# Stock Assessment of eastern Bering Sea snow crab

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April 21, 2008

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## SSC Comments October 2007

*Regarding the stock assessments for snow crab and Bristol Bay red king crab, a number of concerns were raised by the stock assessment authors and by the plan team that should be addressed by the authors in future assessments. Specifically, there are serious concerns about high fishing mortalities on the southern portion of the snow crab stock, which may exacerbate observed northward shifts in their distribution. The SSC recommends an analysis of the potential consequences of this high fishing mortality and of options for apportioning catch spatially. A second issue of concern is the presence of disturbing trends in the residuals of the fit to size frequency data, which may be a result of uncertainty in the practice of using shell condition as a proxy for shell age. We anticipate that these and other issues will be addressed in a requested CIE review of the snow crab assessment and the SSC looks forward to receiving a report on the review.*

## Changes to the Model and response to CIE review and SSC Comments

*A CIE review on the Bering sea snow crab assessment model was conducted in March 2008. The reviewers suggested simplifying the model by not using shell condition in the estimation of fishery selectivities due to uncertainty in shell age and shell condition. The CIE review and SSC noted residual patterns in the first few bins of the length frequency fit.*

To address these issues, the model was reconfigured to fit the pot fishery length frequencies for combined shell condition, equal to the procedure for survey data. One fishery selectivity curve was estimated for the total catch and one curve estimated for the retained catch for combined shell condition males in the directed fishery. To address the residual pattern, the recruitment distribution was shifted toward smaller size crab to better fit survey length data in the first length bin.

*The CIE review also suggested that the mean growth of male and female crab should be equal at some small size.*

The mean growth of males and females was changed so that both sexes had the same intercept in the linear growth equation. The slopes were adjusted so that growth at larger sizes was similar to growth observations, given the change in the intercepts.

*The CIE review, the SSC and CPT have noted patterns in the residuals of the fit to the survey length frequency data.*

A model that estimates a smooth function for the maturity probability for male and female crab provides some improvement in residual patterns, however, projected catches and biomass values were very similar to the base model. Spatial differences in growth and maturity may occur and require development of a spatial model. Plots and tables presented here are for the base model, unless the model with estimated maturity probability is specified.

*The CIE reviewers suggested investigating a simpler model fitting to total biomass and survey length frequency by sex only, with a simple knife-edge maturity function.*

This will be investigated in future assessments, however, knife-edge maturity may not be a reasonable assumption, due to the link between maturity and growth for snow crab. Data on maturity status is collected each year for both males and females as part of the survey data, a knife-edge maturity schedule is unlikely to adequately represent growth with an animal with terminal molt.

**Changes to the Data**

Trawl discard size frequency data were updated to 2007. Catch data were also updated through 2007. The TAC for the 2007/8 fishery season was used as an estimate of the retained catch for the projections and estimation of the OFL for the 2008/9 season.

*An industry sponsored review of the snow crab stock assessment was also conducted in March 2008 and a report produced which was not received in time for responses to be included in this assessment. However, meetings with industry reviewers did allow exchange of ideas and issues previous to the report being available.*

A complete response to the CIE review and industry review will be included in future assessments.

## SUMMARY

A size based model was developed for eastern Bering Sea snow crab (*Chionoecetes opilio*) to estimate population biomass and harvest levels. Model estimates of total mature biomass of snow crab increased from the early 1980's to a peak in 1990 of about 1,600 million lbs. The total mature biomass includes all sizes of mature females and morphometrically mature males. Total mature biomass declined in the late 1990's to about 522 million lbs. in 1999. The stock was declared overfished in 1999 because the survey estimate of mature biomass (330 million lbs) was below the minimum stock size

threshold (MSST = 460 million lbs). A rebuilding plan was implemented in 2000. Despite the imposition of the rebuilding plan, model estimates of total mature biomass continued to decline to 360 million lbs in 2003, however, it increased to 632 million lbs in 2007. The 2006 observed survey total mature biomass was estimated at 519.5 million lbs, about 56% of Bmsy (the Bmsy previous to Amendment 24 was 921.6 million lbs estimated from average survey total mature biomass from 1983 to 1997). The 2007 observed survey total mature biomass increased to 607.8 million lbs, about 66% of Bmsy. The observed survey estimate of males greater than 101 mm increased from about 69 million in 2005 to 135 million in 2006 and again in 2007 to 151 million. In 2006 there was a high degree of uncertainty in the estimated large male (>101mm) numbers. The 2007 survey estimate of 151 million crab has lower uncertainty than in 2006, with an estimated 95% confidence interval +/-40%. Model estimates of large males (>101mm) were about 88 million crab in 2006 and 148 million in 2007.

Catch has followed survey abundance estimates of large males, since the survey estimates have been the basis for calculating the GHL (Guideline Harvest Level for retained catch). Retained catches increased from about 6.7 million lbs at the beginning of the directed fishery in 1973 to a peak of 328 million lbs in 1991, declined thereafter, then increased to another peak of 243 million lbs in 1998. Retained catch in the 2000 fishery was reduced to 33.5 million lbs due to the low abundance estimated by the 1999 survey. A harvest strategy (Zheng et al. 2002) was developed using a simulation model previous to the development of the current stock assessment model, that has been used to set the most recent GHL's. Retained catch in the 2005 fishery was about 25 million lbs, about 20% above the GHL of 20.9 million lb. Retained catch in the 2006 fishery was 37 million lbs and in 2007, 36.4 million lbs. The TAC (retained catch) for the 2007/8 fishery was set at 63 million lbs.

Estimated discard mortality (mostly undersized males and old shell males) in the directed pot fishery has averaged about 15.5% (with assumed mortality of 50%) 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. Discard mortality was assumed to be 50%.

Projected catch and biomass for 2008/9-2012/13 was estimated using mature male biomass at the time of mating (February), using F35% and F40%. The 2007/8 mature male biomass at mating time is projected to be at 84% of B35% if a retained catch equal to the TAC of 63 million lbs occurs. The 2008/9 mature male biomass at mating time is projected to be at 99% of B35% (fishing at the F40% CR) and 93% of B35% (fishing at F35% CR). Using a harvest control rule with B40% and F40%, the 2008/9 total catch was estimated at 96.4 million lbs (F = 0.43), with a retaind catch of 84.6 million lbs. Using a harvest control rule with B35% and F35%, the 2008/9 total catch (OFL) was estimated at 123.0 million lbs (F = 0.59) with a retained catch of 108.4 million lbs.

The rebuilding plan developed for snow crab projected a 50% probability of rebuilding by 2010. The probability of rebuilding to the total survey mature biomass Bmsy of 921.6 million lbs in 2010 is about 6.1% fishing at F35% and 7.7% fishing at F40%. Lower

fishing mortality rates were used to estimate the probability of rebuilding to the survey total mature biomass Bmsy by 2010. A bycatch only scenario is needed to obtain a 50% probability of rebuilding by 2011, other fishing mortality rates will result in longer rebuilding times. The year of rebuilding with fishing at F40% was estimated at 2017.

If snow crab are managed as a Tier 3 stock, then B35% would serve as a proxy for Bmsy, and mature male biomass at the time of mating would be used to assess the stock. Under tier 3 management, the probability of rebuilding to B35% in 2010 is 21.3%, fishing at F35%, and 73.4% fishing at F40%.

Biomass is expected to be higher in 2008/9, then decrease due to recent lower recruitment estimates and using autocorrelation to generate future recruitments in the projections. The OFL and projections may change when the 2008 survey biomass is added to the model. The probability of rebuilding by 2010 is dependent on recruits estimated by the model, while projections in later years will depend on the method of generating future recruitments. The use of random recruitment will result in a higher probability of rebuilding the stock relative to using a spawner recruit curve and autocorrelated recruitment as used in the projections presented here. The trends in future biomass will depend on realized catches and future recruitment and may change in future assessments as more data on the strength of the recent recruitments is obtained.

Exploitation rates in the southern portion of the range of snow crab have been higher than target rates estimated using abundances in the geographic distribution of the stock due the majority of catch occurring in the southern portion of the snow crab range. This prominent feature of the fishery for Bering Sea snow crab has possibly contributed to the shift in distribution to less productive waters in the north. Computing the catch based on the complete survey biomass, then extracting that catch from only the southern component of the stock results in exploitation rates higher than the target rate on crabs in the southern area of the distribution. A biologically meaningful solution would be to split the catch into two regions, north and south, according to the percent distribution of the survey estimate of exploitable males from those regions or the distribution at the time of the fishery if known. In 2003 and 2004, 26% and 24% respectively of male biomass greater than 101 mm measure in the survey was south of 58.5 deg N. The distribution of catch in the 2006/7 fishery is similar to recent fisheries. Synchronizing the population distribution and catch distribution would result in realized exploitation rate at or close to the target rate in all areas.

## 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.

# CATCH 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 328 million lbs in 1991, declined to 65 million lbs in 1996, increased to 243 million lbs in 1998 then declined to 33.5 million lbs in the 2000 fishery (Table 1, Figure 1). Due to low abundance and a reduced harvest rate, retained catches remained low and were 32.7 million lbs in the 2002 fishery (40.0 million lbs total catch (with 50% discard mortality), 28.3 million lbs of retained catch in 2003 (35.1 million lbs total catch). Retained catch in the 2005/6 fishery was 37.0 million lbs and in 2006/7 fishery, 36.4 million lbs. The TAC (retained catch) for the 2007/8 fishery was set at 63 million lbs.

Discard from the directed pot fishery was estimated from observer data since 1992 and ranged from 11% to 64% (averaged about 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 1992 trawl discard mortality was about 9 million lbs, then declined to about 2 to 3 million lbs until 1998, when it declined to below 1 million lbs (except 2005, 1.4 million lbs). Discard in groundfish fisheries from highest to lowest catch 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). In the 2002 fishery about 0.5% of the total pot lifts were observed (Neufeld and Barnard 2003).

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. In the 2006/7 fishery 98% of the new shell males >101mm CW were retained, while 72% of the old shell males >101mm CW were retained. Only 4% of new shell crab were retained between 78mm and 101 mm CW. The average weight of retained crab has varied between 1.1 lbs (1983-1984) and 1.6 lbs(1979), and 1.3 lbs 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 (Anonymous, 2000). 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 harvest strategy was developed based on simulations by Zheng (2002).

The actual retained catch typically exceeded the GHL historically, resulting in exploitation rates for the retained catch (using survey numbers) ranging from about 60% to 100% for most years (Figure 4). The exploitation fraction is calculated using the abundance for male crab over 101 mm estimated from the survey data reduced by the natural mortality from the time of the survey until the fishery occurs, approximately 7 months later, since the late 1980's. The historical GHL calculation did not include the correction for time lapsed between the survey and the fishery. In 1986 and 1987 the exploitation rate exceeded 1.0 because some crabs are retained that are less than 102 mm, discard mortality of small crabs is also included, and survey catchability may be less than 1.0. The exploitation fraction using the total catch divided by the mature male biomass estimated from the model, ranged from 10% to 50% (Figure 5). The exploitation fraction estimated by dividing the total catch by the model estimate of the crabs over 101 mm ranged from about 15% to 80% (Figure 5). The total exploitation rate on males > 101 mm was 50% to 75% for 1986 to 1994 and near 70% for 1998 and 1999 (year when fishery occurred).

Prior to adoption of Amendment xx, Bmsy (921.6 million lbs) was defined as the average total mature biomass (males and females) estimated from the survey for the years 1983 to 1997 (BSAI crab FMP 1998). MSST was defined as 50% of the Bmsy value (MSST=460 million lbs of total mature biomass). 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 Bmsy (921.6 million lbs) (Zheng 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. 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. The maximum full selection fishing mortality rate is close to 1.0 at the maximum harvest rate of 0.225 of mature male biomass.

## ABUNDANCE TRENDS

### Survey Biomass

Abundance is estimated from the annual Bering Sea 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 deg 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 degrees N) and mature crabs deeper areas to the south of the juveniles (Zheng et al. 2001).

The total mature biomass (all sizes of morphometrically mature males and females) estimated from the survey declined to a low of 188 million lbs in 1985, increased to a high of 1,775 million lbs in 1991 (includes northern stations after 1989), then declined to 330 million lbs in 1999, when the stock was declared overfished (Table 2 and Figure 2). The mature biomass increased in 2000 and 2001, mainly due to a few large catches of mature females. Survey estimates of total mature increased from 519 million lbs in 2006 to 607.8 million lbs in 2007.

The term mature for male snow crab will be used here to mean 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 and Orensanz unpub. Data).

Survey abundance by size for males and females indicate a moderate recruitment of small crab in 2004, 2005 and 2006 (Figures 6 through 9). High numbers of small crab in the late 1970's 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 deg 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. In 2003, 66% of the catch was south of 58.5 deg N. (Figure 10), and in 2004 78% of the catch was south of 58.5 deg N. (Figure 11). In 2003 and 2004 the ice edge was farther north than past years, allowing some fishing to occur as far north as 60-61 deg N. Catch in the 2007 fishery was similar to recent years (Figure 12) with most catch south of 58 degrees N. to the west of the Pribilof Islands between about 171 deg. W and 173 deg W.

Summer survey data show that approximately 75% of the mature male snow crab population resides in a region outside of the fishery zone (north of 58.5 deg N Latitude). The 2003 survey estimated about 24% of the male snow crab >101mm were south of 58.5 deg N. About 48% of those males were estimated to be new shell. In 2004 and 2005, about 26 % of the survey abundance of male snow crab > 101 mm and the mature male biomass were south of 58.5 deg N. latitude (Figures 13 through 17). About 53% of those males south of 58.5 deg N. were estimated to be new shell (which are preferred by the fishery). The 2004 fishery retained about 19 million crab of which about 14.8 million were caught south of 58.5 deg south (about 78%). Although these new shell males are morphometrically mature (i.e., large clawed), at the time of the fishery, they are subject to exploitation prior to recruiting to the reproductive stock. The 2003 survey estimate of new shell male crab > 101 mm was about 7.6 million south of 58.5 deg N. which would have been fished on in the 2004 fishery. In the 2004 survey about 9.5 million new shell males >101mm were estimated south of 58.5 deg N. This 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 deg N exceeds the target rate, possibly resulting in a 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. Lower egg production in the south from lower clutch fullness and higher percent barren females possibly due to insufficient males for mating may drive a change in distribution to the north. The northward shift in mature females is particularly problematic in terms of annual reproductive output due to lowered productivity from the shift to biennial spawning of animals in waters < 1.5 deg C in the

north. The lack of males in the southern areas at mating time (after the fishery occurs) may result in insufficient males for mating.

The spatial distribution of large males snow crab in the 2007 survey was similar to 2005 (Figures 17 and 18), however, 2007 had fewer crab in the area to the south and west of St. Matthew Island. Female crab > 49 mm occurred in higher concentration in generally three areas, just north of the Pribilof Islands, just south and west of St. Matthews Island, and to the north and west of St. Matthew Island. Males > 78 mm were distributed in similar areas to females, except the highest concentrations were between the Pribilof Islands and St. Matthews Island.

Armstrong and Ernst (in press) found the centroids of survey summer distributions have moved to the north over time (Figures 19 and 20). In the early 1980's the centroids of mature female distribution were near 58.5 deg N, in the 1990's the centroids were about 59.5 deg N. The centroids of old shell male distribution was south of 58 deg 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 (Figure 20). The distribution of males>101 mm was about at 58 deg N in the early 1980's, then was farther north (58.5 to 59 deg 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 deg N.(Figure 20). The centroids of the catch are generally south of 58 deg N, except in 1987 (Figure 20). 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 deg N in 1997 and 1998, then moved north to above 58.5 deg in 2002.

# ANALYTIC APPROACH

## Data Sources

Catch data and size frequencies of retained crab from the directed snow crab pot fishery from 1978 to the 2007 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 2007. Total discarded catch was estimated from observer data from 1992 to 2007(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 2007. The discard catch estimate was multiplied by the assumed mortality of discards from the pot fishery. The mortality of discarded crab was assumed to be 50%. This estimate differs from the ADF&G harvest strategy used since 2001, which assumes a discard mortality of 25% (Zheng 2002). The discard mortality assumptions will be discussed in a later section. The estimated discards previous to 1992 may be underestimates due to the lack of escape mechanisms for undersized crab in the pots prior to 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 | 1978-2007 (Year when fishery actually occurred) |
| Discarded male and female crab pot fishery size frequency | 1992-2007 |
| Trawl fishery bycatch size frequencies by sex | 1991-2007 |
| Survey size frequencies by sex and shell condition | 1978-2007 |
| Retained catch estimates | 1978-2007 |
| Discard catch estimates from snow crab pot fishery | 1992-2007 from observer data |
| Trawl bycatch estimates | 1973-2007 |
| Total survey biomass estimates and coefficients of variation | 1978-2007 |

## 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.

Details of the population dynamics and estimation equations, description of variables and likelihood equations are presented in Appendix A (Tables A.1, A.2 and A.3). The population dynamics equations, incorporating the growth transition matrix and molting probabilities are similar to other size based crab models (Zheng et al. 1995 and 1998). There were a total of 234 parameters estimated in the model (Table A.4) for the 30 year range of data (1978-2007). The 90 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 30 recruitment parameters estimated in the model, one for the mean recruitment, 29 for each year from 1979 to 2007 (male and female recruitment were fixed to be equal). There were 12 fishery selectivity parameters that did not change over time as in previous assessments. Survey selectivity was estimated for three different periods resulting in 9 parameters estimated. One parameter was estimated to fit the pot fishery CPUE time series.

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 fixed in the model using parameters estimated from growth measurements for Bering Sea snow crab (4 parameters, Table A.5). 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 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 parameters estimated in the model. The alpha parameter of the distribution was fixed at 11.5 and the beta parameter was fixed at 4.0. Eighty-eight 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.

## 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 21).

## 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.

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 and applied to all years of survey data to estimate mature survey numbers. A two-parameter logistic function fit the fraction mature for larger new shell males well, resulting in size at 50% mature for new shell males of 88 mm CW with a slope of 0.12. 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 (Lou Rugolo et al. 2005).

The probability of a new shell crab maturing was estimated outside the model to move crab from immature to mature in the model. The probability of maturing was estimated to match the observed fraction mature for all mature males and females observed in the survey data. While the fraction of all animals that are mature is fit well, the fraction of crab that are old shell is greater than in the survey data. The probability of maturing by size for female crab was about 50% at about 50 mm and increased to 100% at 80mm (Figure 22). The probability of maturing for male crab was 20% at 80 mm, increased to 50% at 100mm, about 905 at 120mm and 100% at 135 mm.

## Selectivity

Selectivity curves for the retained and total catch were estimated as two-parameter ascending logistic curves (Figure 23). 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 the retention curve by the selectivities for the retained plus discarded size compositions.

The selectivities for the survey and trawl bycatch were estimated with two-parameter, ascending logistic functions (Survey selectivities in Figure 24). Survey selectivities were set equal for males and females. Separate survey selectivities were estimated for the period 1978 to 1981, 1982 to 1988, and 1989 to the present. The maximum selectivity was estimated in the 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) (Figure 24). 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.

## Growth

Very little information exists on growth for Bering Sea snow crab. 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, 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.

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 25). 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. No growth measurements exist for Bering Sea snow crab females. North Atlantic growth data indicate growth is slightly less for females than males.

Growth was modeled using a linear function to estimate the mean width after molting given the mean width before molting (Figure 25),

$$\text{Width}_{t+1} = a + b^* \text{ width}_t$$

The parameters a and b were estimated from the observed growth data for Bering Sea male snow crab. However, the intercept for both male and female crab was estimated as the average of the intercepts estimated for males from the Bering Sea data and the value assumed for females. Equal intercepts were used because growth of both sexes is probably equal at some small size.

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

$$Gr_{s,l\to l'} = \int_{l'-2.5}^{l'+2.5} Gamma(\alpha_{s,l}, \beta_s)$$

Where Gr is the growth transition matrix for sex, s and length bin l (premolt size). l' is the postmolt size. The Gamma distribution is,

$$g(x \mid \alpha_{s,l}, \beta_s) = \frac{x^{\alpha_{s,l}-1} e^{-\frac{x}{\beta_s}}}{\beta^{\alpha_{s,l}} \Gamma(\alpha_{s,l})} \quad .$$

Where x is length and alpha and beta are parameters. Beta for both males and females was fixed in the model at 0.75.

