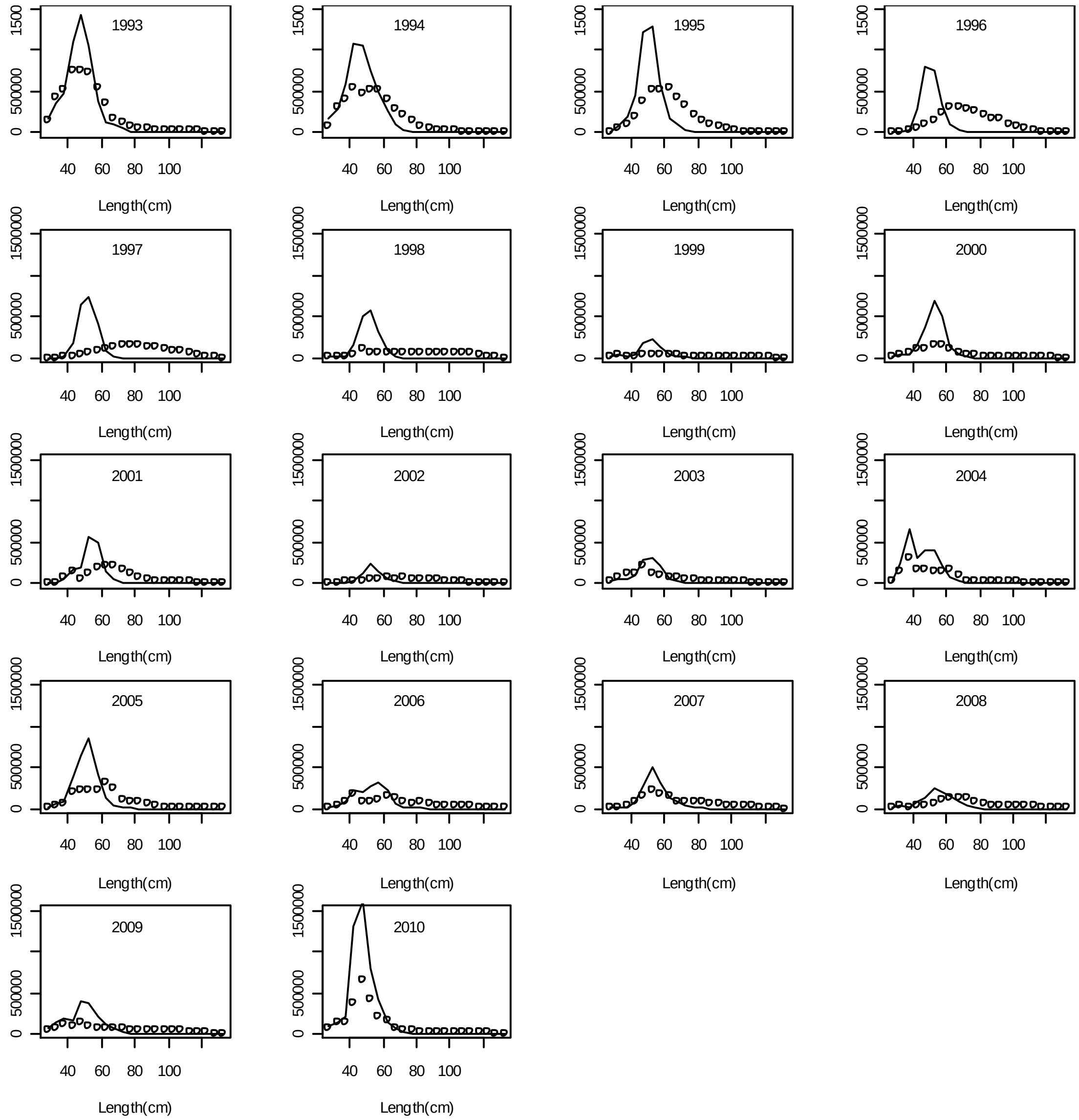

Figure 8 continued. Observed survey numbers 1993 to 2010 by length, males circles, females solid line.

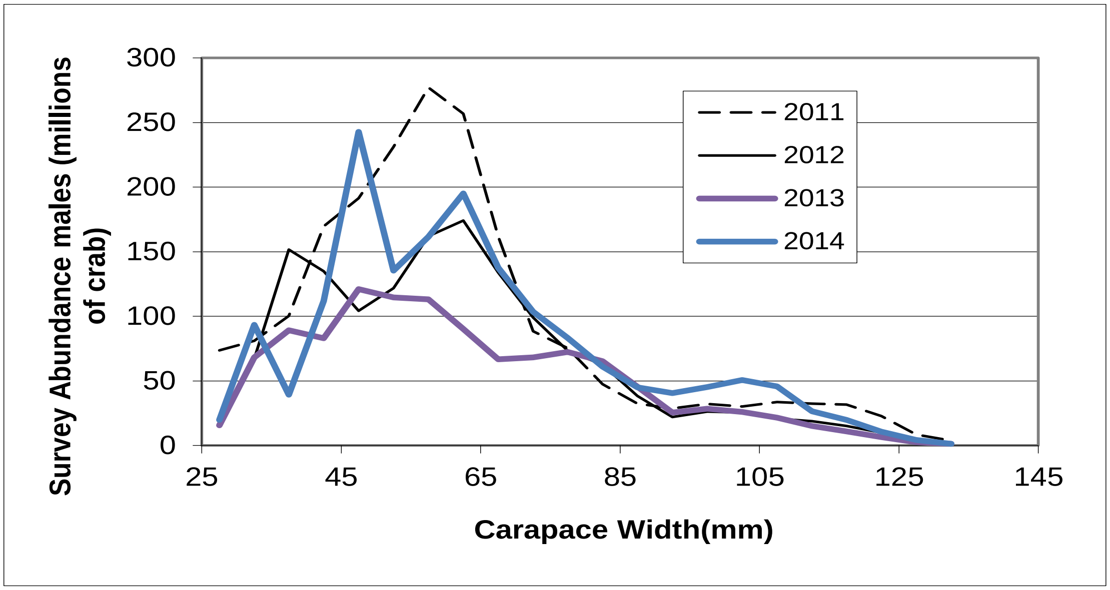

Figure 8a. Survey male abundance by length for 2011 to 2014.

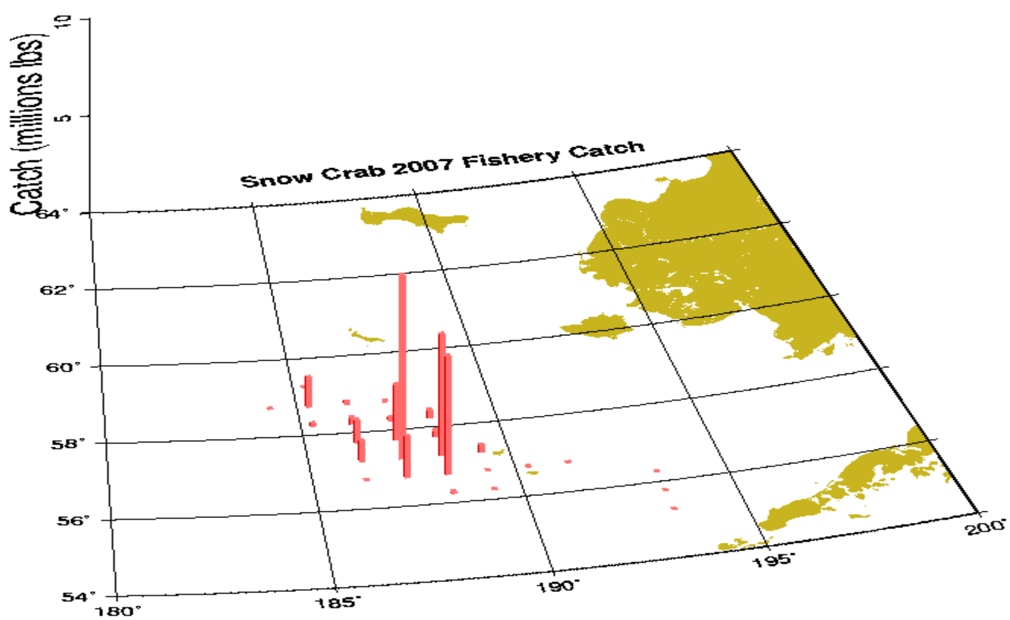

Figure 9. 2006/07 snow crab pot fishery retained catch(million lbs) by statistical area. Longitude increases from west to east (190 degrees = 170 degrees W longitude). Areas are 1 degree longitude by 0.5 degree latitude.

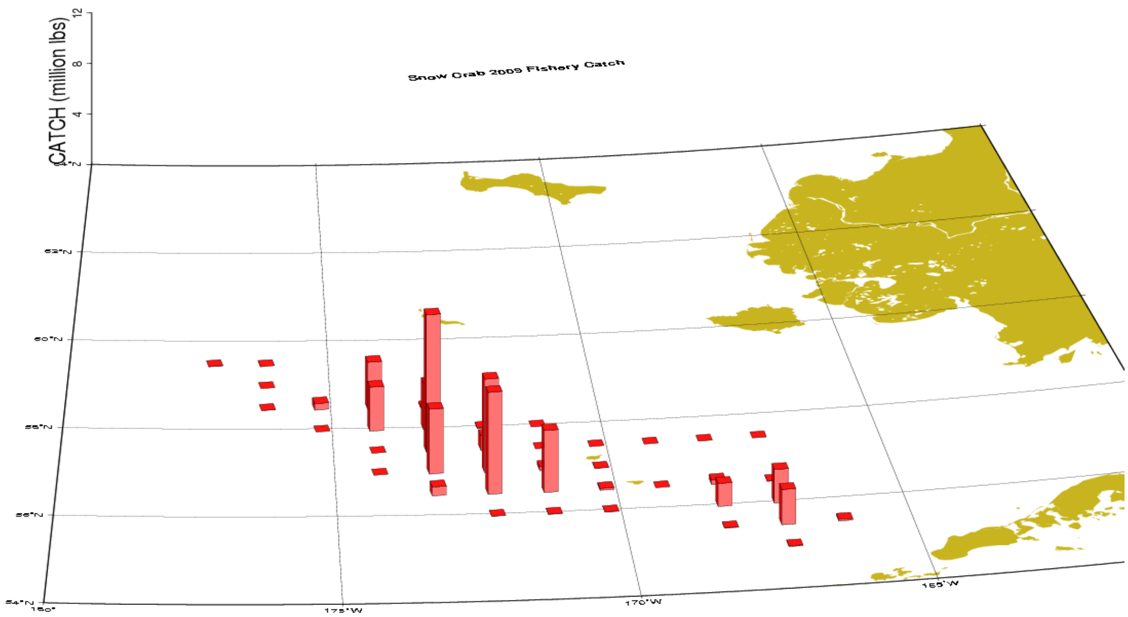

Figure 10. 2008/09 snow crab pot fishery retained catch(million lbs) by statistical area. Statistical areas are 1 degree longitude by 0.5 degree latitude.

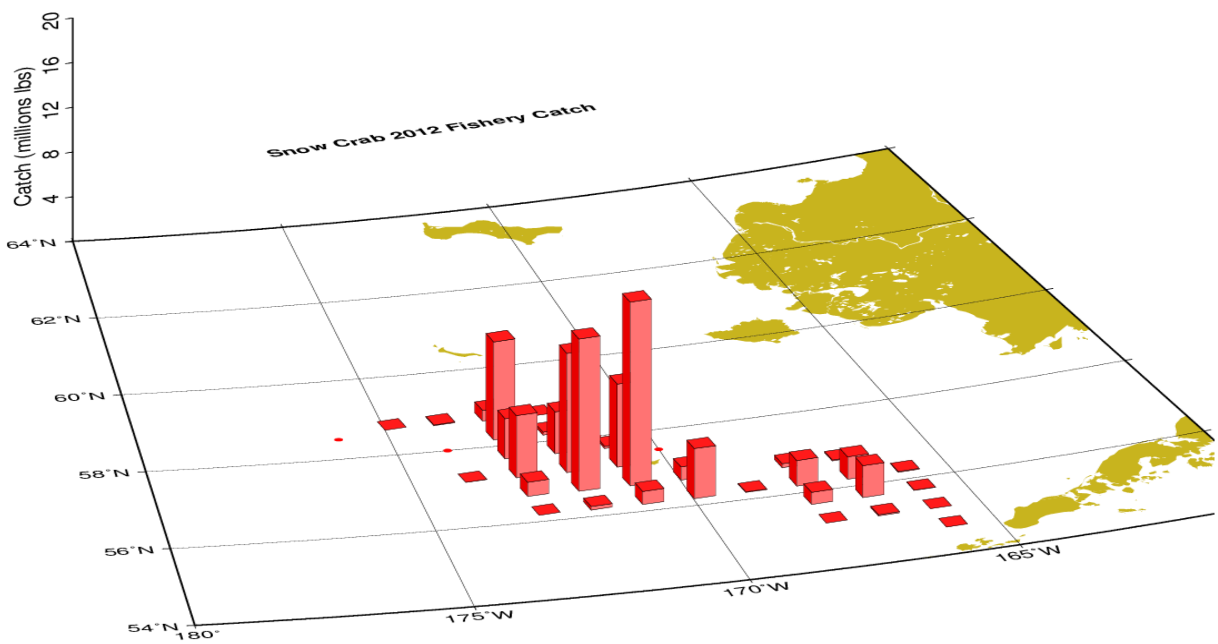

Figure 11. 2011/12 snow crab pot fishery retained catch(million lbs) by statistical area. Statistical areas are 1 degree longitude by 0.5 degree latitude.

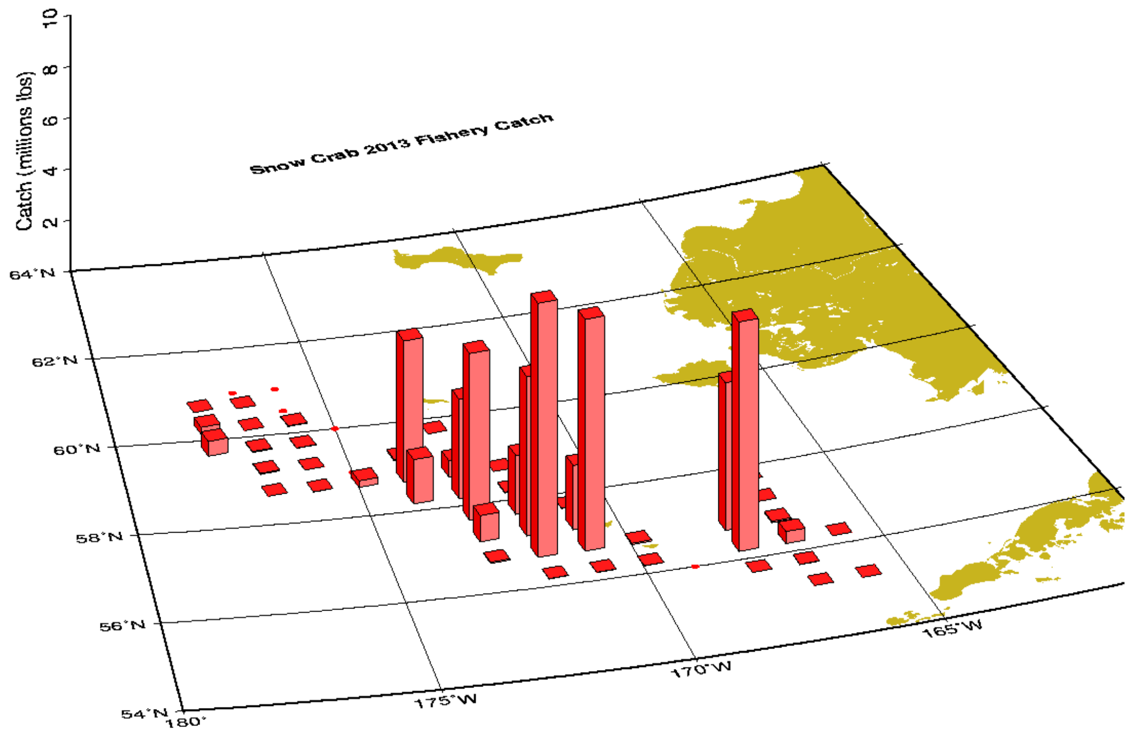

Figure 11b. 2012/13 snow crab pot fishery retained catch(million lbs) by statistical area. Statistical areas are 1 degree longitude by 0.5 degree latitude.

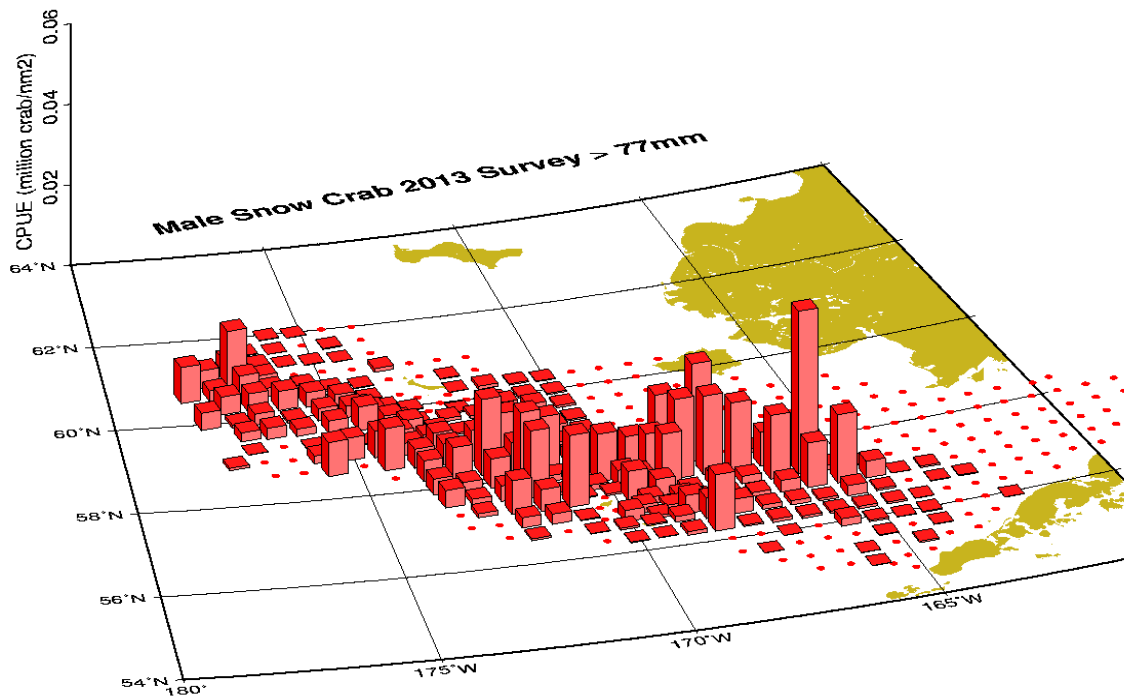

Figure 12. 2013 Survey CPUE (million crab per nm2) of males > 77mm by tow. Filled circles are tows with 0 cpue.

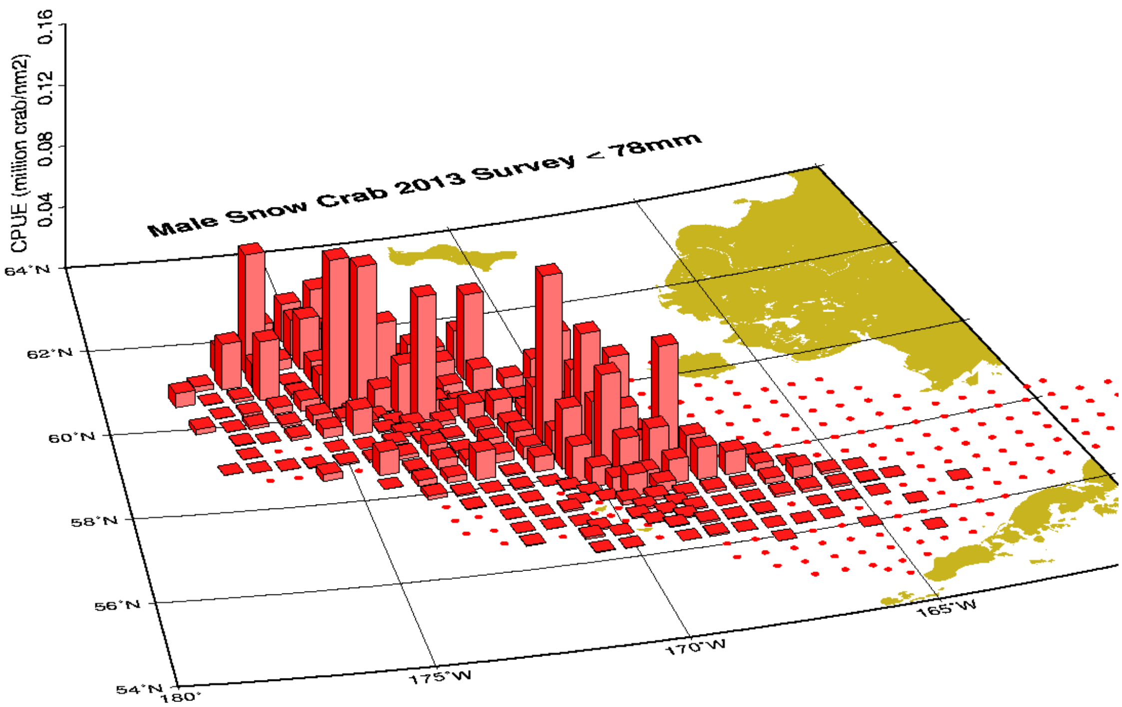

Figure 13. 2013 Survey CPUE (million crab per nm2) of males < 78mm by tow. Filled circles are tows with 0 cpue.

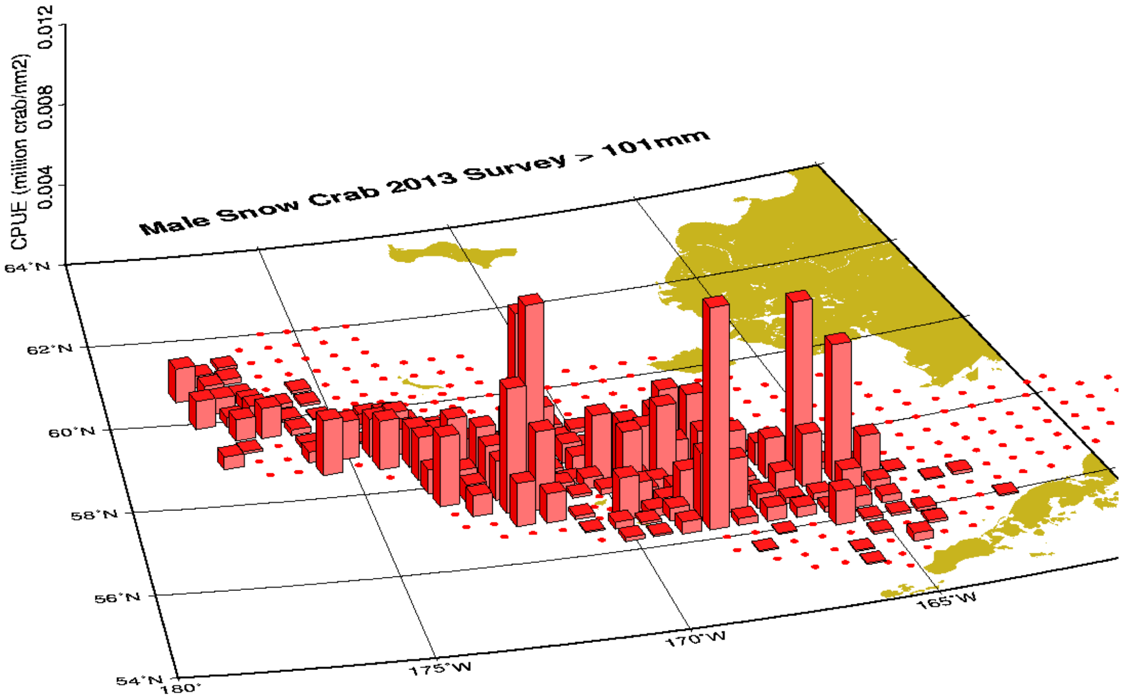

Figure 14. 2013 Survey CPUE (million crab per nm2) of males > 101mm by tow. Filled circles are tows with 0 cpue.

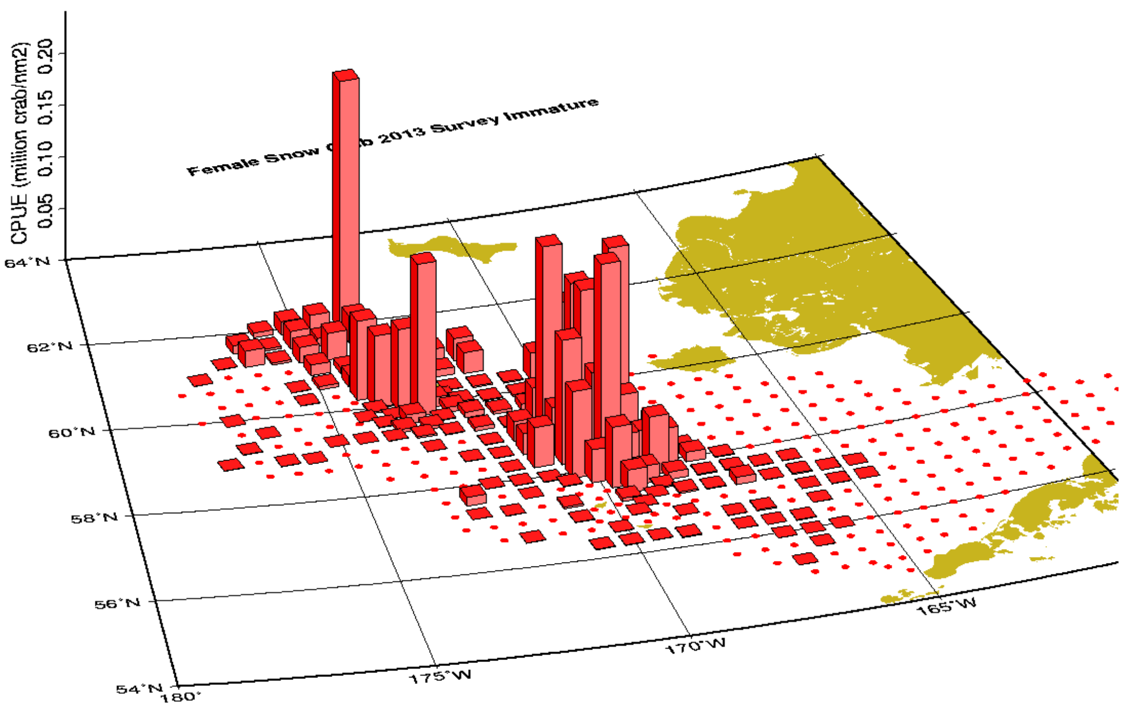

Figure 15. 2013 Survey CPUE (million crab per nm2) of immature females by tow. Filled circles are tows with 0 cpue.

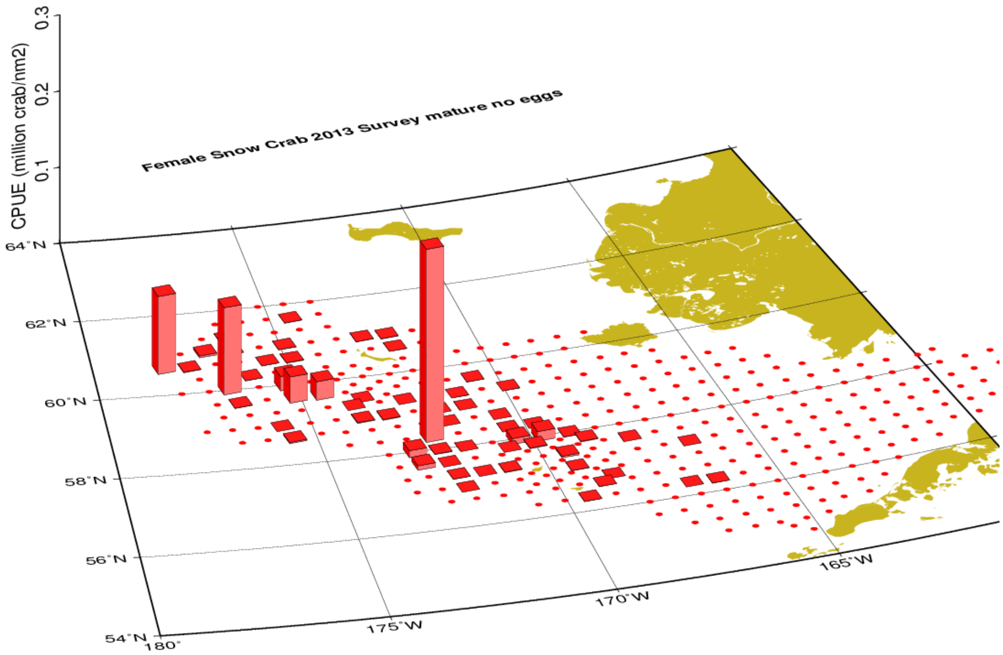

Figure 16. 2013 Survey CPUE (million crab per nm2) of mature females with no eggs by tow. Filled circles are tows with 0 cpue.Figure 25g. 2013 Survey CPUE (million crab per nm2) of mature females with eggs by tow. Filled circles are tows with 0 cpue.

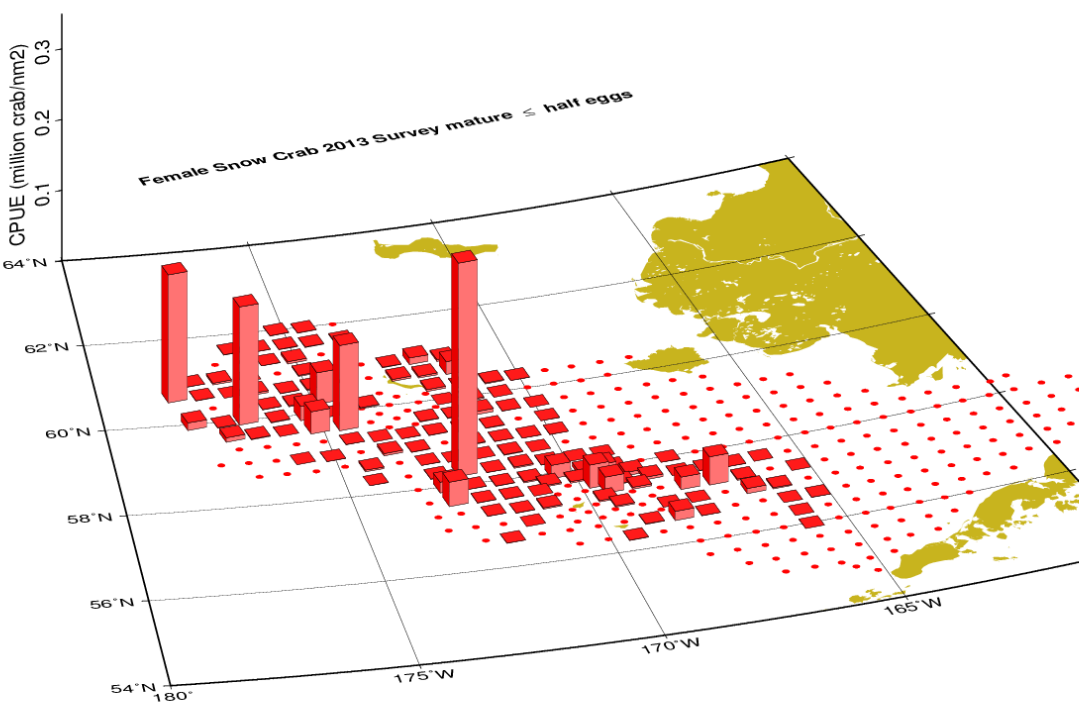

Figure 17. 2013 Survey CPUE (million crab per nm2) of mature females with <= half clutch of eggs by tow. Filled circles are tows with 0 cpue.

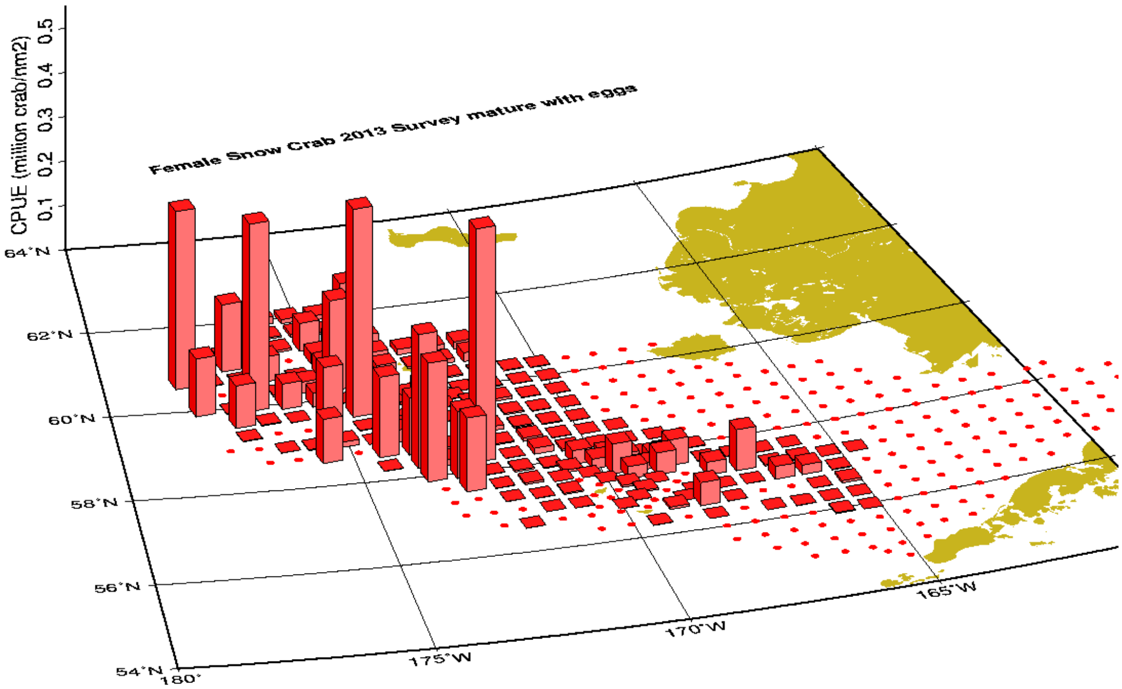

Figure 18. 2013 Survey CPUE (million crab per nm2) of mature females with eggs by tow. Filled circles are tows with 0 cpue.

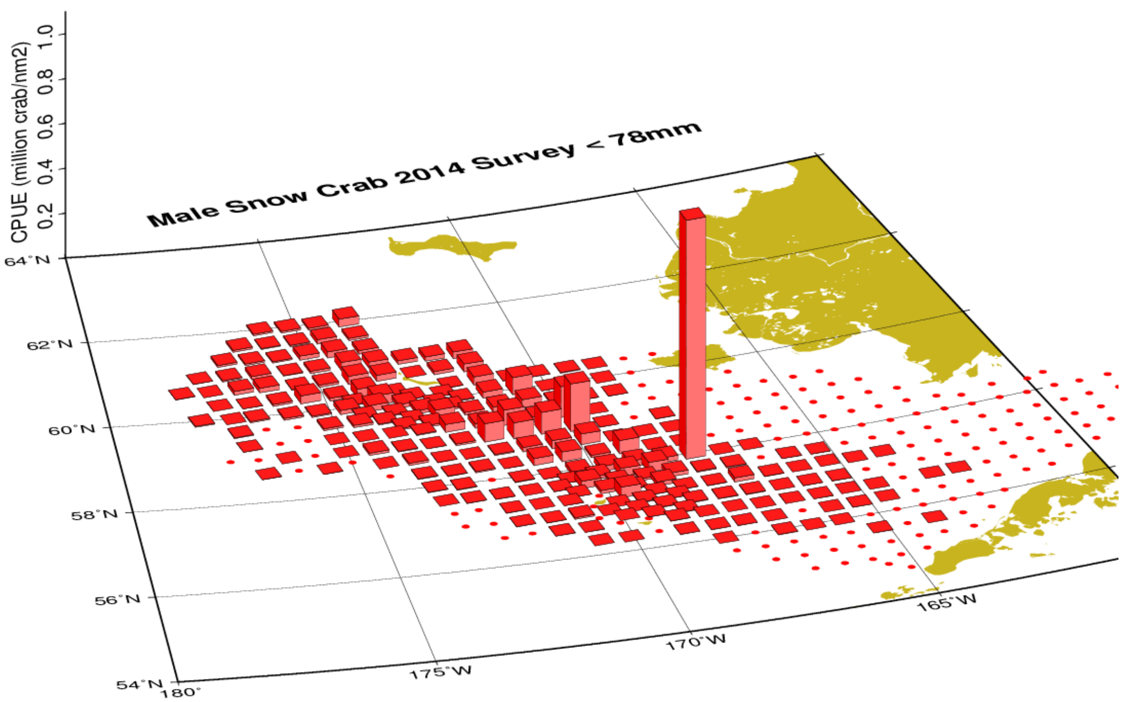

Figure 19. 2014 Survey CPUE (million crab per nm2) of males < 78mm by tow. Filled circles are tows with 0 cpue.