## Natural Mortality

Natural mortality is an essential control 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 it may be correlated with other parameters, and therefore is usually fixed. However, a large portion of the uncertainty in model results (e.g. current biomass), will be attributed to uncertainty in natural mortality, when natural mortality is estimated in the model. 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).

### Estimation Techniques

#### Hoenig, 5% Rule and maximum age

In the 2004 snow crab SAFE, natural mortality was assumed to be between 0.2 for males and females. A maximum age of 20 years would result from an M of about 0.21 (Table 5) (Hoenig 1983). A natural mortality of 0.3 would indicate a maximum age of about 14 years (Hoenig 1983). Anthony (1982) proposed that the 95% percentile of age be used to limit the maximum age in yield modeling. This procedure would result in an M of 0.2 for a maximum observed age of 15 years. A natural mortality of 0.3 results in about 5% of animals remaining after 10 yrs of age. Research is currently underway to assess a method using lipofuscin for age determination (Se-Jong, et al. 1999). A maximum age of about 13 years for females and 19 years for males has been hypothesized for North Atlantic snow crab by Comeau, et al (1998) based on size frequency analysis and growth data. Sainte-Marie, et al (1995) estimated an age of about 9 years for a 95 mm male snow crab and 11 years for a 131 mm crab for a different sub-population of Atlantic snow crab than Comeau, et al (1998) using size frequency analysis and growth data. A maximum time at large of 8 years for tag returns of terminally molted mature male snow crab in the North Atlantic has been recorded since tagging started about 1993 (Sainte-Marie, pers. comm.).

#### Model based

Otto (1998) estimated natural mortality of male snow crab based on survey data and retained catches to be greater than 1.0. The snow crab fishery generally occurs over a

short time span, about 7 months after the survey. Otto (1998) overestimates M because the method assumed no time lapse between the survey and the fishery removals (during which natural mortality would be occurring) and no bycatch mortality. Otto (1998) assumed that shell condition is an accurate indicator of age since last molt (new shell less than one year, old shell crabs more than one, but less than two years from molting), and that new and old shell crabs were accurately categorized by shell condition. Radiometric aging and tagging data indicate shell condition is not an accurate measure of shell age (discussed in Maximum post-terminal molt age and shell classification section).

Zheng (unpub) investigated natural mortality of Bering Sea snow crab using a modeling approach, accounting for natural mortality between the time of the survey and the fishery. Estimates of natural mortality ranged from 0.0 to 0.97, depending on assumptions made for molting probabilities, growth per molt and survey selectivities (Zheng unpub.).

Tanner crab

Tanner crab have a similar life history to snow crab and probably have similar longevity. Zheng et al. (1998) estimated natural mortality and bycatch mortality together to be about 0.5 for male and female Bering Sea Tanner crab (*Chionecites bairdi*) in a population dynamics model. He did not estimate bycatch mortality separately, but, natural mortality would have been less than the reported 0.5 value. Somerton (1981) estimated natural mortality for male Tanner crab less than commercial size to be 0.35. M was estimated to be between 0.13 and 0.28 for commercial size male Tanner crab (Somerton 1981).

Maximum age post-terminal molt and shell classification

Crab are classified by shell condition at the time of the survey. SC1 crab are soft shell crab indicating they have recently molted. SC2 crab (new shell) have clean, hard shells. SC3 crab (old shell) show some wear and scratches and encrusting organisms are frequently present. SC4 crab (very old shell) have more wear and growth on the shell and encrusting organisms are almost always present. SC5 (very very old shell) have shells extensively stained and usually with extensive cover of encrusting organisms.

Orensanz (unpub.) used radiometric techniques to estimate shell age from last molt (Table 4). 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. 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, crabs older than the maximum age of 7 to 8 years are reasonably expected in the population. Maximum life span defined for a virgin stock is reasonably expected to be longer than these observed maximum ages of exploited populations.

Male snow crab during the mid to late 1980's were subjected to increasing exploitation with the maximum catch occurring in 1991. The maximum age in the sample of 6.85 years would be the result of fishing mortality as well as natural mortality. Using this maximum age would result in an upper bound on natural mortality. If crabs mature at about age 7 to 9, an additional 7 or 8 years gives a maximum total age of about 14 to 17 years. However, due to exploitation occurring at the same time, the maximum age that would occur due to M alone would be greater than 14 to 17 years.

Tag recovery data for Bristol Bay red king crab males in the 1968 Japanese fishery contains shell condition and carapace length at time of tagging and time of recapture (INPFC 1969). Thirty two of 98 animals tagged in July to August, 1967 and recaptured May to October 1968 did not grow, however, were assigned shell condition 2 (new shell) at recapture. Those 32 animals were 12 to 18 months from molting, if they had molted in spring of 1967. This would indicate that about 33% of animals that are clean shell (SC2) are actually more than a year from molting. There were 47 crabs assigned new shell of 52 animals that were at large more than two years that did not grow (tagged in 1966 and recaptured in 1968). These animals would have been at least 2 years from molting. Tagging of Bristol Bay male red king crab was also conducted in 1990, 1991 and 1993. Recoveries occurred in the fishery that took place in October to November of each year. Recovery information was recorded primarily by ADF&G research staff, dockside samplers and observers on board vessels. Only the 1991 tagging data had sufficient recaptures in 1992 and 1993 for analysis. There were 56 animals that were recaptured in November, 1992 that were tagged in September to October, 1991 that had carapace length measured and were recorded as new shell at recapture. Of those 56 new shell animals, 21 did not grow in the 1 year between tagging and recapture. Those 21 animals (37.5 % of the new shell animals) were more than 1 ½ years from molting and were recorded as new shell. This is similar to the results from the 1968 tag recaptures, indicating that shell condition as prescribed is suspect as a rigorously quantified index of shell age. Based on these results, molting probabilities and natural mortality will be overestimated by using shell condition as an index of true shell age.

We examined the empirical evidence for reliable estimates of oldest observed age for male snow crab. Radiometric aging of male snow crab carapaces sampled in the Bering Sea stock in 1992 and 1993, as well as the ongoing tag recovery evidence from eastern Canada reveal observed maximum ages in exploited populations of 17-19 years (Nevissi, et al 1995, St. Marie 2002). 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 99$^{th}$ percentile of the distribution of ages in an unexploited population if observable. Under negative exponential depletion, the 99$^{th}$ percentile corresponding to age 20 of an unexploited population corresponds to a natural mortality rate of 0.23. M=0.23 was used for all immature crab and for mature male crab. M was set at 0.29 for mature female crab assuming that maturity occurs at a younger age and post–mature longevity is similar to mature male crab. Information of longevity of female crab is needed for estimation of M.

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).

## 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 have 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 (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. Additional radiometric aging for male and female snow crab shells is being investigated to improve the estimate of radiometric ages from Orensanz (unpub. data).

## 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. Resorbtion 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 26 and 27). 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 relative and the resulting sex ratio in areas of highest reproductive potential. The faction of barren females was low in 2006, however, increased to high levels in 2007. Clutch fullness was high in 2006, then declined in 2007.

The fraction of barren females in the 2003 and 2004 survey south of 58.5 deg N latitude was generally higher than north of 58.5 deg N latitude (Figures 28 and 29). In 2004 the fraction barren females south of 58.5 deg 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 deg N latitude.

Laboratory analysis of female snow crab collected in waters less than 1.5 deg C and colder 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 deg C) were estimated from the summer survey data for 1982 to 2006 (Figure 30). The centroid is the average latitude and average longitude. In the 1980's the cold pool was farther south(about 58 to 59 deg N latitude) except for 1987 when the centroid shifted to north of 60 deg N latitude. The cold pool moved north from about 58 deg N latitude in 1999 to about 60.5 deg N latitude in 2003. The cold pool

was farthest south in 1989, 1999 and 1982 and farthest north in 1987, 1998, 2002 and 2003. 2005 the cold pool was north, then in 2006 back to the south.

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.

## Discard mortality

Discard mortality was assumed to be 50% for this assessment. 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.

# RESULTS

The total mature biomass increased from about 950 million lbs in 1978 to the peak biomass of 1,598 million lbs in 1990. Biomass declined sharply after 1997 to about 360 million lbs in 2003, then increased to 632 million lbs in 2007 (Table 3 and Figure 2). The model is constrained 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 animals in 1987, which followed through the population and resulted in the highest catches recorded in the early 1990's.

Average discard catch mortality for 1978 to 2007 was estimated to be about 16.7% of the retained catch (with 50% mortality applied), similar to the average observed discards from 1992 to 2007 (15.5%) (Table 1 and Figure 31). Parameter estimates for the 50% discard mortality model are in Table 7. During the last four years (2004 to 2007 fishery seasons) model estimates of discard mortality averaged 15% of the retained catch. Estimates of observed discard mortality ranged from 6% of the retained catch to 32% of the retained catch (assuming 50% discard mortality).

Mature male and female biomass show similar trends (Table 3, Figures 32 and 34). Mature male biomass increased from 282 million lbs in 2006 to 384 million lbs in 2007 (adjusted by survey selectivity), while observed survey mature male biomass increased from 331 million lbs to 385 million lbs. Model estimates of mature female biomass increased from 234 million lbs in 2006 to 248 million lbs in 2007. Mature female biomass observed from the survey increased from 189 million lbs in 2006 to 223 million lbs in 2007. Estimated biomass was lower in this assessment than in the 2007 assessment (Turnock and Rugolo 2007) due to the change in estimated survey selectivities, which resulted from the changes in fishery selectivity, growth and recruitment distribution (Figures 33 and 35).

Fishery selectivities and retention curves were estimated using ascending logistic curves (Figures 23 and 36). Selectivities for trawl bycatch were estimated as ascending logistic curves (Figure 37). Plots of model fits to the survey size frequency data are presented in Figures 38, and 42 by sex for shell conditions combined with residual plots in Figures 39 and 43. 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.

Patterns in the residual fits to the survey length frequency data are partly due to the linkage between growth and size at terminal molt. The terminal molt results in crabs within one year class ceasing to growth at various sizes. If shell age of mature crab could be accurately measured then the probability of crab maturing by size could be estimated from the survey data and shell age. However, since shell age is uncertain, a model was configured to estimate 22 parameters for each sex (one for each length bin). The sum of squared first differences of the parameters was added to the likelihood to produce a

smooth function over length (Figures 46 and 47). The resulting curves for males was higher at small sizes (40-65mm), lower at intermediate sizes (70-95mm) and higher at larger sizes (>100mm) than previously estimated outside the model. A higher probability of maturing results in more crab reaching terminal molt at smaller sizes, a lower probability results in crab growing to a larger size before terminal molt. The female curve was slightly lower at small sizes and higher at larger sizes, resulting in a more peaked length distribution, with fewer crab growing to larger sizes. The pattern of residuals for females for the model with estimated maturity is improved (Figures 40 and 41). Negative residuals at intermediate sizes for 1985 to 1995 are reduced for male survey length frequency fit using the model with estimated maturity (Figures 44 and 45), however, the pattern of residuals is similar to the base model.

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 the inconsistency in growth indicated by the observed survey length frequency data.

Survey selectivities for the period 1978 to 1981 were estimated at about 95% at 30 mm (Figure 24 and Table 9). Survey selectivities for the period 1982 to 1988 were estimated at 50% at about 43 mm and 95% at 69 mm. Survey selectivities for the period 1989 to the present were estimated at 50% at about 34 mm and 95% at 45 mm. These selectivities were the best fit determined by the model. An underbag experiment estimated survey selectivity of 50% at 78 mm and a maximum of about 89% at 135 mm (Somerton and Otto 1998) with the survey net in use since 1982. The survey selectivities are multiplied by the population numbers by length to estimate survey numbers for fitting to the survey data.

The estimated number of males > 101mm generally follows the observed survey numbers except for a few peak survey years where the model estimates are lower than the survey estimates (Figure 48). The observed survey estimate of males greater than 101 mm increased from about 69 million in 2005 to 135 million in 2006 and 151 million in 2007. The estimated 95% confidence interval for the observed survey large males in 2007was +/-40% of the estimate. Model estimates of large males were about 88 million crab in 2006 and 148 million crab in 2007.

Two main periods of high recruitment were estimated by the model, in 1981 (fertilization year) and in 1987-1988 (Figure 49). Recruits are 25mm to about 40 mm and may be about 4 years from hatching, 5 years from fertilization (Figure 50, although age is approximated). Low recruitments were estimated from 1990 to 1996 and in 2000 to 2002. The 1998-1999 year classes appear to be a above average recruitment that has resulted in an increase in biomass in 2006 and 2007. The estimated recruitments lagged by 5 years (approximate fertilization year) from the model are close to the higher survey estimates of abundance of females with eggs and abundance of females with eggs

multiplied by the fraction full clutch from 1975 to 1988 (Figure 51). Recruitment was low from 1990 to 1996, showing little relationship to the reproductive index. Exploitation rates were generally higher in 1986 to 1994, and in 1998-99 than prior to 1986 (Figure 4).

The size at 50% selected for the pot fishery for total catch (retained plus discarded) was 100.99 mm for males (shell condition combined, Figure 23). The size at 50% selected for the retained catch was 103.1 mm. The fishery generally targets new shell animals > 101mm with clean hard shells and all legs intact. The fits to the fishery size frequencies are in Figures 52 through 54. Fits to the trawl fishery bycatch size frequency data are in Figures 55 and 56.

Fishing mortality rates ranged from about 0.19 to 1.85 (Figure 57). Fishing mortality rates were 0.53 to 1.85, for the 1986 to 2003 fishery seasons. Full selection fishing mortality was estimated at 0.32 for 2005, 0.52 for the 2006 and 0.43 for 2007 (year fishery occurred).

## Harvest Strategy and Projected Catch

### Current Harvest Strategy

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 and was applied to survey biomass estimates to calculate the 2007/2008 fishery season retained catch of 63 million lbs. Prior to the passage of Amendment xx, 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 (230.4 million lbs of total mature biomass(TMB), 0.25*Bmsy), a minimum GHL of 15 million lbs for opening the fishery, and rules for computing the GHL.

In previous years, the MSY biomass ($B_{MSY}$ = 921.6 million pounds TMB) and overfishing rate ($F_{MSY}$ =M=0.3, the exploitation rate to apply to current mature male biomass (MMB)), was determined as a function of TMB as,

$$E = \frac{0.75 * Fmsy * \left[ \frac{TMB}{Bmsy} - \alpha \right]}{(1-\alpha)}$$

for TMB ≥ 0.25*Bmsy and TMB<Bmsy, where $\alpha$ = -0.35, and,

- E = (Fmsy * 0.75) = 0.225, for TMB ≥ Bmsy, and E = 0 for TMB < 0.25*Bmsy.

The maximum for a $GHL_{max}$ is determined by using the E determined from the control rule as an exploitation rate on mature male biomass at the time of the survey,

- $GHL_{max} = E \bullet MMB$.

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 legal males >=4.0-in (102 mm) CW plus a percentage of the estimated abundance of old shell legal males >=4.0-in CW. The percentage to be used is determined using fishery selectivities for old shell males.

**Overfishing Control Rule**

Amendment xx 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 (EA 2007) (Figure 60).

$$F = \frac{F35\% * \left[ \frac{MMB}{B35\%} - \alpha \right]}{(1-\alpha)}$$

$\alpha$ = 0.1. F on the directed fishery is set to zero when mature male biomass is below 25% of B35% (Figure 60). MMB is mature male biomass at the time of mating. Biomass and catch projections based on F35% and B35% were used to estimate the catch OFL (Table 6). Projections with F40% and B40% were used to evaluate the effect of a reduced catch on rebuilding probabilities and to provide catch projections with a buffer below the OFL to reduce the probability of overfishing, given uncertainty in current biomass and reference points. F35% was estimated at 0.642, lower than the value from the 2007 assessment (F35%=0.99, Turnock and Rugolo 2007) due to the change in fishery selectivities from combining shell condition. B35% was estimated at 328.8 million lbs, also lower than estimated in 2007 (355 million lbs) due to the changes in growth, recruitment distribution, fishery selectivities and the resulting change in estimated survey selectivity. F40% was estimated at 0.498 and B40% at 375.8 million lbs. B40% and B35% were estimated using average recruitment from1978 to 2007 and spawning biomass per recruit for males fishing at F40% or F35% respectively. The Bmsy of total mature biomass used the average from 1983 to 1997 as representative of the current productivity regime and the biomass reference point for the rebuilding plan. A measure of productivity can be estimated from the natural log of the ratio of recruitment to mature male biomass (Figures 63 and 64). The period from 1978 to 1988(fertilization year) has the highest productivity and 1989 to 2002 the lowest. The most recent period since 1997 has an average productivity that is higher than 1989 -1996 and is near the average for the whole time period (1978-2002).

Estimated fishing mortality from 1979 fishing season to 2007 have been above the F35% control rule except for five years (1979, 1984-1985, 1996-97) (Figure 60). The target F historically (pre-2000 fishery season) was about 1.1 which was exceeded in many years. The last three fishery seasons (2005-2007) F was estimated at 0.32, 0.52 and 0.43. The F in 2007 was just below the F35% control rule. Full selection fishing mortality for the 2007/8 season with a retained catch of 63 million lbs was estimated at 0.45, just below the F35% control rule.

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 2008 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, 0.62 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 2008 mature male biomass projected forward to the time of mating time (spring 2009), 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 23).

**Harvest recommendations**

Fishing mortality, biomass values and total catches were projected for the 2008/9 to 2012/13 fishery seasons (Table 6). The MMB in spring 2008 was estimated to be 275.8 mill lbs, about 84% of B35% if the 63 million lb TAC (retained catch) is taken. The MMB in spring 2009 is estimated to be 304.3 mill lbs, about 93% of B35%. The F35% total catch for 2008/9 was estimated at 123 million lbs with a retained catch of 108.4 million lbs. The 2008/9 F40% total catch was estimated at 96.4 million lbs, with a retained catch of 84.6 million lbs. Total catch includes retained directed pot fishery, discard pot fishery (with 50% mortality of discards) and trawl bycatch (80% mortality). However, the probability of rebuilding to the survey total mature biomass (Bmsy 921.6 million lbs) by 2010 is low for both these control rules. The probability of rebuilding and OFL for 2008/9 were estimated using F50%, F60%, F75% and groundfish bycatch only control rules (Table 7). The bycatch only control rule estimates rebuilding by 2011 (probability = 0.5 of being above Bmsy). The year of rebuilding for the other control rules varies from 2018 for F35% to 2012 for F75%. A reduced catch may be needed to increase the probability of rebuilding the stock to Bmsy (921.6 million lbs of total mature biomass). These probabilities were estimated using a lognormal distribution with cv = 0.15 on biomass, which is similar to recent estimates on survey biomass. Higher levels of uncertainty will result in higher probability of rebuilding in the initial years of the projection. Variability in recruitment will dominate the uncertainty in later years.

Catch and biomass projections using the model with maturity estimated were slightly lower, however, very similar to the base model (Table 8). Fishing mortality reference

points were higher, however, fishery selectivities were estimated lower, due to the changes in sizes at terminal molt in the population.

Computing the catch based on the total survey area may result in exploitation rates higher than the target rate on crabs in the southern area of the distribution. One solution would be to split the catch into two regions, north and south, according to the percent distribution of the survey estimate of large males or mature males from those regions. This would require knowing the location of catch inseason. Two other approaches would not require knowledge on inseason catch location. One approach would be to compute the catch from that portion of the stock where most of the catch is extracted. Another approach would be to compute a catch that would result in the target harvest rate for the southern portion of the stock and increase that catch according to the percent catch in the north.

**Projections and Rebuilding Scenarios**

Projections and rebuilding trajectories were estimated using simulation with F35% and F40% harvest control rules and lognormally distributed, autocorrelated recruitment from a Beverton-Holt spawner recruit curve (steepness= 0.68, R0=2.0 billion, cv recruitment =0.86, autocorrelation = 0.6). The rebuilding plan developed for snow crab projected a 50% probability of rebuilding by 2010. The probability of rebuilding to the total survey biomass Bmsy of 921.6 million lbs is 6.1% in 2010, fishing at F35% and 7.7% fishing at F40% (Table 6). While male mature biomass is projected to increase, female biomass is projected to decline in the next few years. The probability of rebuilding in the first few years of the projection depends on the variance on biomass used in the projections (cv=0.15). In later years, as recruitments enter the mature stock, then most variability is due to variability in recruitment. The use of random recruitment will result in a higher probability of rebuilding the stock relative to using a spawner recruit curve and autocorrelated recruitment as used in the projections presented here.

Biomass and catch projections for F35% increase in 2008, then decrease. Biomass and catch projections for F40% increase in 2008 and 2009, then decrease (Table 6). The probability of rebuilding to B35% is about 21.3% in 2010/11 fishing at F35% and 73.4% fishing at F40%. The model and observed biomass estimates have followed the expected trends in biomass from the snow crab rebuilding plan for 2002 to 2007 (Figures 61 and 62). Catches in the early years of the rebuilding period (2001 to 2006) exceeded the expected catches due to higher realized biomass and to a change in the minimum GHL that kept the snow crab fishery open. Catches estimated from the F35% control rule are higher than the expected value from the rebuilding, while F40% catches are projected to be higher in the 2008/9 season and then equal to the expected value in 2009/10. Future survey data will reduce uncertainty in the estimate of the strength of recent recruitments.

**Conservation concerns**

- The Bering Sea snow crab survey estimates of total mature biomass in 2007 were 65% of the survey Bmsy (921.6 million lbs). The probability of rebuilding to total survey mature biomass Bmsy by 2010 is low under the F35% and F40% control rules.

- Moderate recruitment is estimated in 1998-1999 fertilization year, however, in general recruitment has been at low levels in the last 10 years (since 1994). The stock is projected to increase then decline slowly, unless higher recruitments appear.

- Discard mortality has been assumed to be 50%, however there is a high level of uncertainty in this parameter. While sensitivity studies have shown only small differences in long term catch and biomass with different assumptions on discard mortality, higher discard mortality would necessitate lower retained catches in the short term.

- 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.

**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. Additional sampling of crabs that are close to molting is needed to estimate growth for immature males and females.

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.

The experiment to estimate catchability of the survey trawl net needs to be repeated with larger sample sizes to allow the estimation of catchability by length, sex and shell condition for snow crab (and Tanner crab). This is needed to determine if the number of mature old shell crabs in the observed survey (which are lower than expected in the model) are due to mortality (fishery discard or natural mortality) or due to lower catchability in the trawl survey.

Female opilio in waters less than 1.5 deg 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.

A full management strategy evaluation of the snow crab model has been proposed that may be conducted in 2008-2010.

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Table 1. Catch (1,000s of lbs) 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 2007 were estimated from observer data. Model estimates of male discard include a 50% mortality of discarded crab.

| Year fishery occurred | Retained catch(1,000s of lbs) | Observed Discard male catch | Observed Retained + discard male catch | Model estimate of male discard | Discard female catch | Model estimate total directed catch | Year of trawl bycatch | trawl bycatch |
|---|---|---|---|---|---|---|---|---|
| 1973 | 6,711 | | | | | | 1973 | 30,046 |
| 1974 | 5,033 | | | | | | 1974 | 41,582 |
| 1975 | 8,250 | | | | | | 1975 | 16,096 |
| 1976 | 10,050 | | | | | | 1976 | 6,975 |
| 1977 | 16,284 | | | | | | 1977 | 4,722 |
| 1978-79 | 52,272 | | | 12,711 | 73 | 65,056 | 1978 | 5,422 |
| 1979-80 | 75,025 | | | 11,988 | 91 | 87,104 | 1979 | 4,357 |
| 1980-81 | 66,933 | | | 15,352 | 81 | 82,366 | 1980 | 3,170 |
| 1982 | 29,355 | | | 11,392 | 46 | 40,793 | 1981 | 1,323 |
| 1983 | 26,128 | | | 6,142 | 62 | 32,332 | 1982 | 538 |
| 1984 | 26,813 | | | 3,289 | 44 | 30,146 | 1983 | 693 |
| 1985 | 65,999 | | | 7,278 | 43 | 73,320 | 1984 | 737 |
| 1986 | 97,984 | | | 14,930 | 44 | 112,958 | 1985 | 632 |
| 1987 | 101,903 | | | 24,072 | 96 | 126,071 | 1986 | 2,716 |
| 1988 | 135,355 | | | 34,065 | 139 | 169,559 | 1987 | 8 |
| 1989 | 149,456 | | | 40,910 | 148 | 190,514 | 1988 | 974 |
| 1990 | 161,821 | | | 46,669 | 192 | 208,682 | 1989 | 1,131 |
| 1991 | 328,647 | | | 73,657 | 204 | 402,508 | 1990 | 865 |
| 1992 | 315,302 | 96,214 | 411,516 | 53,970 | 234 | 369,506 | 1991 | 9,578 |
| 1993 | 230,787 | 124,865 | 355,652 | 41,689 | 481 | 272,957 | 1992 | 4,669 |
| 1994 | 149,776 | 38,922 | 188,698 | 28,458 | 321 | 178,555 | 1993 | 3,010 |
| 1995 | 75,253 | 29,436 | 104,689 | 19,698 | 232 | 95,183 | 1994 | 3,393 |
| 1996 | 65,713 | 42,104 | 107,817 | 18,216 | 63 | 83,992 | 1995 | 1,844 |
| 1997 | 119,543 | 54,391 | 173,934 | 23,462 | 277 | 143,282 | 1996 | 2,074 |
| 1998 | 243,342 | 41,982 | 285,324 | 36,701 | 22 | 280,065 | 1997 | 2,906 |
| 1999 | 194,000 | 34,158 | 228,158 | 30,716 | 26 | 224,742 | 1998 | 2,159 |
| 2000 | 33,500 | 3,790 | 37,290 | 5,416 | 2 | 38,918 | 1999 | 796 |
| 2001 | 25,256 | 4,537 | 29,793 | 4,138 | 2 | 29,396 | 2000 | 889 |
| 2002 | 32,722 | 13,824 | 46,546 | 7,280 | 17 | 40,019 | 2001 | 635 |
| 2003 | 28,307 | 9,938 | 38,245 | 6,837 | 3 | 35,147 | 2002 | 384 |
| 2004 | 23,942 | 4,196 | 28,138 | 4,011 | 6 | 27,959 | 2003 | 289 |
| 2005 | 24,892 | 3,716 | 28,608 | 3,012 | 3 | 27,907 | 2004 | 740 |
| 2006 | 36,974 | 9,965 | 46,939 | 5,311 | 12 | 42,297 | 2005 | 1,378 |
| 2007 | 36,356 | 12,995 | 49,351 | 7,040 | 5 | 43,401 | 2006 | 385 |
| | | | | | | | 2007 | 702 |

**Table 2. Observed survey female, male and total spawning biomass(millions of lbs) and numbers of males > 101mm (millions of crab).**

| Year | Observed survey female mature biomass | Observed survey male mature biomass | Observed survey total mature biomass | Observed number of males > 101mm (millions) |
|---|---|---|---|---|
| 1978 | 336.6 | 424.9 | 761.5 | 163.4 |
| 1979 | 712.2 | 528.7 | 1,240.9 | 169.1 |
| 1980 | 894.8 | 385.1 | 1,279.9 | 109.0 |
| 1981 | 480.2 | 262.1 | 742.3 | 45.4 |
| 1982 | 507.0 | 403.0 | 910.1 | 65.0 |
| 1983 | 316.6 | 355.3 | 671.9 | 71.5 |
| 1984 | 145.2 | 387.5 | 532.6 | 154.2 |
| 1985 | 21.2 | 167.2 | 188.4 | 78.2 |
| 1986 | 55.8 | 200.9 | 256.7 | 80.0 |
| 1987 | 448.4 | 462.2 | 910.6 | 141.9 |
| 1988 | 556.1 | 538.8 | 1,094.9 | 167.3 |
| 1989 | 1,006.2 | 712.3 | 1,718.4 | 175.4 |
| 1990 | 649.6 | 905.4 | 1,555.0 | 407.2 |
| 1991 | 793.0 | 981.8 | 1,774.8 | 466.6 |
| 1992 | 463.9 | 574.8 | 1,038.8 | 251.4 |
| 1993 | 505.0 | 545.3 | 1,050.3 | 140.8 |
| 1994 | 473.6 | 379.4 | 853.0 | 80.3 |
| 1995 | 622.0 | 507.8 | 1,129.8 | 69.0 |
| 1996 | 435.0 | 744.9 | 1,179.9 | 170.1 |
| 1997 | 387.6 | 663.5 | 1,051.2 | 308.5 |
| 1998 | 285.4 | 529.3 | 814.7 | 244.0 |
| 1999 | 113.5 | 216.6 | 330.1 | 92.2 |
| 2000 | 374.7 | 227.1 | 601.8 | 75.6 |
| 2001 | 318.4 | 339.2 | 657.5 | 79.4 |
| 2002 | 120.5 | 232.8 | 353.3 | 73.5 |
| 2003 | 130.2 | 197.8 | 328.0 | 64.6 |
| 2004 | 194.3 | 196.6 | 390.9 | 65.8 |
| 2005 | 256.7 | 294.8 | 551.4 | 68.9 |
| 2006 | 188.9 | 330.5 | 519.5 | 135.3 |
| 2007 | 222.6 | 385.2 | 607.8 | 150.8 |

**Table 3. Model estimates of population biomass, population numbers, male, female and total mature biomass(million lbs) and number of males greater than 101 mm in millions. Recruits enter the population at the beginning of the survey year after molting occurs.**

| Year | Biomass (million lbs 25mm+) | numbers (million crabs 25mm+) | female mature biomass | Male mature biomass | total mature biomass | Number of males >101mm (millions) | Recruitment (millions, 25 mm to 50 mm) | Male mature biomass at mating time(Feb of survey year+1) | Ratio mature females to mature males at mating time |
|---|---|---|---|---|---|---|---|---|---|
| 1978 | 1,355 | 7,124 | 465 | 485 | 950 | 96 | * | 349 | 2.8 |
| 1979 | 1,310 | 6,134 | 548 | 452 | 1,000 | 110 | 647 | 289 | 3.6 |
| 1980 | 1,186 | 5,213 | 561 | 352 | 914 | 69 | 536 | 217 | 4.1 |
| 1981 | 1,063 | 4,277 | 517 | 287 | 804 | 43 | 328 | 206 | 3.8 |
| 1982 | 1,037 | 4,389 | 443 | 328 | 771 | 89 | 1,140 | 247 | 3.1 |
| 1983 | 1,060 | 5,016 | 381 | 392 | 773 | 142 | 1,648 | 298 | 2.6 |
| 1984 | 1,115 | 5,677 | 352 | 409 | 761 | 150 | 1,794 | 265 | 2.6 |
| 1985 | 1,200 | 6,646 | 353 | 373 | 726 | 121 | 2,265 | 217 | 2.7 |
| 1986 | 1,552 | 11,612 | 380 | 360 | 740 | 105 | 6,492 | 212 | 2.7 |
| 1987 | 1,864 | 11,016 | 494 | 431 | 925 | 132 | 1,977 | 252 | 2.9 |
| 1988 | 2,154 | 10,500 | 600 | 542 | 1,142 | 162 | 1,996 | 314 | 2.7 |
| 1989 | 2,318 | 8,729 | 656 | 708 | 1,364 | 223 | 691 | 449 | 2.3 |
| 1990 | 2,338 | 7,108 | 638 | 960 | 1,598 | 389 | 504 | 494 | 2.1 |
| 1991 | 1,994 | 6,634 | 568 | 919 | 1,487 | 378 | 1,468 | 458 | 2.0 |
| 1992 | 1,680 | 7,871 | 498 | 702 | 1,199 | 250 | 3,023 | 368 | 2.1 |
| 1993 | 1,505 | 7,865 | 477 | 514 | 991 | 150 | 1,932 | 297 | 2.3 |
| 1994 | 1,457 | 6,818 | 487 | 423 | 910 | 91 | 808 | 290 | 2.4 |
| 1995 | 1,487 | 5,412 | 482 | 482 | 964 | 123 | 184 | 355 | 2.1 |
| 1996 | 1,482 | 4,297 | 441 | 633 | 1,074 | 230 | 173 | 431 | 1.8 |
| 1997 | 1,313 | 3,398 | 374 | 695 | 1,069 | 287 | 194 | 360 | 1.8 |
| 1998 | 931 | 2,902 | 304 | 490 | 794 | 177 | 492 | 233 | 1.9 |
| 1999 | 641 | 2,772 | 248 | 275 | 522 | 65 | 694 | 204 | 1.9 |
| 2000 | 572 | 2,450 | 214 | 231 | 445 | 51 | 326 | 165 | 1.9 |
| 2001 | 531 | 2,116 | 191 | 204 | 394 | 44 | 236 | 141 | 2.0 |
| 2002 | 517 | 2,299 | 170 | 190 | 360 | 45 | 690 | 137 | 1.9 |
| 2003 | 577 | 3,420 | 157 | 203 | 360 | 63 | 1,657 | 154 | 1.8 |
| 2004 | 691 | 4,405 | 170 | 223 | 393 | 76 | 1,742 | 169 | 1.9 |
| 2005 | 784 | 3,879 | 208 | 242 | 450 | 76 | 436 | 171 | 2.2 |
| 2006 | 902 | 4,121 | 234 | 282 | 516 | 88 | 1,118 | 209 | 2.0 |
| 2007 | 982 | 3,432 | 248 | 384 | 632 | 148 | 244 | | |

*** Numbers by length estimated in the first year, so recruitment estimates start in second year.**

Table 4. 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 5. Natural mortality estimates for Hoenig (1983) and the 5% rule given the oldest observed age.

| | Natural Mortality | |
|---|---|---|
| oldest observed age | Hoenig (1983) empirical | 5% rule |
| 10 | 0.42 | 0.3 |
| 15 | 0.28 | 0.2 |
| 17 | 0.25 | 0.18 |
| 20 | 0.21 | 0.15 |

Table 6. Projections using F35% and F40% rules for 2007/8 to 2012/2013 fishery seasons. Values for the 2007/2008 retained catch were set to the TAC of 63 million lbs. Mature male biomass is at time of mating (millions of lbs). Large male biomass (>101mm) is at the beginning of the fishery. Survey total mature biomass is at the time of the survey (millions of lbs). Probability of rebuilding was estimated using total survey mature biomass with a target of 921.6 million lbs and for mature male biomass at the time of mating using B35% (328.8 million lbs). F35% = 0.642, F40%= 0.498, B40%= 375.8 million lbs. Total catch includes retained pot fishery catch (males), discard pot fishery catch (with 50% mortality)(males and females) and trawl bycatch (with 80% mortality) (males and females).

| F35% | Total catch | Lower 95% C.I. total catch | Upper 95% C.I. total catch | Retained catch | Maximum F (full selection) | Mature male biomass at mating time | Male Biomass (>101mm) at beginning of Fishery | Total survey mature biomass | Prob. of rebuilding to Bmsy (921.6 mill lbs) | Prob. of rebuilding to B35% | Exp. Rate for total catch on MMB at time of fishery |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | | | | | | | | | | | |
| 2007/8 | 74.7 | 74.7 | 74.7 | 63 | 0.45 | 275.8 | 172.8 | 634.6 | 0.001 | 0.025 | 0.21 |
| 2008/9 | 123 | 79 | 162.1 | 108.4 | 0.59 | 304.3 | 246.5 | 714.4 | 0.036 | 0.116 | 0.29 |
| 2009/10 | 110.8 | 75.5 | 144.1 | 98.9 | 0.57 | 291.9 | 233.0 | 680.4 | 0.052 | 0.185 | 0.27 |
| 2010/11 | 85.8 | 57.8 | 119.2 | 75.8 | 0.52 | 266.4 | 193.4 | 618 | 0.061 | 0.213 | 0.24 |
| 2011/12 | 71.7 | 44.5 | 105.9 | 63.1 | 0.48 | 252.1 | 169.7 | 594.4 | 0.069 | 0.236 | 0.22 |
| 2012/13 | 68.8 | 33.7 | 139.6 | 59.1 | 0.47 | 251.4 | 157.3 | 597.9 | 0.107 | 0.281 | 0.21 |

| F40% | Total catch | Lower 95% C.I. total catch | Upper 95% C.I. total catch | Retained catch | Maximum F (Full selection) | Mature male biomass at mating time | Male Biomass (>101mm) at beginning of Fishery | Total survey mature biomass | Prob. of rebuilding to Bmsy (921.6 mill lbs) | Prob. of rebuilding to B35% | Exp. Rate for total catch on MMB at time of fishery |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | | | | | | | | | | | |
| 2007/8 | 74.7 | 74.7 | 74.7 | 63.0 | 0.45 | 275.8 | 172.8 | 634.6 | 0.001 | 0.094 | 0.21 |
| 2008/9 | 96.4 | 59.1 | 134.8 | 84.6 | 0.43 | 326.7 | 246.5 | 714.4 | 0.036 | 0.493 | 0.23 |
| 2009/10 | 96.7 | 64.0 | 129.7 | 86.4 | 0.44 | 327.0 | 254.0 | 707.4 | 0.063 | 0.697 | 0.23 |
| 2010/11 | 78.8 | 51.7 | 112.0 | 69.9 | 0.40 | 302.9 | 221.1 | 654.1 | 0.077 | 0.734 | 0.21 |
| 2011/12 | 66.8 | 41.1 | 100.1 | 59.1 | 0.37 | 287.1 | 197.3 | 631.1 | 0.097 | 0.749 | 0.19 |
| 2012/13 | 63.6 | 31.8 | 126.8 | 55.0 | 0.36 | 284.7 | 183.0 | 632.7 | 0.144 | 0.774 | 0.18 |

Table 7. Rebuilding (survey total mature biomass bmsy=921.6 million lbs) and catch projects for F35%, F40%, F60%, F75% and bycatch only control rules (CR).

| CR | Rebuild Year | Probability of rebuilding 2010 | total catch 2008/9 | Retained catch 2008/9 |
|---|---|---|---|---|
| F35% | 2018 | 0.061 | 123 | 108.4 |
| F40% | 2017 | 0.077 | 96.4 | 84.6 |
| F50% | 2015 | 0.147 | 58.4 | 50.5 |
| F60% | 2014 | 0.22 | 34.9 | 29.3 |
| F75% | 2012 | 0.291 | 15.4 | 11.7 |
| Bycatch only | 2011 | 0.344 | 2.5 | 0 |

Table 8. Projections for model with maturity probability estimated, using F35% and F40% rules for 2007/8 to 2012/2013. Values for the 2007/2008 retained catch were set to the TAC of 63 million lbs. Mature male biomass is at time of mating (millions of lbs). Large male biomass (>101mm) is at the beginning of the fishery. Survey total mature biomass is at the time of the survey (millions of lbs). Probability of rebuilding was estimated using total survey mature biomass with a target of 921.6 million lbs and for mature male biomass at the time of mating using B35% (321.0 million lbs). F35% = 0.73, F40%= ??, B40%= ?? million lbs. Total catch includes retained pot fishery catch (males), discard pot fishery catch (with 50% mortality)(males and females) and trawl bycatch (with 80% mortality) (males and females).

| F35% | Total catch | Lower 95% C.I. total catch | Upper 95% C.I. total catch | Retained catch | Maximum F (full selection) | Mature male biomass at mating time | Male Biomass (>101mm) at beginning of Fishery | Total survey mature biomass | Prob. of rebuilding to Bmsy (921.6 mill lbs) | Prob. of rebuilding to B35% | Exp. Rate for total catch on MMB at time of fishery |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | | | | | | | | | | | |
| 2007/8 | 75.2 | 75.2 | 75.2 | 63.0 | 0.53 | 268.7 | 165.7 | 627.5 | 0 | 0.092 | 0.22 |
| 2008/9 | 120.0 | 77.4 | 157. | 105.2 | 0.67 | 297.8 | 235.1 | 703.6 | 0.023 | 0.201 | 0.29 |
| 2009/10 | 106.1 | 72.3 | 138.3 | 94.0 | 0.64 | 282.1 | 219.4 | 661.6 | 0.035 | 0.211 | 0.27 |
| 2010/11 | 83.1 | 56.1 | 114.9 | 72.9 | 0.58 | 259.4 | 183.8 | 607.1 | 0.041 | 0.213 | 0.24 |
| 2011/12 | 71.5 | 44.3 | 106.5 | 62.3 | 0.55 | 248.0 | 164.0 | 593.5 | 0.054 | 0.228 | 0.22 |
| 2012/13 | 70.9 | 33.9 | 146.1 | 60.3 | 0.54 | 250.3 | 155.8 | 605.1 | 0.102 | 0.278 | 0.22 |

| F40% | Total catch | Lower 95% C.I. total catch | Upper 95% C.I. total catch | Retained catch | Maximum F (full selection) | Mature male biomass at mating time | Male Biomass (>101mm) at beginning of Fishery | Total survey mature biomass | Prob. of rebuilding to Bmsy (921.6 mill lbs) | Prob. of rebuilding to B35% | Exp. Rate for total catch on MMB at time of fishery |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | | | | | | | | | | | |
| 2007/8 | 75.2 | 75.2 | 75.2 | 63.0 | 0.53 | 268.7 | 165.7 | 627.5 | 0 | 0.092 | 0.22 |
| 2008/9 | 94.9 | 58.5 | 131.9 | 82.9 | 0.50 | 320.7 | 235.1 | 703.6 | 0.023 | 0.512 | 0.23 |
| 2009/10 | 92.6 | 61.2 | 125.1 | 82.2 | 0.49 | 315.8 | 238.0 | 686.4 | 0.041 | 0.689 | 0.23 |
| 2010/11 | 76.0 | 49.7 | 107.7 | 66.9 | 0.45 | 294.0 | 208.3 | 640.0 | 0.056 | 0.73 | 0.21 |
| 2011/12 | 66.2 | 40.4 | 100.2 | 58.0 | 0.43 | 281.5 | 188.6 | 627.4 | 0.079 | 0.748 | 0.19 |
| 2012/13 | 65.1 | 31.5 | 131.8 | 55.8 | 0.42 | 282.8 | 179.2 | 637.7 | 0.133 | 0.778 | 0.19 |