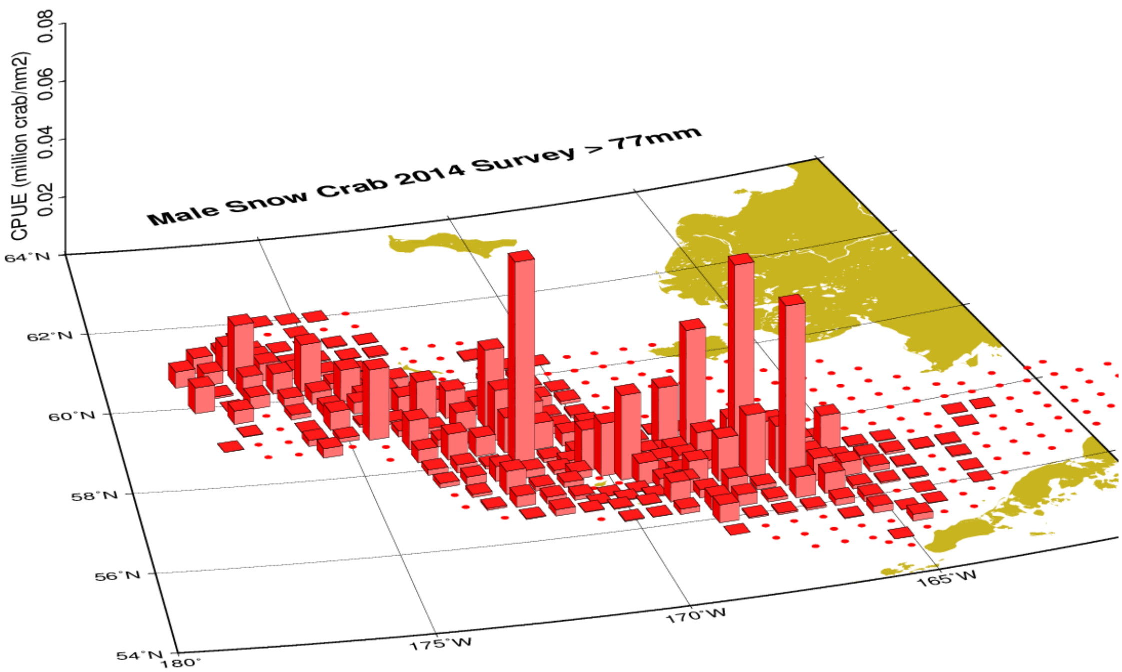

Figure 20. 2014 Survey CPUE (million crab per nm2) of males > 77mm by tow. Filled circles are tows with 0 cpue.

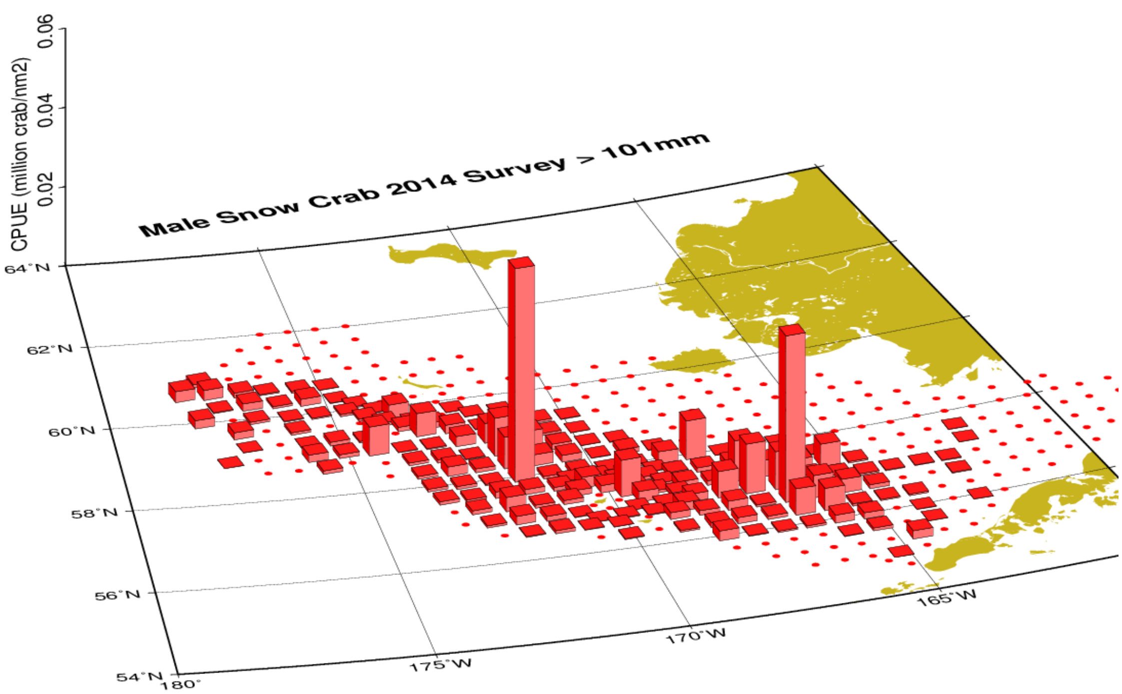

Figure 21. 2014 Survey CPUE (million crab per nm2) of males > 101mm by tow. Filled circles are tows with 0 cpue.

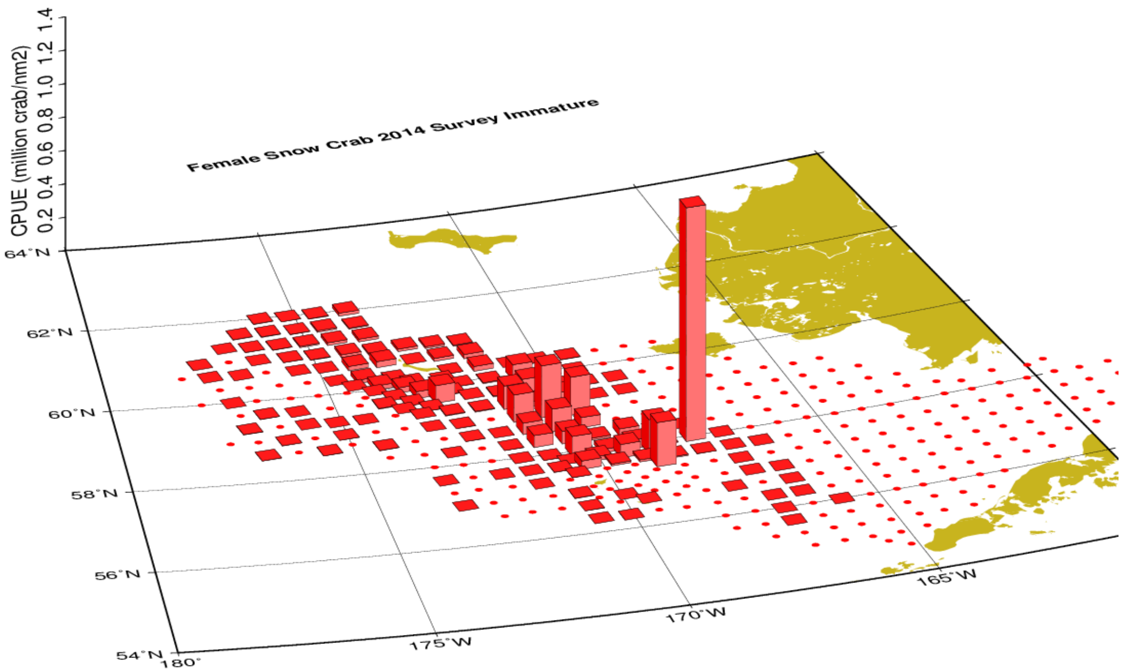

Figure 22. 2014 Survey CPUE (million crab per nm2) of immature females by tow. Filled circles are tows with 0 cpue.

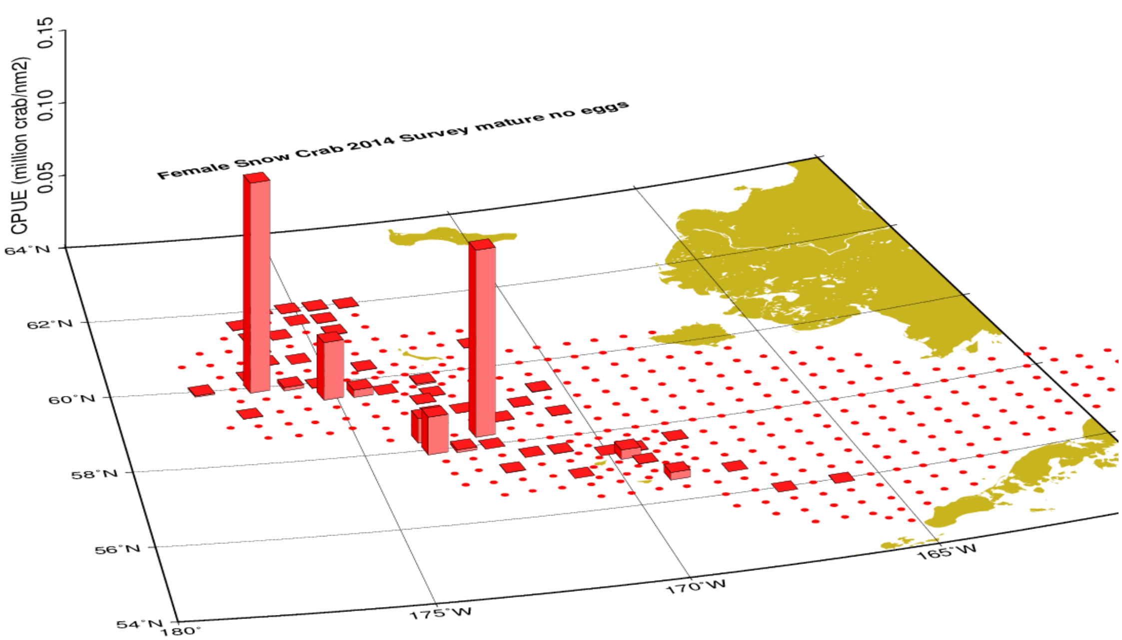

Figure 23. 2014 Survey CPUE (million crab per nm2) of mature females with no eggs by tow. Filled circles are tows with 0 cpue.

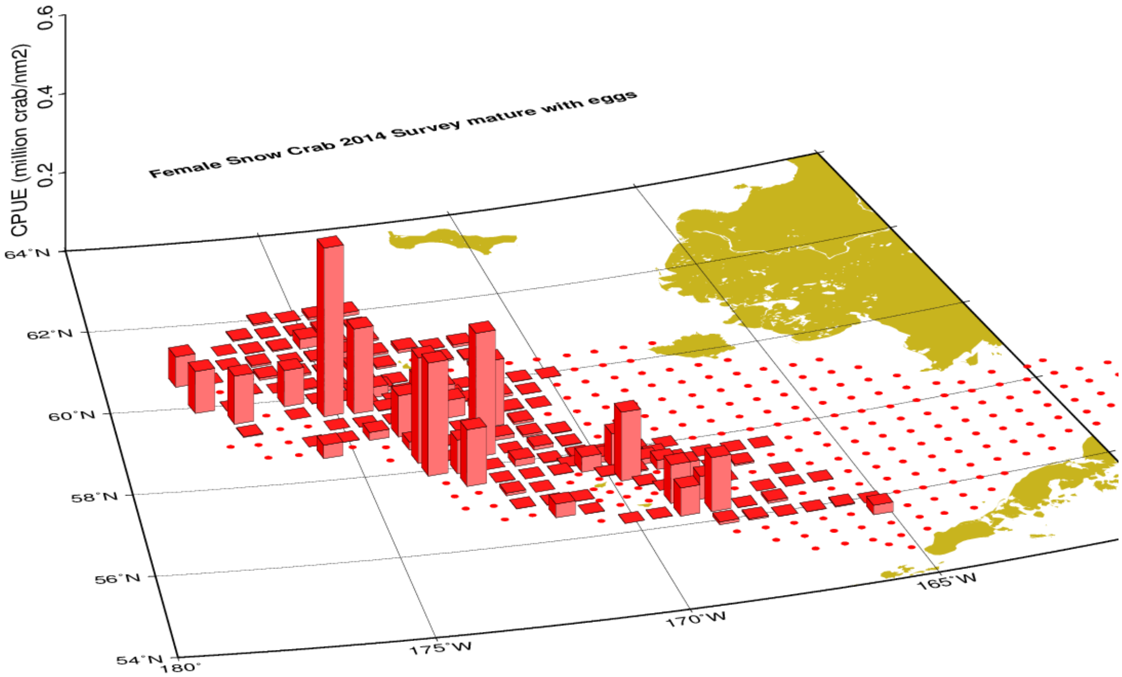

Figure 24. 2014 Survey CPUE (million crab per nm2) of mature females with eggs (all clutch sizes) by tow. Filled circles are tows with 0 cpue.

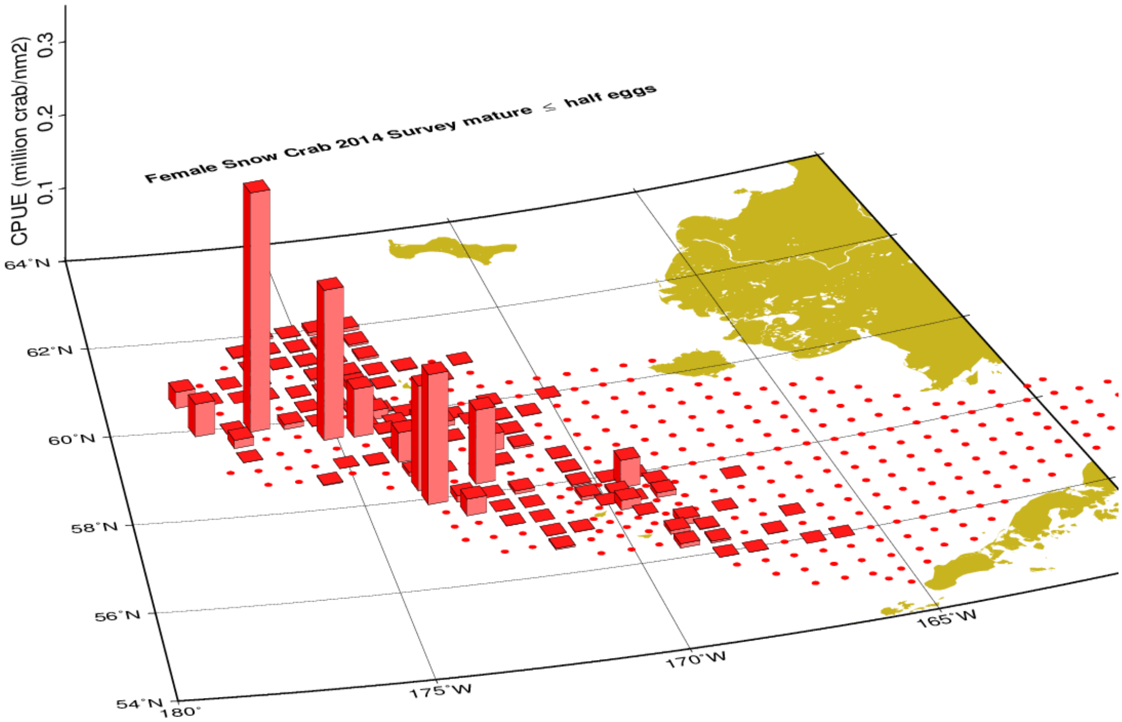

Figure 25. 2014 Survey CPUE (million crab per nm2) of mature females with <= half clutch of eggs by tow. Filled circles are tows with 0 cpue.

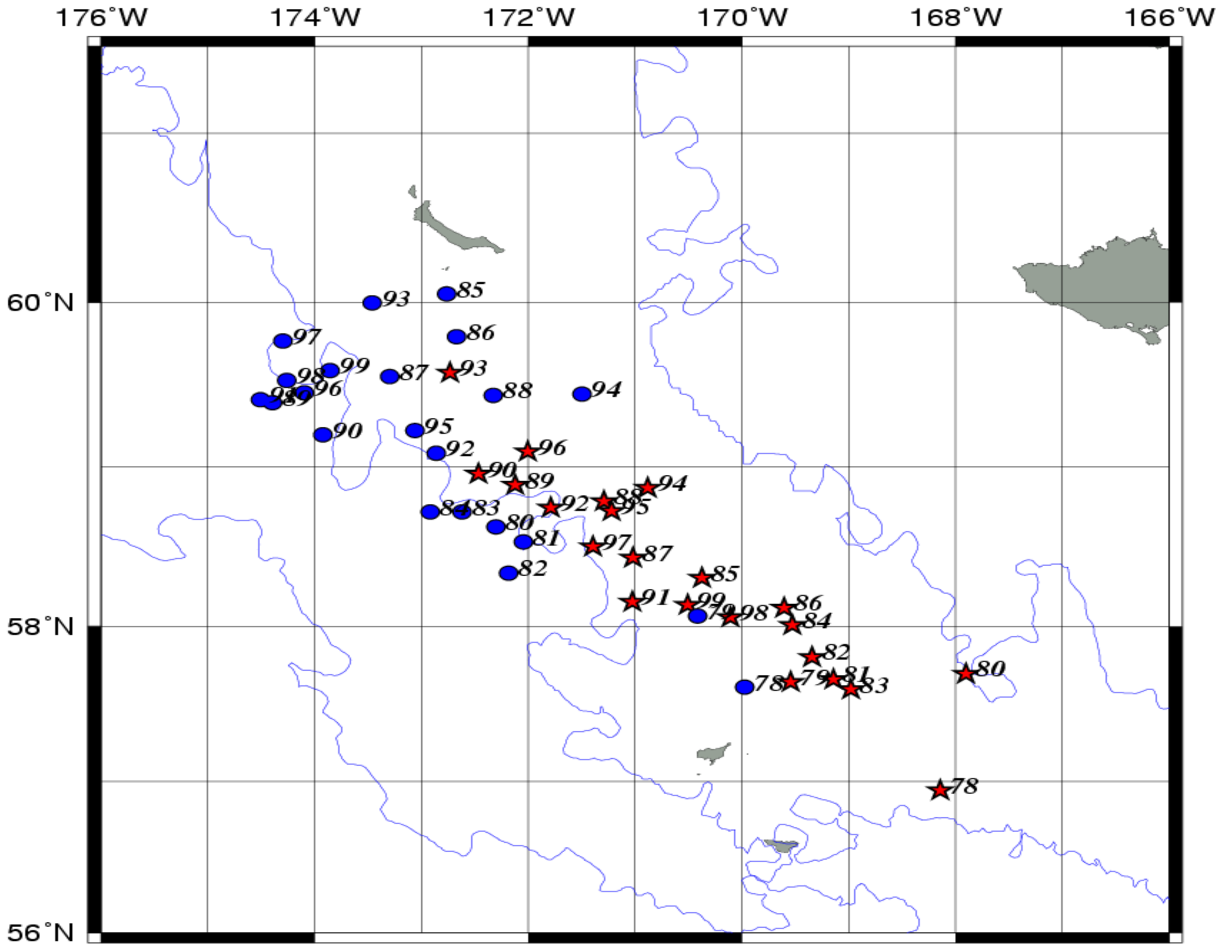

Figure 26. Centroids of abundance of mature female snow crabs (shell condition 2+) in blue circles and mature males (shell condition 3+) in red stars (Ernst, et al. 2005).

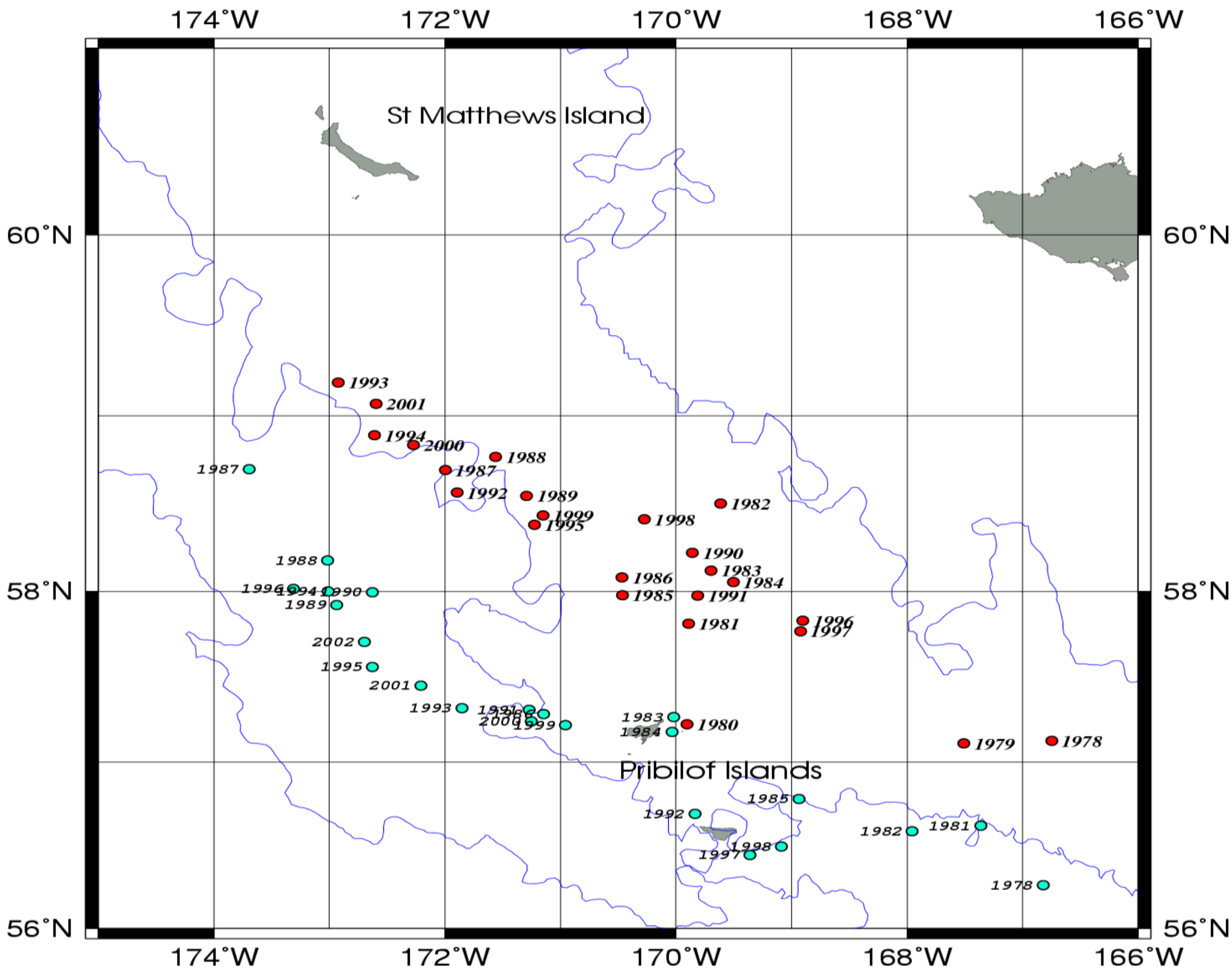

Figure 27. Centroids abundance (numbers) of snow crab males > 101 mm from the summer NMFS trawl survey (red) and from the winter fishery (blue-green) (Ernst, et al. 2005).

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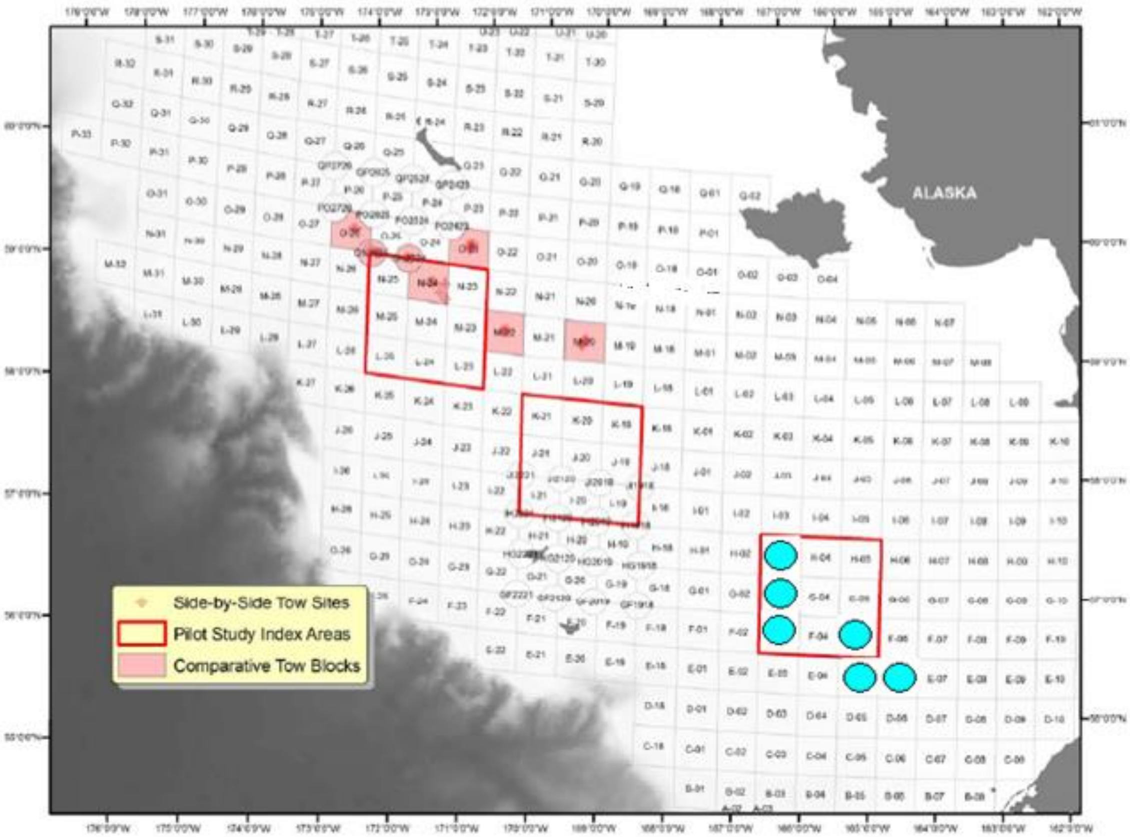


Figure 28. Location of the side-by-side trawling areas (shown with pink shading) and the 3 BSFRF survey areas encompassing the 27 NMFS survey blocks (shown with a red line). Location of the 1998 auxiliary bag experiment sampling areas are the blue circles.

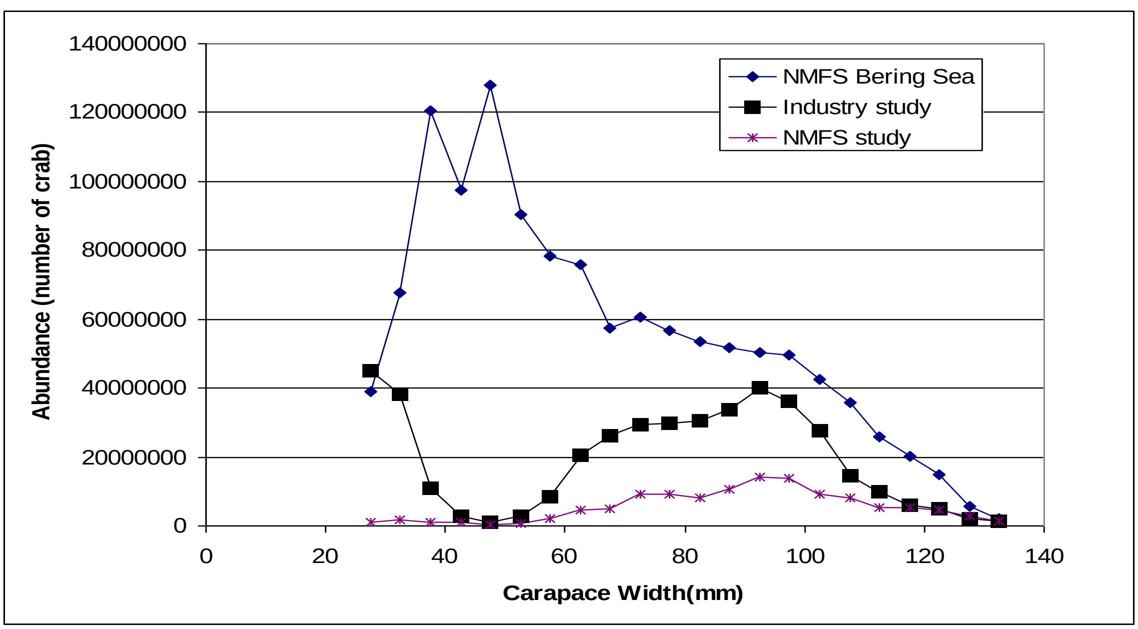


Figure 29. Abundance estimates of male snow crab by 5 mm carapace width(>=25mm) for the NMFS survey of the entire Bering Sea survey area (NMFS Bering Sea), the BSFRF net in the study area (108 tows) and the NMFS survey in the 2009 study area.

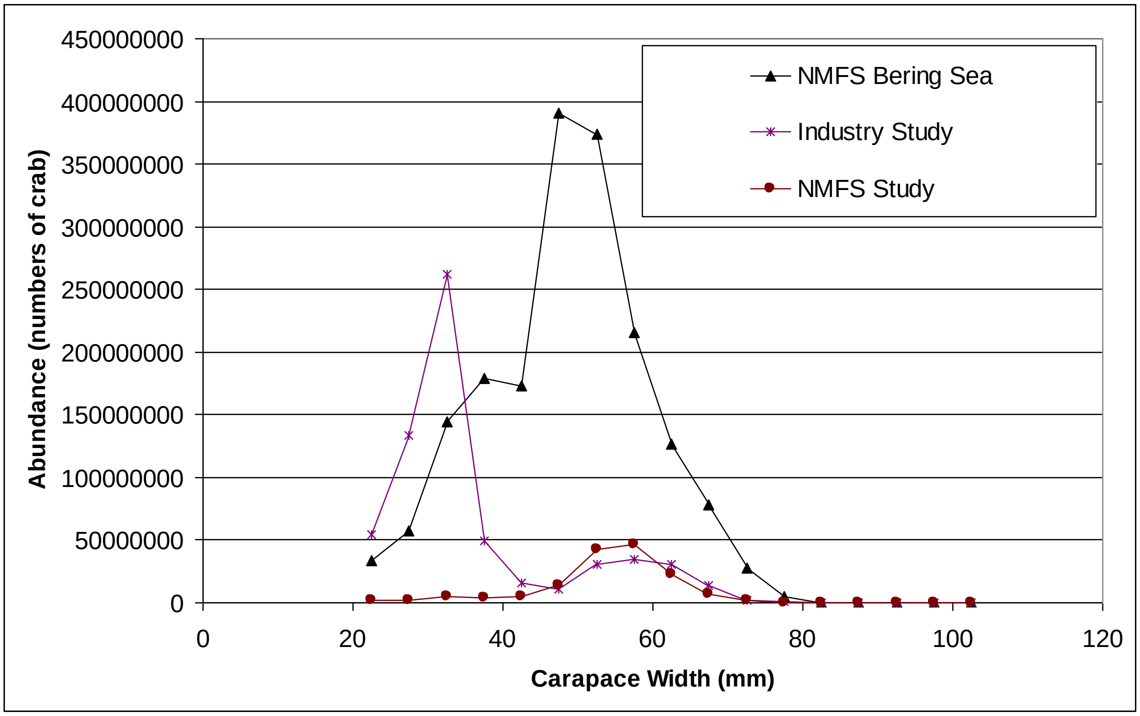


Figure 30. Abundance estimates of female snow crab by 5 mm carapace width for the NMFS survey of the entire Bering Sea survey area (NMFS Bering Sea), the BSFRF net in the study area (108 tows) and the NMFS survey in the 2009 study area.

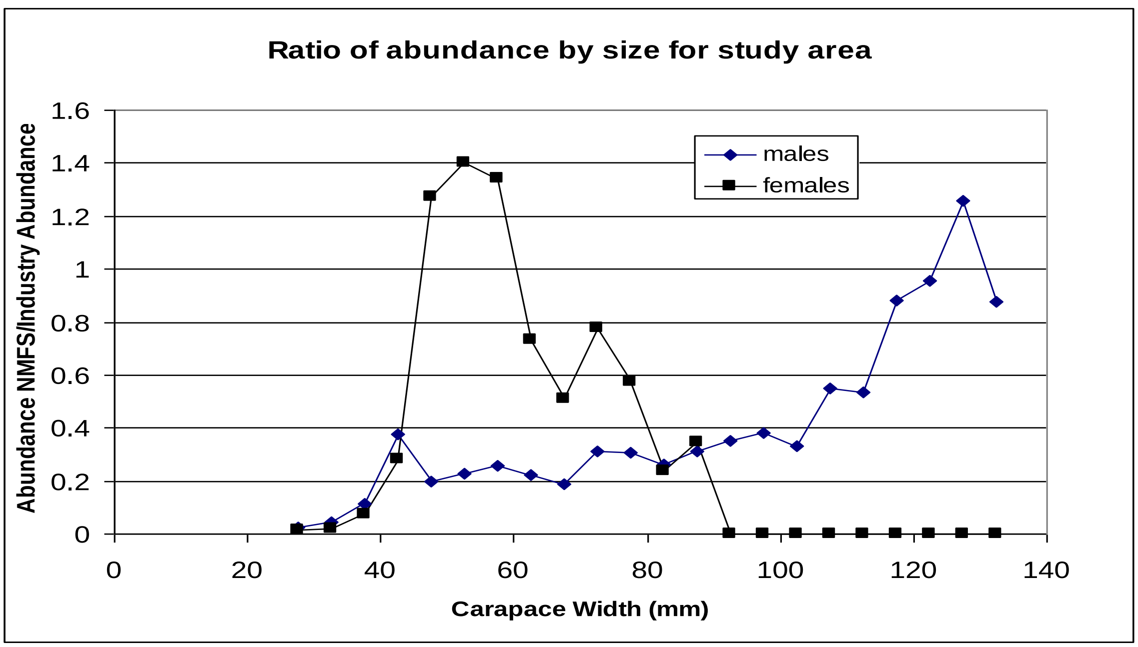


Figure 31. Ratio of abundance in the 2009 study area from the NMFS net to the BSFRF net for male and female crab.

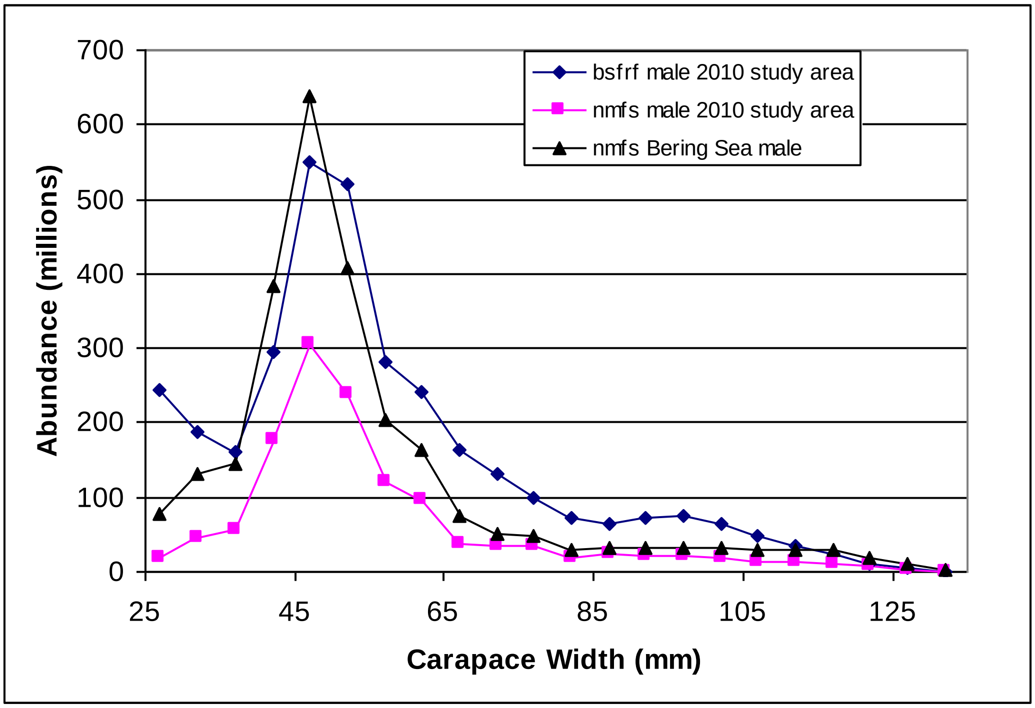


Figure 32. 2010 study area Male abundance.