Table 8. Parameters values for the model, excluding recruitments and fishing mortality parameters.

| | |
|---|---|
| Natural Mortality immature both sexes and mature males | 0.23 |
| Natural Mortality mature females | 0.29 |
| Female intercept (a) growth | 6.773 |
| Male intercept(a) growth | 6.773 |
| Female slope(b) growth | 1.05 |
| Male slope (b) growth | 1.16 |
| Alpha for gamma distribution of recruits | 11.5 |
| Beta for gamma distribution of recruits | 4.0 |
| Beta for gamma distribution female growth | 0.75 |
| Beta for gamma distribution male growth | 0.75 |
| Fishery selectivity total males slope | 0.2074 |
| Fishery selectivity total males length at 50% | 100.99 |
| Fishery selectivity retention curve males slope | 0.2563 |
| Fishery selectivity retention curve males length at 50% | 97.102 |
| Pot Fishery discard selectivity female slope | 0.3173 |
| Pot Fishery discard selectivity female length at 50% | 60.736 |
| Trawl Fishery selectivity slope | 0.0739 |
| Trawl Fishery selectivity length at 50% | 117.32 |
| Survey Q 1978-1981 | 1 |
| Survey 1978-1981 length at 95% selected | 30.0 |
| Survey 1978-1981 length at 50% selected | 15.7 |
| Survey Q 1982-1988 | 0.965 |
| Survey 1982-1988 length at 95% selected | 68.89 |
| Survey 1982-1988 length at 50% selected | 43.36 |
| Survey Q 1989-present | 1.0 |
| Survey 1989-present, length at 95% selected | 45.27 |
| Survey 1989-present length at 50% selected | 33.65 |
| Fishery cpue q | 0.00116 |

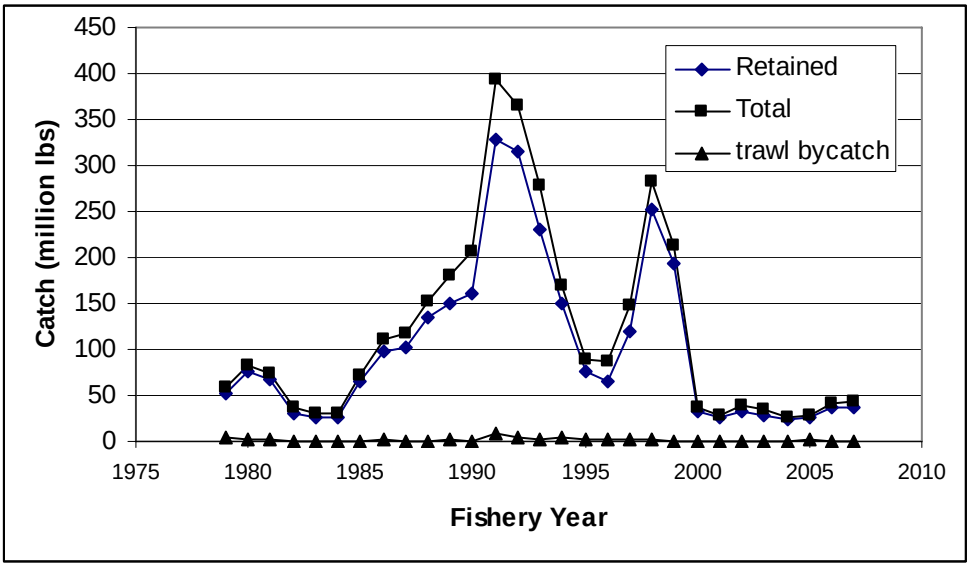


**Figure 1. Catch (million lbs) from the directed snow crab pot fishery and groundfish trawl bycatch. Total catch is retained catch plus discarded catch after 50% discard mortality was applied. Trawl bycatch is male and female bycatch from groundfish trawl fisheries with 80% mortality applied.**

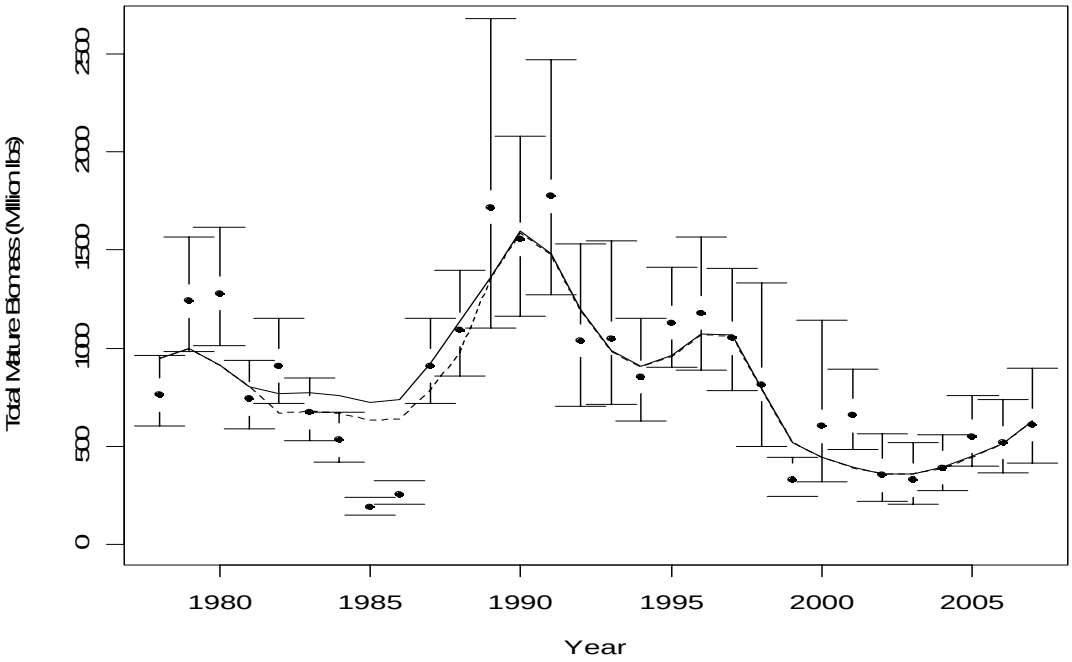


Figure 2. Population total mature biomass (millions of pounds, solid line), model estimate of survey mature biomass (dotted line) and observed survey mature biomass with approximate lognormal 95% confidence intervals.

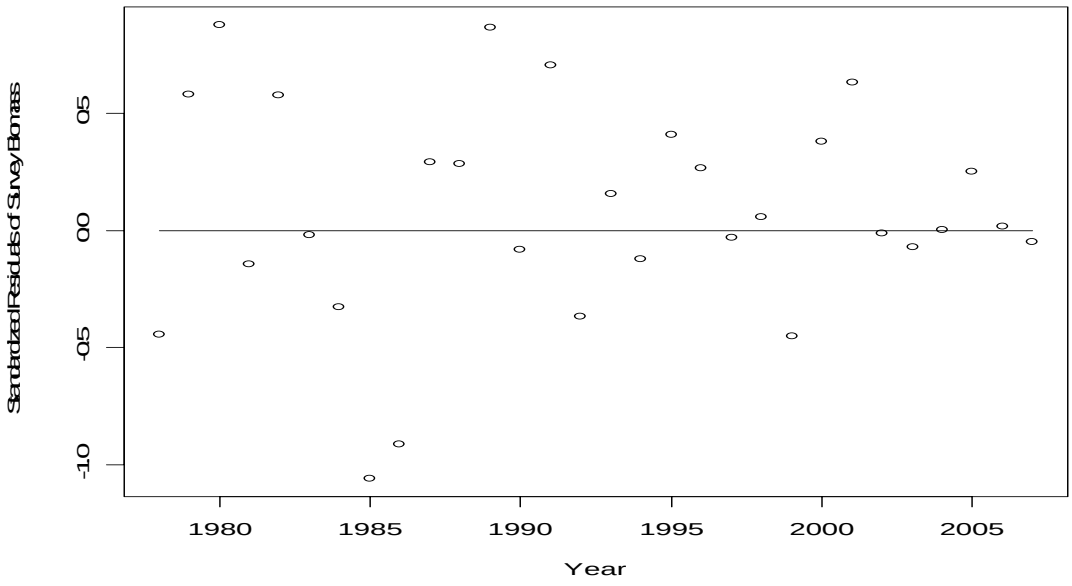


Figure 3. Standardized residuals for model fit to total mature biomass from Figure 2.

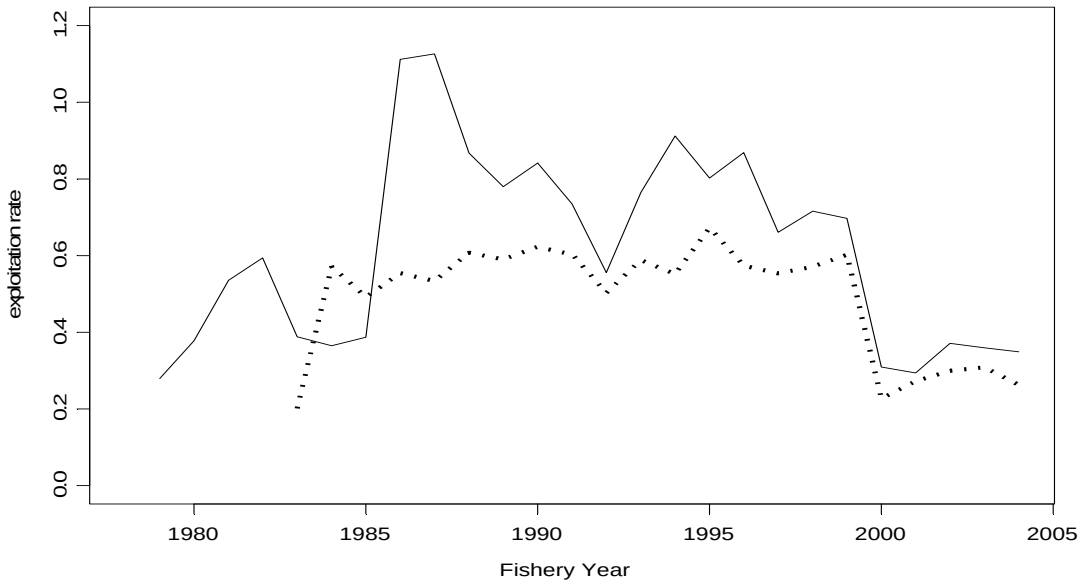


Figure 4. Exploitation rate estimated as the preseason GHL divided by the survey estimate of large male biomass (>101 mm) at the time the survey occurs (dotted line). The solid line is the retained catch divided by the survey estimate of large male biomass at the time the fishery occurs. Year is the year the fishery occurred.

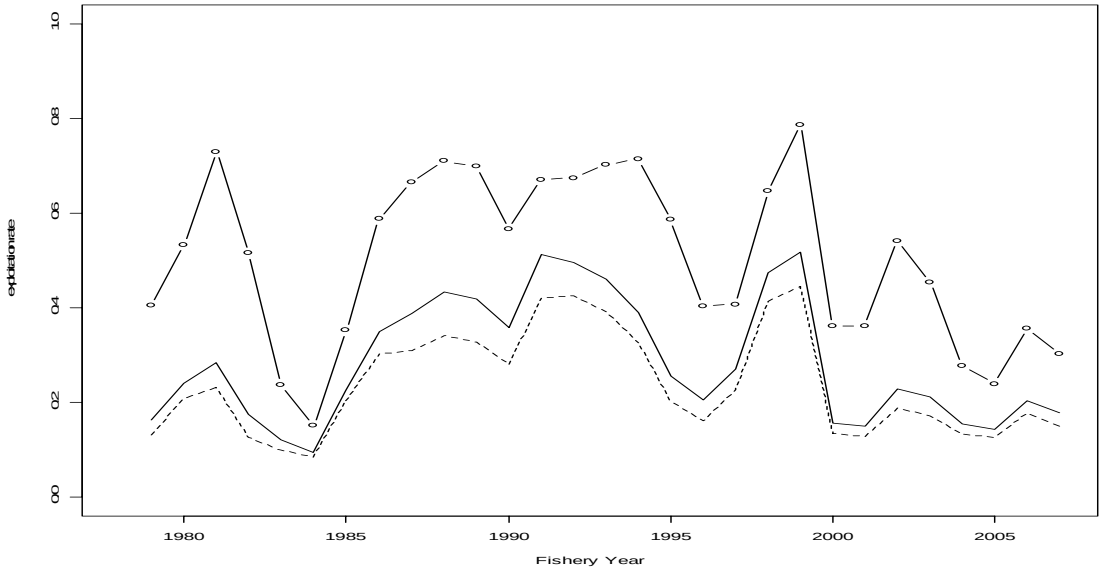


Figure 5. Exploitation fraction estimated as the catch biomass (total or retained) divided by the mature male biomass from the model at the time of the fishery (solid line and dotted line). The exploitation rate for total catch divided by the male biomass greater than 101 mm is the solid line with dots. Year is the year of the fishery.

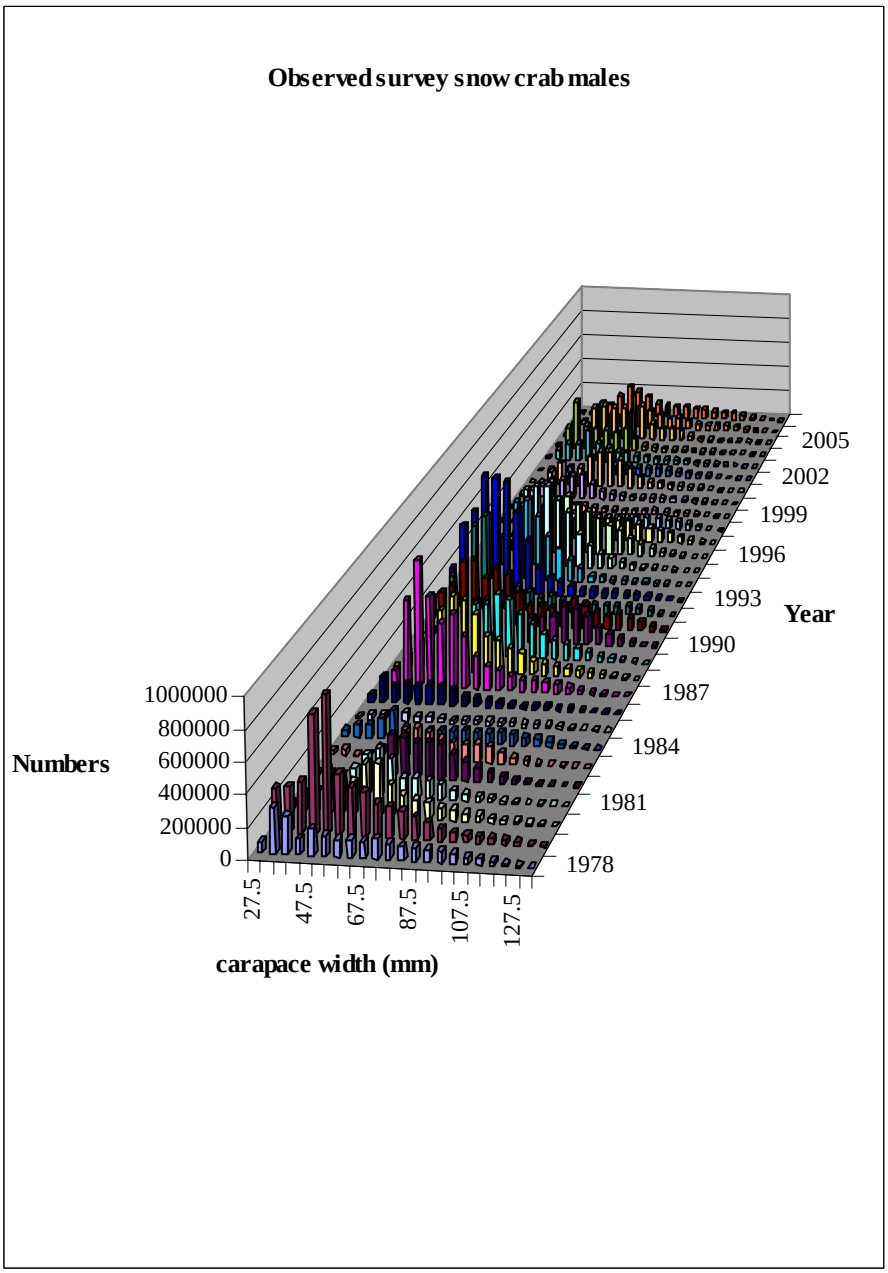


Figure 6. Observed survey numbers (1000's of crab) by carapace width and year fo r male snow crab.

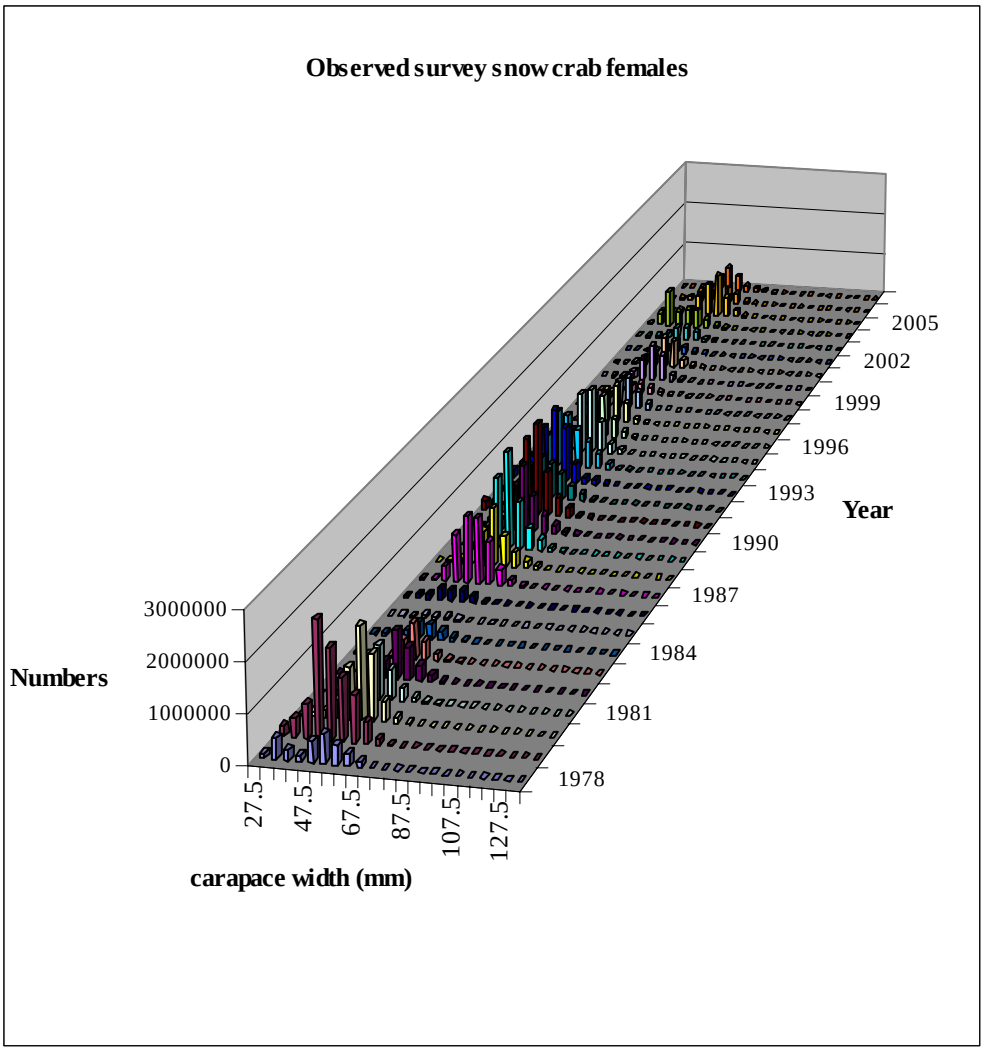


Figure 7. Observed survey numbers (1000's of crab) by carapace width and year for female snow crab.

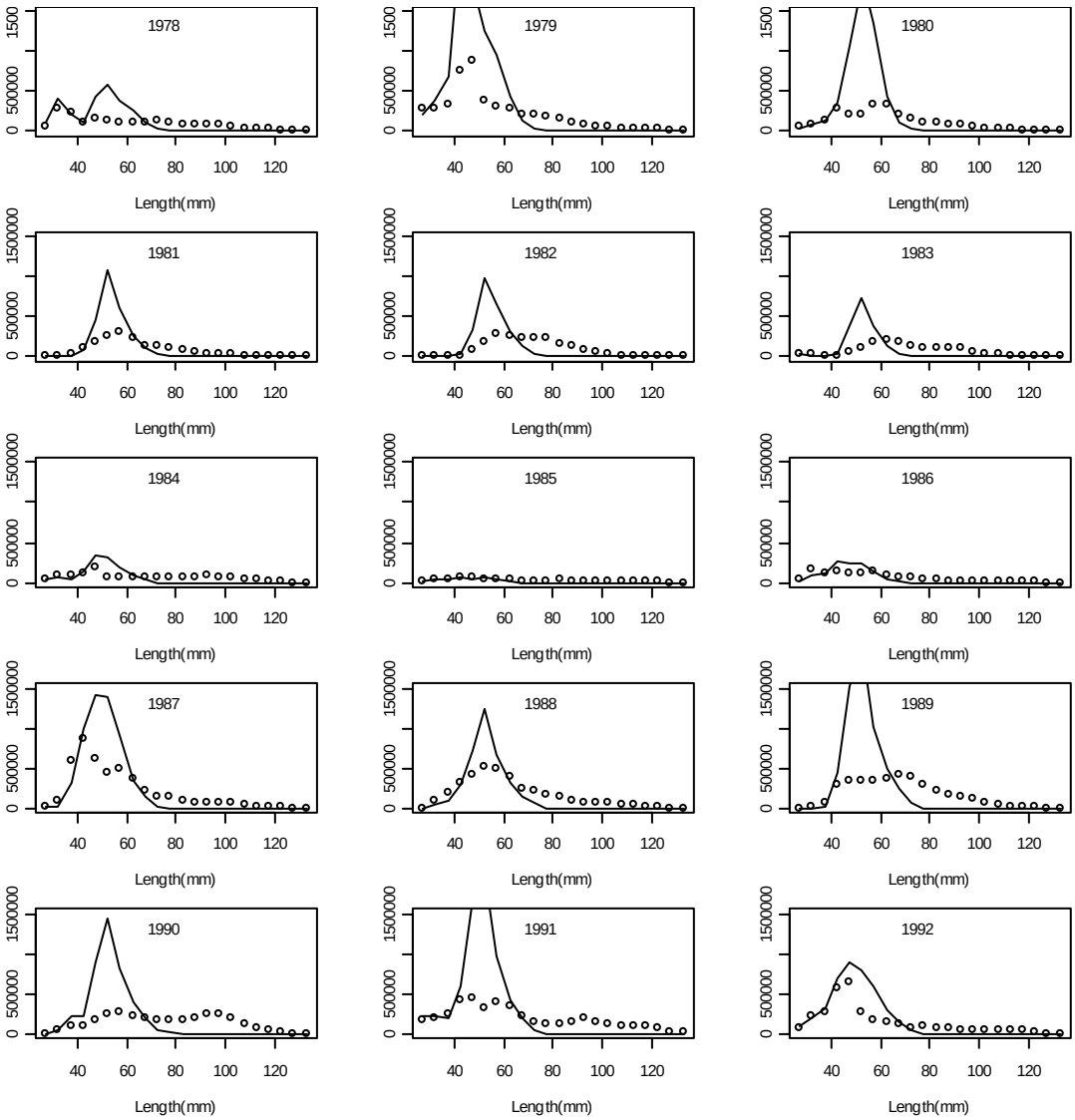


Figure 8. Survey numbers by length, males circles, females solid line.

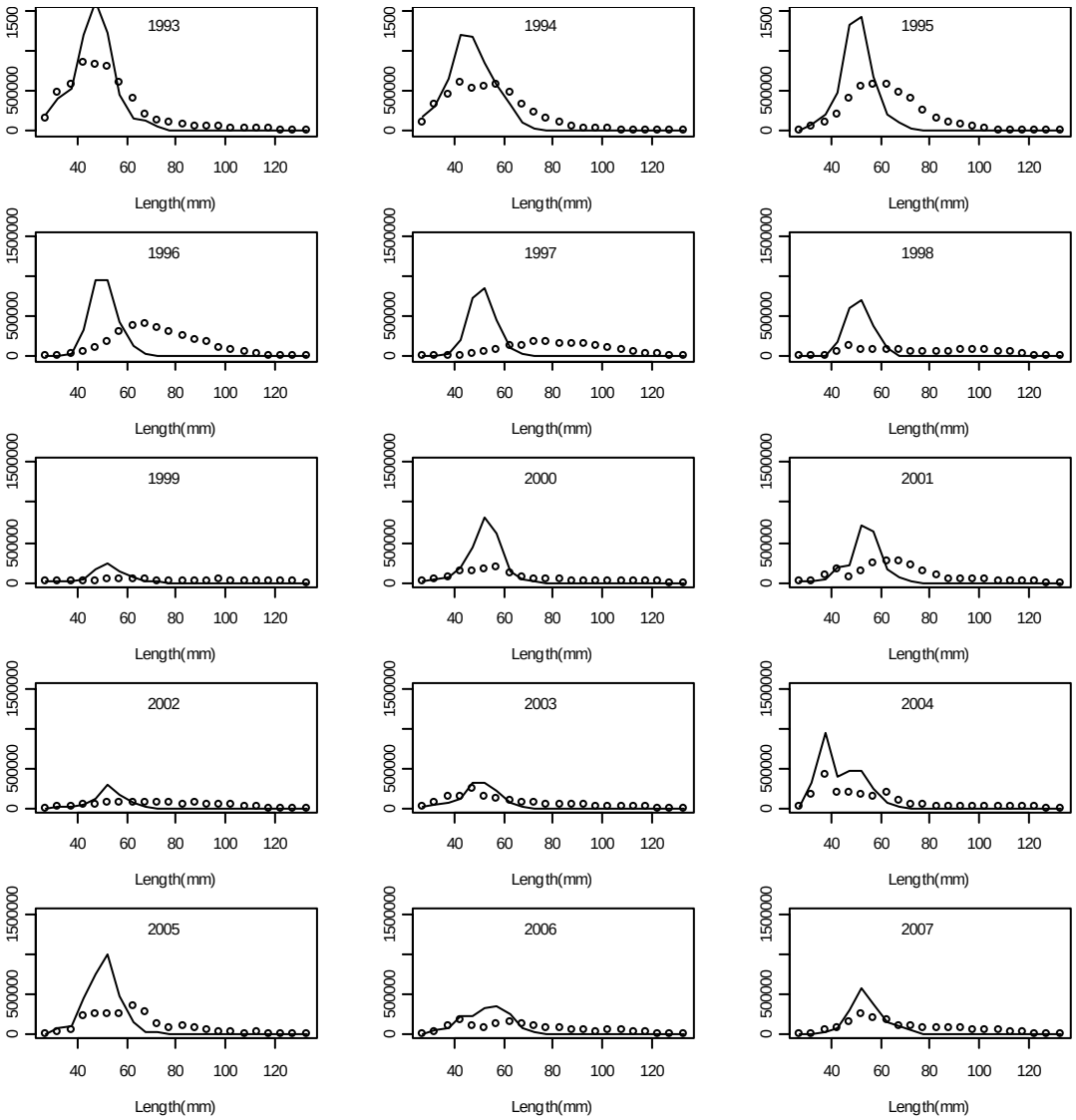


Figure 9. Survey numbers by length, males circles, females solid line.

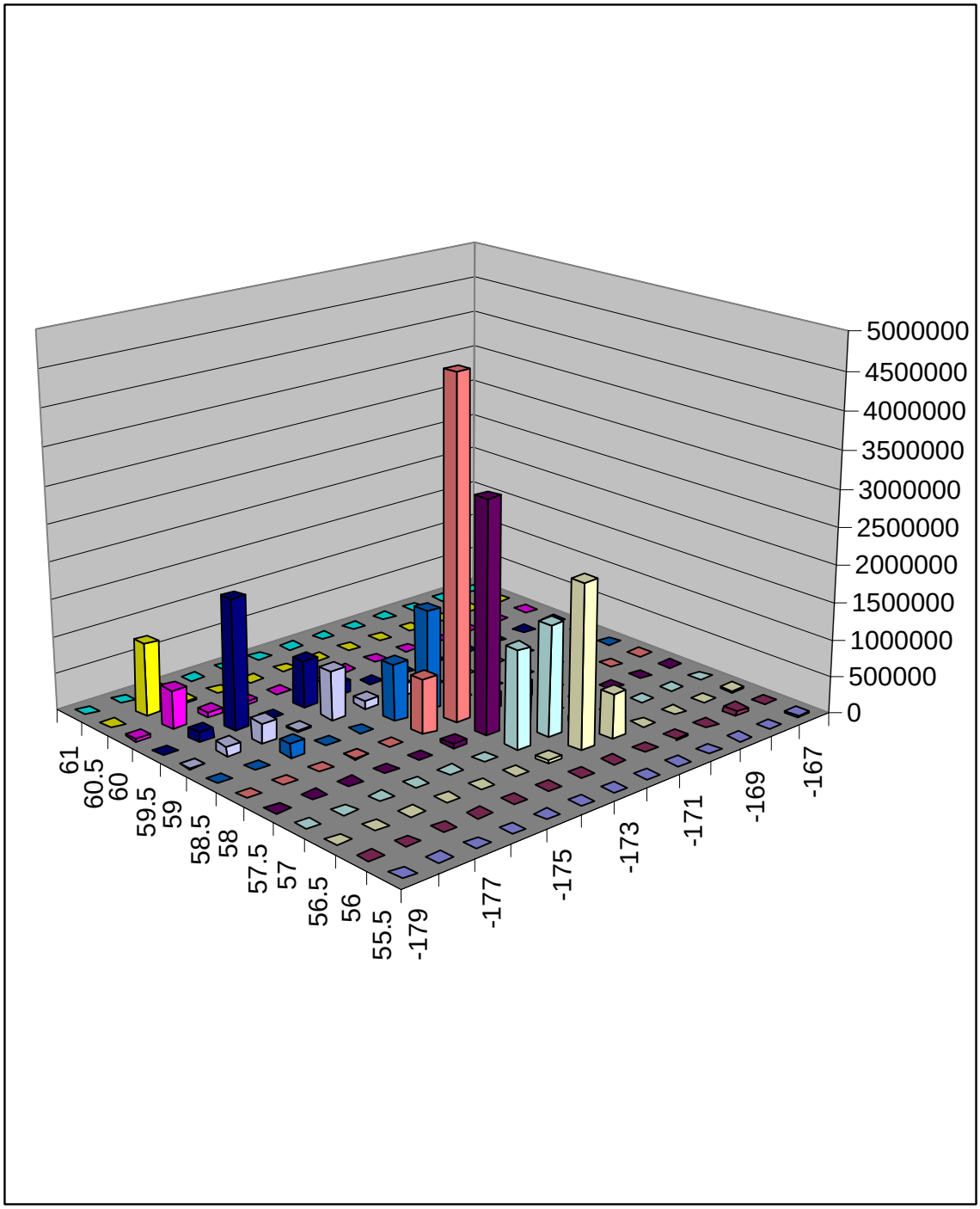


Figure 10. 2003 pot fishery retained catch in numbers by statistical area. Longitude in negative degrees. Areas are 1 degree longitude by 0.5 degree latitude.

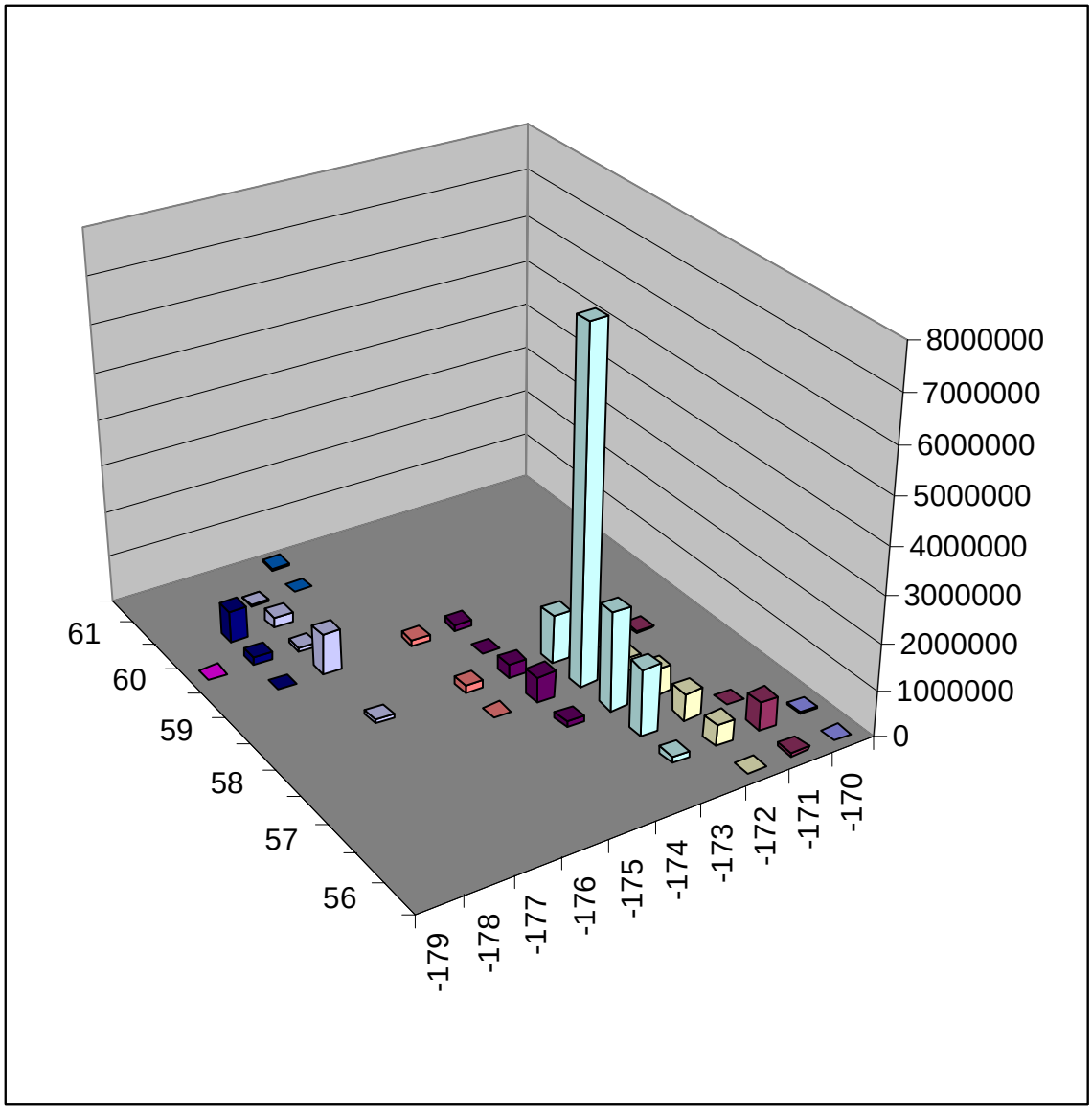


Figure 11. 2004 pot fishery retained catch in numbers by statistical area. Longitude in negative degrees. Areas are 1 degree longitude by 0.5 degree latitude.

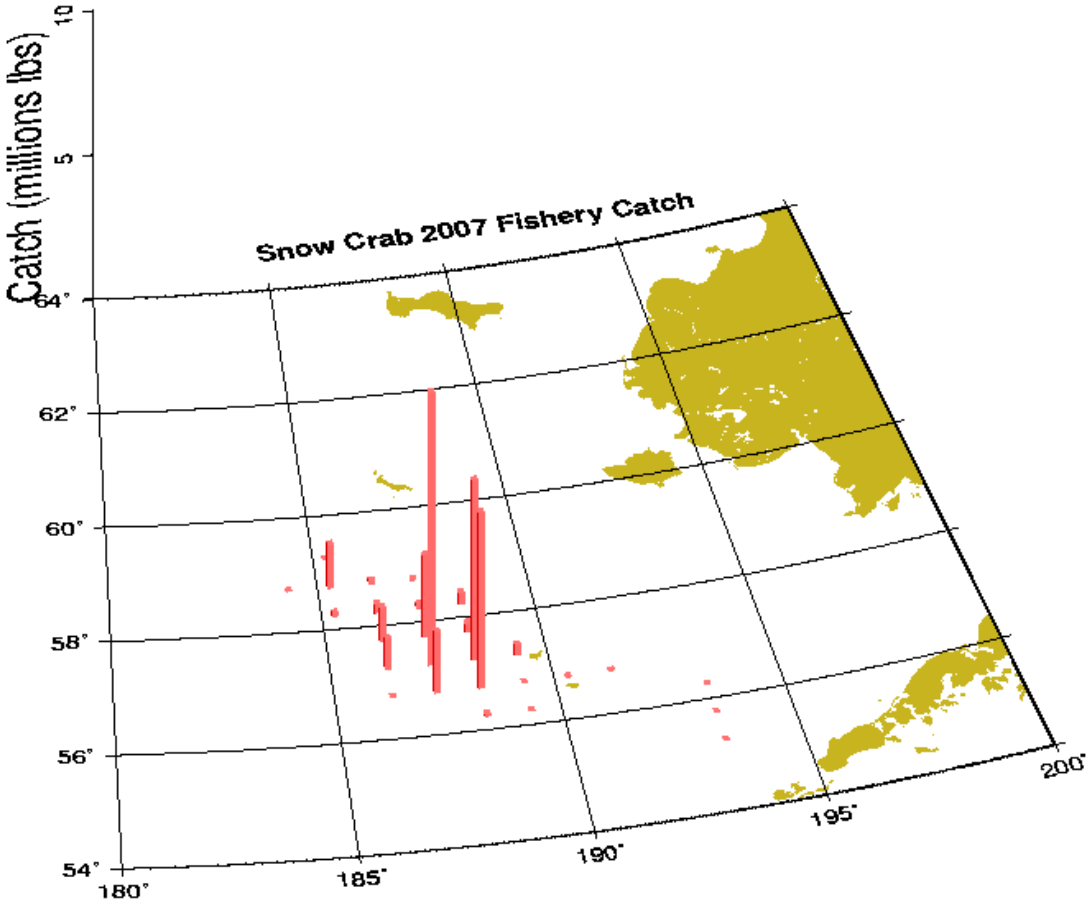


Figure 12. 2007 pot fishery retained catch(million lbs) by statistical area. Longitude increases from west to east (190 degrees = 170 degrees W longitude). Areas are 1 degree longitude by 0.5 degree latitude.