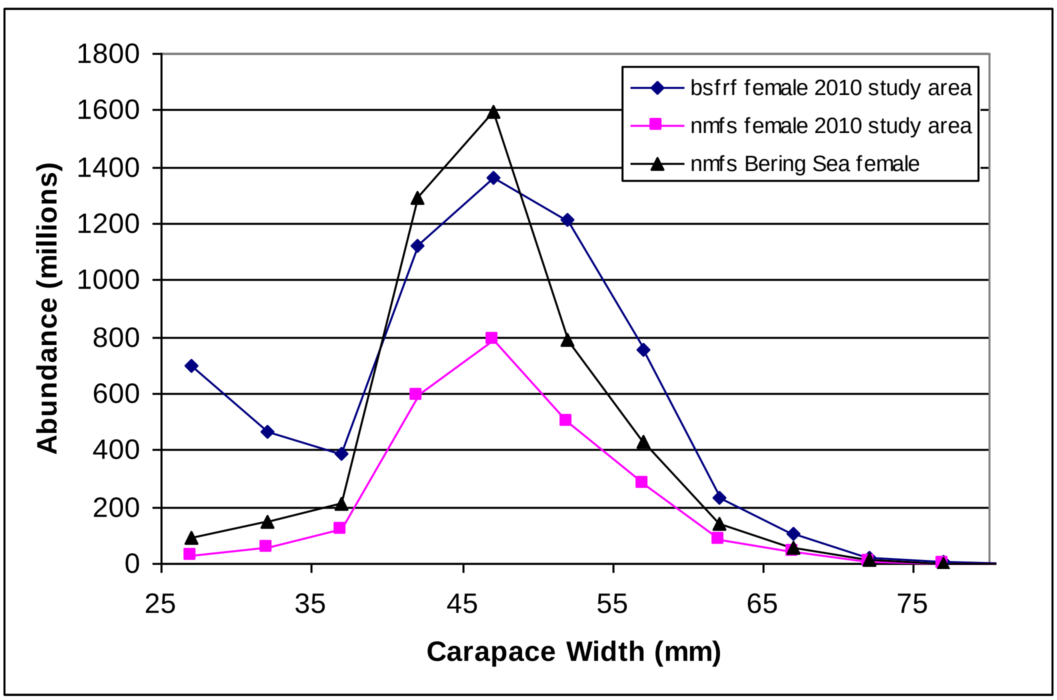


Figure 33. 2010 study area Female abundance.

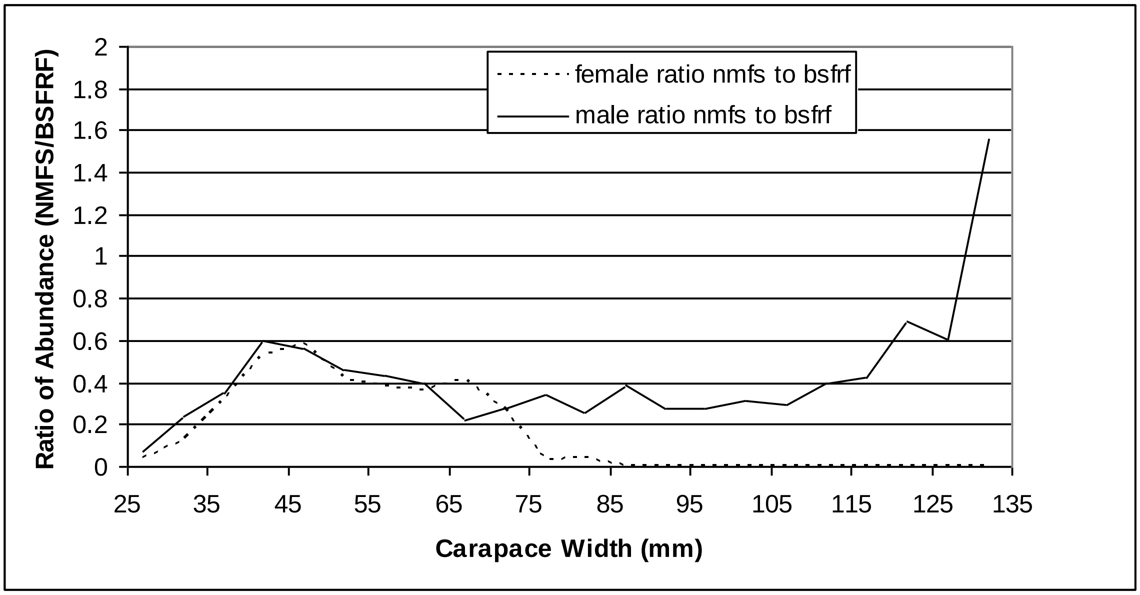


Figure 34. 2010 study area ratio of abundance

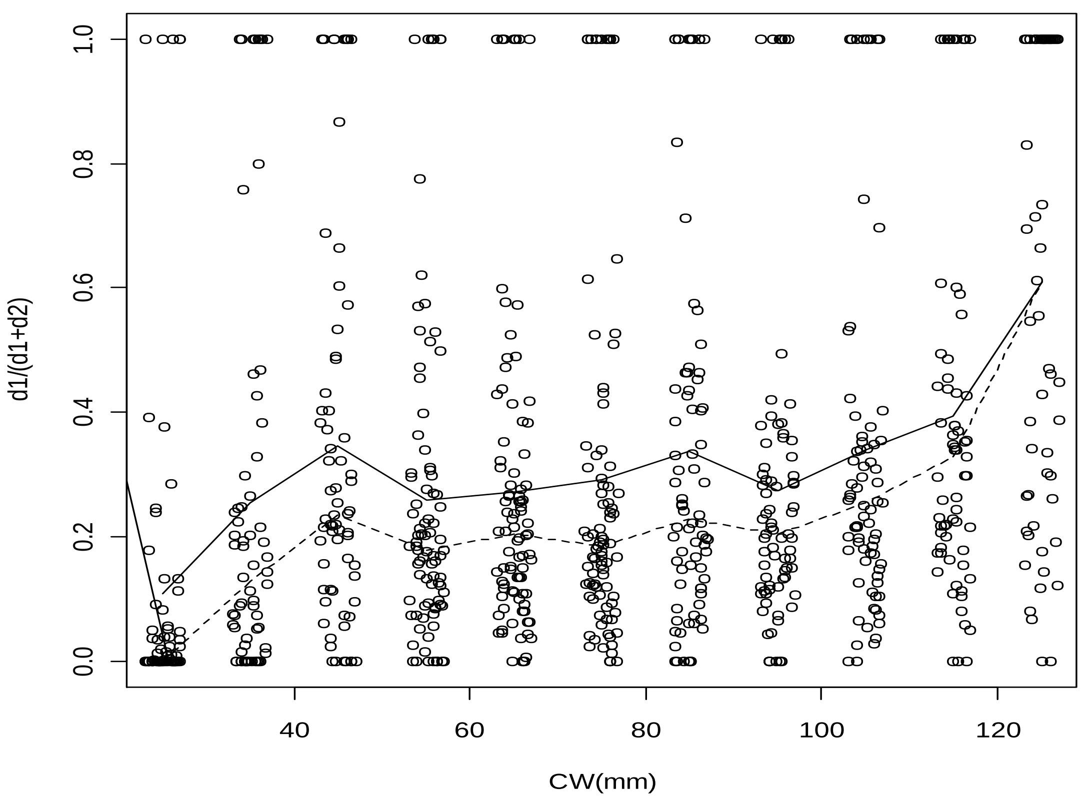


Figure 35. Male crab. Density (catch/nm2) of NMFS tow (d1) divided by sum of density (d2 is density of BSFRF tow). Solid line is unweighted mean, dotted line median of each length bin. A value of 0.5 is equal density (d1=d2). Length values are jittered to show multiple 1.0 and 0.0 data.

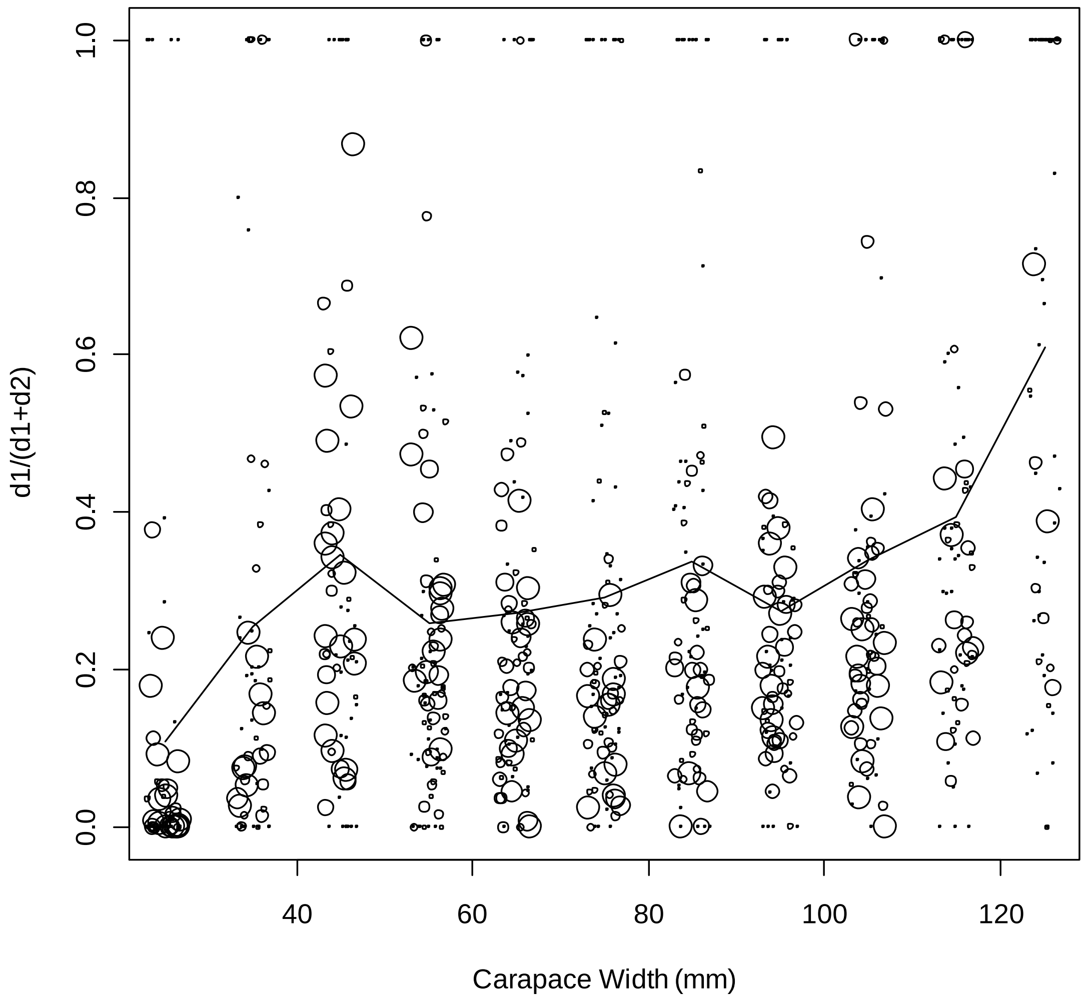


Figure 36. Density of NMFS tow (d1) divided by the sum of the density of the NMFS tow (d1) and the Industry tow (d2). The radius of the circle at each point is proportional to the sum of the catch in numbers where the Industry numbers are adjusted by the ratio of the NMFS area swept to the Industry area swept. The line is the unweighted mean values of d1/(d1+d2) in each size bin.

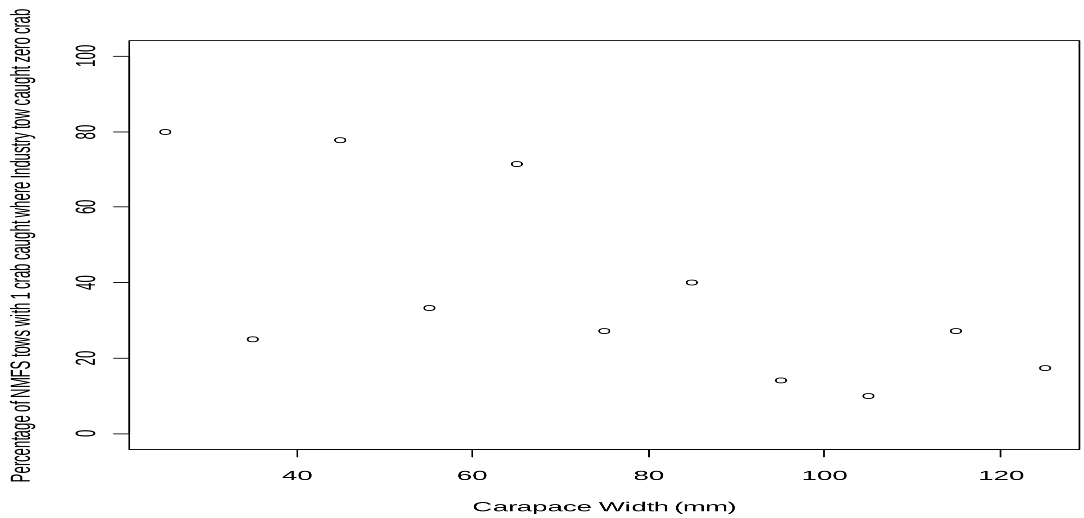


Figure 37. Percentage of paired tows where BSFRF caught no crab and NMFS caught only 1 crab.

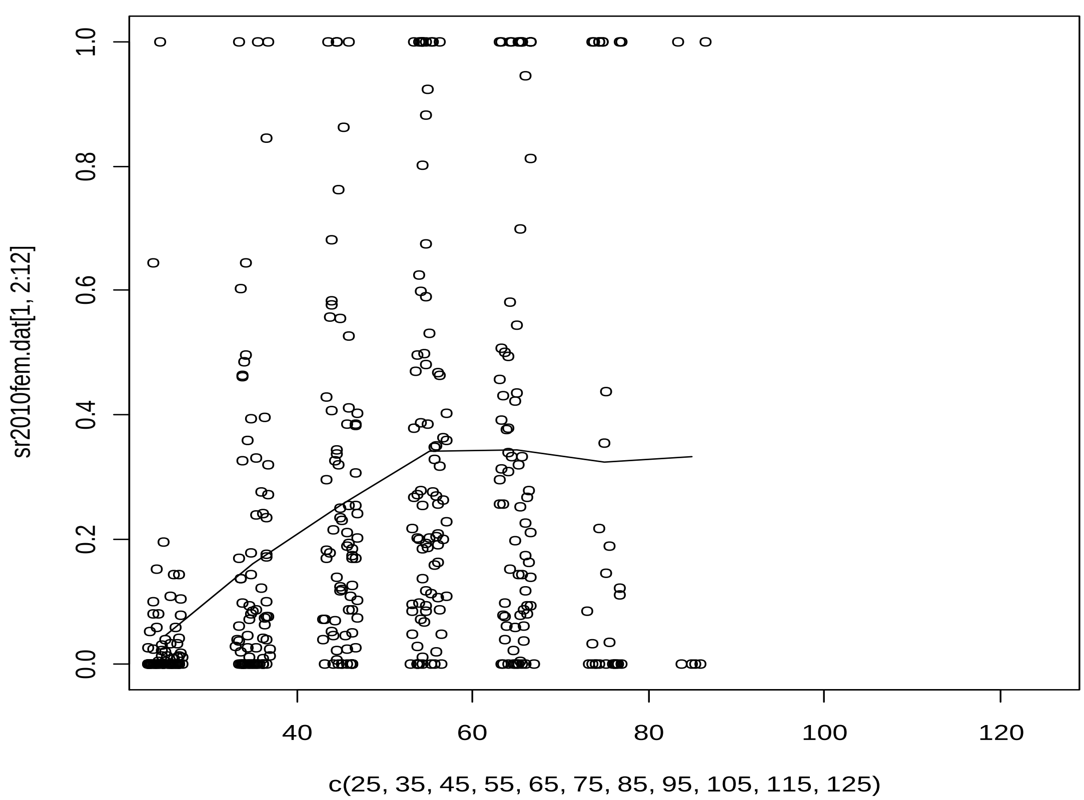


Figure 38. Female d1/(d1+d2) with mean. Density (catch/nm2) of NMFS tow (d1) divided by sum of density (d2 is density of BSFRF tow). Solid line is mean, dotted line median of each length bin. A value of 0.5 is equal density (d1=d2). Length values are jittered to show multiple 1.0 and 0.0 data.

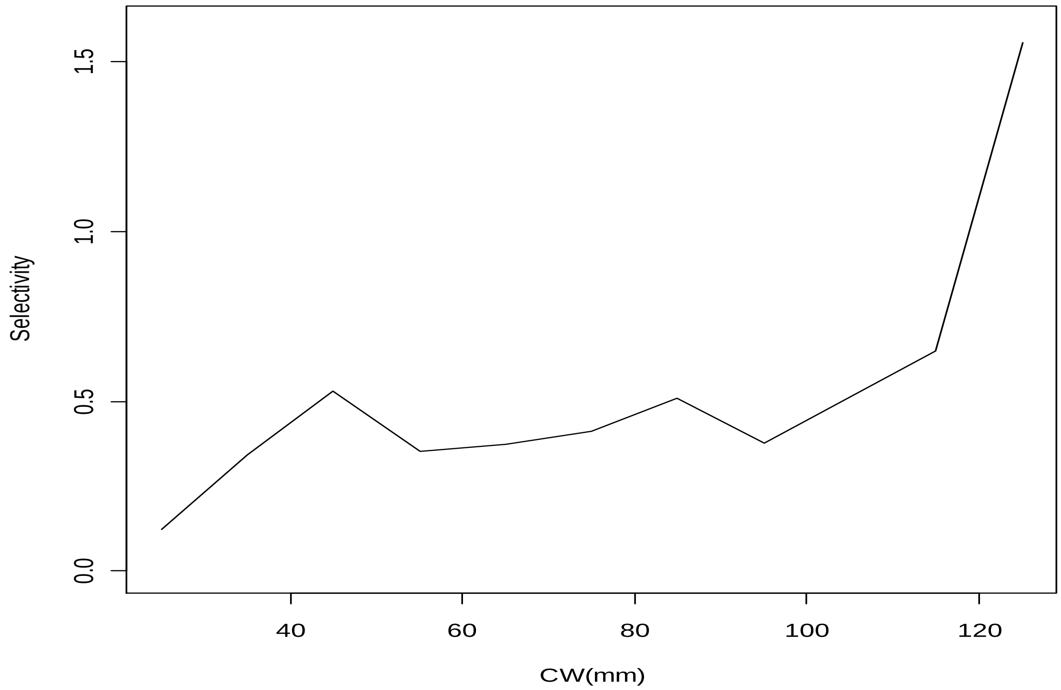


Figure 39. Mean from Figure 9 translated to selectivity (selectivity = p/(1-p), where p= d1/(d1+d2)).

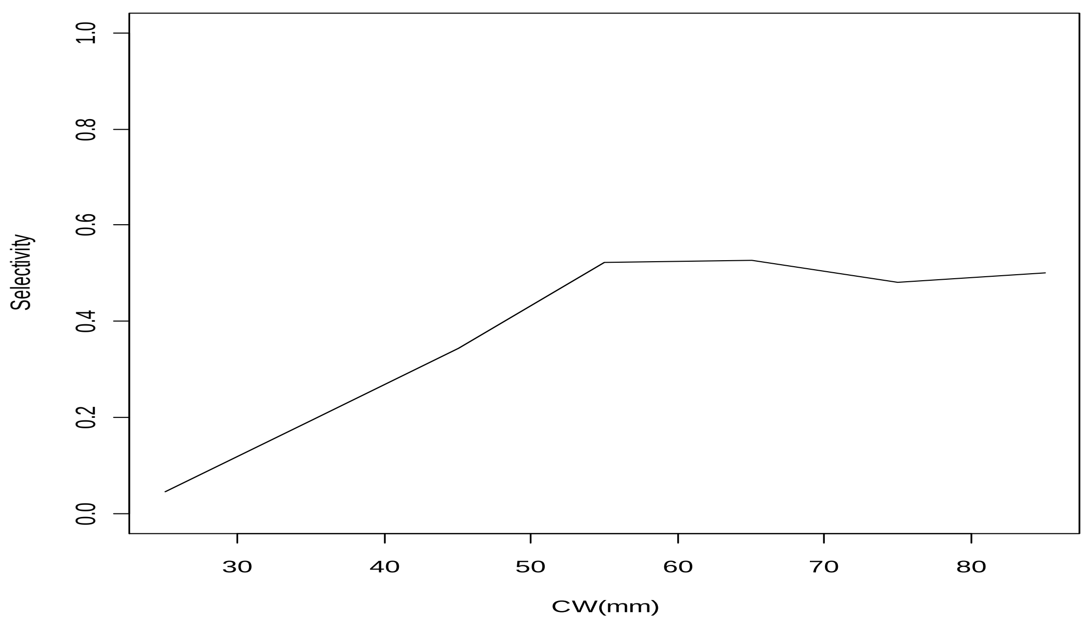


Figure 40. Mean from Figure 38, female crab translated to selectivity (selectivity = p/(1-p), where p= d1/(d1+d2))

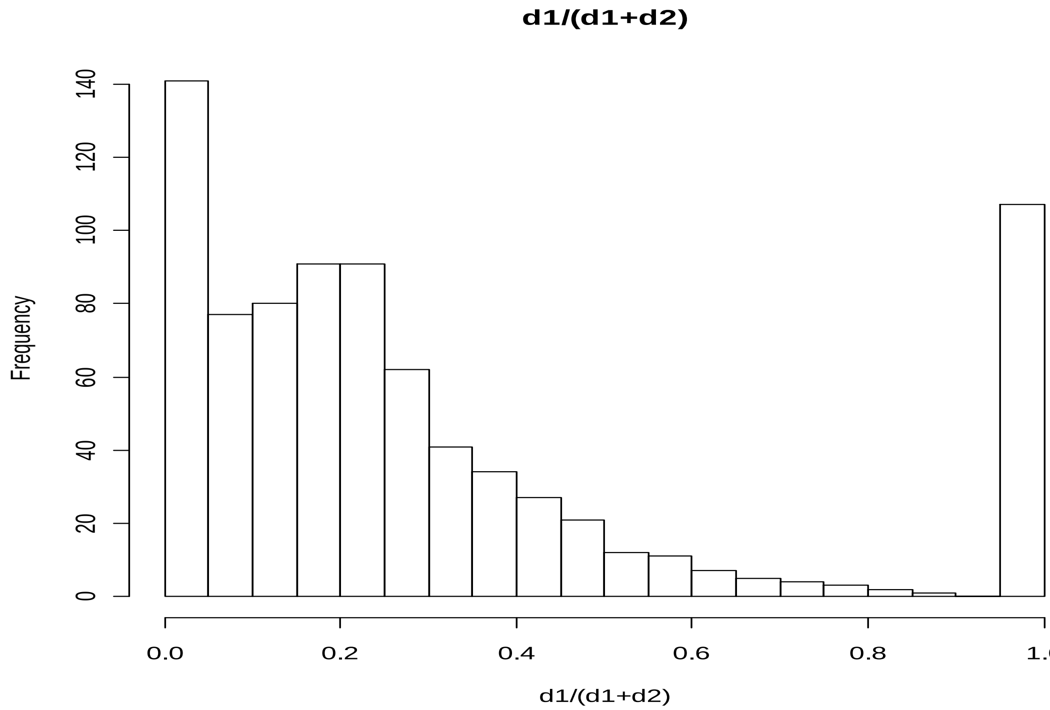


Figure 41. Histogram of d1/(d1+d2) over all sizes and tows. A value of 1.0 is a positive catch in the NMFS tow and a zero catch in the BSFRF tow. A value of 0.0 is a 0 catch in the NMFS tow and a positive catch in the BSRFR tow.

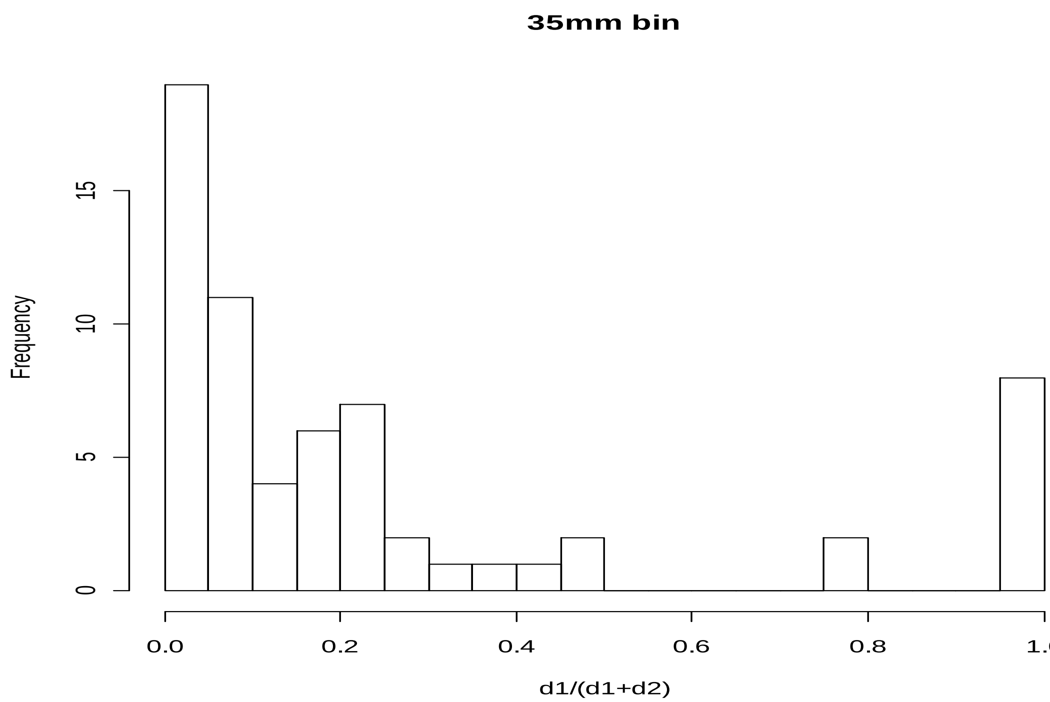


Figure 42. Histogram of d1/(d1+d2) for the 30 to 40 mm size bin. A value of 1.0 is a positive catch in the NMFS tow and a zero catch in the BSFRF tow. A value of 0.0 is a 0 catch in the NMFS tow and a positive catch in the BSRFR tow.

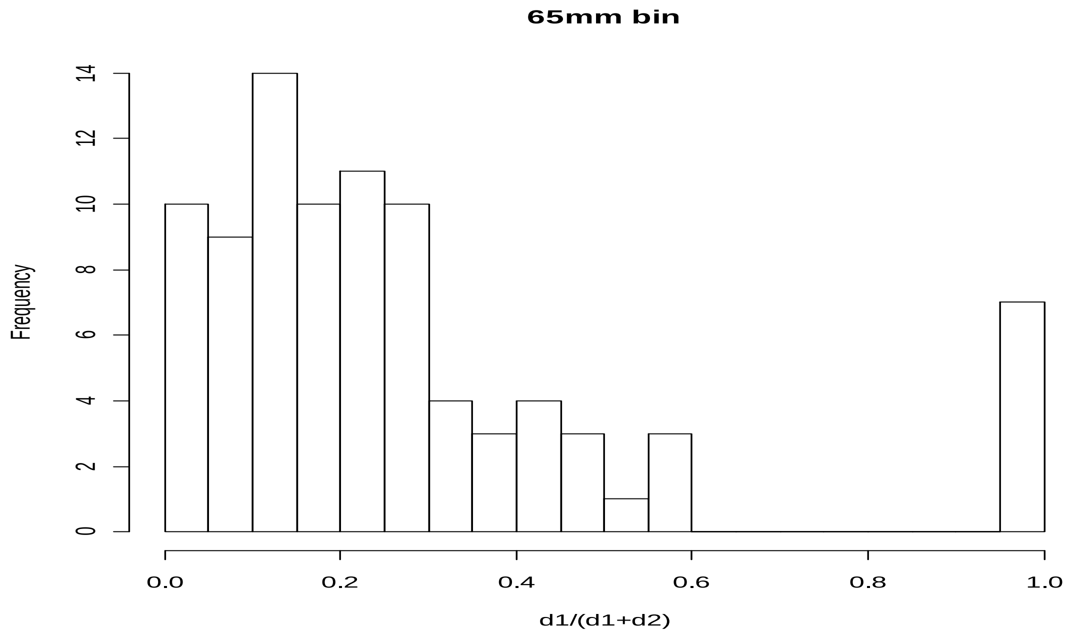


Figure 43. Histogram of d1/(d1+d2) for the 60 to 70 mm size bin. A value of 1.0 is a positive catch in the NMFS tow and a zero catch in the BSFRF tow. A value of 0.0 is a 0 catch in the NMFS tow and a positive catch in the BSRFR tow.

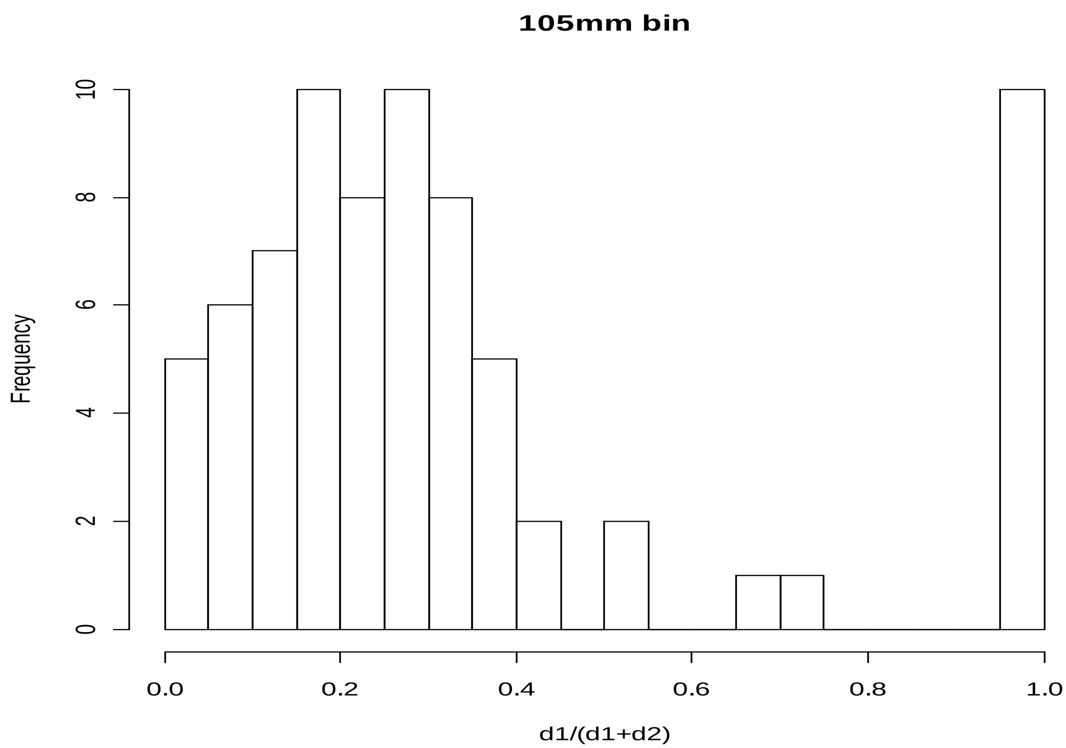


Figure 44. Histogram of d1/(d1+d2) for the 100 to 110 mm size bin. A value of 1.0 is a positive catch in the NMFS tow and a zero catch in the BSFRF tow. A value of 0.0 is a 0 catch in the NMFS tow and a positive catch in the BSRFR tow.

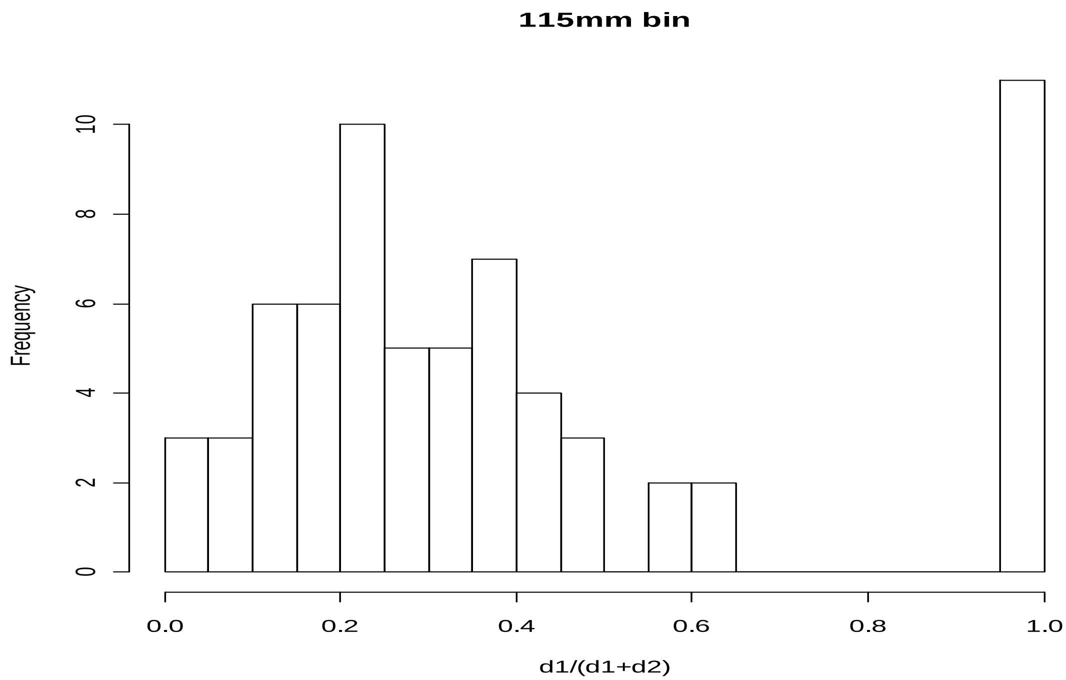


Figure 45. Histogram of d1/(d1+d2) for the 100 to 120 mm size bin. A value of 1.0 is a positive catch in the NMFS tow and a zero catch in the BSFRF tow. A value of 0.0 is a 0 catch in the NMFS tow and a positive catch in the BSRFR tow.

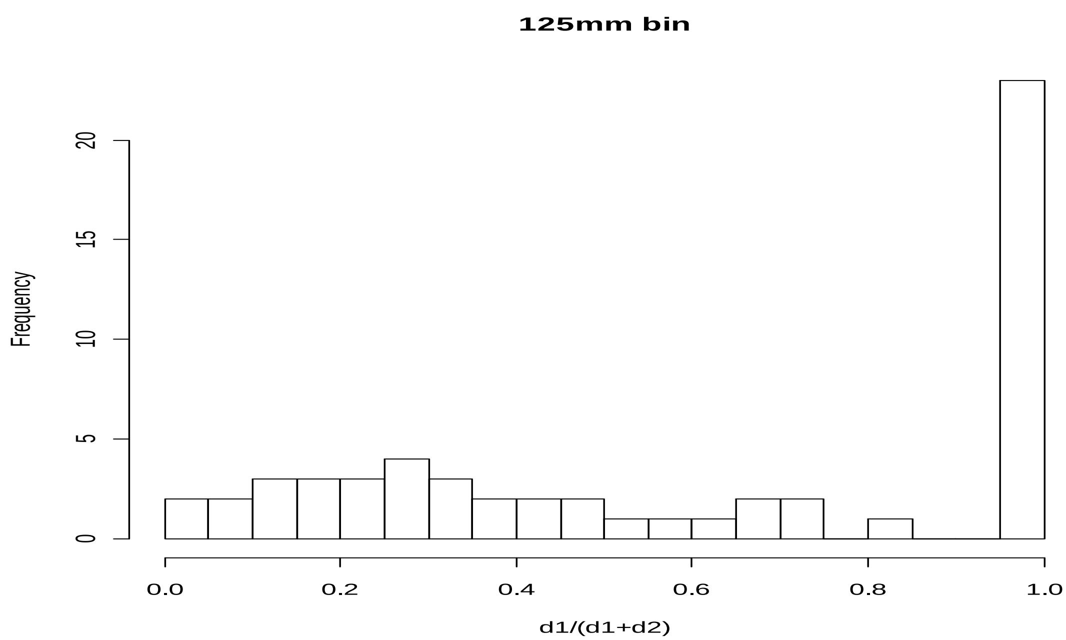


Figure 46. Histogram of d1/(d1+d2) for the 120+mm size bin. A value of 1.0 is a positive catch in the NMFS tow and a zero catch in the BSFRF tow. A value of 0.0 is a 0 catch in the NMFS tow and a positive catch in the BSRFR tow.

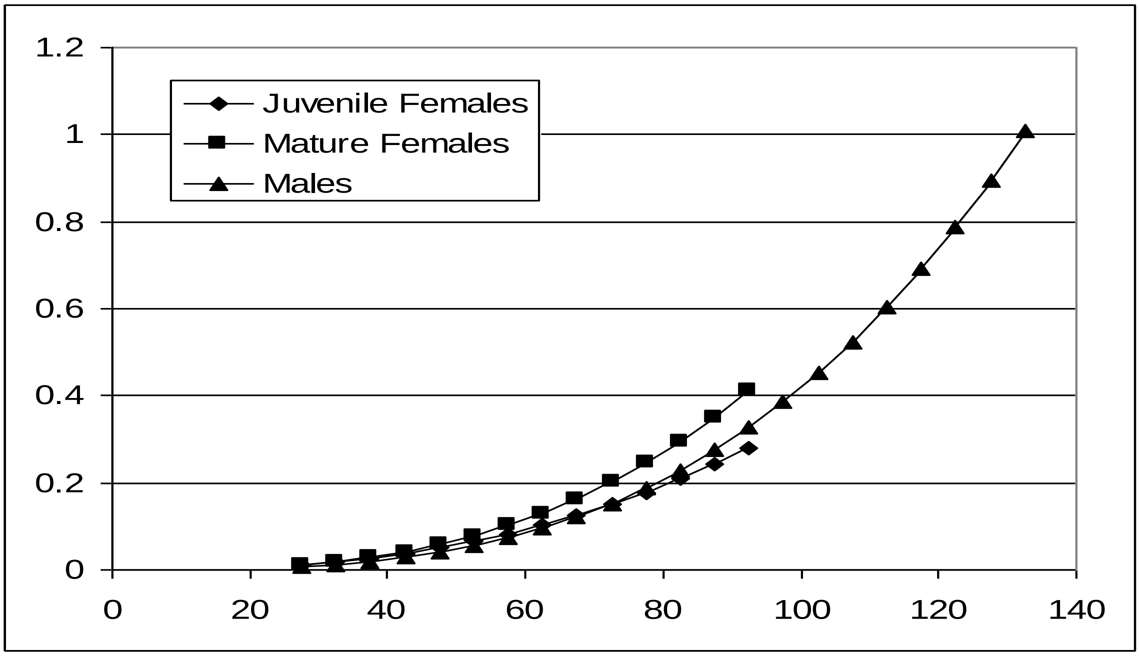


Figure 47. Weight (kg) – size (mm) relationship for male, juvenile female and mature female snow crab.