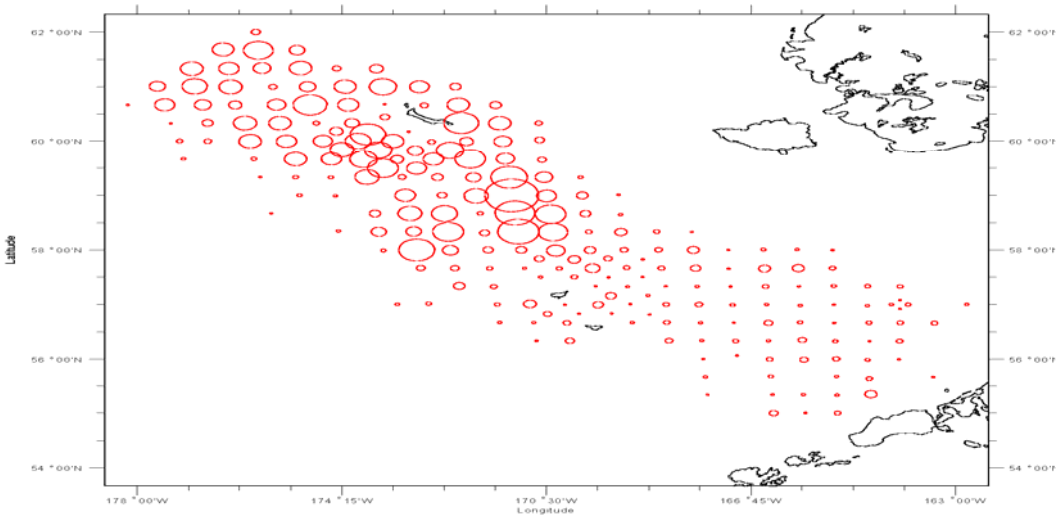


Figure 13. 2004 Survey abundance of males > 79 mm (approximately mature abundance) by tow. Abundance is proportional to the area of the circle.

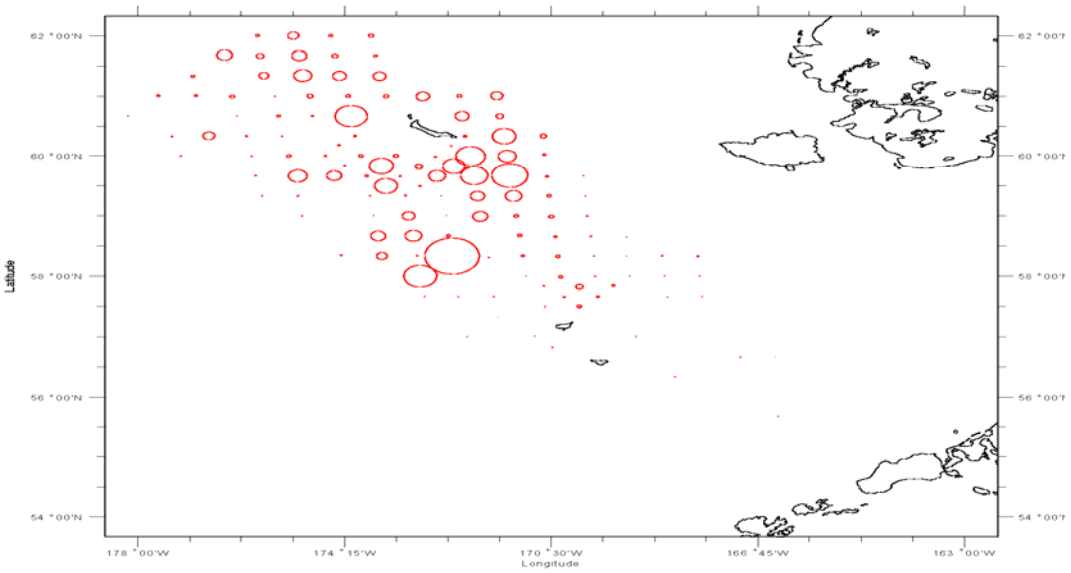


Figure 14. 2004 Survey abundance of females > 49 mm (approximately mature abundance) by tow. Abundance is proportional to the area of the circle.

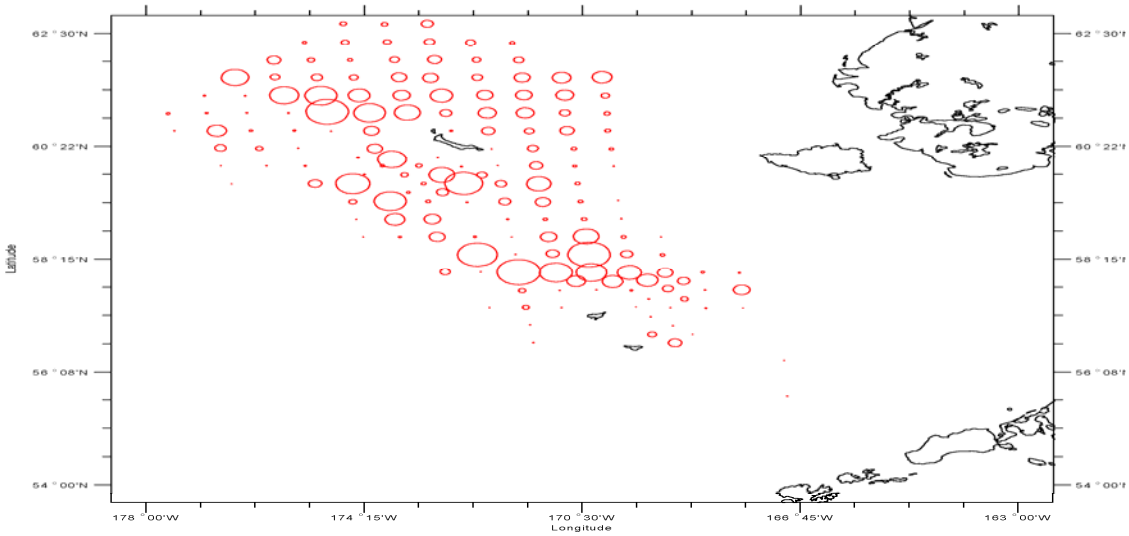


Figure 15. 2005 Survey abundance of females > 49 mm (approximately mature abundance) by tow. Abundance is proportional to the area of the circle (not on the same scale as male abundance in Figure 54). Includes stations to the north of the standard survey area.

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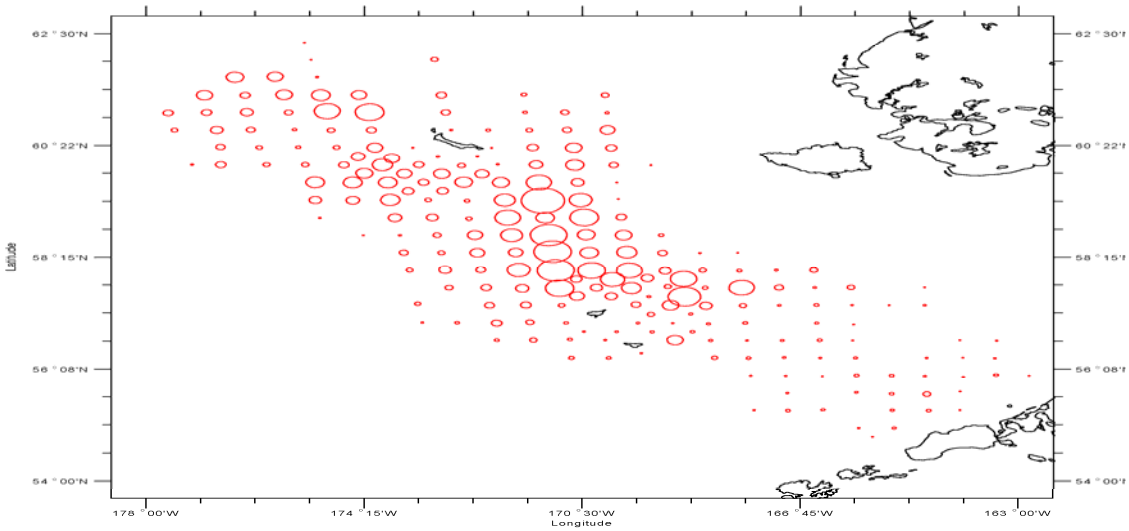


Figure 16. 2005 Survey abundance of males > 79 mm (approximately mature abundance) by tow. Abundance is proportional to the area of the circle (not on same scale as female abundance in Figure 53).

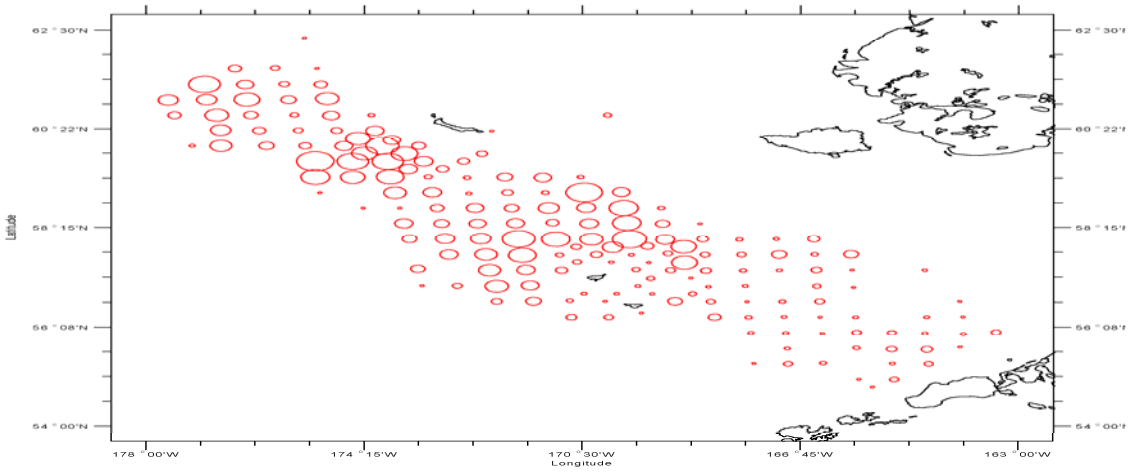


Figure 17. 2005 Survey abundance of males > 101 mm by tow. Abundance is proportional to the area of the circle.

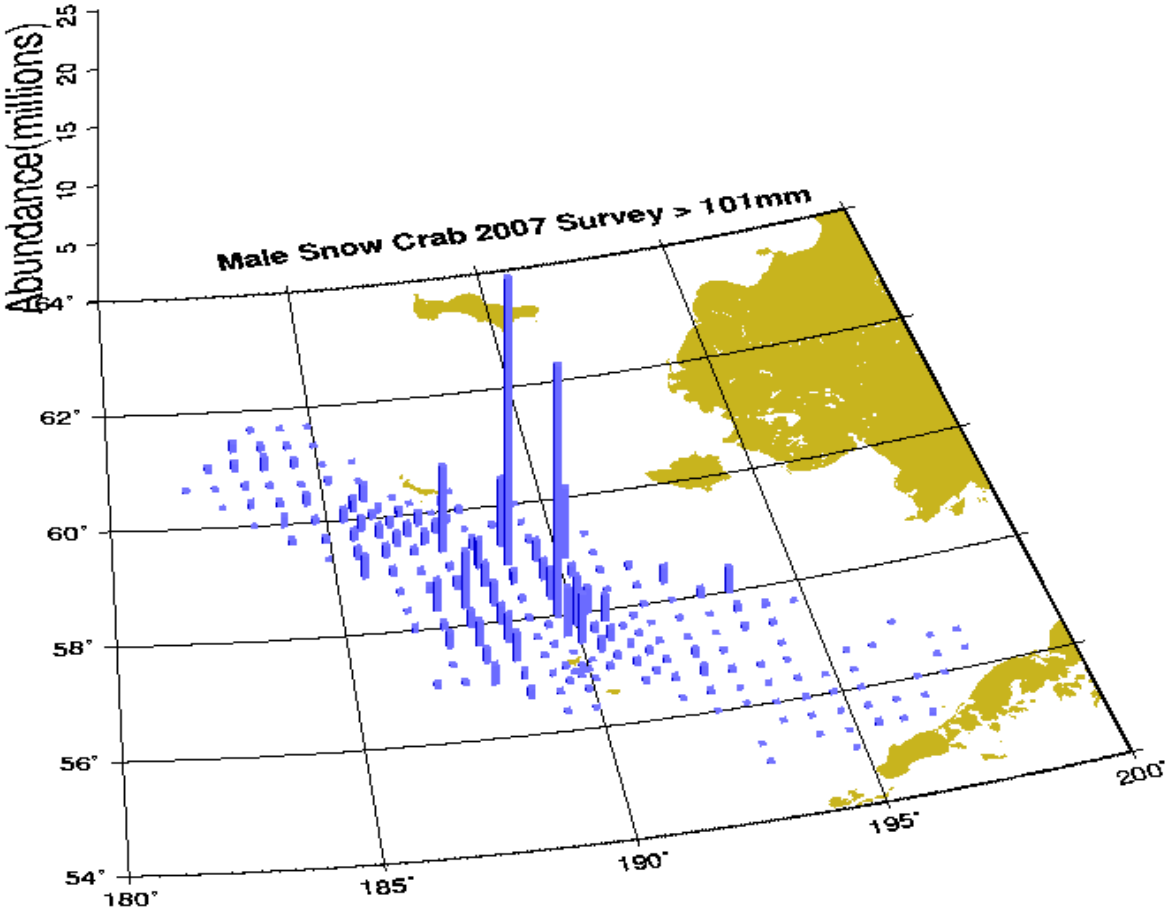


Figure 18. 2007 Survey abundance of males > 101 mm by tow. Abundance is in millions of crab.

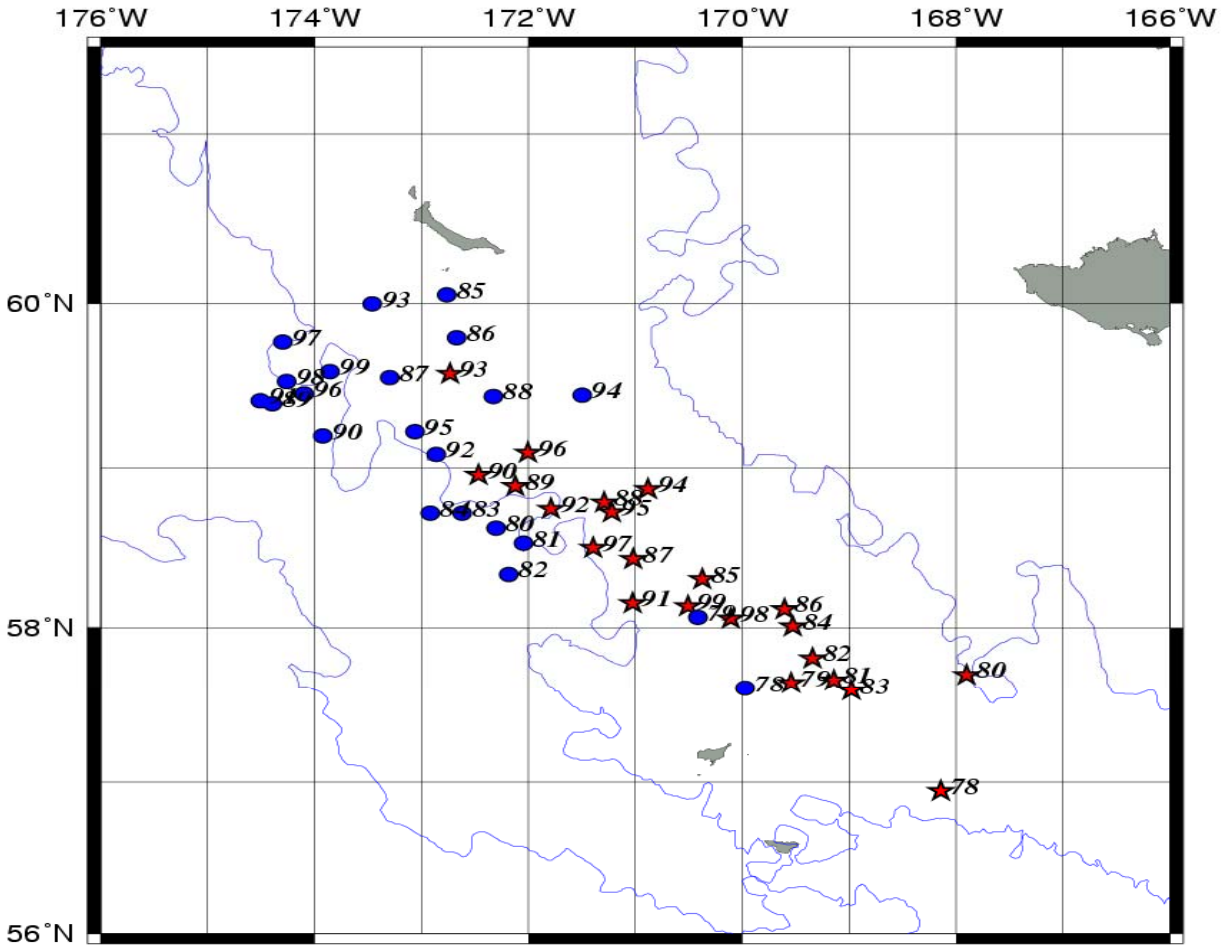


Figure 19. Centroids of abundance of mature female snow crabs (shell condition 2+) in blue circles and mature males (shell condition 3+) in red stars. Reprinted from Orensanz, Armstong and Ernst (in press).

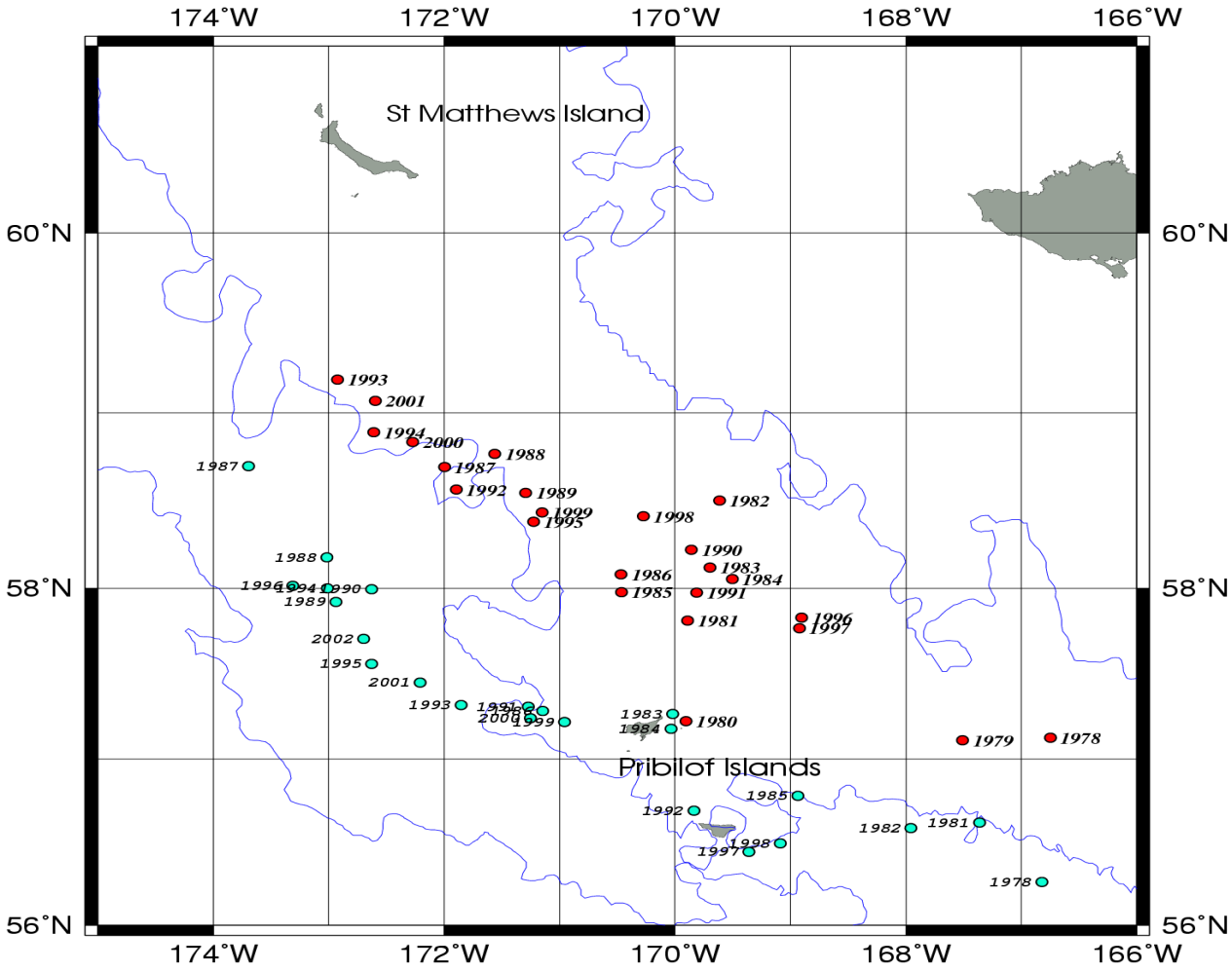


Figure 20. Centroids abundance (numbers) of snow crab males > 101 mm from the summer NMFS trawl survey (red) and from the winter fishery (blue-green), from Orensanz, Armstong and Ernst (in press).

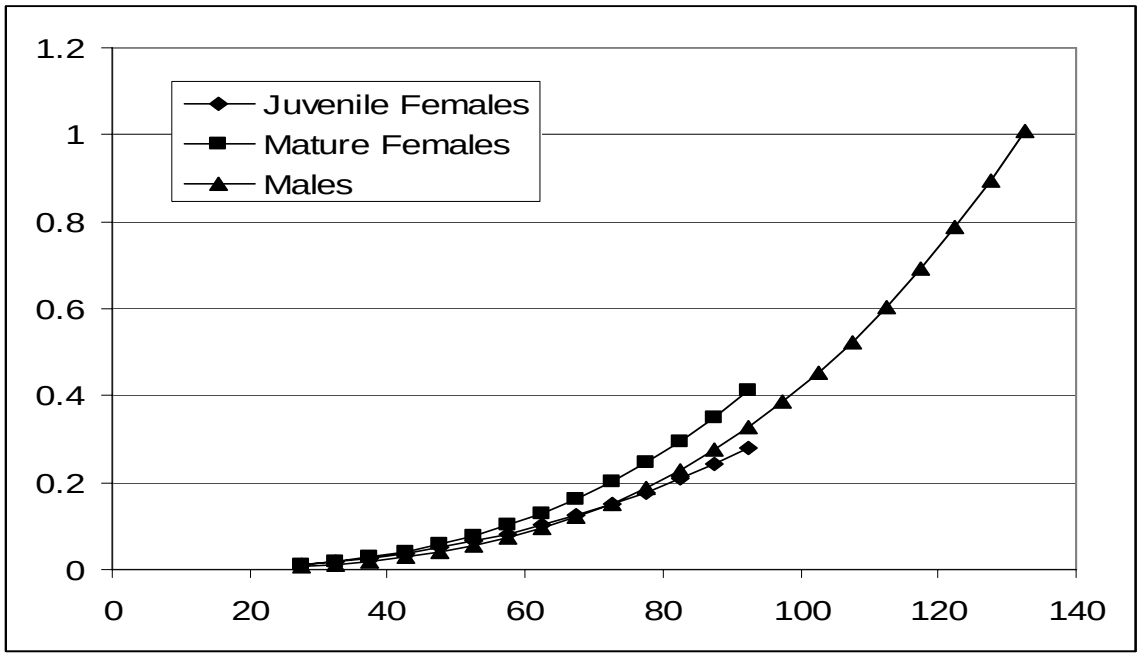


**Figure 21. Weight (kg) – size (mm) relationship for male, juvenile female and mature female snow crab.**

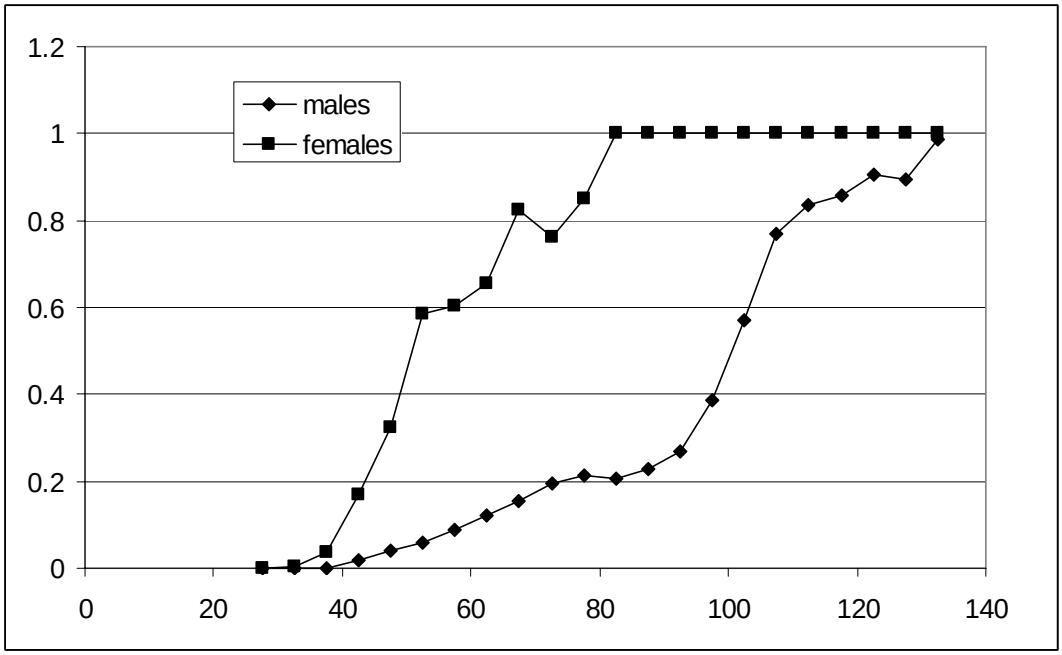


**Figure 22. Probability of maturing by size for male and female snow crab (<u>not</u> the average fraction mature).**

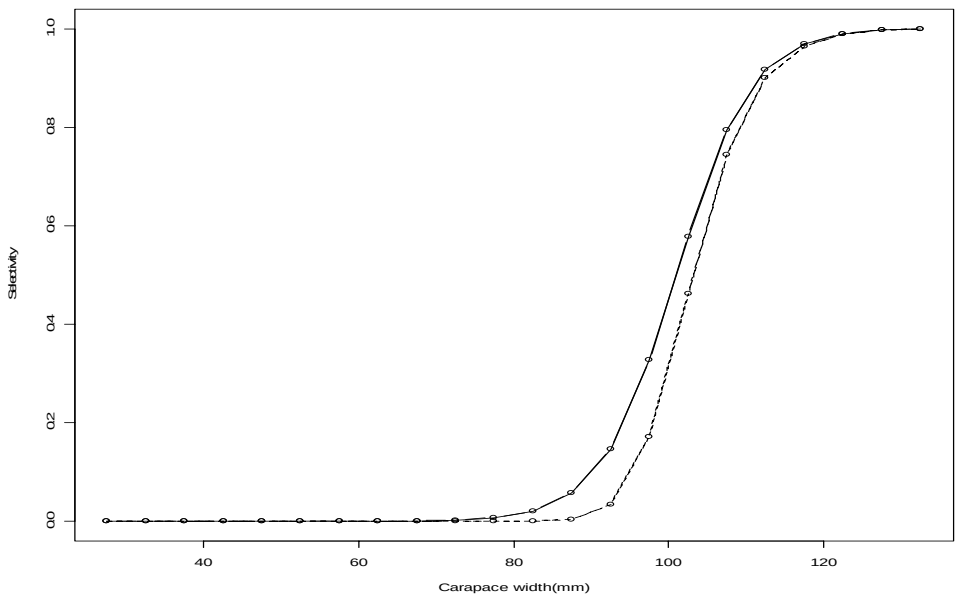


Figure 23. Selectivity curve for total catch (discard plus retained, solid line) and retained catch (dotted line) for combined shell condition male snow crab.

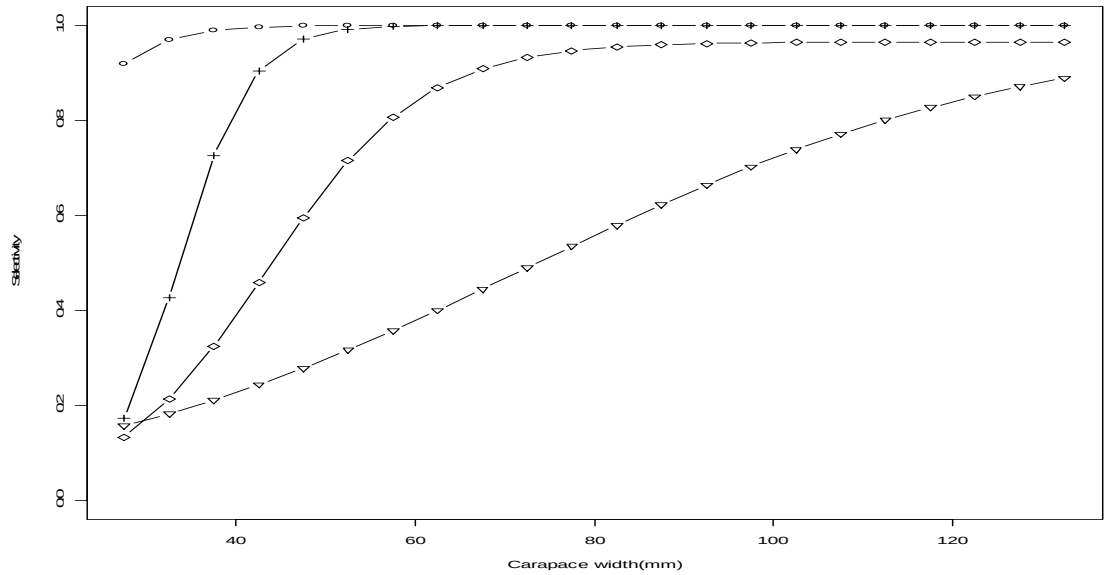


Figure 24. Survey selectivity curves for female and male snow crab estimated by the model for 1978-1981(solid line with circles), for 1982 to 1988 (solid line with diamonds), and 1989 to present (solid line with pluses). Survey selectivities estimated by Somerton and Otto (1998) are the solid line with triangles.

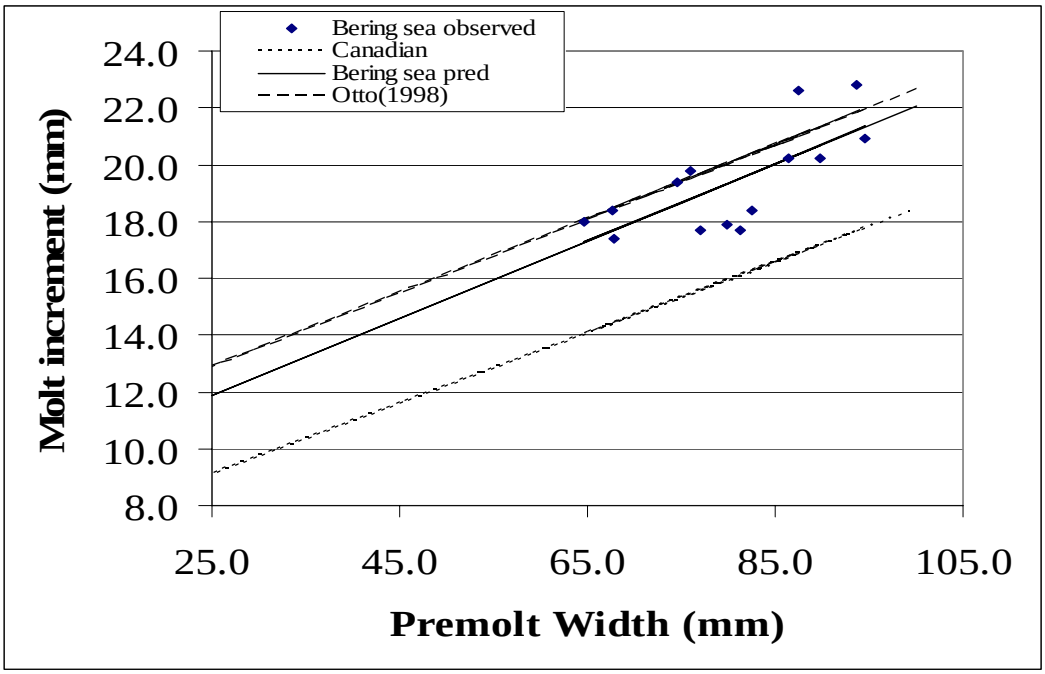


Figure 25. Growth increment as a function of premolt size for male snow crab. Points labeled Bering sea observed are observed growth increments from Rugolo (unpub data). The line labeled Bering sea pred is the predicted line from the Bering sea observed growth, which is used as a prior for the growth parameters estimated in the model. 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.

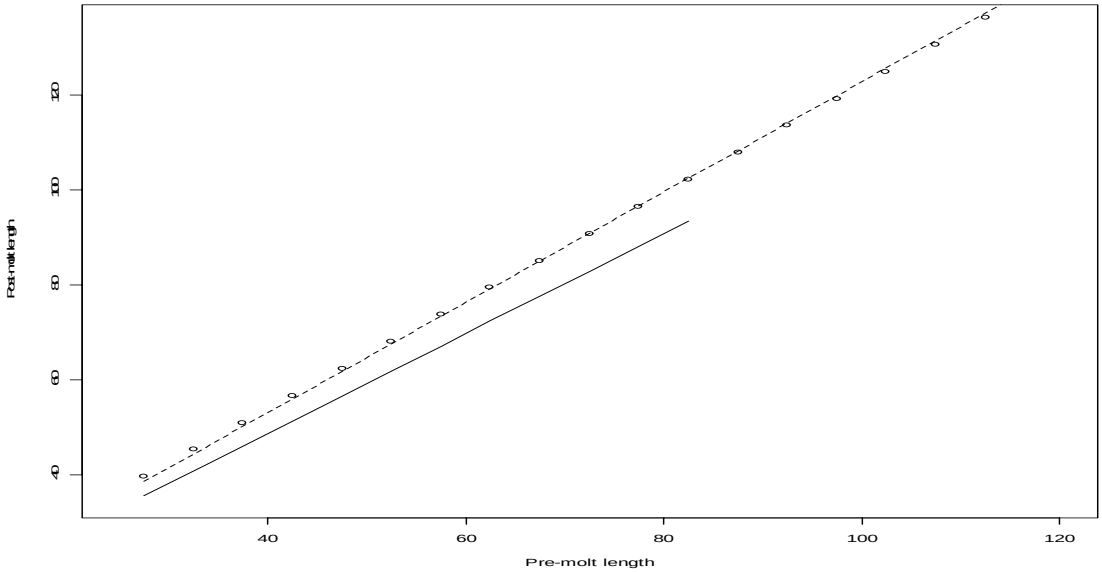


Figure 25. Growth(mm) for male(dotted line) and female snow crab (solid line) estimated from the model. Circles are the observed growth curve.

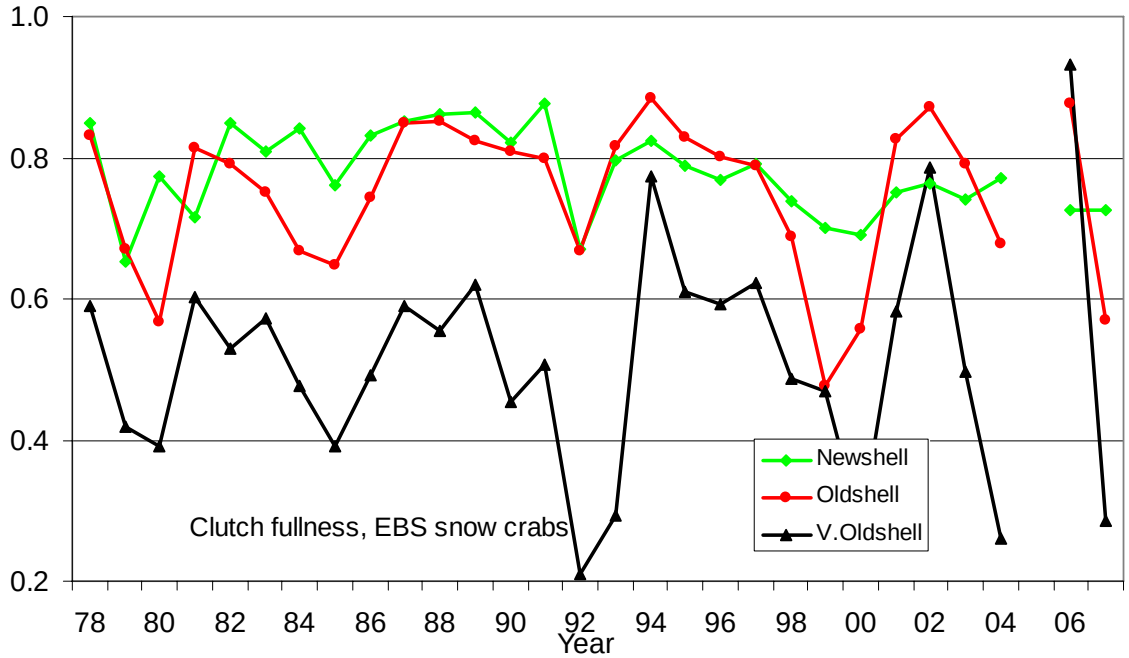


Figure 26. Clutch fullness for Bering sea snow crab survey data by shell condition for 1978 to 2007.

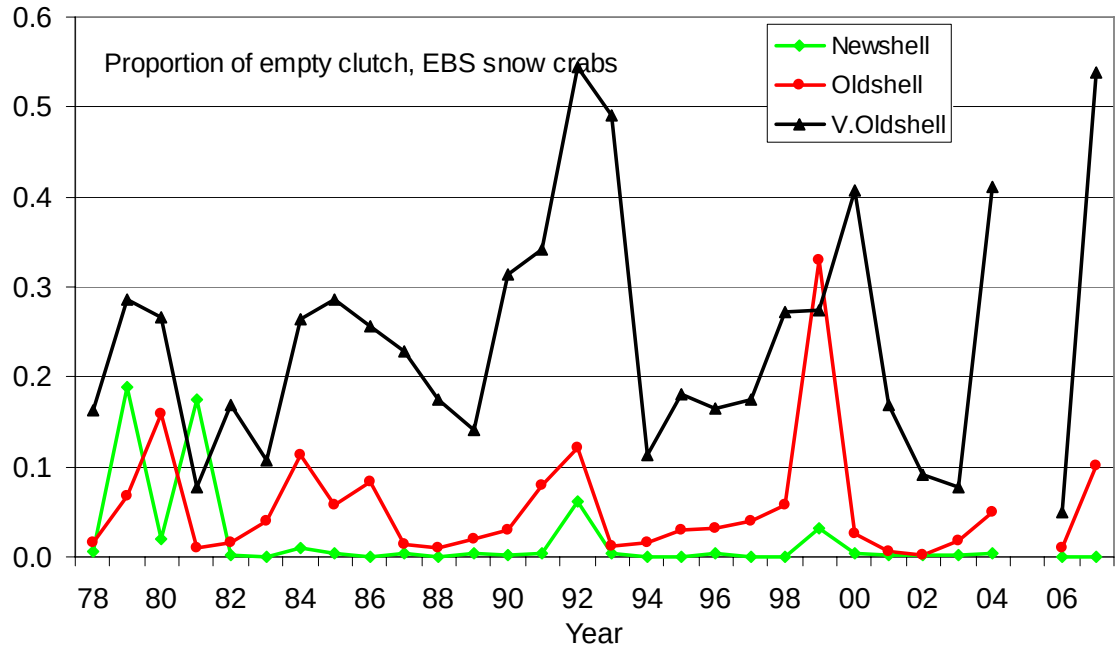


Figure 27. Proportion of barren females by shell condition from survey data 1978 to 2007.

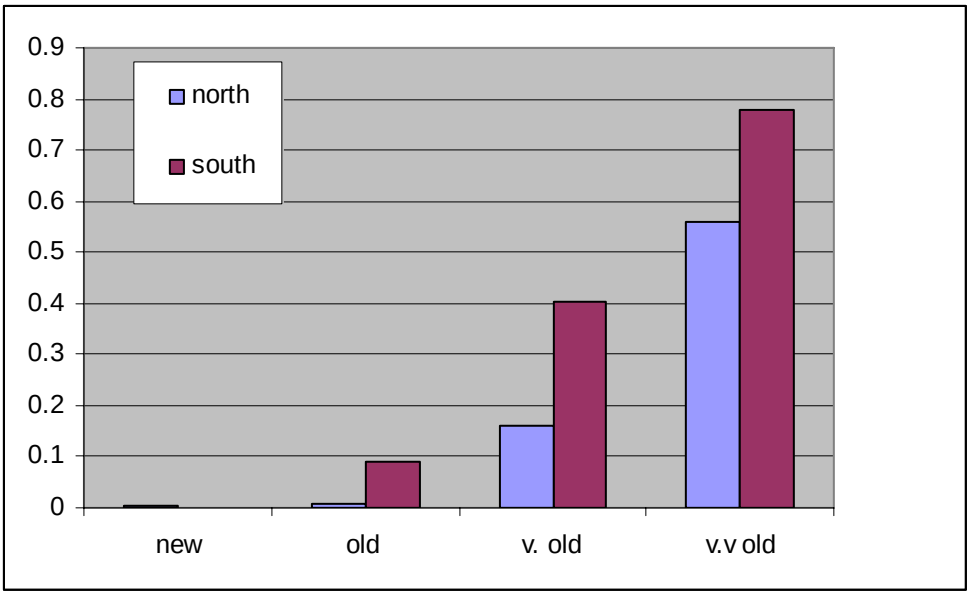


Figure 28. Fraction of barren females in the 2004 survey by shell condition and area north of 58.5 deg N and south of 58.5 deg N.