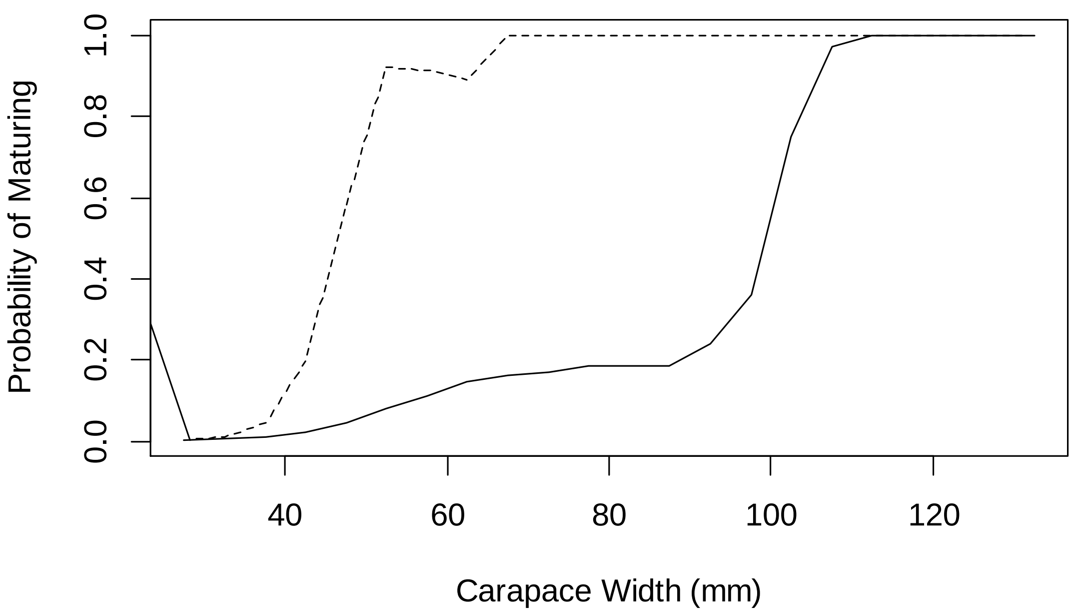


Figure 48. Probability of maturing by size estimated in the model for male(solid line) and female (dashed line) snow crab (not the average fraction mature.

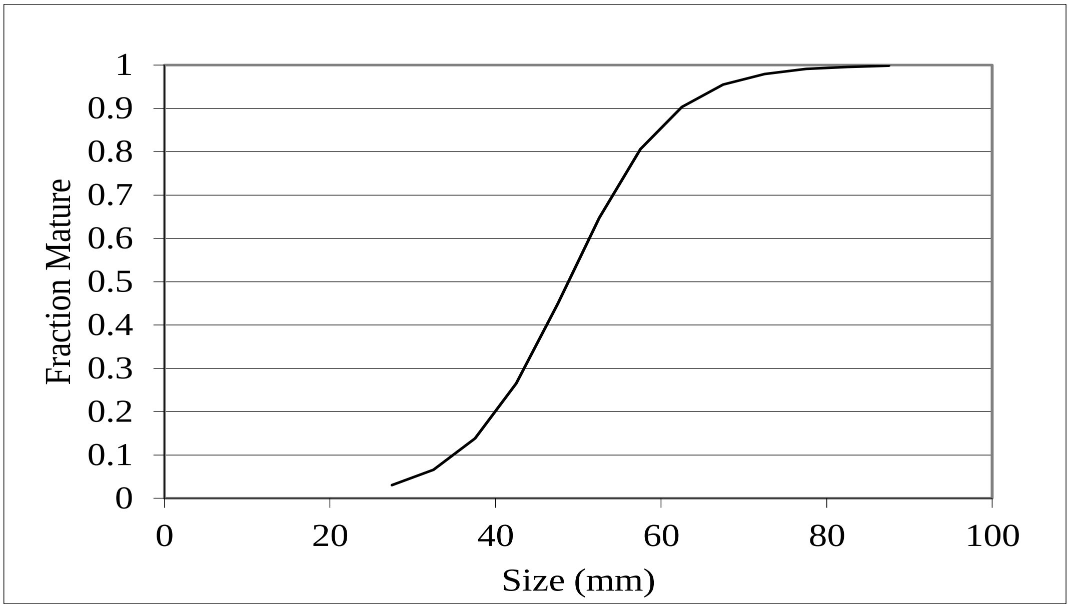


Figure 48b. Logistic fit to fraction mature for female snow crab (not used in model).

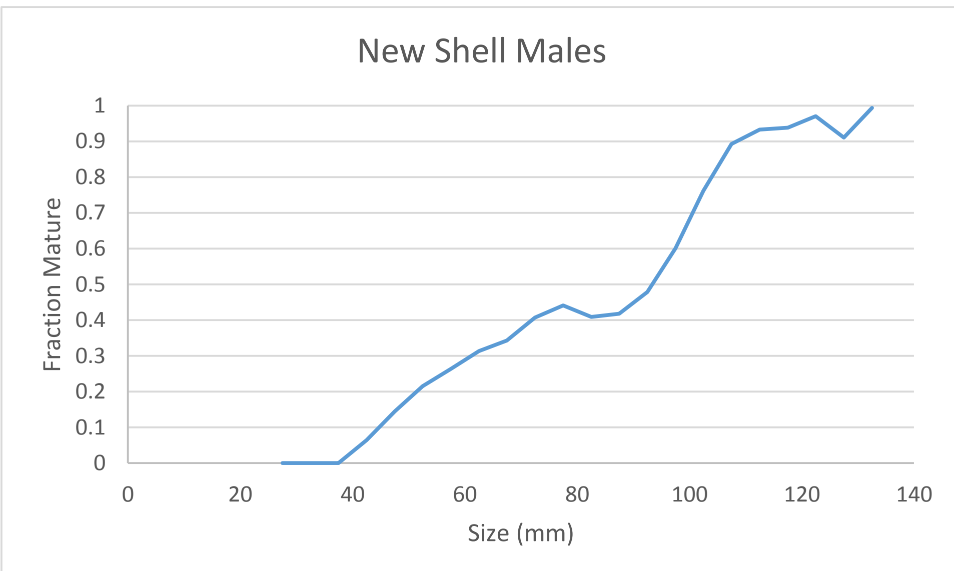


Figure 48c. Average fraction mature for new shell males from chela height data 1989-2007.

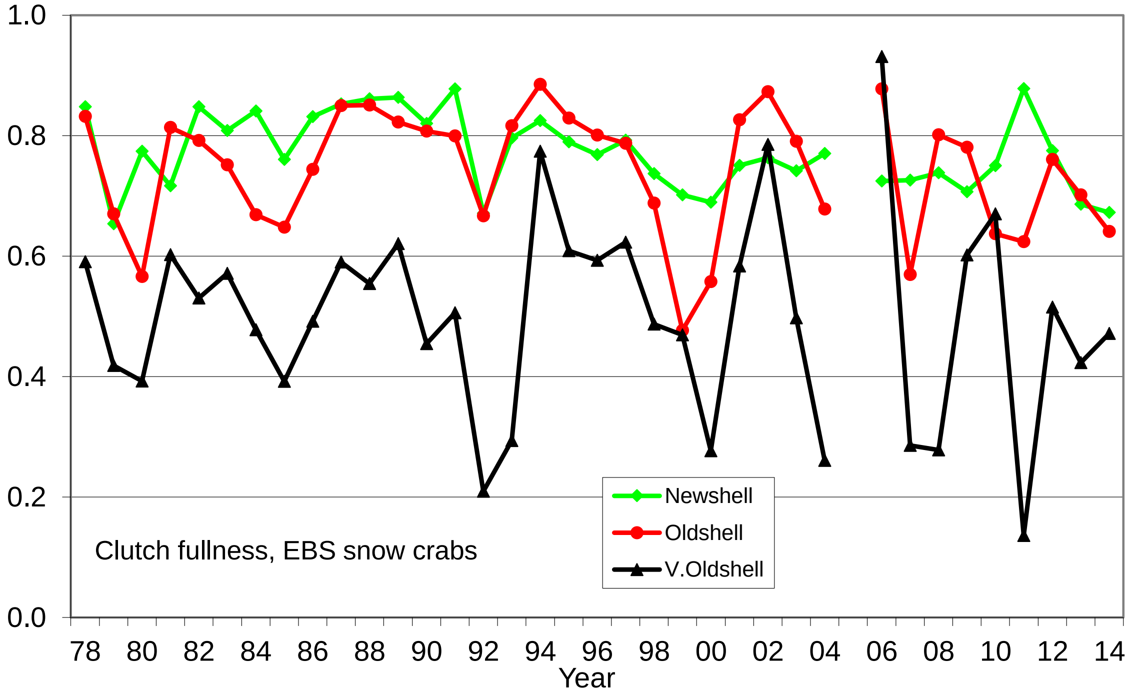


Figure 49. Clutch fullness for Bering Sea snow crab survey data by shell condition for 1978 to 2014.

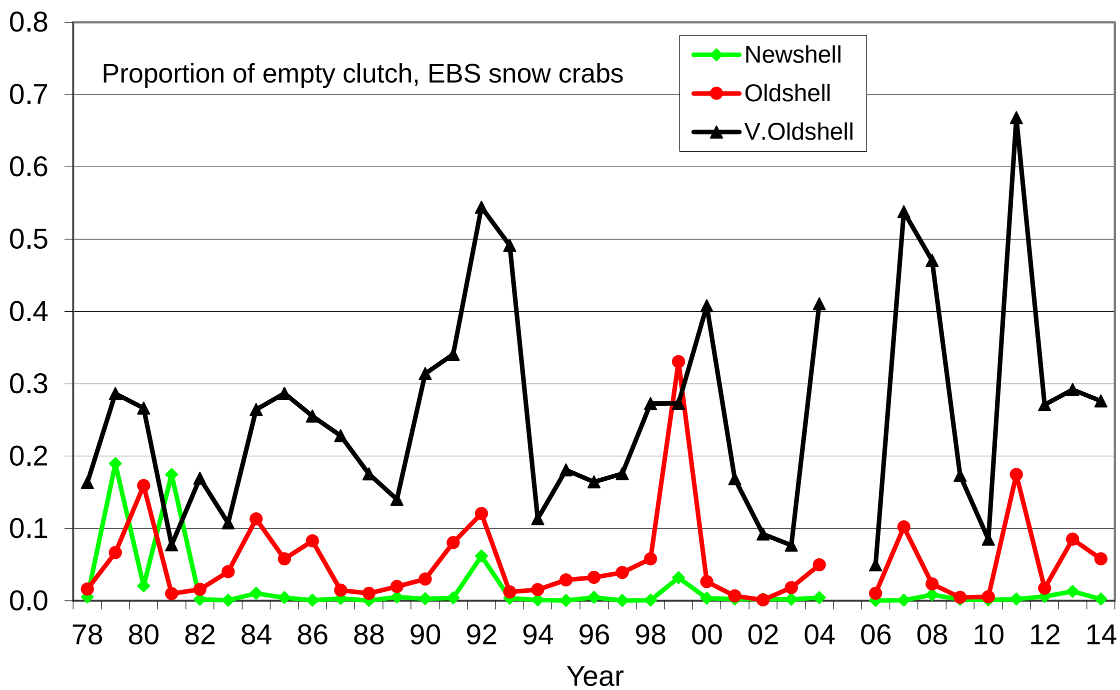


Figure 50. Proportion of barren females by shell condition from survey data 1978 to 2014.

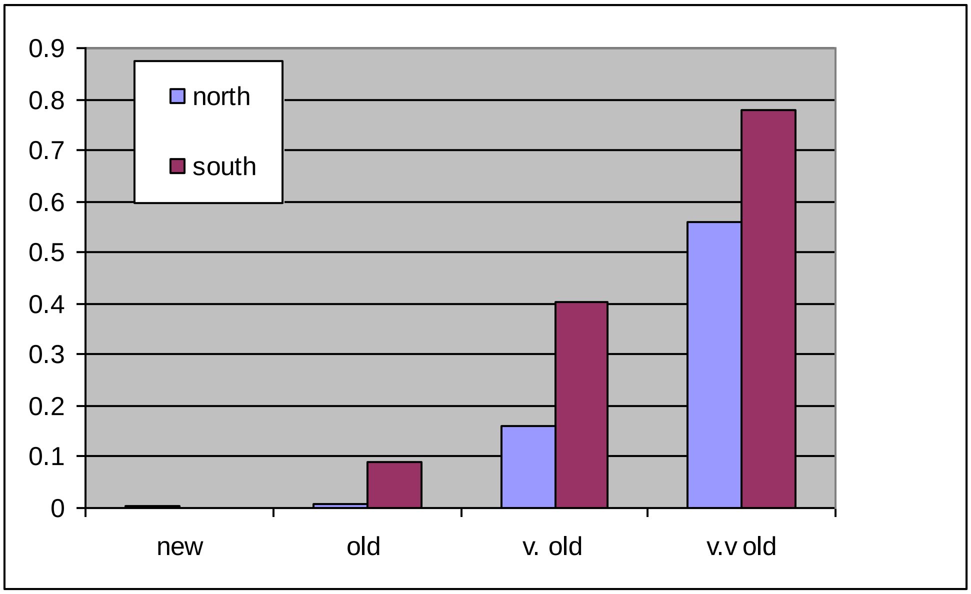


Figure 51. Fraction of barren females in the 2004 survey by shell condition and area north of 58.5 deg N and south of 58.5 deg N.

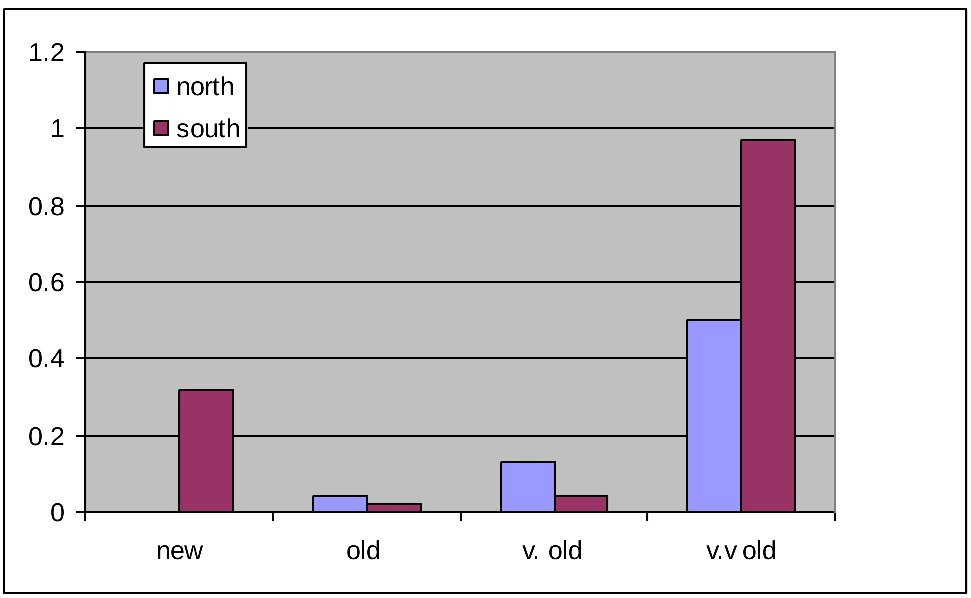


Figure 52. Fraction of barren females in the 2003 survey by shell condition and area north of 58.5 deg N and south of 58.5 deg N. The number of new shell mature females south of 58.5 deg N was very small in 2003.

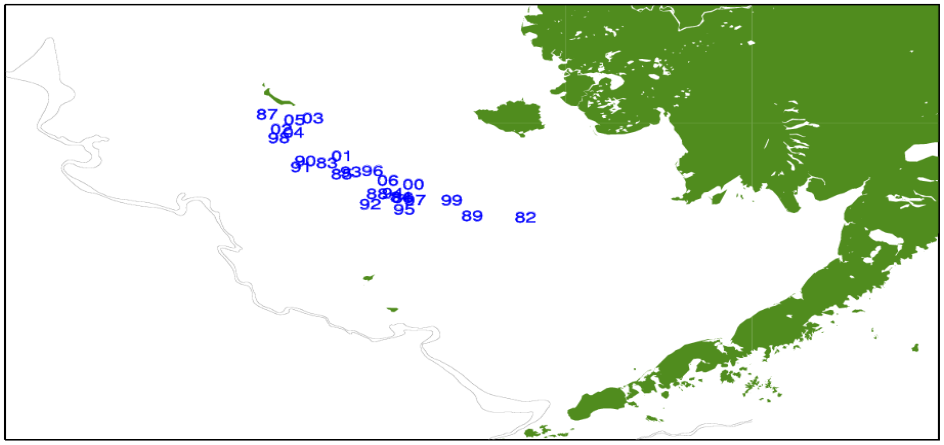


Figure 53. Centroids of cold pool (<2.0 deg C) from 1982 to 2006. Centroids are average latitude and longitude.

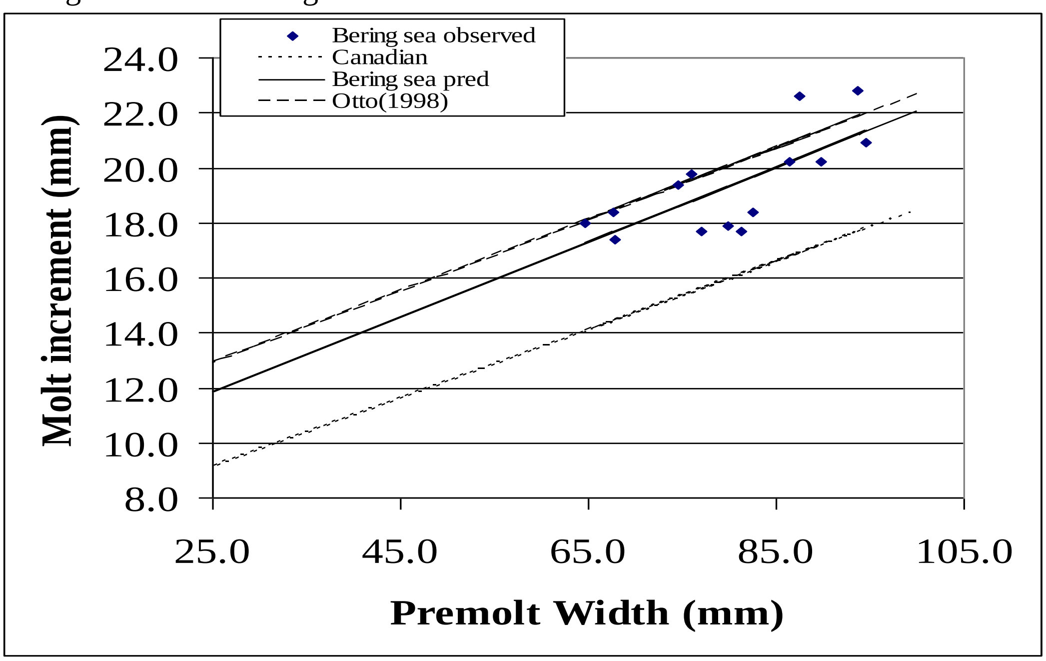
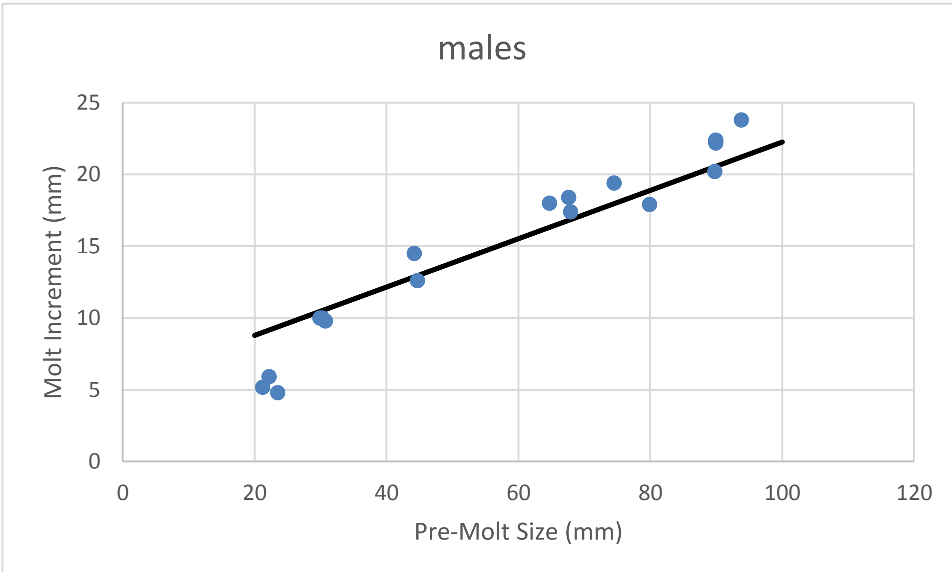


Figure 54. Growth increment as a function of premolt size for male snow crab. Points labeled Bering Sea observed are observed growth increments from Rugolo (unpub data). The line labeled Bering Sea pred is the predicted line from the Bering Sea observed growth, which was used as a prior for the growth parameters estimated in Scenarios 3 and 4. The line labeled Canadian is estimated from Atlantic snow crab (Sainte-Marie data). The line labeled Otto(1998) was estimated from tagging data from Atlantic snow crab less than 67 mm, from a different area from Sainte-Marie data.



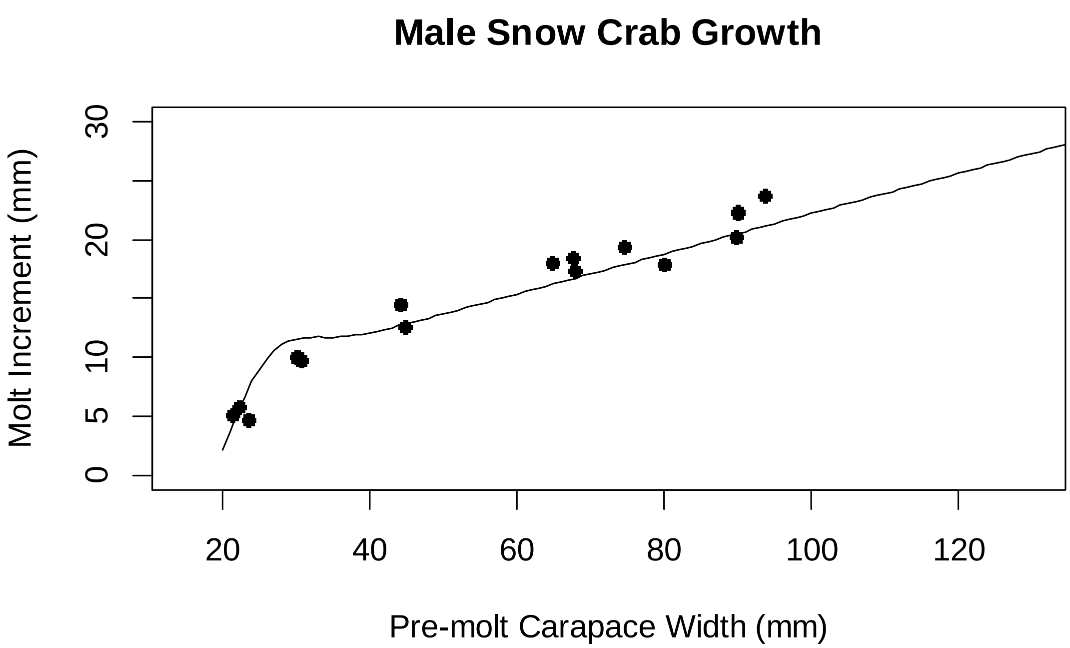
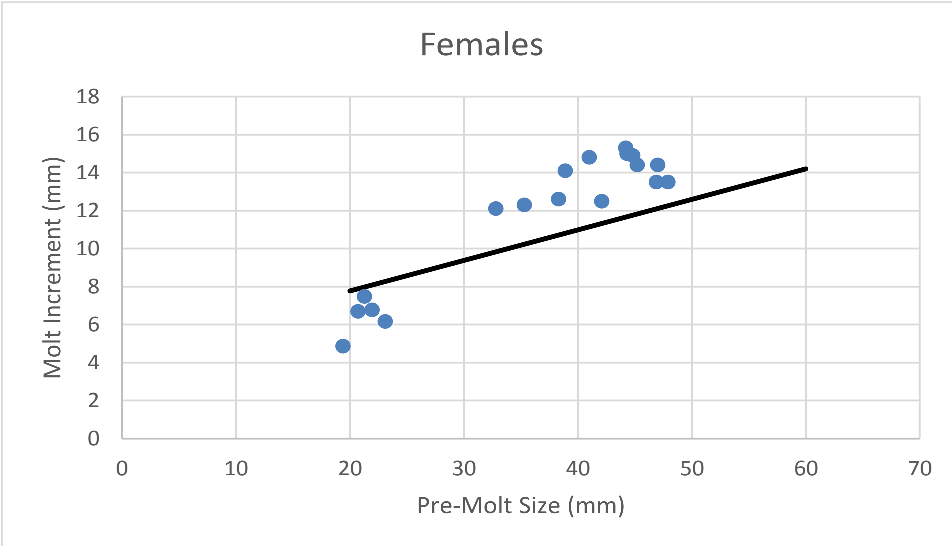


Figure 54b. Male growth data from 2011 growth study with estimated linear growth function (top panel last year's assessment - September 2013 assessment base model) and using the Cadigan method (Base model this assessment – Model 2b).



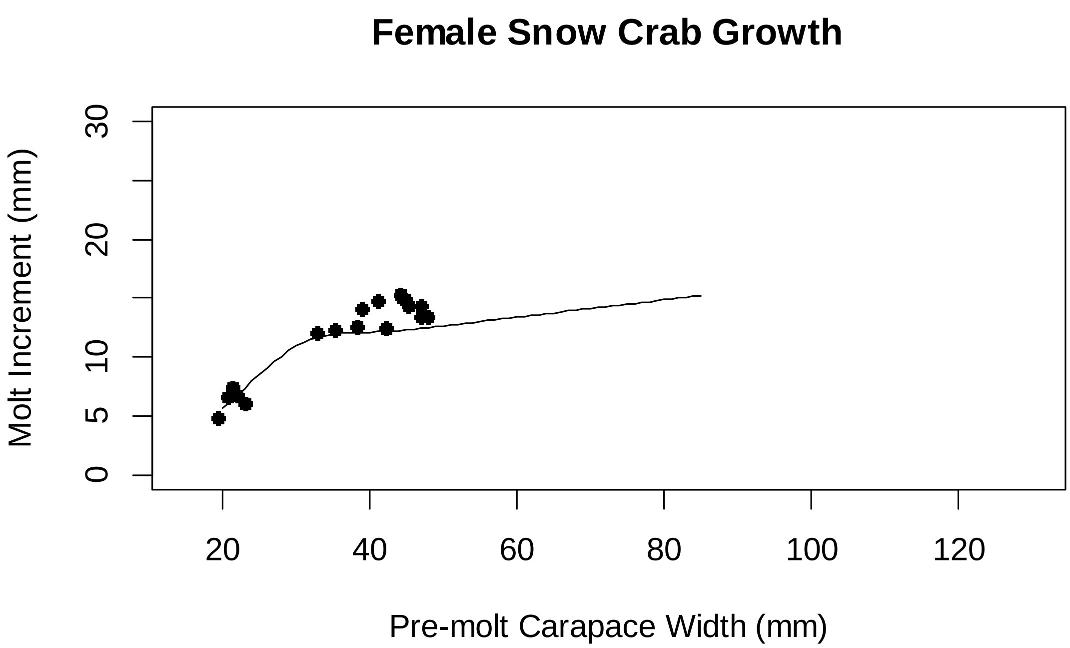


Figure 54c. Female growth data from 2011 growth study with estimated linear growth function (top panel last year's assessment - September 2013 assessment base model) and using the Cadigan method (Base model this assessment, model 2b).

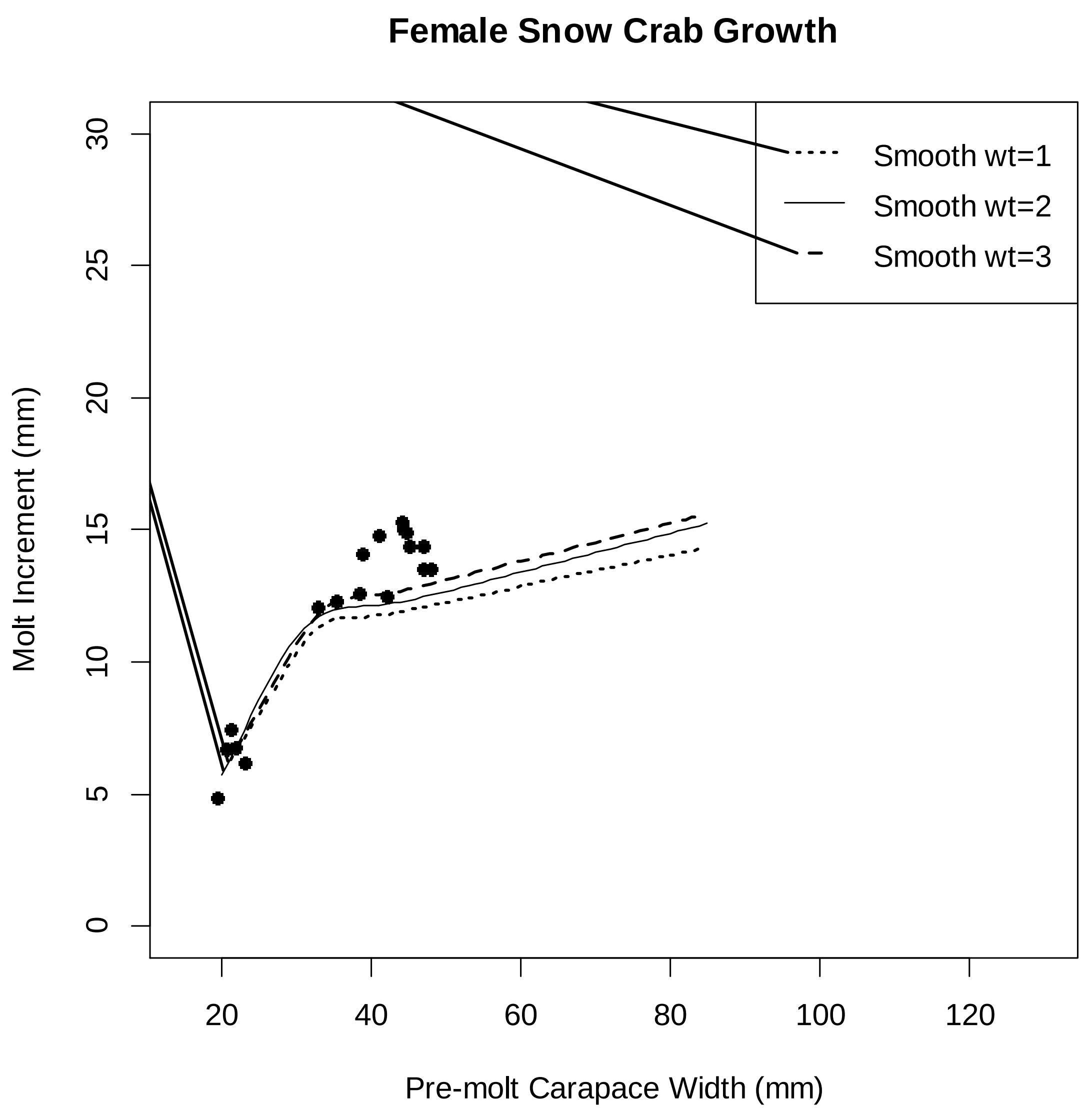


Figure 54d. Estimated female growth for cardigan smooth with weights 1, 2 and 3 on growth likelihood(2a, 2b and 2c model scenarios).

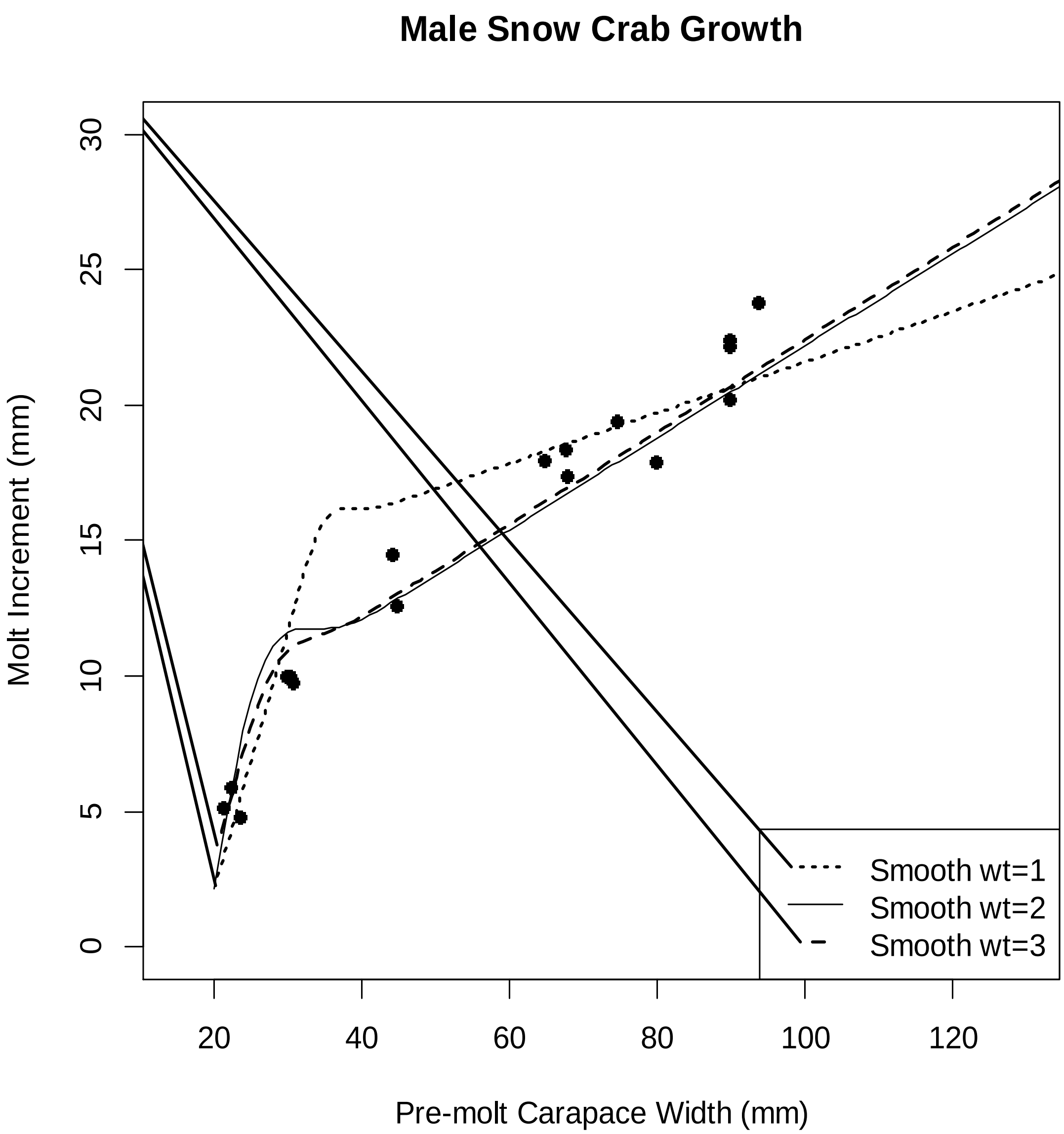


Figure 54e. Estimated male growth for cardigan smooth with weights 1, 2 and 3 on growth likelihood (2a, 2b and 2c model scenarios).

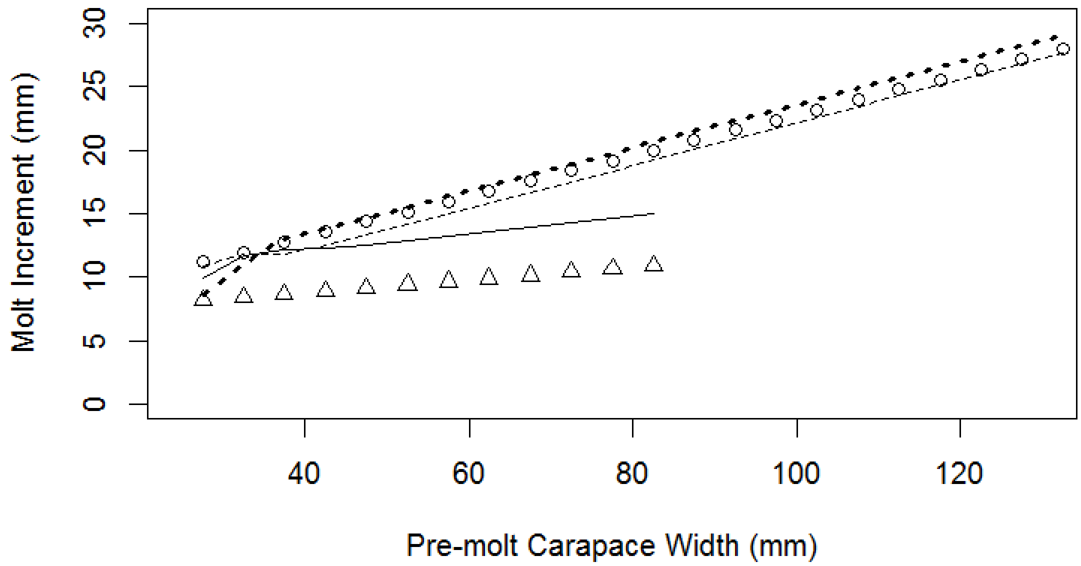


Figure 55. Growth(mm) for male(dotted line) and female snow crab (solid line) estimated from the base model. The priors for the growth curve used in models before September 2013 are circles (males) and triangle (females). Heavy dotted line is the growth curve estimated by Somerton for males and females from the 2011 growth study (Somerton 2012).

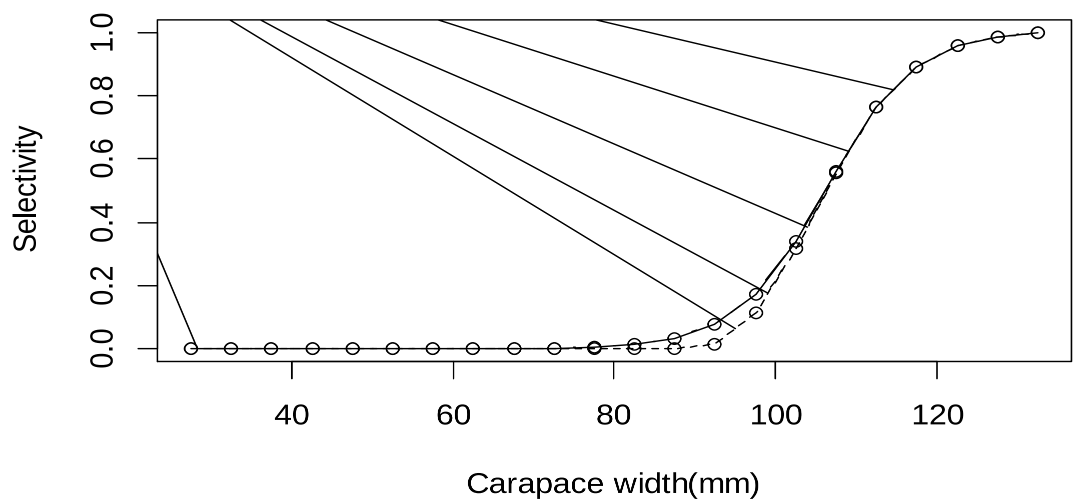


Figure 56. Base Model. Selectivity curve for total catch (discard plus retained, solid line) and retained catch (dotted line) for combined shell condition male snow crab.

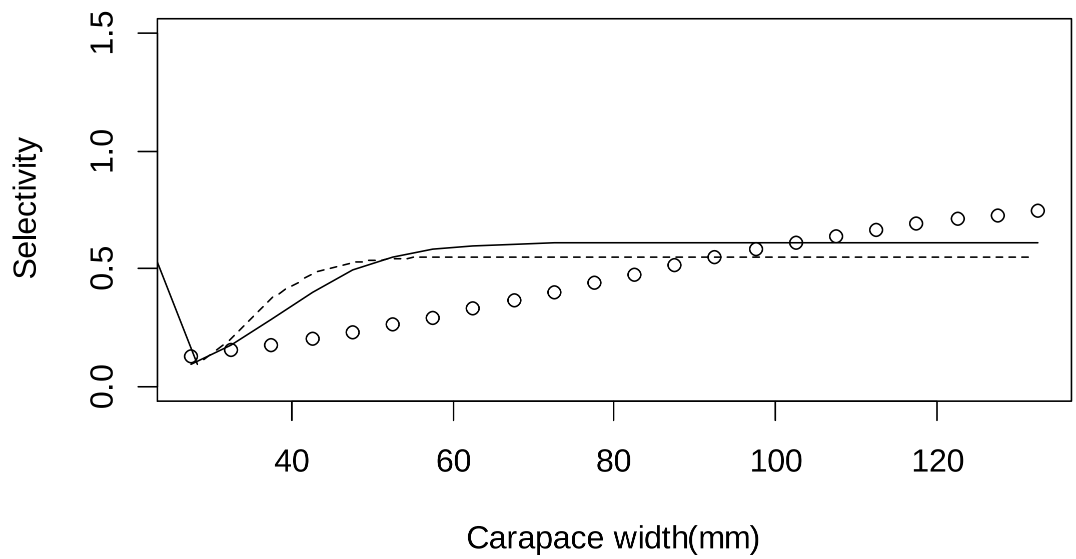


Figure 57. Base Model. Survey selectivity curves for female (dotted lines) and male snow crab (solid lines) estimated by the model for 1989 to present. Survey selectivities estimated by Somerton from 2009 study area data (2010) are the circles.

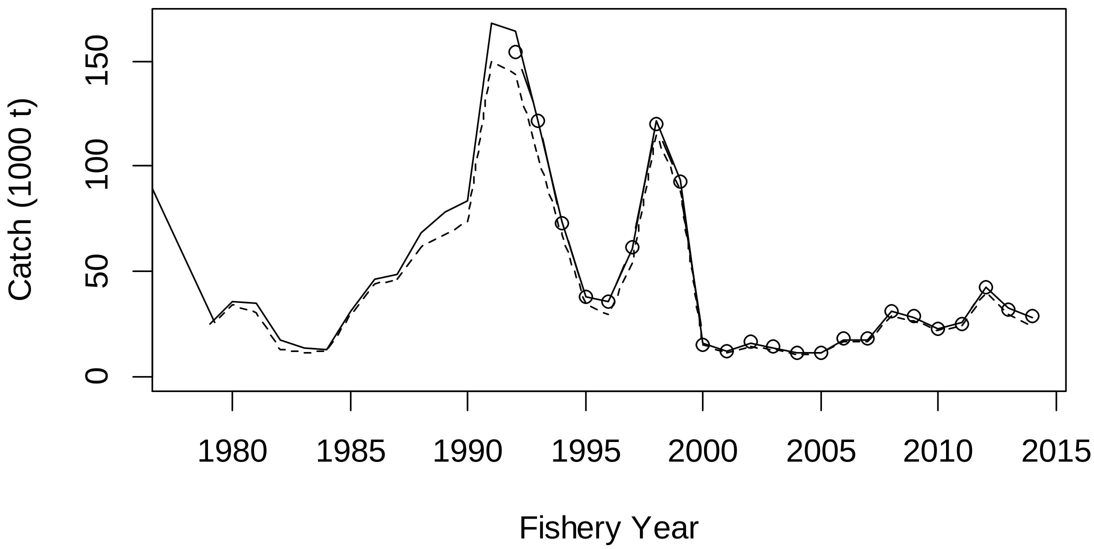


Figure 58. Base Model. Estimated total catch(discard + retained) (solid line), observed total catch (solid line with circles) (assuming 30% mortality of discarded crab) and observed retained catch (dotted line).

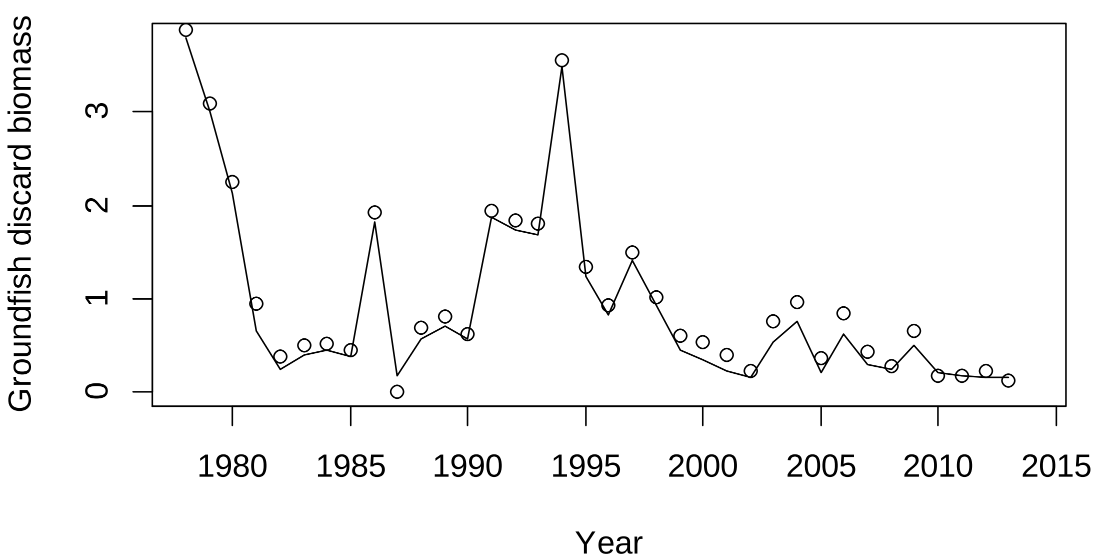


Figure 59. Base Model. Model fit to groundfish bycatch. Circles are observed catch, line is model estimate.

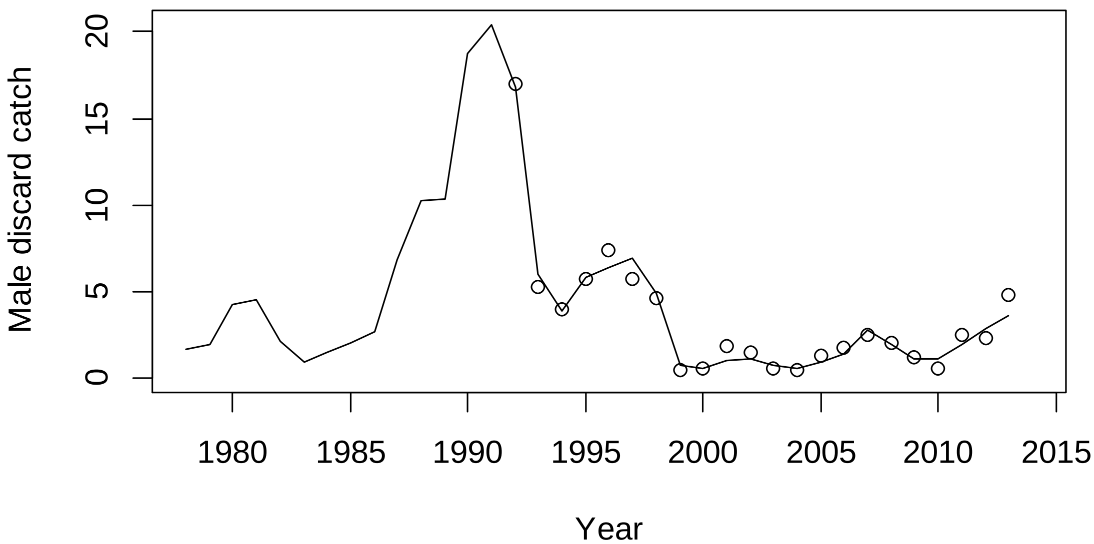


Figure 60. Base Model. Model fit to male directed discard catch for 1992/93 to present and model estimated male discard catch from 1978 to 1991.

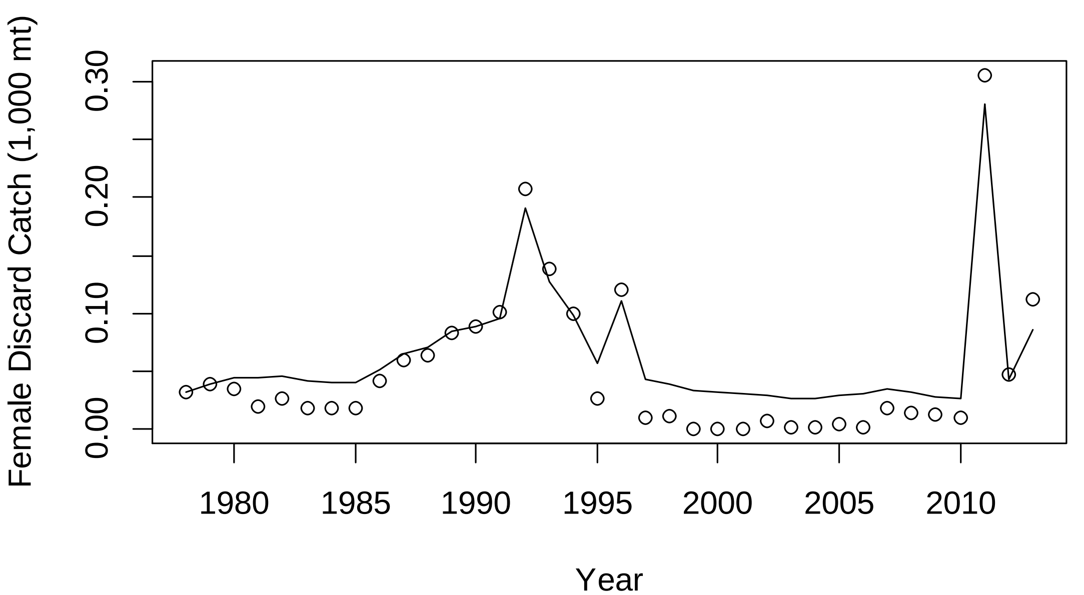


Figure 61. Base Model. Model fit to female discard bycatch in the directed fishery from 1992/93 to present and model estimates of discard from 1978 to 1991.

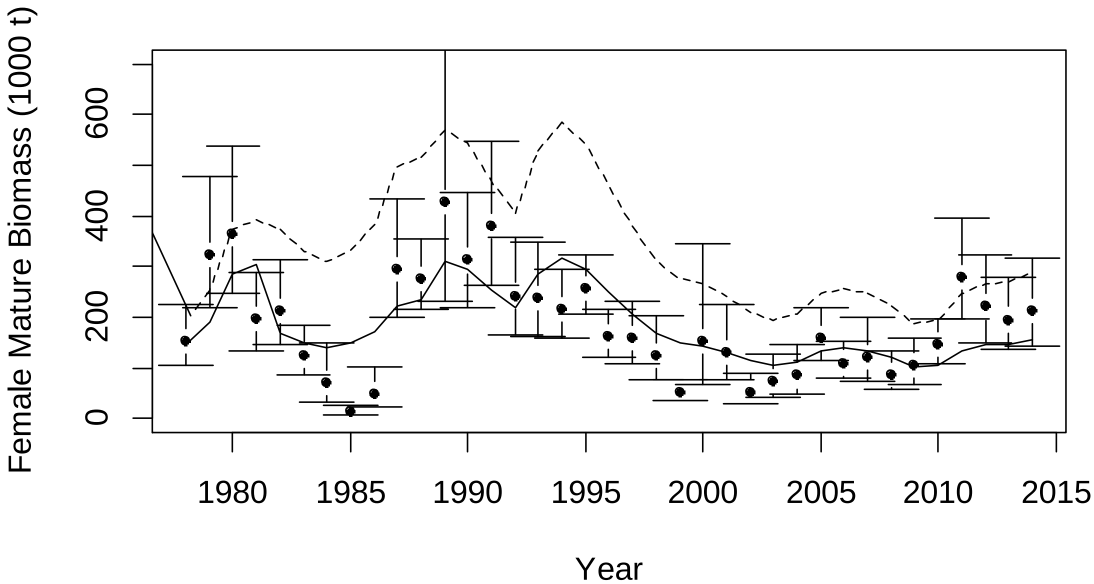


Figure 62. Base Model. Population female mature biomass (1000 t, dotted line), model estimate of survey female mature biomass (solid line) and observed survey female mature biomass with approximate lognormal 95% confidence intervals.

Figure 63. Population female mature biomass for the Base model and scenarios 2, 3 and 4.

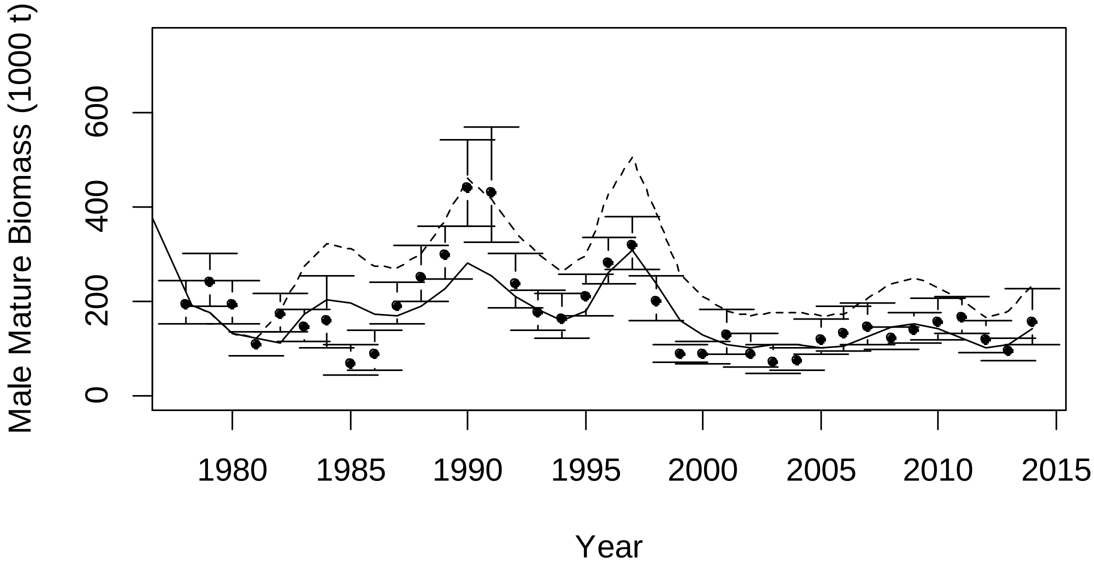


Figure 64. Base Model. Population male mature biomass (1000 t, dotted line), model estimate of survey male mature biomass (solid line) and observed survey male mature biomass with approximate lognormal 95% confidence intervals.

Figure 65. Population male mature for the Base model and scenarios 2, 3 and 4.

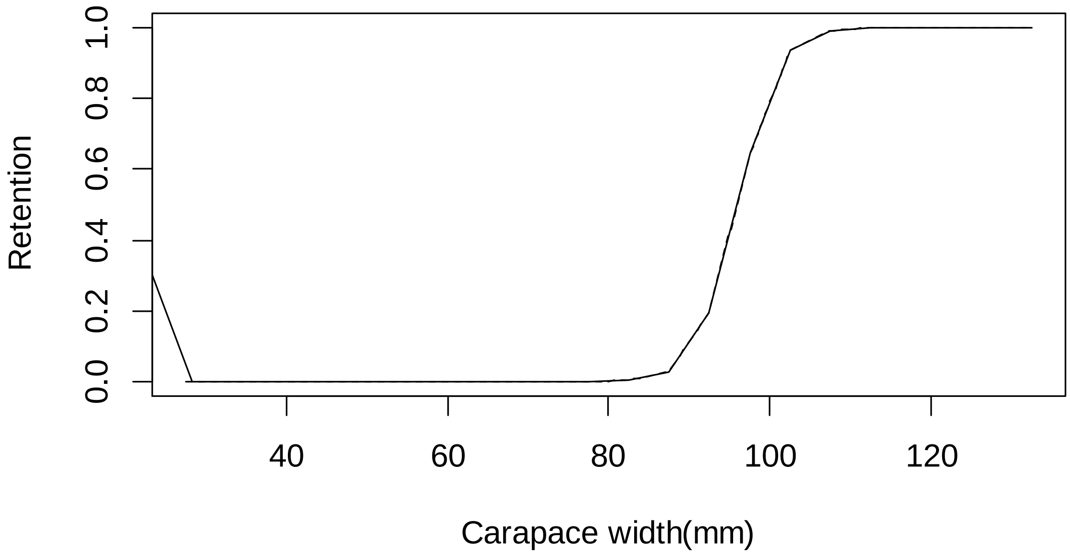


Figure 66. Base Model. Model estimated fraction of the total catch that is retained by size for male snow crab combined shell condition.

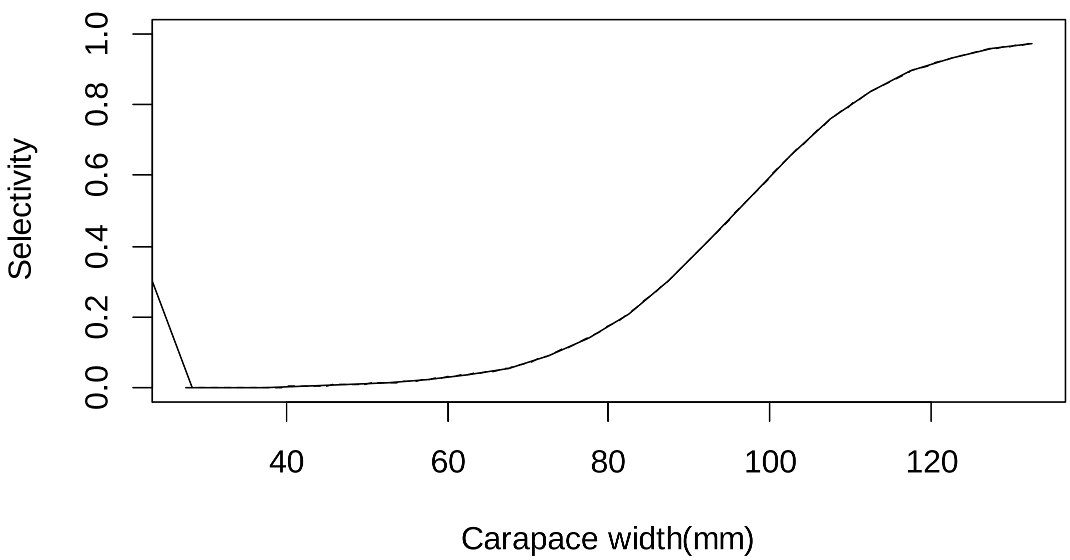


Figure 67. Base Model. Selectivity curve estimated by the model for bycatch in the groundfish trawl fishery for females and males.

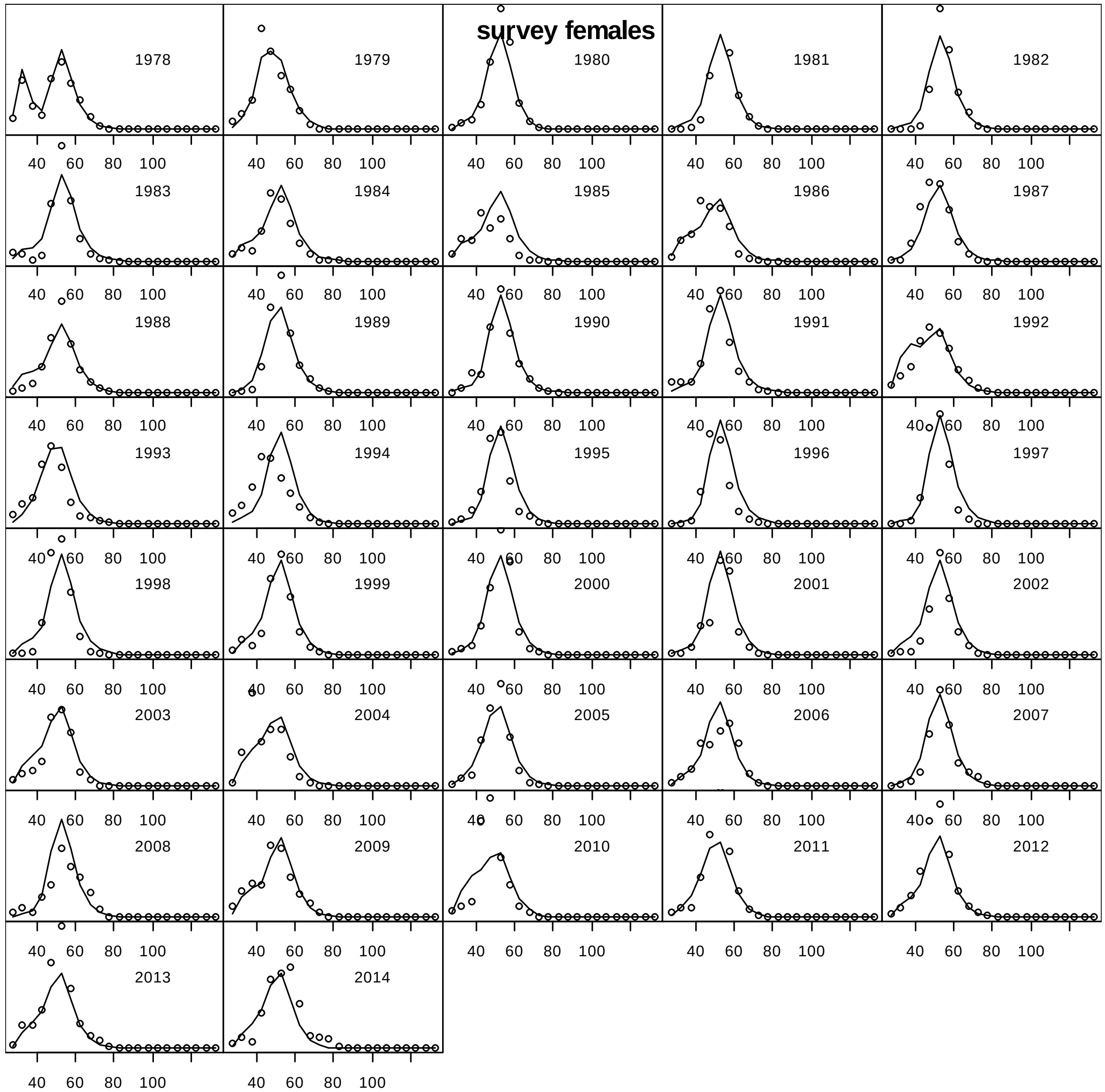


Figure 68. Base Model. Model fit to the survey female size frequency data. Circles are observed survey data. Solid line is the model fit.

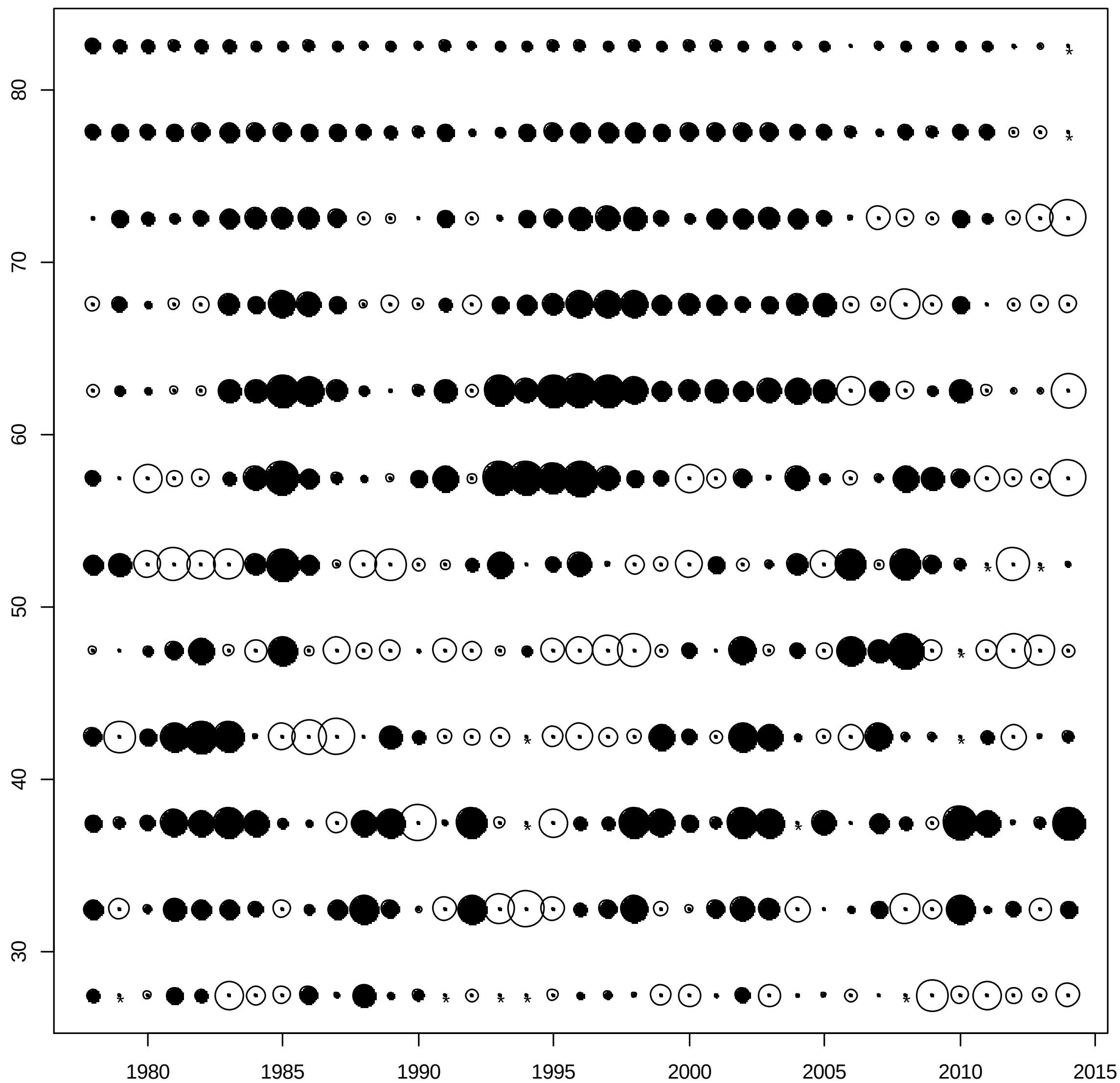


Figure 69. Base Model. Residuals of fit to survey female size frequency. Filled circles are negative residuals.

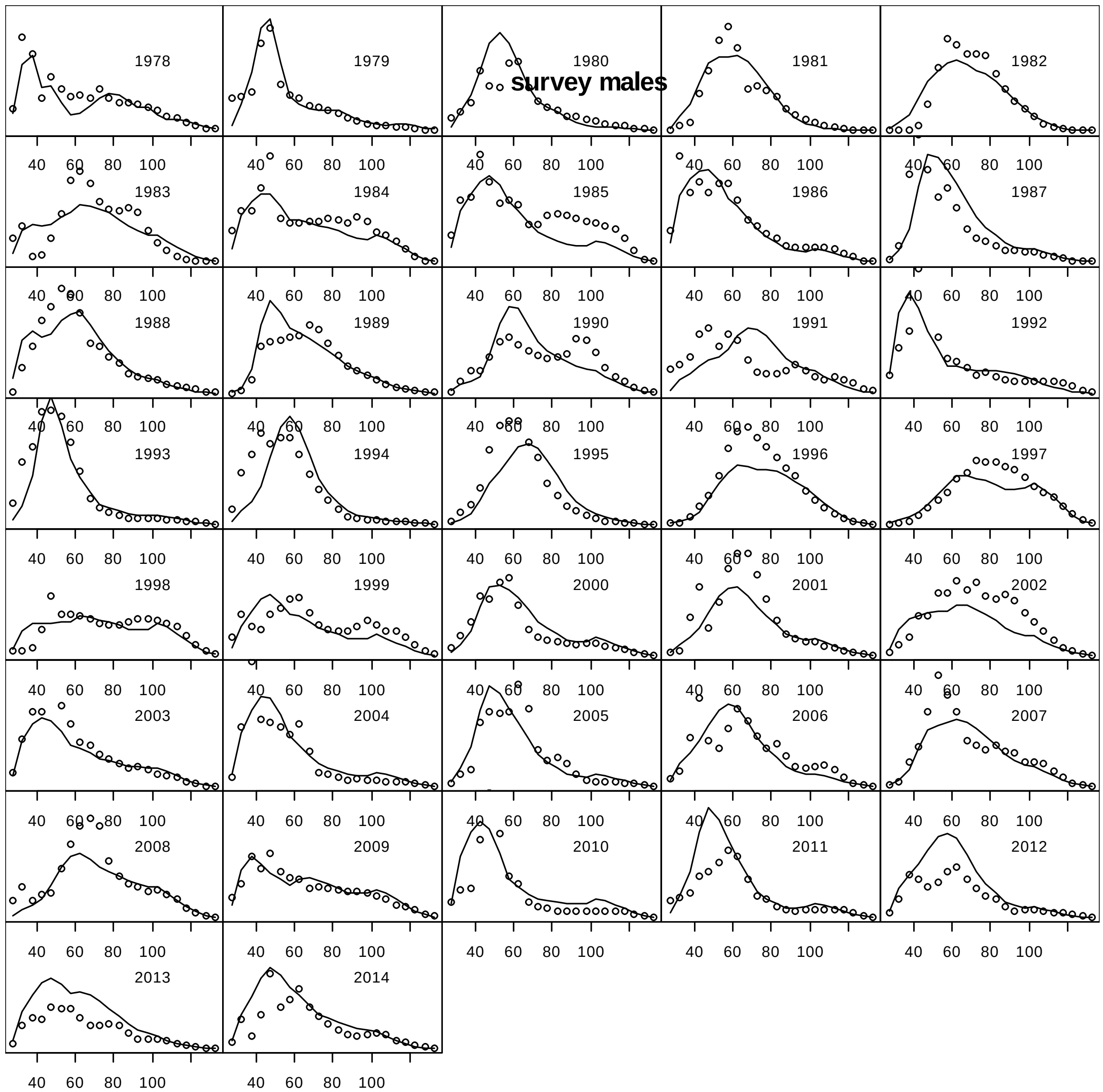


Figure 70. Base Model. Model fit to the survey male size frequency data. Circles are observed survey data. Solid line is the model fit.

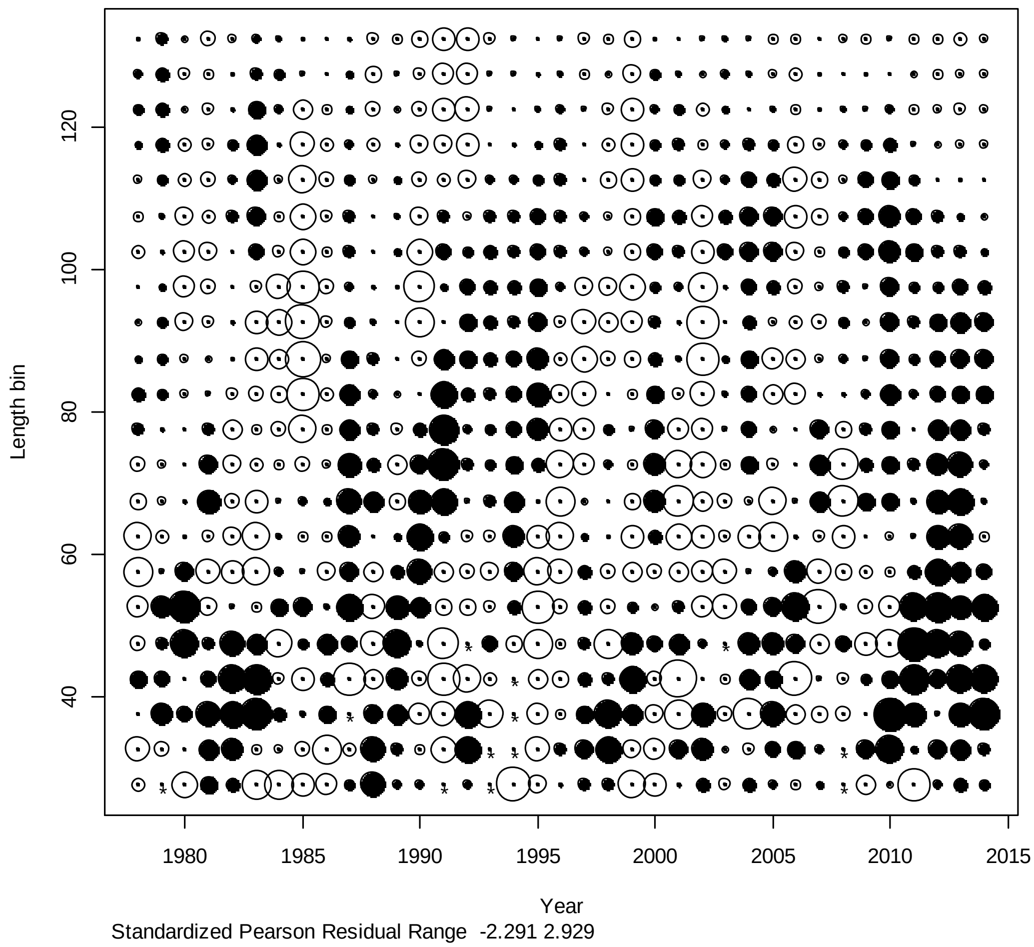


Figure 71. Base Model. Residuals for fit to survey male size frequency. Filled circles are negative residuals (predicted higher than observed).

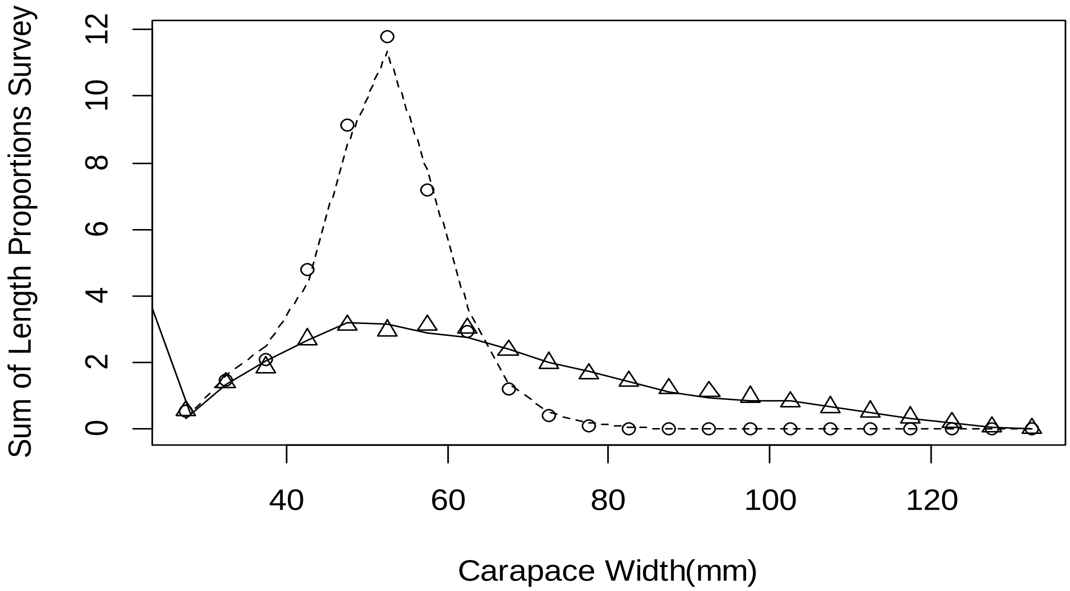


Figure 72. Base Model. Summary over years of fit to survey length frequency data by sex. Dotted line is fit for females, circles are observed. Solid line is fit for males, triangles are observed.

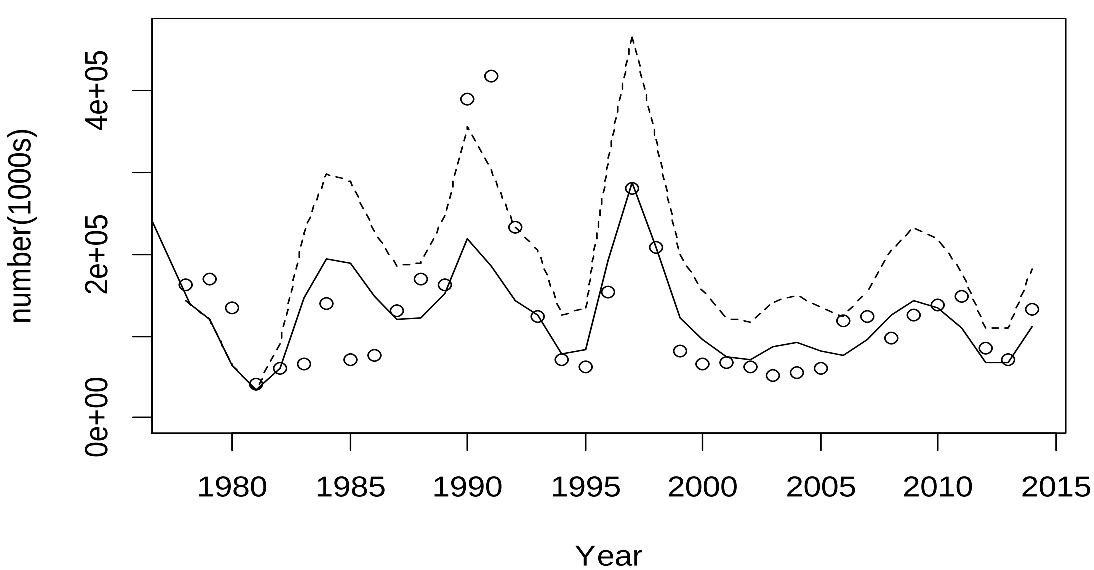


Figure 73. Base Model. Observed survey numbers of males >101mm (circles), model estimates of the population number of males >101mm(solid line) and model estimates of survey numbers of males >101 mm (dotted line).

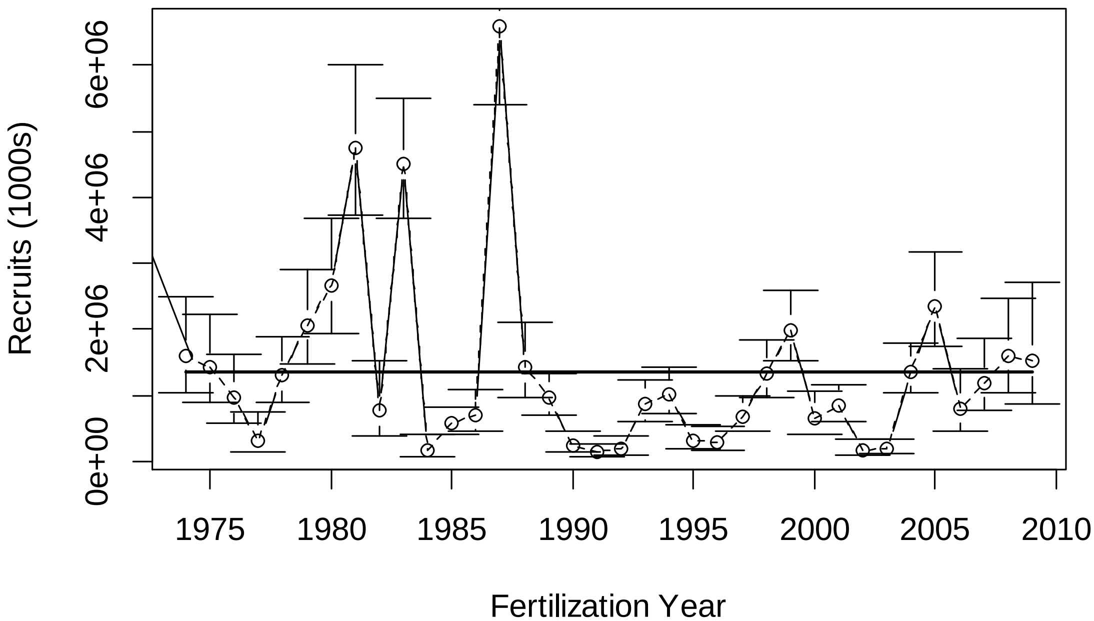


Figure 74. Base Model. Recruitment to the model for crab 25 mm to 50 mm. Total recruitment is 2 times recruitment in the plot. Male and female recruitment fixed to be equal. Solid horizontal line is average recruitment. Error bars are 95% C.I.

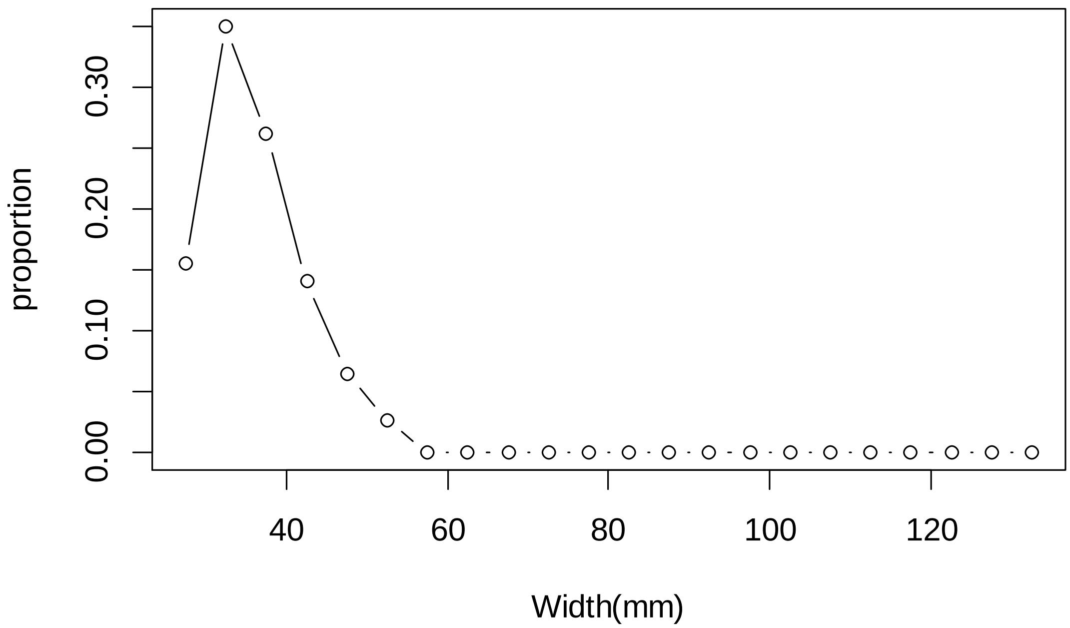


Figure 75. Base Model. Distribution of recruits to length bins estimated by the model.

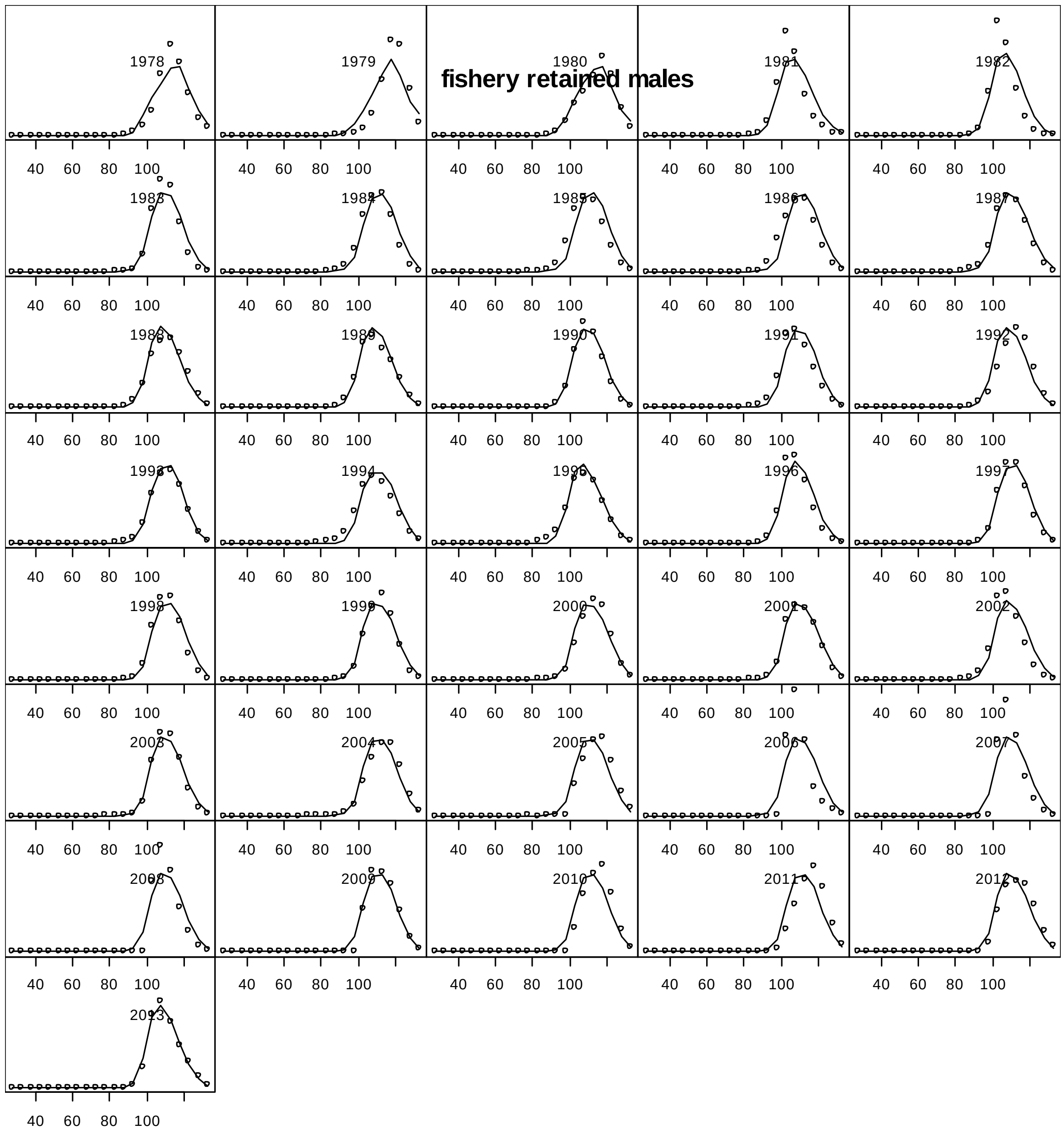


Figure 76. Base Model. Model fit to the retained male size frequency data, shell condition combined. Solid line is the model fit. Circles are observed data. Year is the survey year.

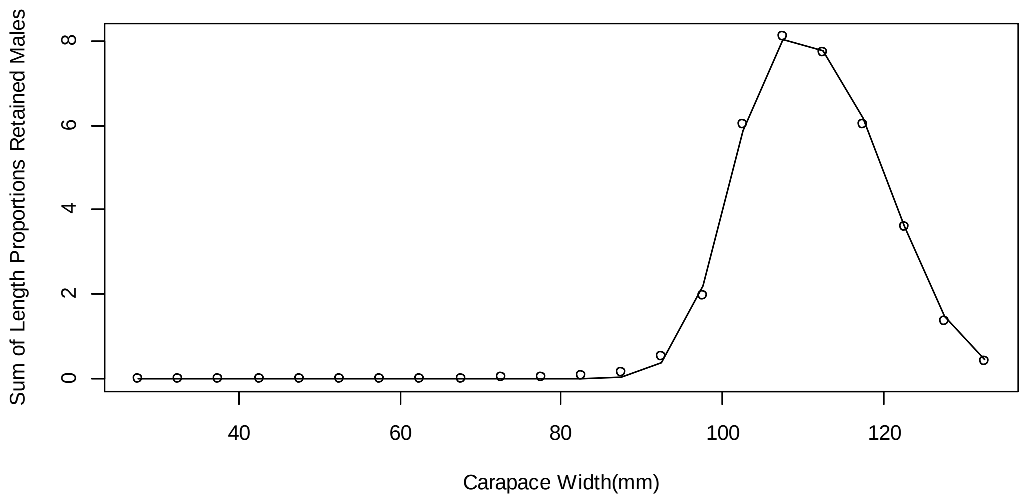


Figure 77. Base Model. Summary fit to retained male length.

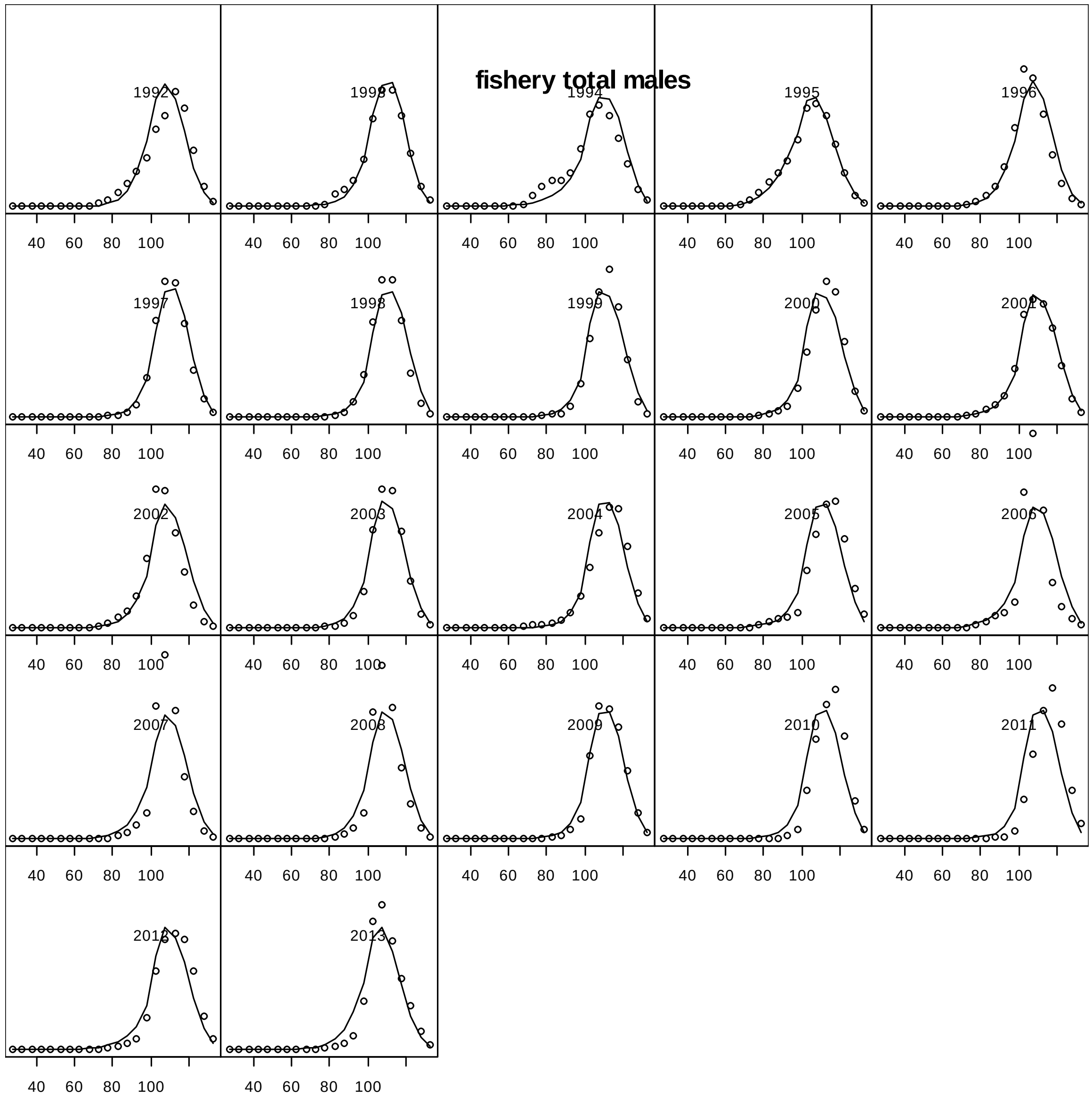


Figure 78. Base Model. Model fit to the total (discard plus retained) male size frequency data, shell condition combined. Solid line is the model fit. Circles are observed data. Year is the survey year.

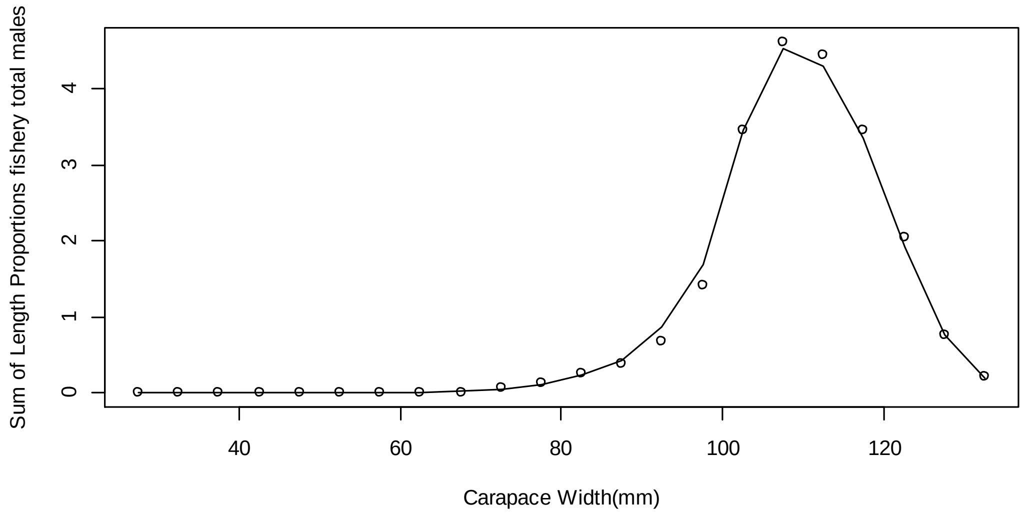


Figure 79. Base Model. Summary fit to total length frequency male catch.

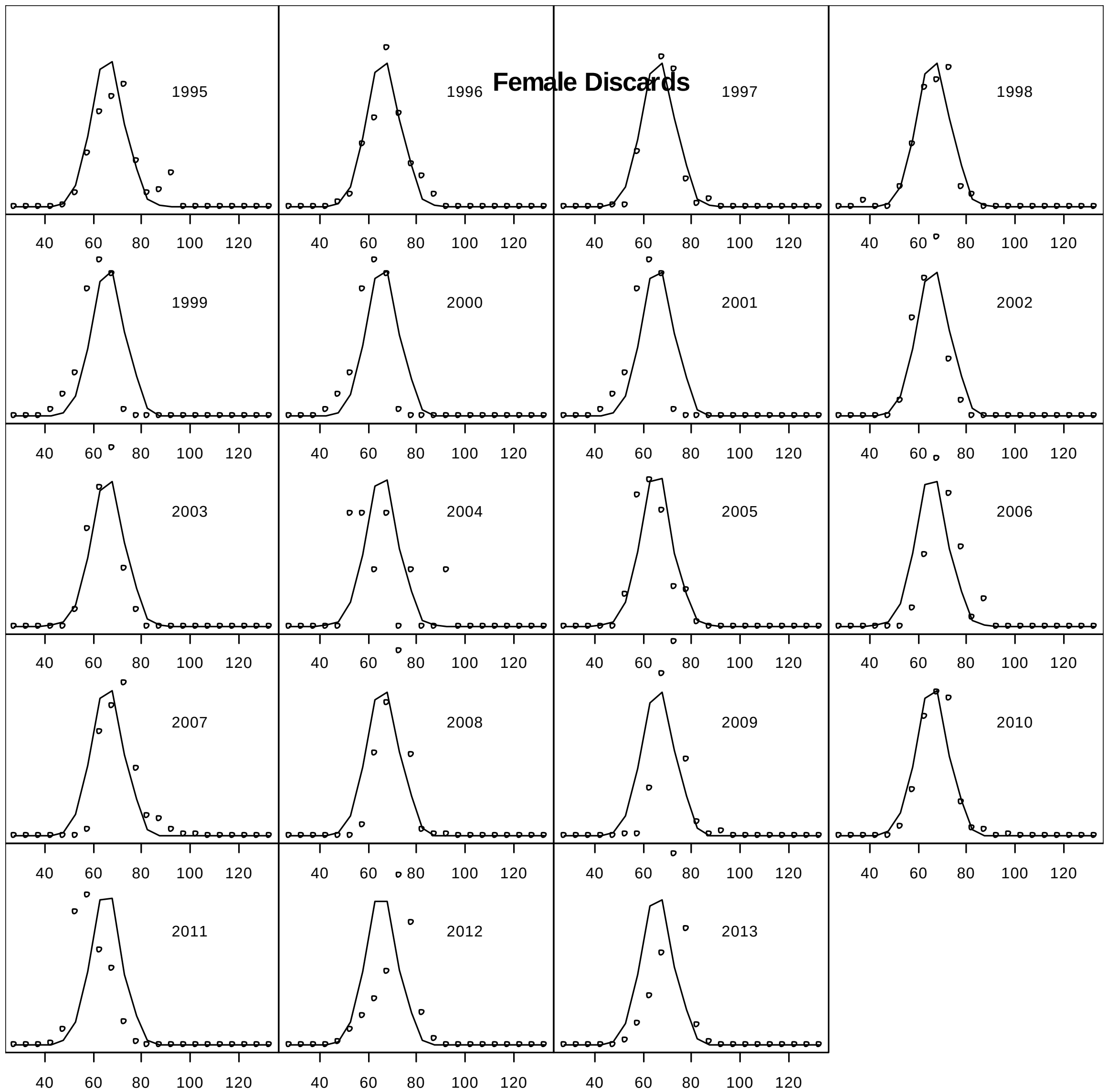


Figure 80. Base Model. Model fit to the discard female size frequency data. Solid line is the model fit. Circles are observed data. Year is the survey year.

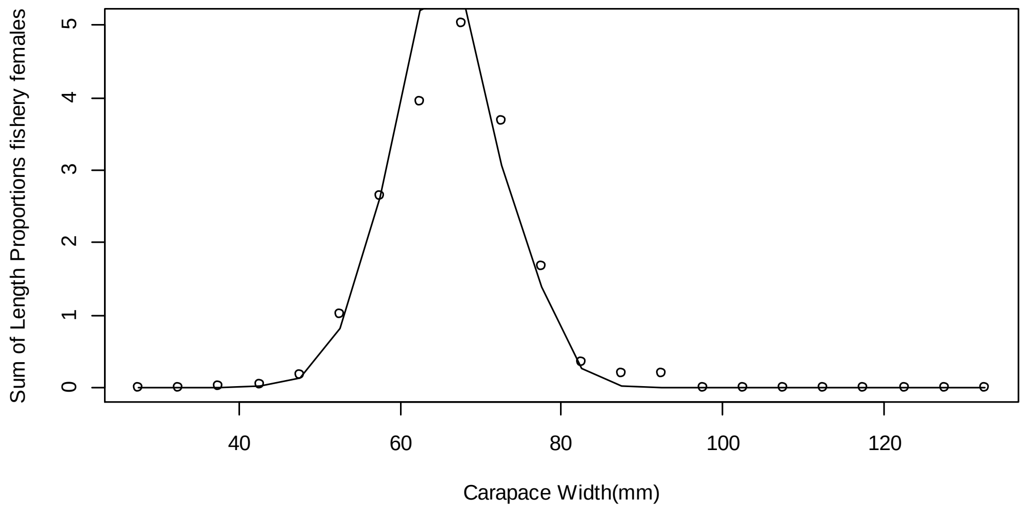


Figure 81. Base Model. Summary fit to directed fishery female discards.

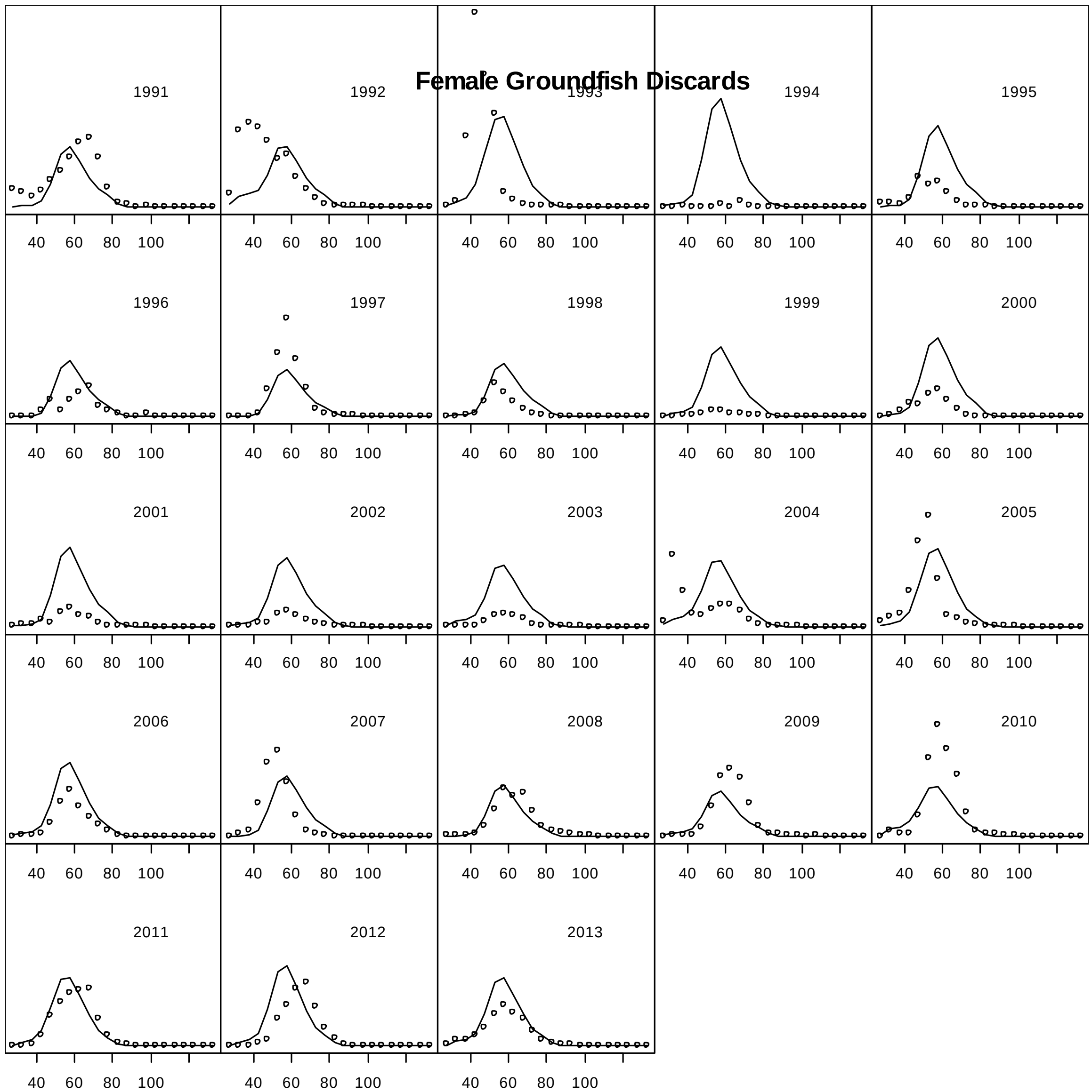


Figure 82. Base Model. Model fit to the groundfish trawl discard female size frequency data. Solid line is the model fit. Circles are observed data. Year is the survey year.

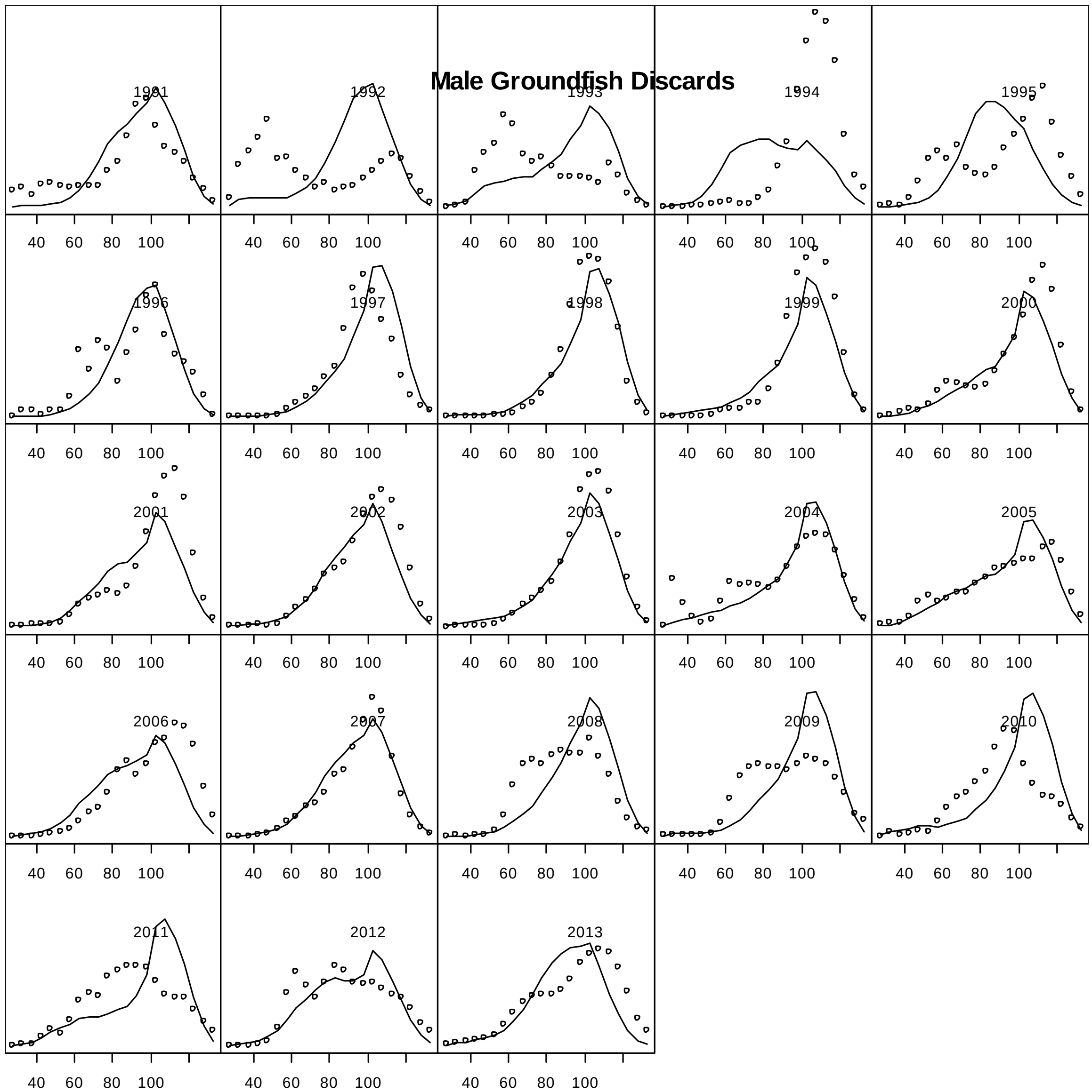


Figure 83. Base Model. Model fit to the groundfish trawl discard male size frequency data. Solid line is the model fit. Circles are observed data.

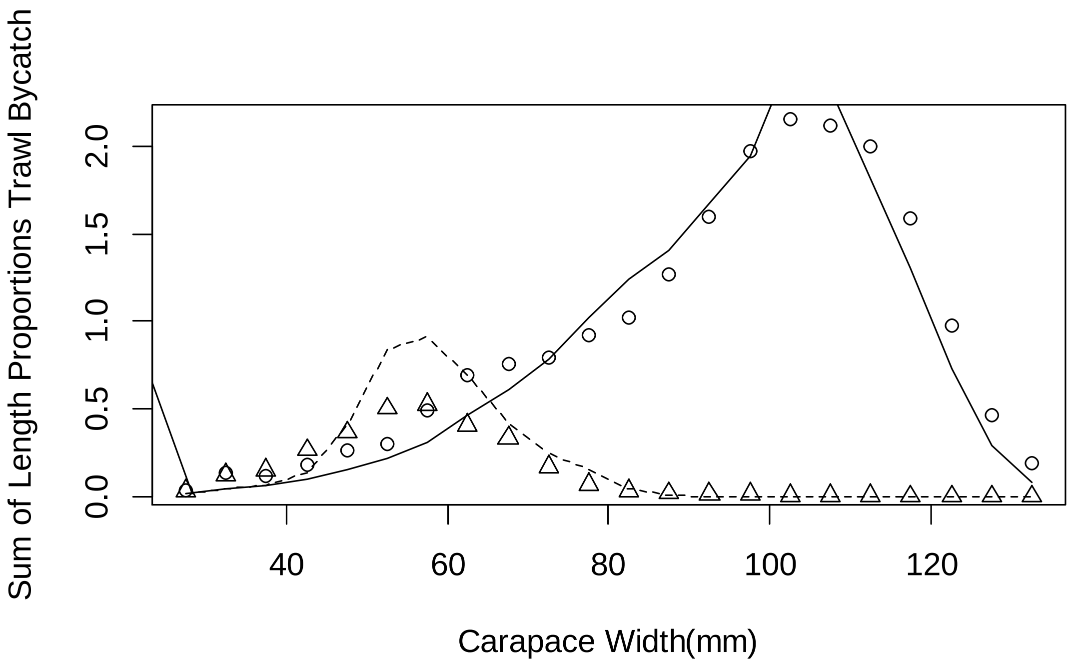


Figure 84. Base Model. Summary fit to groundfish length frequency.

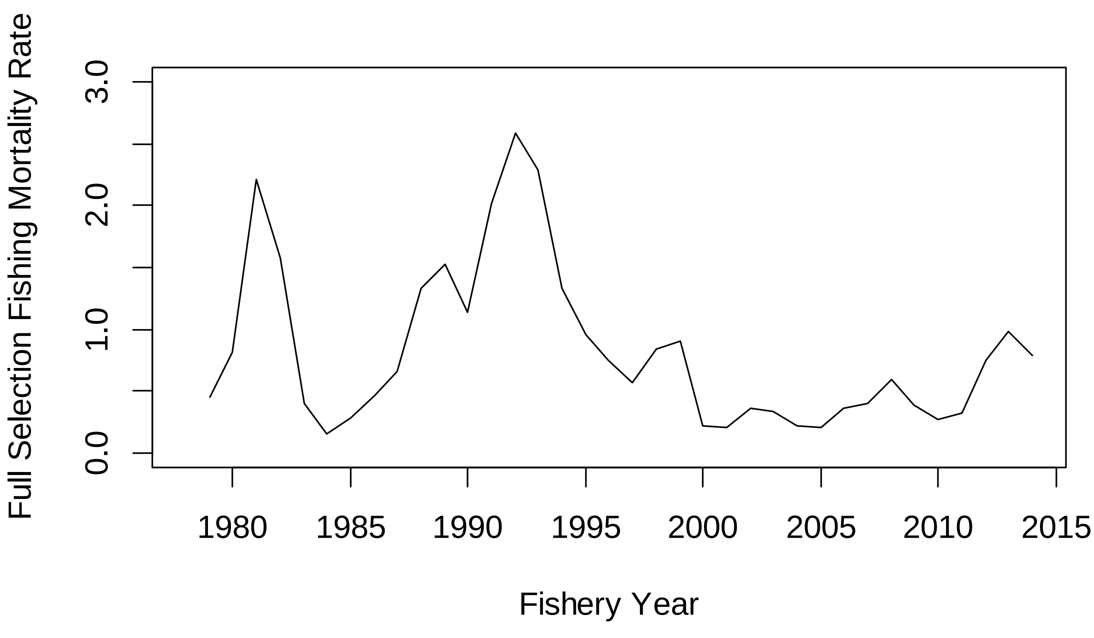


Figure 85. Base Model. Full selection fishing mortality estimated in the model from 1978/79 to present.

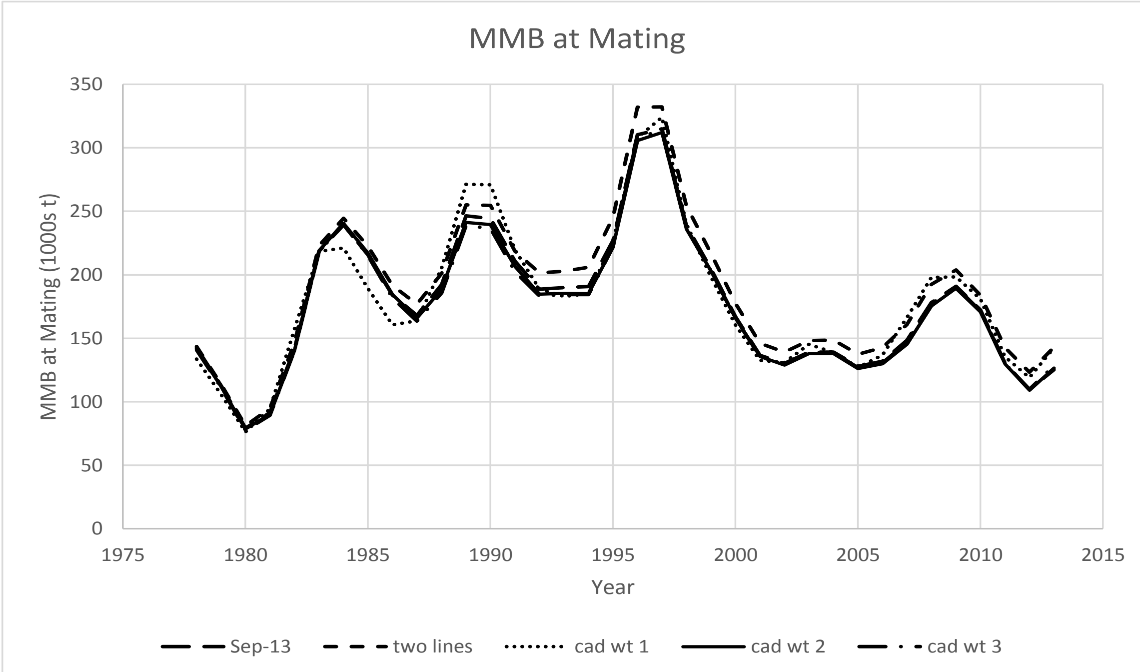


Figure 86. Mature male biomass at mating for the Base model (2b) and scenarios 0, 1, 2a and 2c.

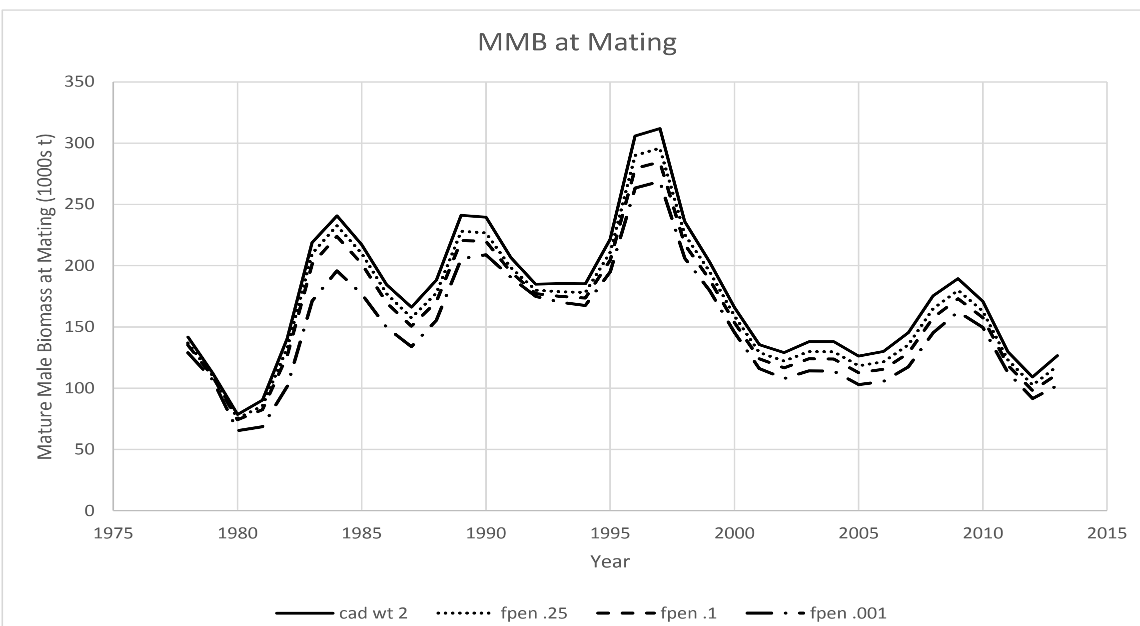


Figure 87. Mature male biomass at mating for the Base model (2b) and scenarios 2e, 2f and 2g.

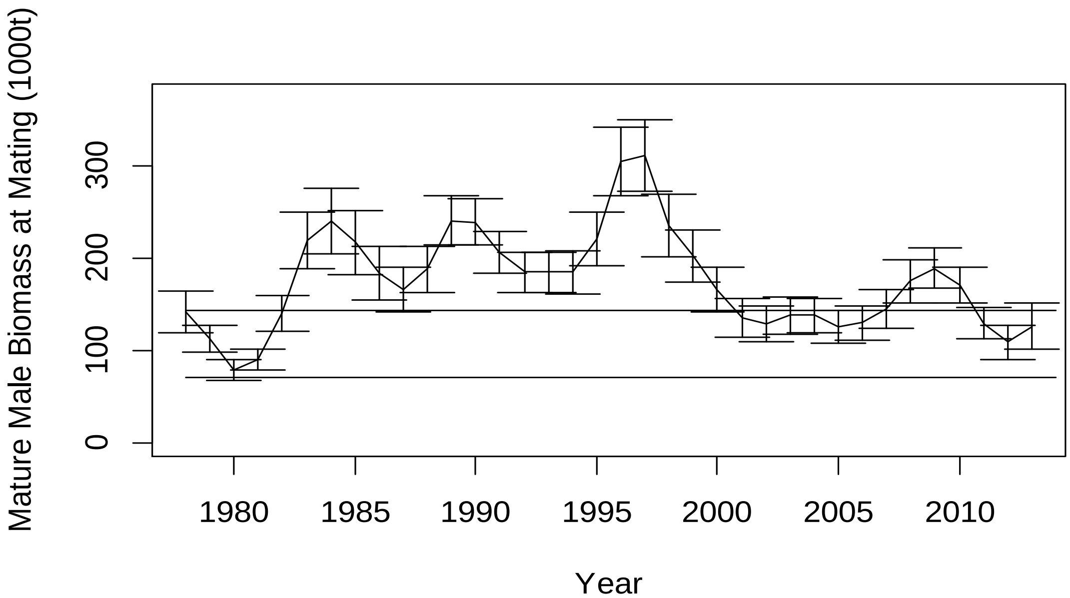


Figure 88. Base Model. Mature Male Biomass at mating with 95% confidence intervals. Top horizontal line is B35%, lower line is ½ B35%.

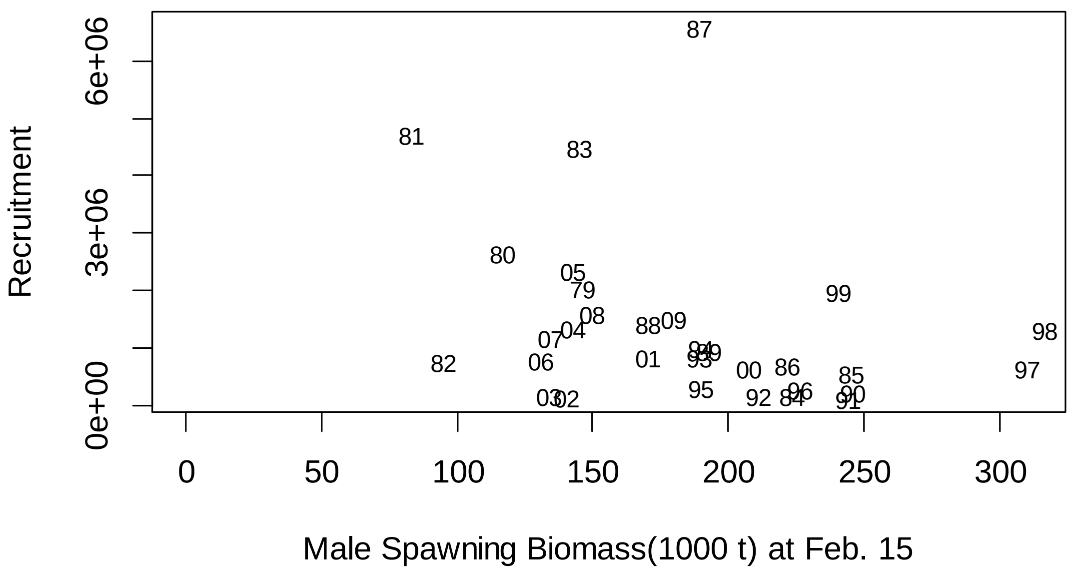


Figure 89. Base Model. Spawner recruit estimates using male mature biomass at time of mating (1000t). Numbers are fertilization year assuming a lag of 5 years. Recruitment is half total recruits in thousands of crab.

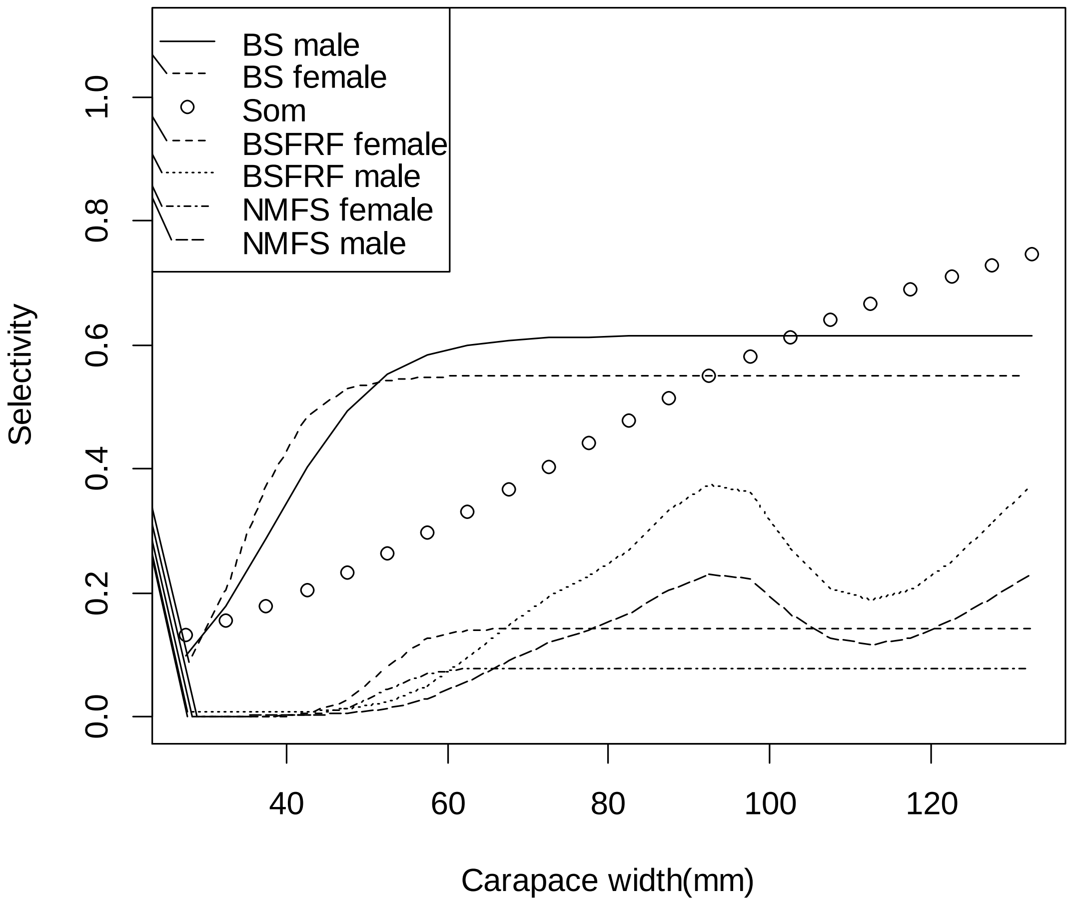


Figure 90. Base Model. Survey selectivity curves entire Bering Sea survey for female (upper dashed line) and male snow crab (solid lines) estimated by the model for 1989 to present. Survey selectivities estimated by Somerton(2010) from 2009 study area data are the circles. Lower lines are survey selectivities in the study area for BSFRF male and female crab and NMFS male and female crab.

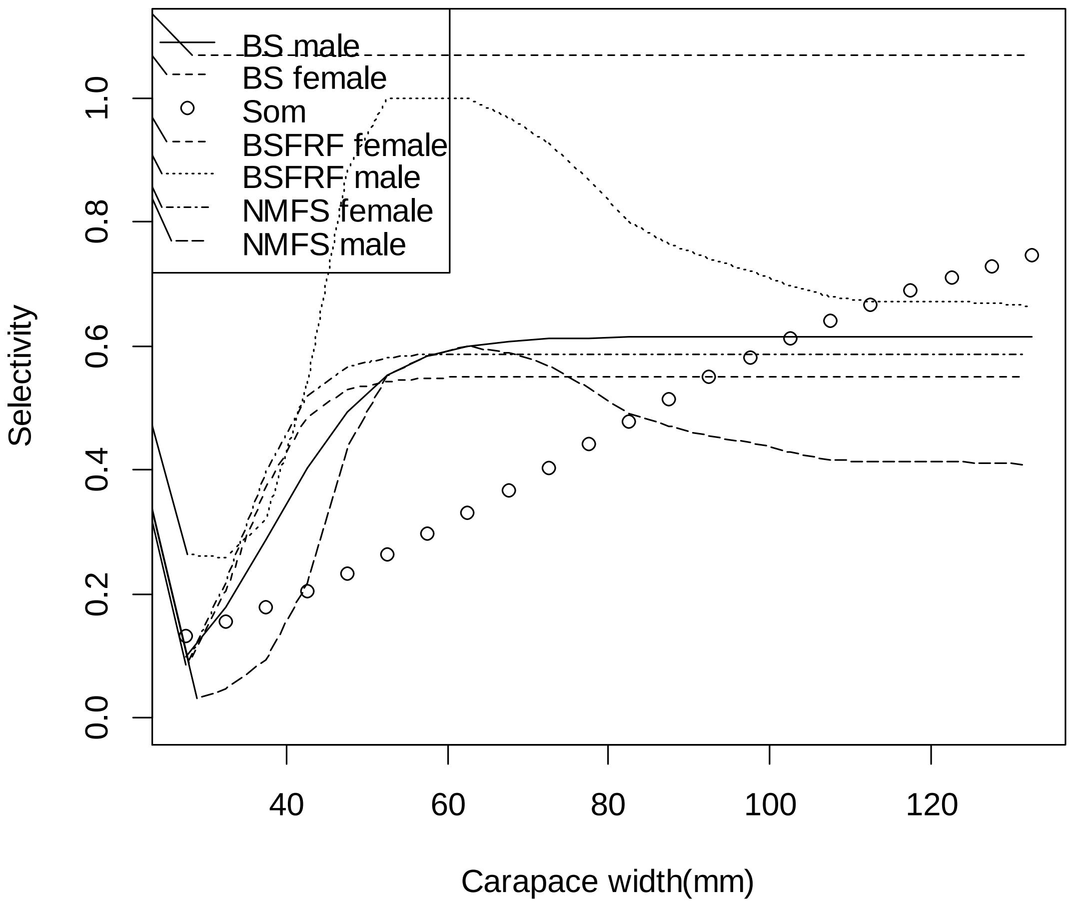


Figure 91. Base Model. 2010 study area survey availability curve (BSFRF) and selectivity curves (NMFS). BSFRF female is 1.0 all sizes (need to extend y axis). BS are survey selectivity curves for the entire Bering Sea. Som is the selectivity curve estimated by Somerton from the 2009 study area data.

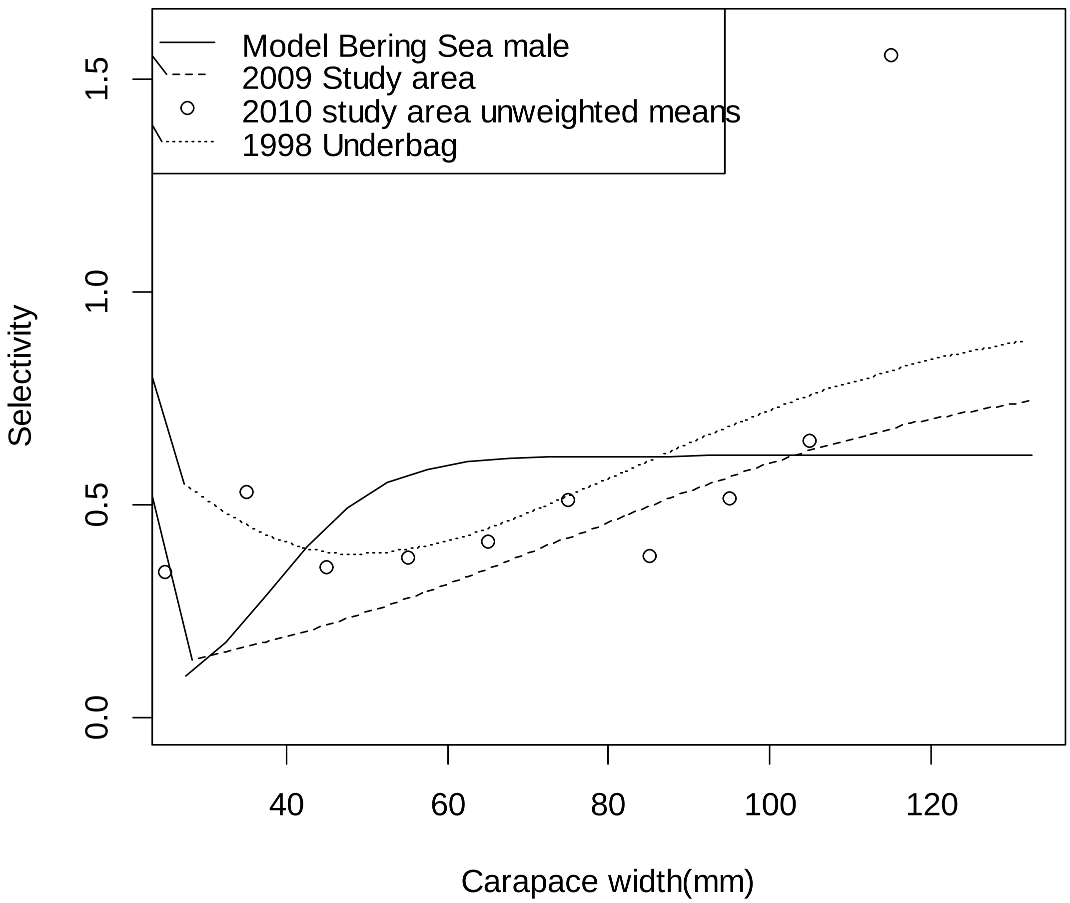


Figure 92. Base Model. Survey selectivity for male crab 1989- present (Model Bering Sea male), with selectivity curves estimated outside the model. 2009 study area is the curve estimated by Somerton from the 2009 study area data.

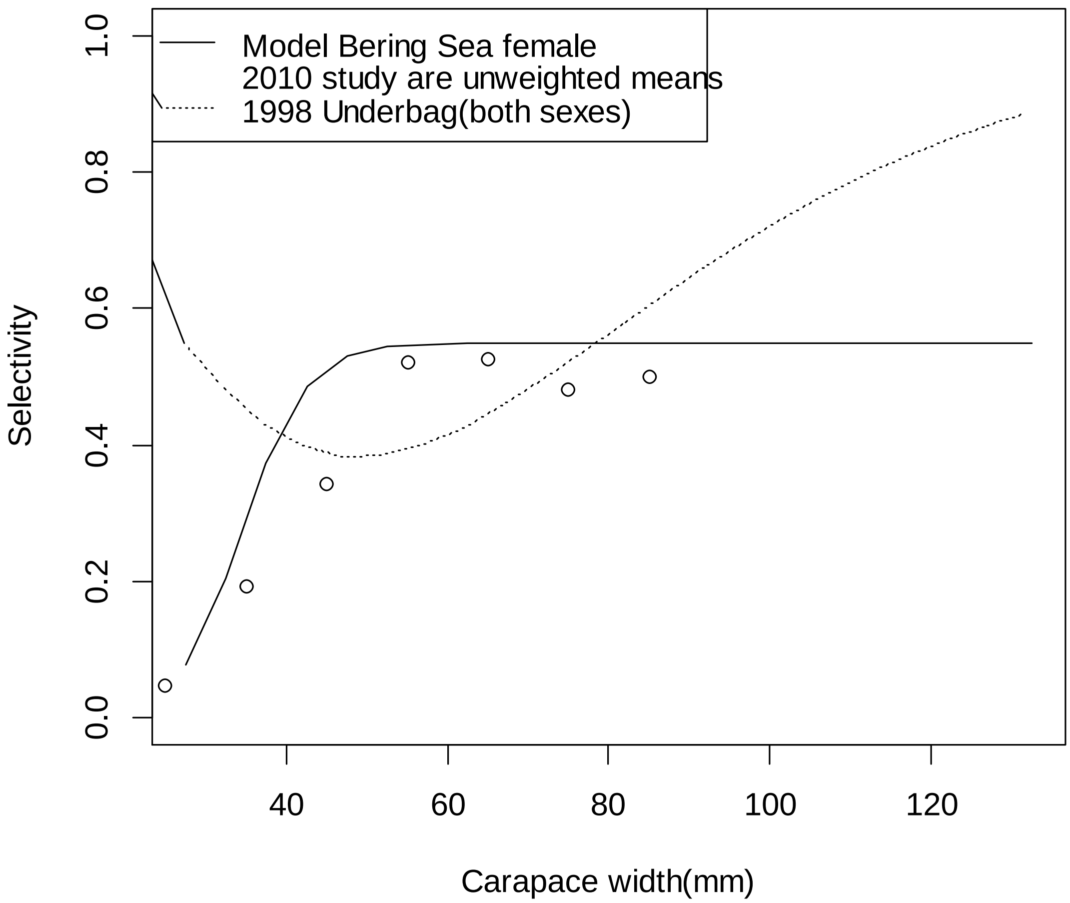


Figure 93. Base Model. Survey selectivity for female crab 1989- present (Model Bering Sea female).

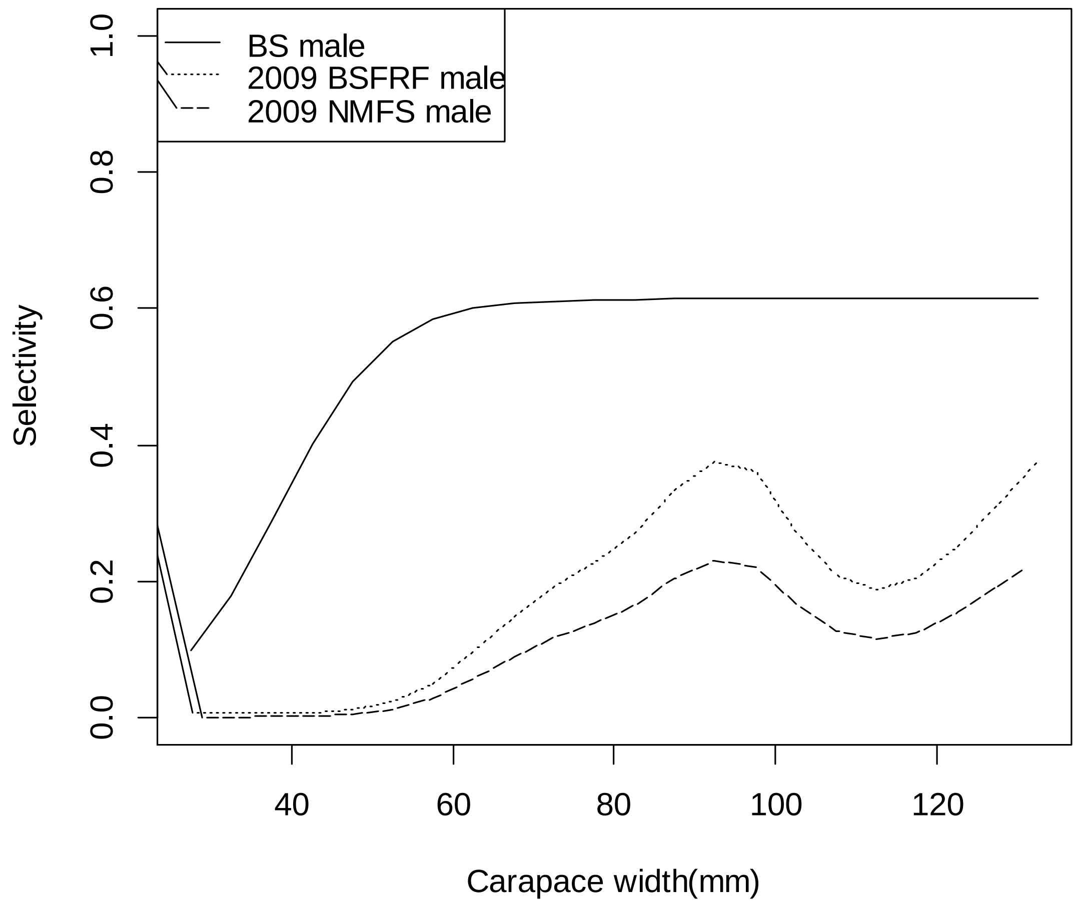


Figure 94. Base Model. Survey selectivity curves for male crab in the entire Bering sea 1989-present (BS male), 2009 study area BSFRF male and 2009 study area NMFS male.

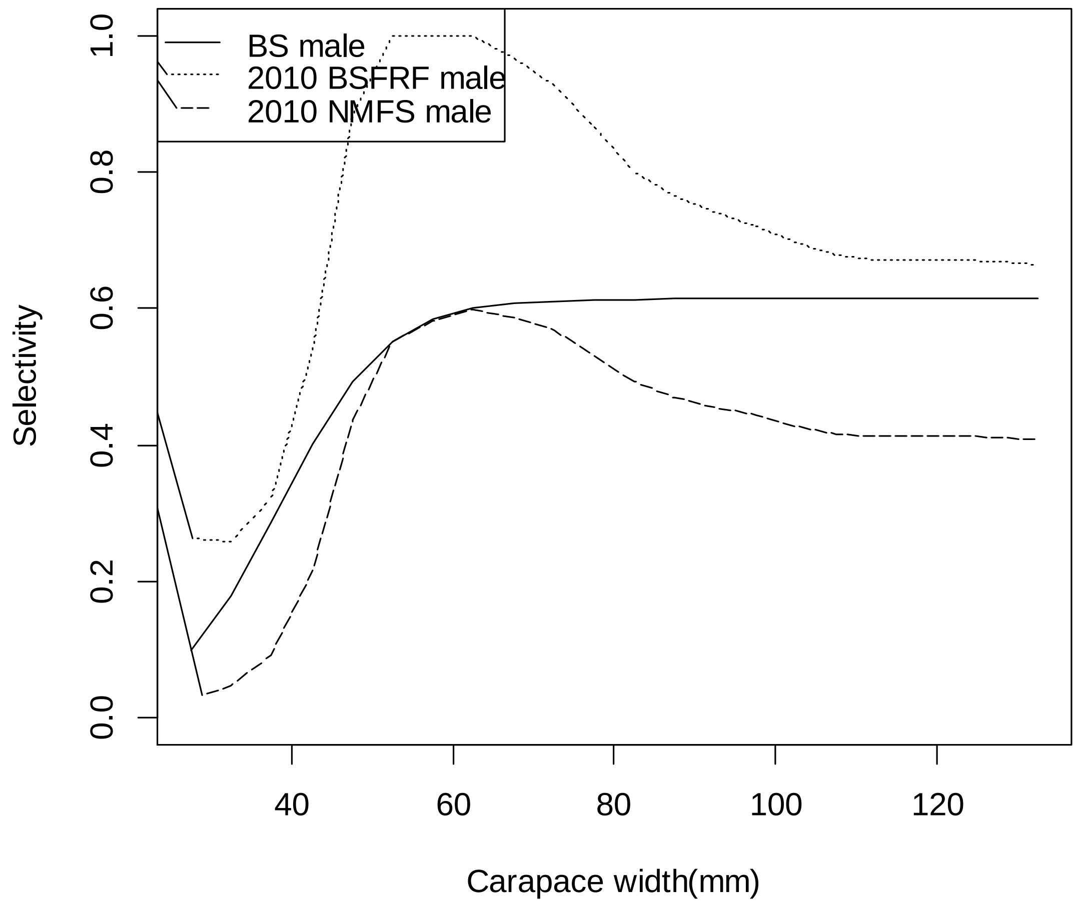


Figure 95. Base Model. Survey selectivity curves for male crab in the entire Bering sea 1989-present (BS male), 2010 study area BSFRF male and 2010 study area NMFS male.

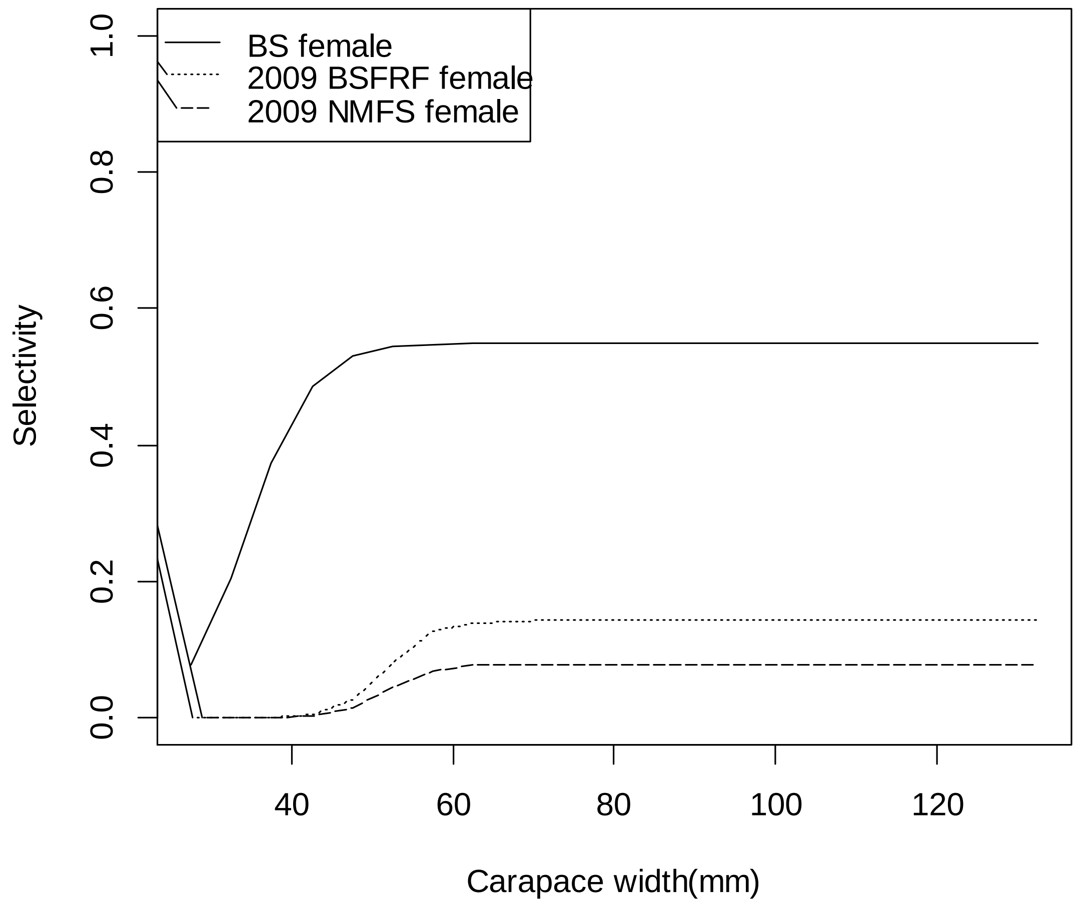


Figure 96. Base Model. Survey selectivity curves for female crab in the entire Bering sea 1989-present (BS female), 2009 study area BSFRF female and 2009 study area NMFS female.

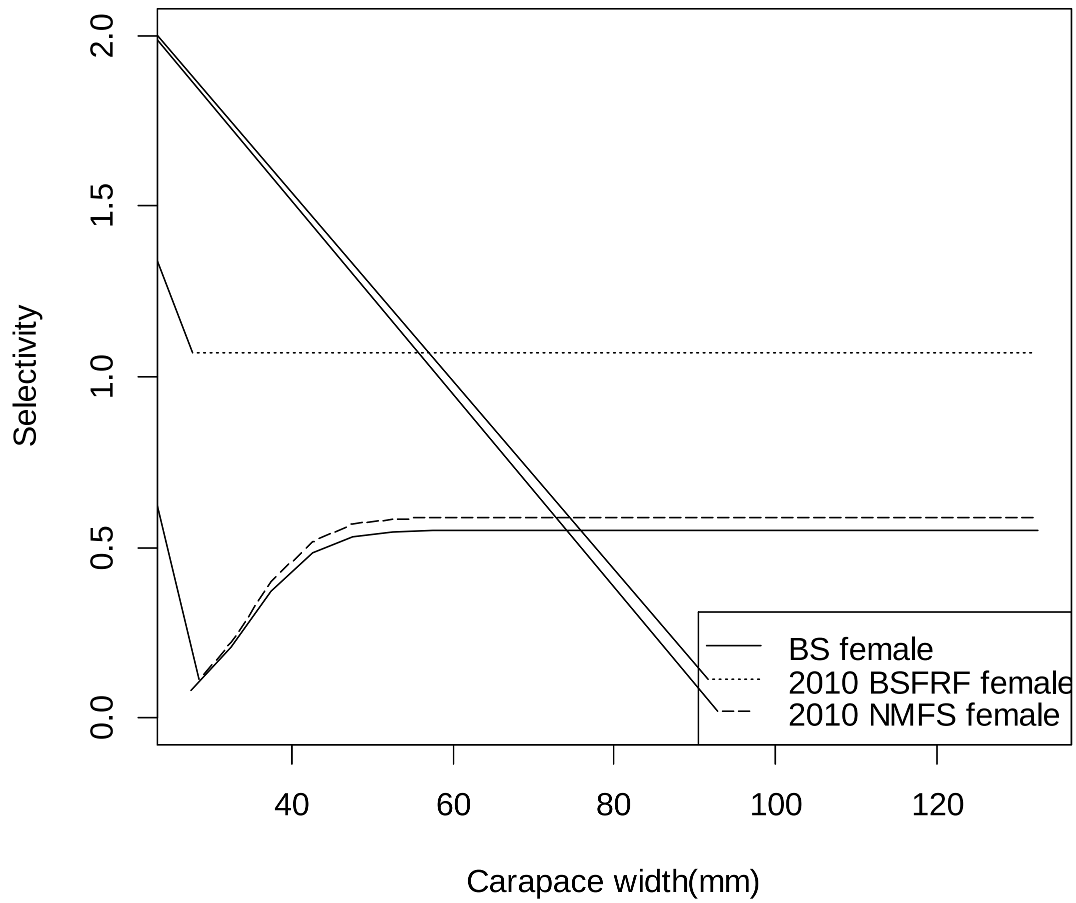


Figure 97. Base Model. Survey selectivity curves for female crab in the entire Bering sea 1989-present (BS female), 2010 study area BSFRF female and 2010 study area NMFS female.

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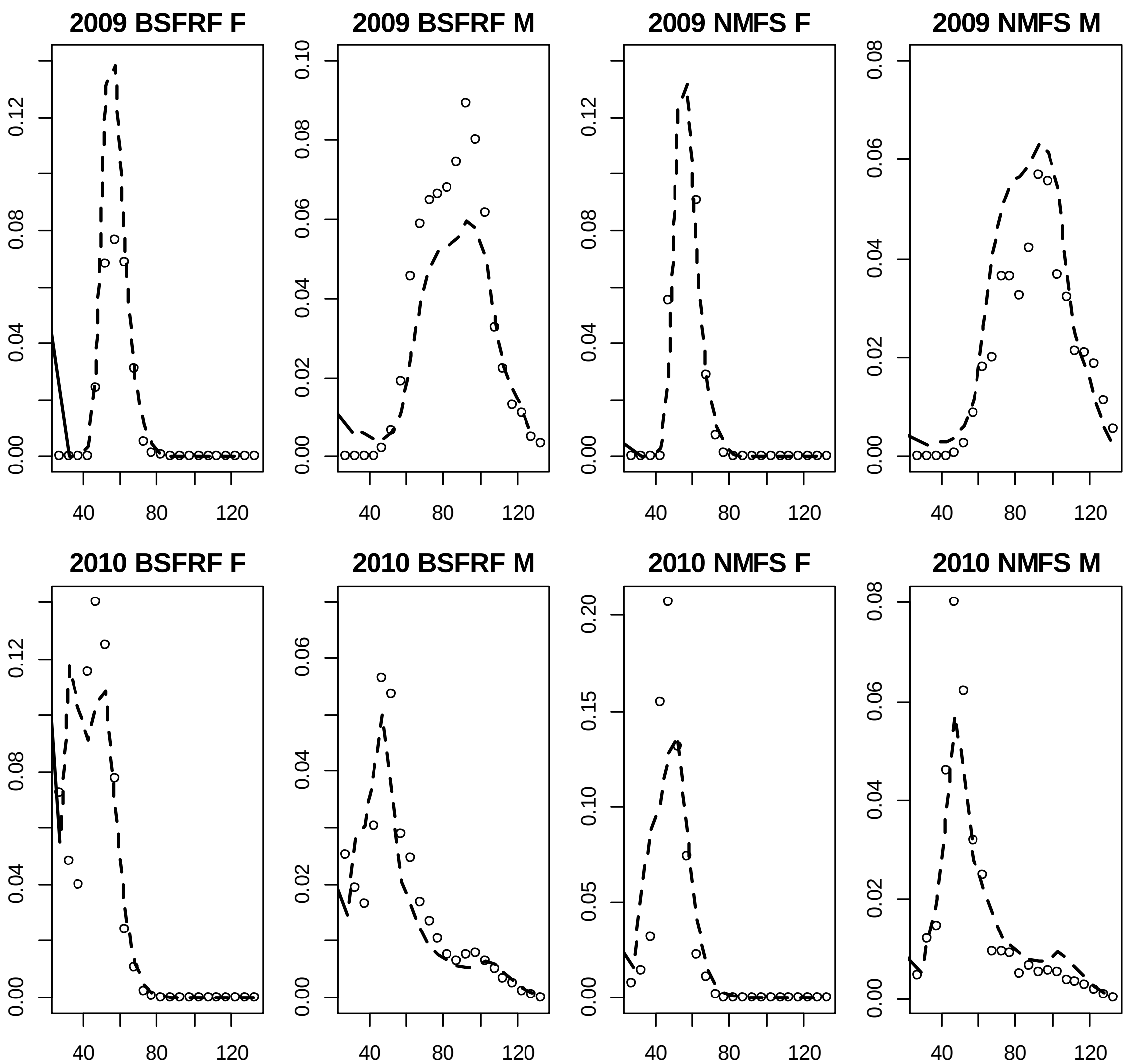

Figure 98. Base Model. Model fit to length frequency for BSFRF and NMFS females and males in the study area.

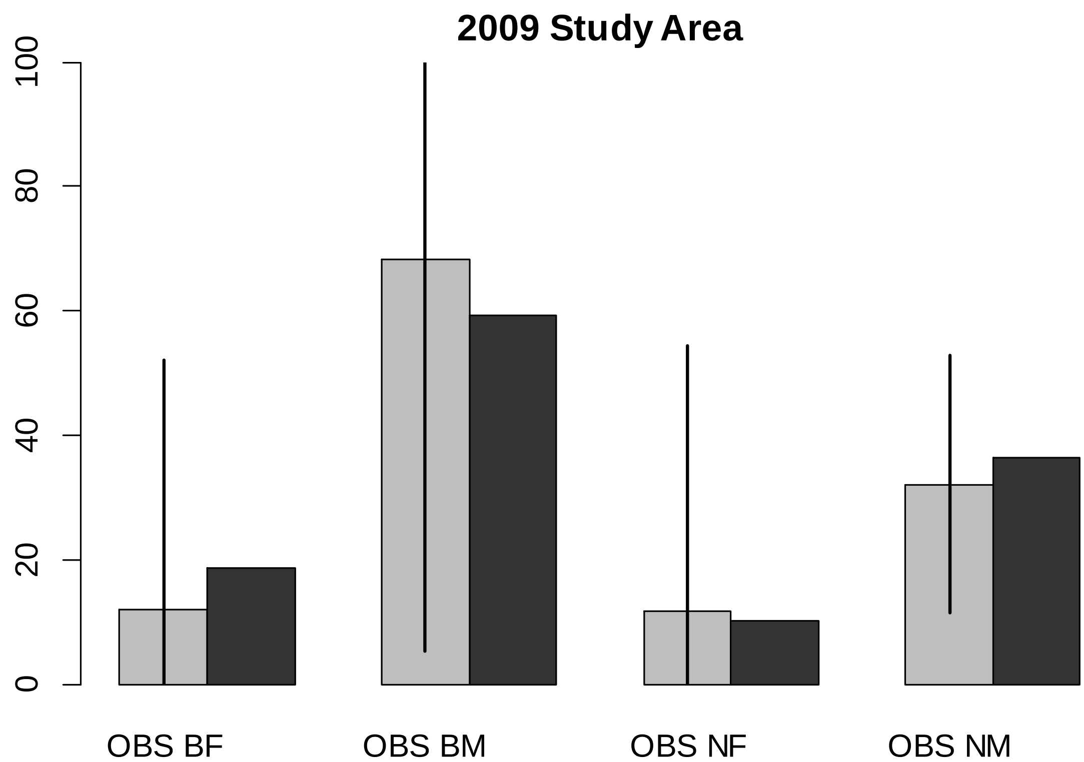

Figure 99. Base Model. Fits to 2009 study area mature biomass by sex for BSFRF and NMFS data.

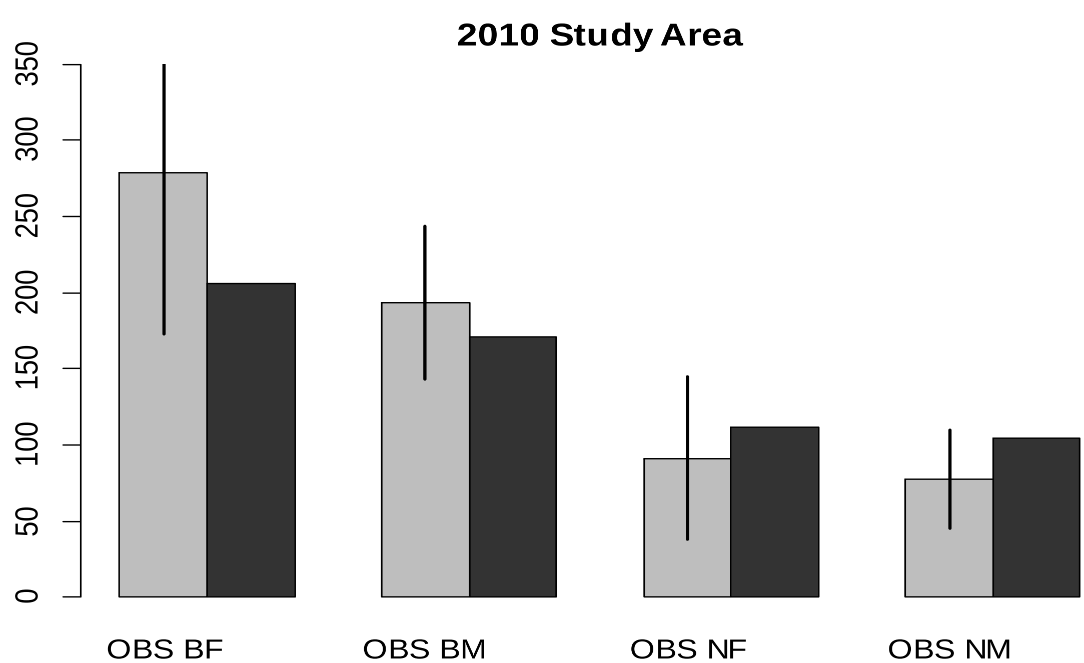

Figure 100. Base Model. Fits to 2010 study area mature biomass by sex for BSFRF and NMFS data.

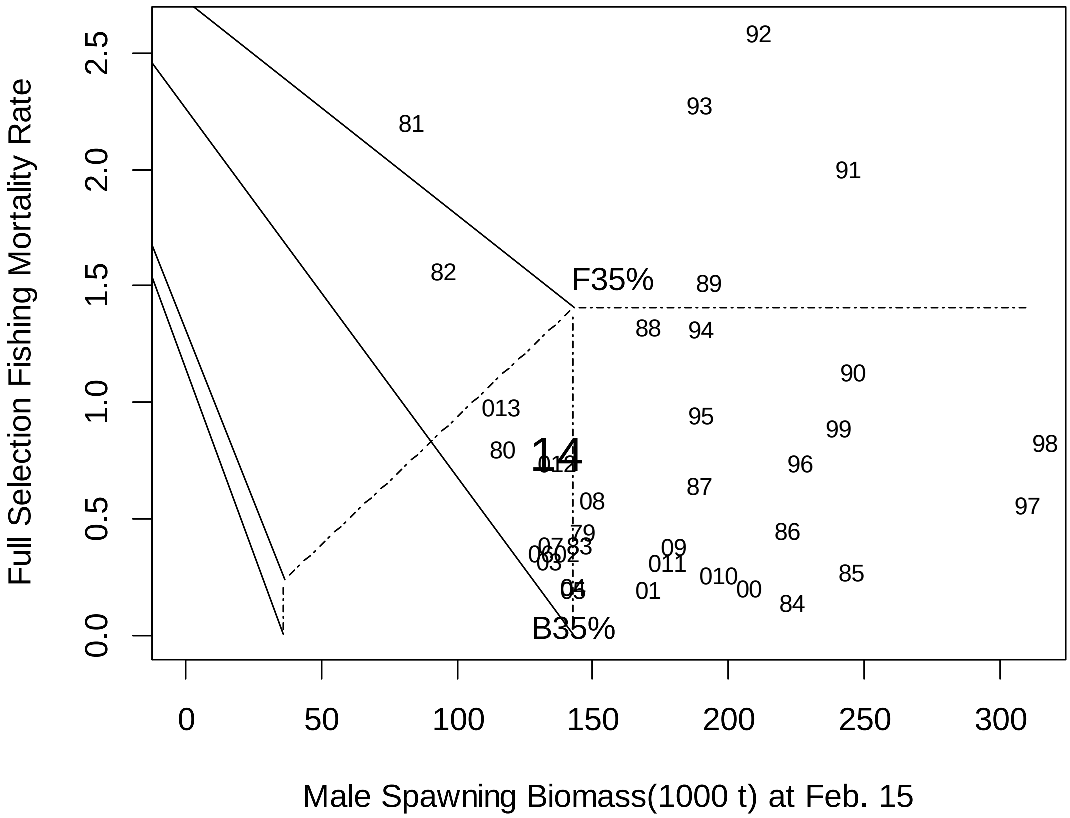

Figure 101. Base Model. Fishing mortality estimated from fishing years 1979 to 20013/14 (labeled 14 in the plot). The OFL control rule (F35%) is shown for comparison. The vertical line is B35%, estimated from the product of spawning biomass per recruit fishing at F35% and mean recruitment from the stock assessment model.

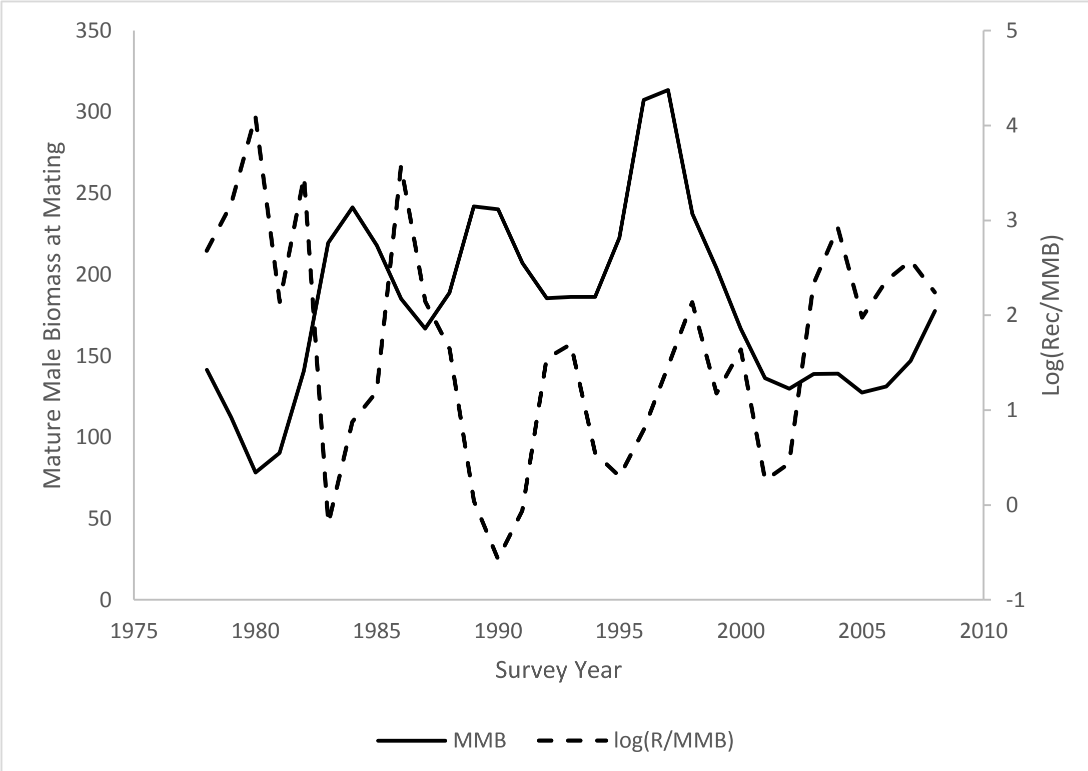

Figure 102. Log of recruits/MMB at mating with a 5 yr lag for recruitment and mature male biomass at mating.

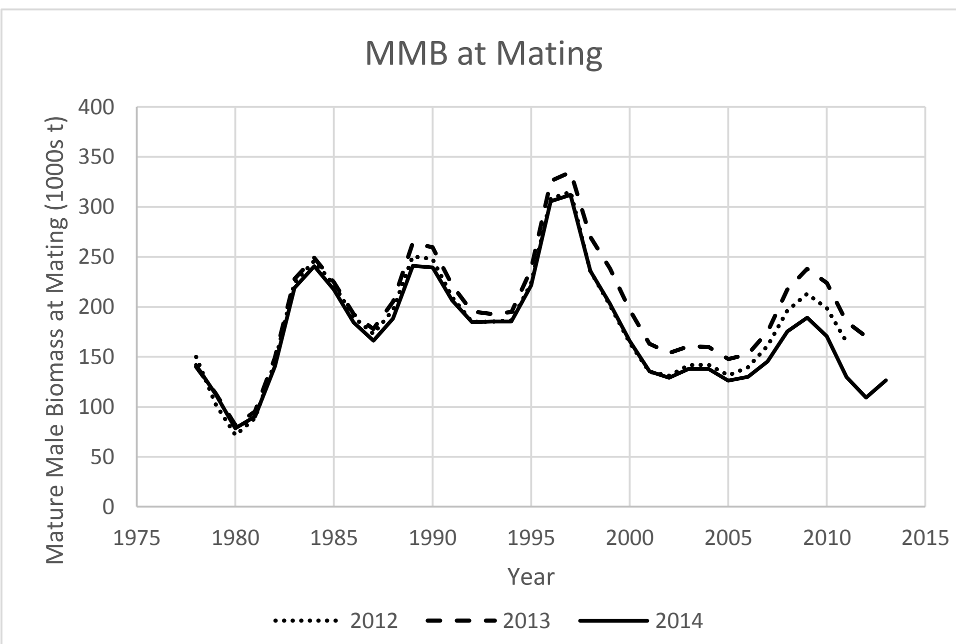

Figure 103. MMB at mating from the 2012 and 2013 assessments, and the Base model (2014).

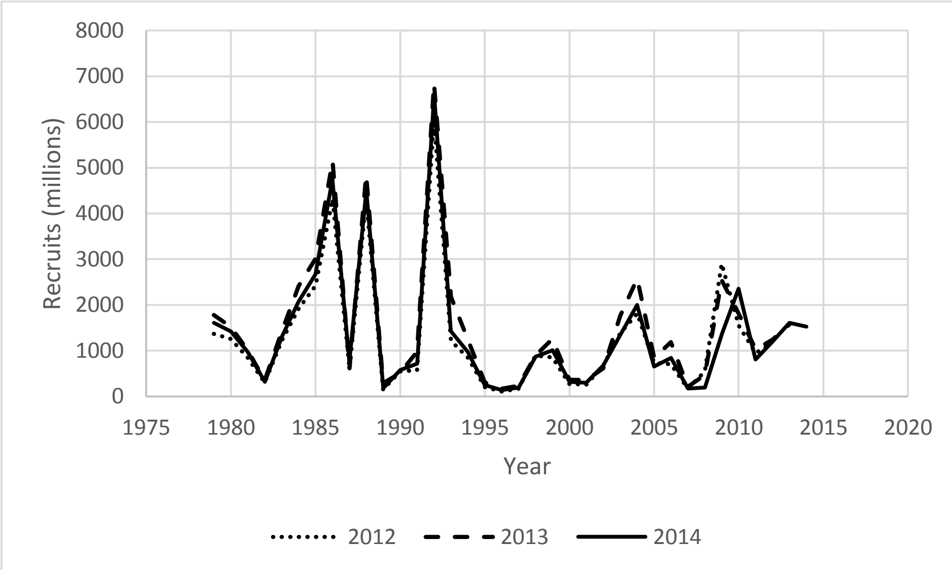

Figure 104. Recruitment estimates from the 2012 and 2013 assessments, and the Base model (2014).

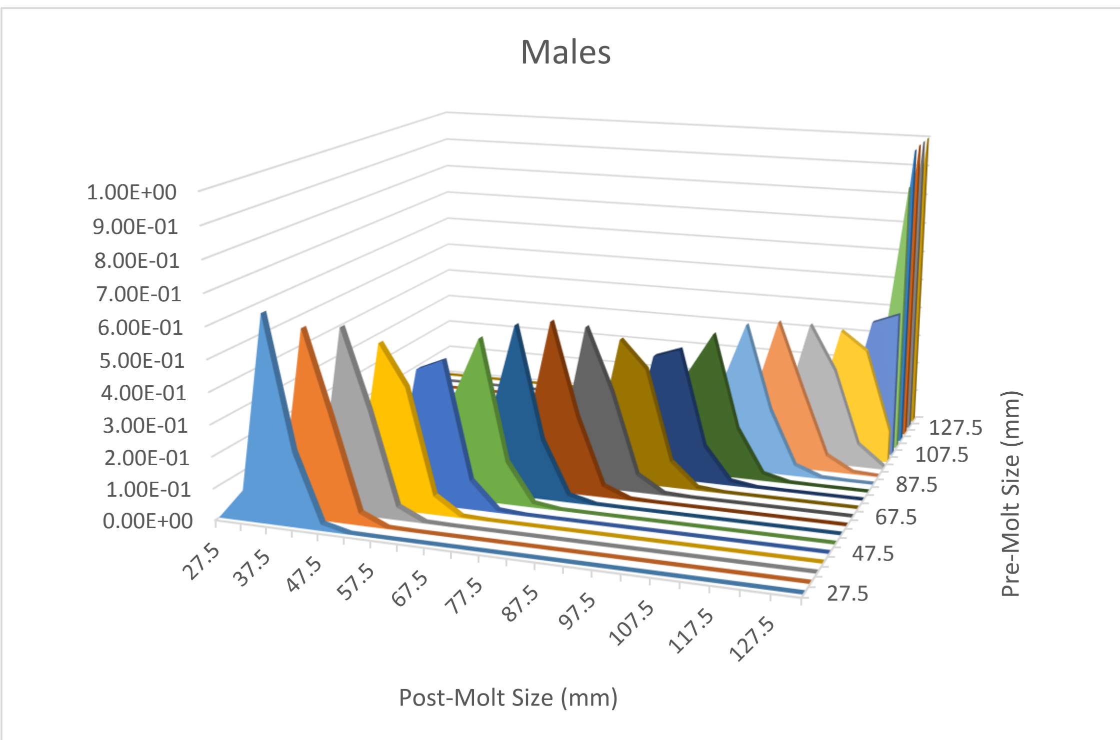

Figure 105. Male growth matrix for the Base model.

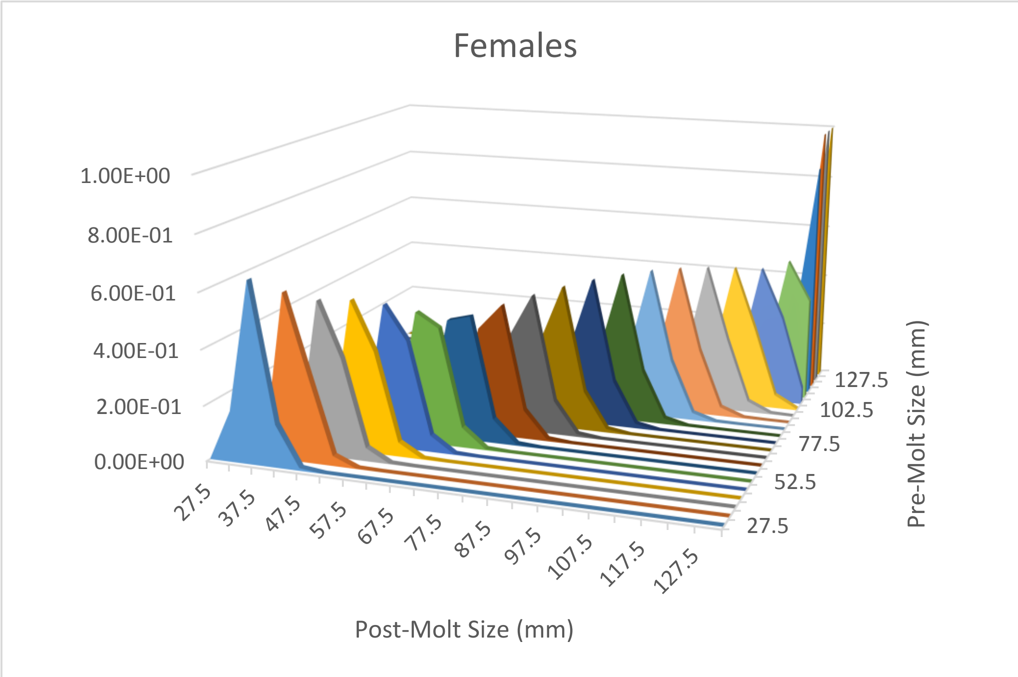

Figure 106. Female growth matrix for the Base model.

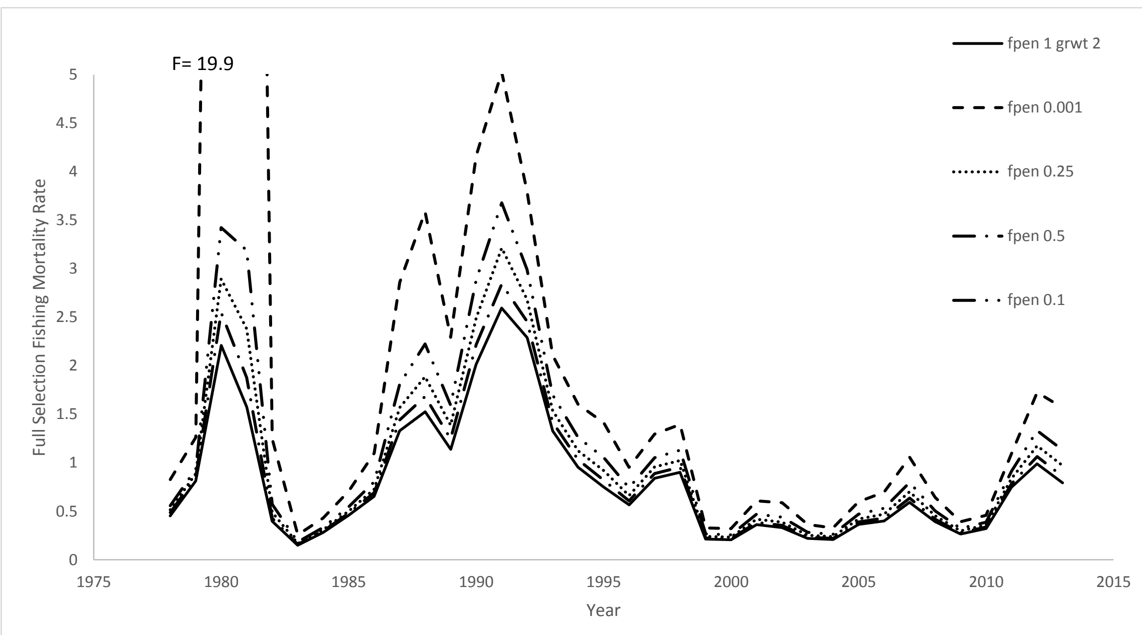

Figure 107. Full selection fishing mortality rate for models 2b (base model), 2d, 2e, 2f and 2g.

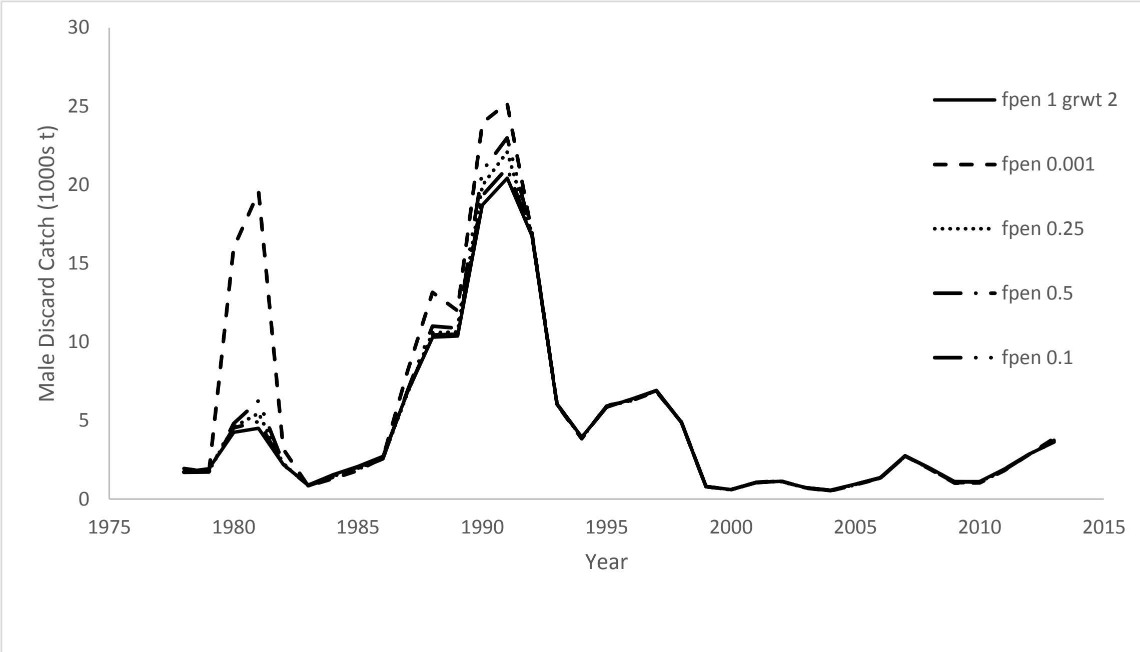

Figure 108. Male discard catch estimates from models 2b (base model), 2d, 2e, 2f and 2g.

Appendix A

Minutes of Crab Plan Team May 2013 on Handling Mortality

Dan Urban (AFSC – Kodiak) provided a presentation on application of the "reflex action mortality predictor" (RAMP) method to estimating handling mortality of discarded crab in the commercial BSAI crab fisheries.

Urban reviewed information on the short and long term handling mortality of discarded crab relevant to crab stock assessment and development of fishery management measures, with an emphasis on EBS snow crab. Estimates of bycatch biomass during the fishery are multiplied by the handling mortality rate and that product is added to the retained catch biomass to estimate total fishery mortality. Hence, assumptions about handling mortality will affect the time series of estimates of total fishery mortality used in stock assessment models, the determination of annual OFLs, and annual total-catch accounting.

In the EBS snow crab fishery, the discarded catch of snow crab is about 1/3 of the catch of retained crab; the discarded snow crab are mainly males smaller than the size preferred by processors (4 inches carapace width). The EBS snow crab assessment model has been using 0.5 as the handling mortality rate for snow crab discarded during the directed fishery. Urban noted that there is high uncertainty on this value; consensus of the CPT discussion during the presentation was that, rather than being directly estimated from data, the 0.5 value was largely based on balancing the concerns that handling mortality could be close to 100% versus an assumption closer to 0% based on an inferred low retained-crab deadloss rate
(~2%).

Urban reviewed the sources of short term handling mortality for discards during crab fisheries, which include trauma at dumping and sorting of the catch, on-deck anoxia, and temperature stress on deck.

Temperature stress and freezing is a particular concern for the winter snow crab fishery, which is often conducted during sub-freezing temperatures that are known from laboratory studies to induce mortality in snow crab (e.g., Shirley and Warrenchuck) and to freeze eyestalks (ongoing project). On-deck sorting and discarding may induce short-term mortality, long-term mortality, and long-term reductions in reproductive potential. Short-term mortality can be directly studied and estimated; estimation of longterm effects is more difficult. Long-term effects could include: increased risk to predation, decreased ability to feed or mate, and increased mortality during molting. Laboratory studies have confirmed that increased mortality of molting Tanner crab after exposure to sub-freezing temperatures and freezing of eye stalks could be reasonably assumed to have long-term effects on survival and reproduction.

The RAMP approach provides a means to estimate short-term (< 2 weeks) mortality due to discarding by scoring a suite of reflex responses of crab captured during fisheries prior to their being discarded.

Previous studies by Allan Stoner allow short-term mortality rates to be predicted from the RAMP reflex response scores. With RAMP scores recorded from uninjured snow crab caught on 22 vessels during
2009/10 season, the predicted handling mortality of discards varied from 1.4% to 32% among vessels; overall RAMP-predicted mortality of discards using the data from all vessels was 5.9%. Additional studies on commercial fishing vessels were conducted on one vessel during the 2010/11 snow crab season and on four vessels during the 2011/12 season. The RAMP-predicted handling mortality from the 2010/11
study was 4.6% and from the 2011/12 study was 4.5%.
The predicted handling mortality was negatively correlated with back-deck temperature on the vessel during the time that RAMP-scoring occurred, such that temperature can be used to predict handling mortality; e.g., predicted mortality was approximately 35% at -14° C and <10% at temperatures ≥ -6° C.
Directly obtaining back-deck temperatures on all vessels throughout the season is not feasible. Urban therefore used the temperatures recorded at the St. Paul airport as a proxy for on-deck temperatures to extend the results to all vessels fishing. Most of the temperatures recorded at the St. Paul airport during the 2009/10 season were at levels associated with low RAMP-predicted mortality. Urban estimated the average per-season handling mortality rate during the 1990/91–2010/11 seasons to be 4%, with the highest estimate for any single season to be 8% (during the early 1990s) using the historical St. Paul airport temperatures to estimate the freezing-related handling mortality. Urban provided ADF&G's estimates of injury rates of snow crab captured during the fishery. Those estimates of injury rates (from data collected by observers during the 1997/98 and 1998/99 seasons) are approximately 10% (it should be noted that data on injury rates observed during the 2009/10–2011/12 seasons in conjunction with the
RAMP study were lower). Urban suggested that the injury rates could be used to predict short-term mortality due to factors other than temperature.
Urban acknowledged that a determination of the true handling mortality rate is difficult, particularly when considering the long-term mortality. Nonetheless, he felt that evidence from the RAMP studies and the observed injury rates suggest that the 0.5 currently assumed for handling mortality in the snow crab assessment and for determining the OFL is too high. Urban proposed three options for handling mortality rates for use in the snow crab assessment: status quo (handling mortality rate = 0.5, a conservative approach); a constant in the range of 0.15–0.20 (based on adding the highest or average estimate of RAMP-predicted mortality and the highest observed injury rate); or using the historic St. Paul airport temperatures and applying the temperature-mortality relationship to obtain an annual handling mortality rate.
Urban concluded his presentation with a summary of the attempts to develop a RAMP-based method to estimate handling mortality for red and golden king crab. Those attempts were not successful and suggested that the RAMP approach may have no useful application to king crab. Red king crab mortality showed no relationship with reflex-response scores, whereas experimenters had a difficult time inducing the golden king crab subjects to die. Urban noted that one observation from this study was that golden king crab appear to be more hardy than red king crab. As an example, clipping the leg of a golden king crab caused only 3% mortality; significant mortality (80%) required complete severing of the leg.

The CPT discussed how to apply the findings presented for use in the snow crab stock assessment. The
CPT was reminded that estimates used in the stock assessment should be unbiased and that conservation concerns due to uncertainty should enter in the consideration of the ABC. Much of the initial CPT discussion focused on the uncertainty related to long-term handling mortality and on the effects due to discarding itself (as opposed to the injuries suffered when brought on deck). The CPT felt that the weight of evidence is that 0.5 is too high, but struggled with reconciling the results presented by Urban with the uncertainty associated with other, long-term effects to survival, growth, and reproduction (e.g., predation, displacement, affects to hormone regulation, additional stresses during molting, etc). Some voiced concerns that, given those uncertainties, the CPT may be placing more weight on the results of recent studies than is warranted. With regard to some of the concerns, it was noted that most of the discards are males > 3 inches carapace width, which Urban noted may have low risk of predation relative to smaller crab. In addition, although the long-term effects will be much higher for crab that will molt, data collected on chela heights of males captured during the fishery suggest that most of the discarded males have already completed their terminal molt.

Discussion provided four options to consider for a total handling mortality rate for snow crab:

1. 0.2, derived by summing the highest estimate due to freezing (0.08) with the highest estimate of injury rates (0.12); i.e., one of the options that Urban presented
2. 0.25, derived as a balance between the extremes of 0.0 and 0.5; the argument for this was that it was consistent with the approach to obtain the currently-used 0.5, which was derived as a balance between the two extremes of 0.0 and 1.0
3. 0.3, derived by taking the "base" of 20% handling mortality that is applied to king crab stocks and adding the highest estimate of freezing-related handling mortality (0.08) and rounding up to the nearest 0.1.
4. 0.3, derived by summing the highest estimate due to freezing (0.08) with the highest estimate of injury rates (0.12) to capture the short-term mortality and multiplying that sum by 1.5 to provide an estimate that includes long-term mortality. Since there is no information on long-term mortality, the CPT agreed that the best first-order estimate of the long-term mortality is 50% of the short-term mortality.

The consensus of the CPT was that the best current estimate of handling mortality of snow crab was 0.3, based on the argument of the last bullet (above). The CPT requested that the next snow crab assessment use 0.3 as handling mortality for all pot fisheries (crab and fish) in the base run and 0.5 as an alternative scenario (there was some discussion as to whether 0.3 or 0.5 should be the base, but if 0.3 is chosen it should be the base run so that the new handling mortality is included in the remaining alternative runs).
The 0.5 run should be included so that the effects on OFL, stock status, etc., can be evaluated.

The CPT recommended that the 0.3 handling mortality not be applied to Tanner crab, neither as bycatch in the snow crab fishery or in the directed Tanner crab fishery; i.e., the recommended handling mortality for Tanner crab remains at 0.5 until sufficient data suggests otherwise. Stoner's work suggests that Tanner crab may suffer higher handling mortality than snow crab, but no data were presented at this meeting for
Tanner crab similar to what were presented for snow crab. The CPT recommended that a sensitivity analysis on handling mortality be done in the Tanner crab assessment to provide impetus for research on
Tanner handling mortality during the snow crab fishery because Tanner bycatch mortality during snow crab fishery has a large effect on the Tanner crab stock assessment, OFL setting, and available TAC.

Discussion turned to the results that Urban presented on king crabs, for which the RAMP approach appears to be not useful. Currently, the Bristol Bay red king crab and the golden king crab assessments assume that handling mortality is 0.2. Although on-deck injury rates for king crab during the red and golden king crab fisheries have been estimated using data collected by ADF&G during the late 1990s, no new data was presented on king crab handling mortality at the meeting. The CPT discussed the apparently greater "hardiness" of golden king crab relative to red king crab and some members of the public suggested that this observation could justify reducing the handling mortality used for golden king crab to less than 0.2. The CPT was unable to recommend a change to the golden king crab handling mortality on the basis of what was presented during the meeting and recommended that it stay at the status quo 0.2 until some data providing estimates of the handling mortality rate are presented. It was noted that both the golden king crab stocks (Aleutian Islands and Pribilof Islands) are currently managed as Tier 5 stocks, for which the assumed handling mortality rates have no impact on the retained-catch portion of the OFL or of the ABC; handling mortality would become an important consideration if the golden king crab stocks become managed under Tier 4.

The CPT emphasizes that handling mortality remains a priority research objective for king crab species and Tanner crab.