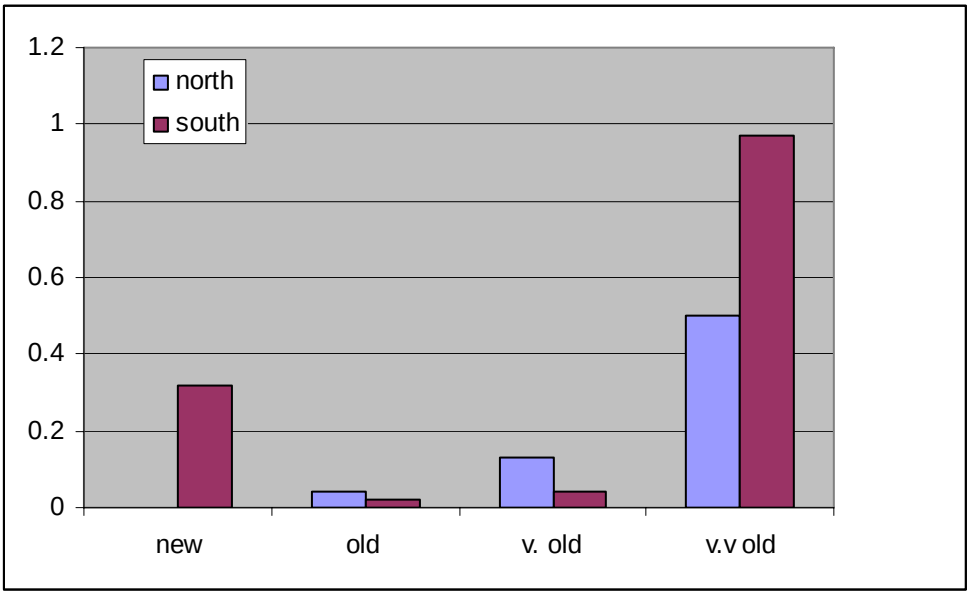


Figure 29. Fraction of barren females in the 2003 survey by shell condition and area north of 58.5 deg N and south of 58.5 deg N. The number of new shell mature females south of 58.5 deg N was very small in 2003.

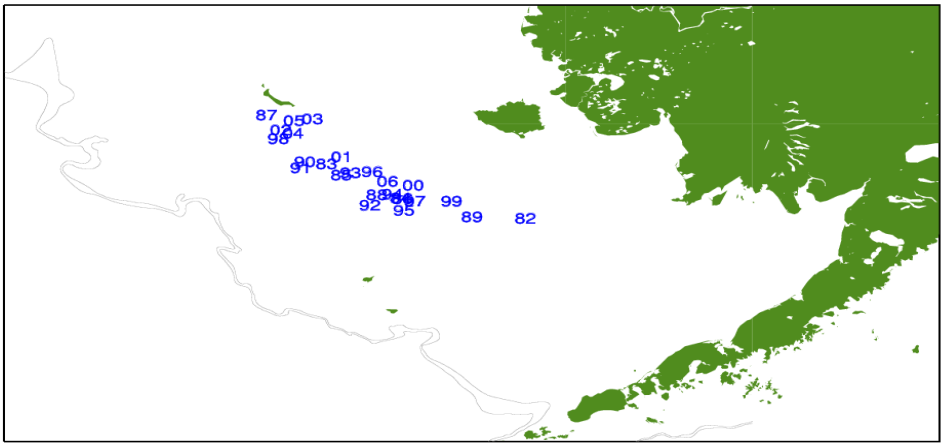


**Figure 30. Centroids of cold pool (<2.0 deg C) from 1982 to 2006. Centroids are average latitude and longitude.**

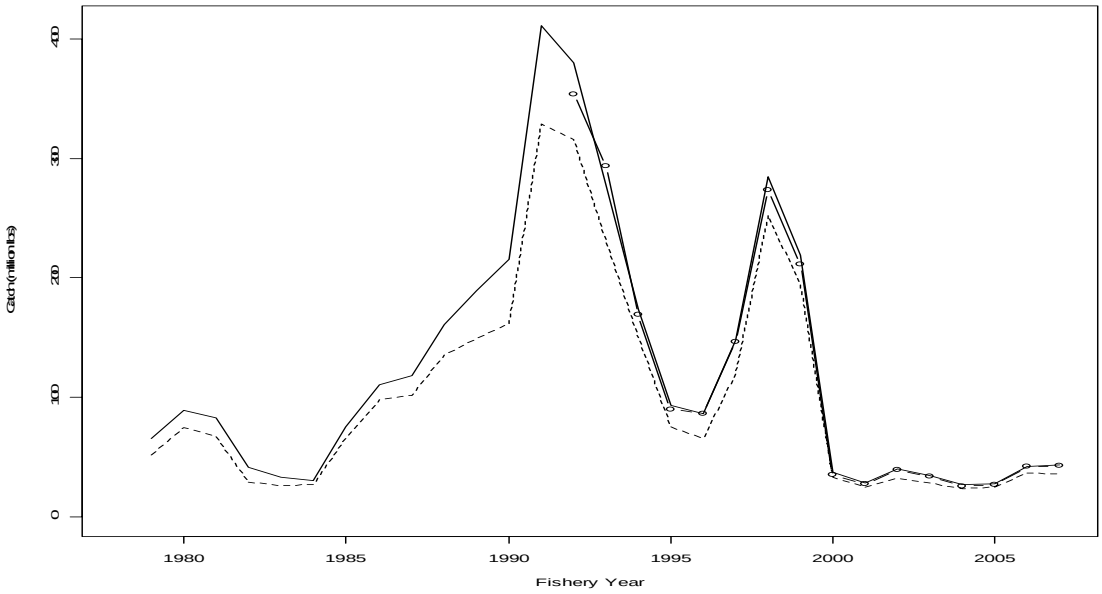


Figure 31. Estimated total catch(discard + retained) (solid line), observed total catch (solid line with circles) (assuming 50% mortality of discarded crab) and observed retained catch (dotted line) for 1979 to 2007 fishery seasons.

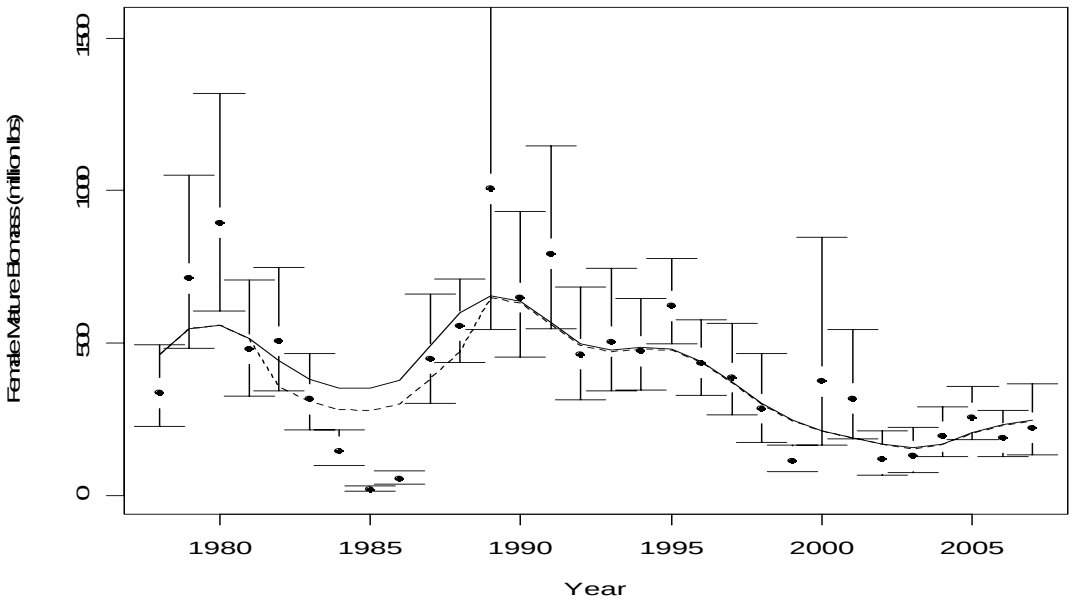


Figure 32. Population female mature biomass (millions of pounds, solid line), model estimate of survey female mature biomass (dotted line) and observed survey female mature biomass with approximate lognormal 95% confidence intervals.

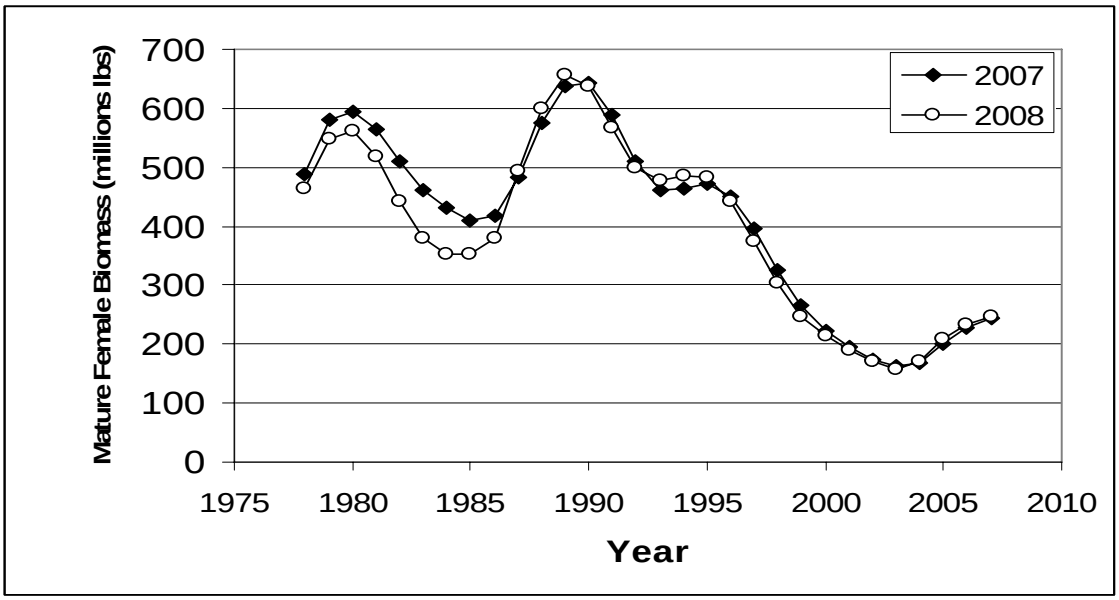


Figure 33. Population female mature biomass from the 2007 assessment and this assessment.

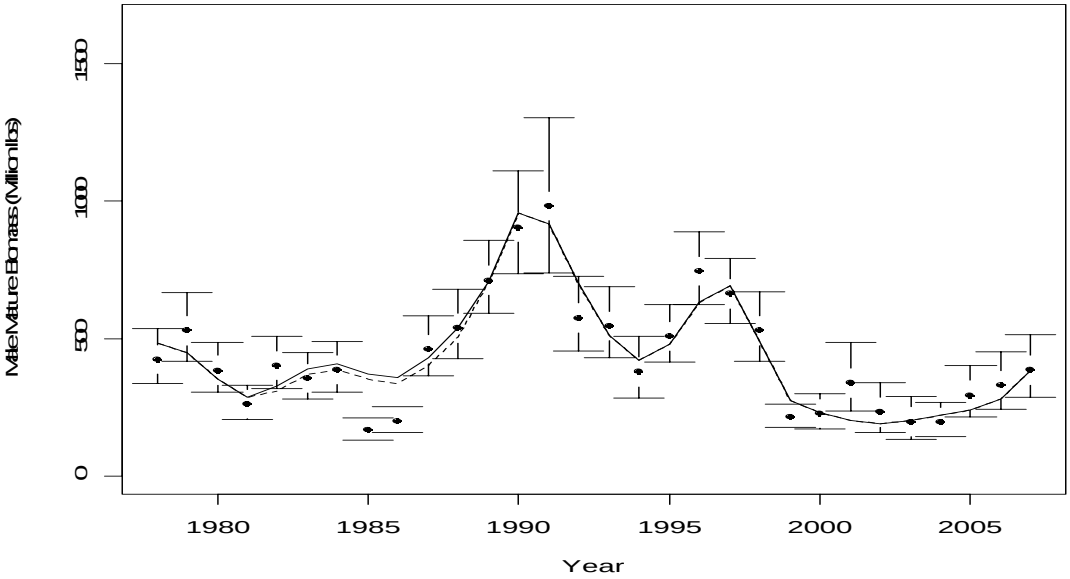


Figure 34. Population male mature biomass (millions of pounds, solid line), model estimate of survey male mature biomass (dotted line) and observed survey male mature biomass with approximate lognormal 95% confidence intervals.

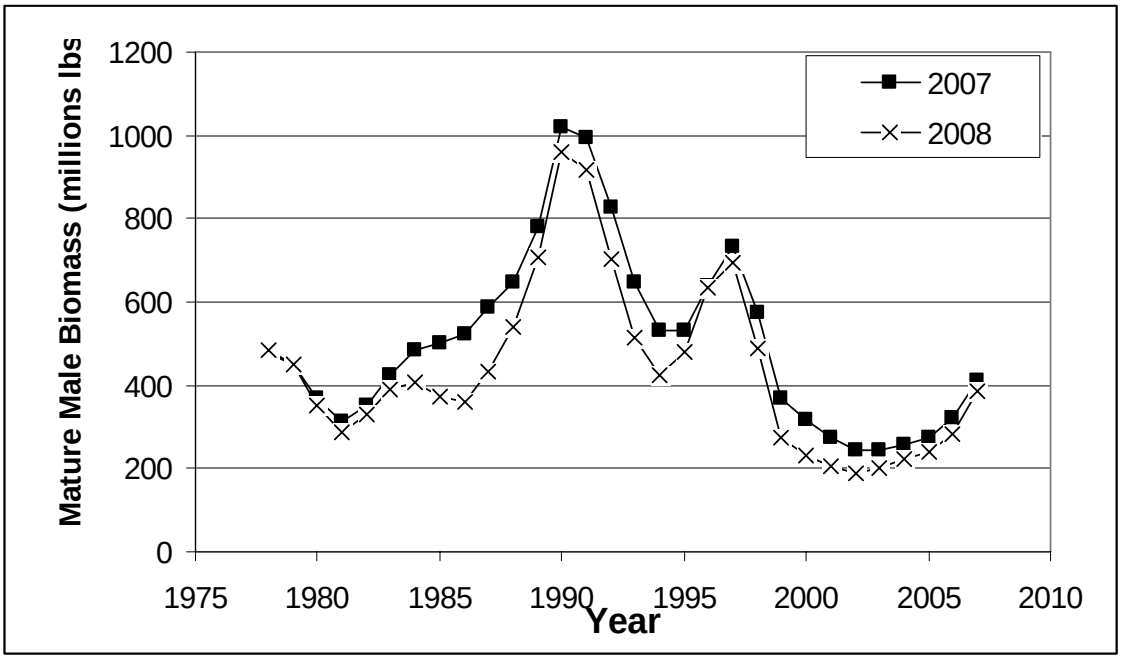


Figure 35. Population male mature biomass from the 2007 assessment and this assessment.

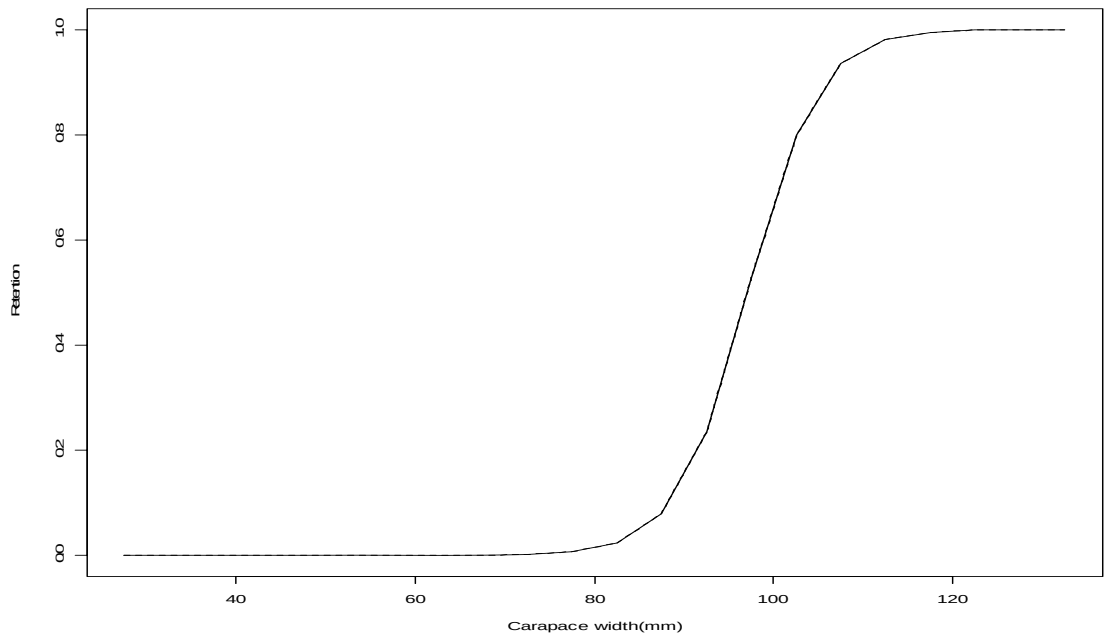


Figure 36. Model estimated fraction of the total catch that is retained by size for male snow crab combined shell condition.

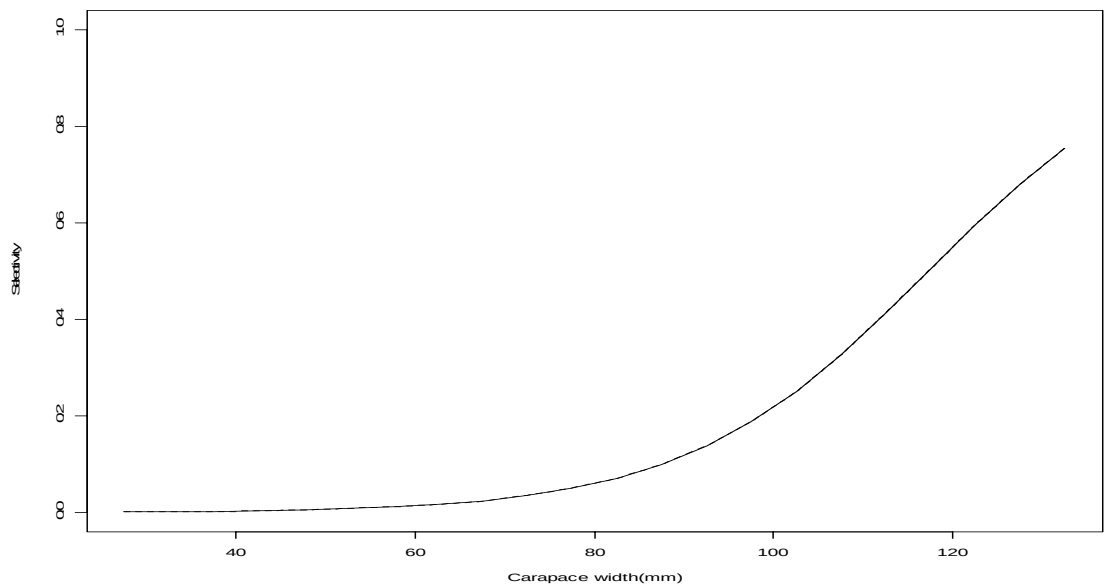


Figure 37. Selectivity curve estimated by the model for bycatch in the groundfish trawl fishery for females and males.

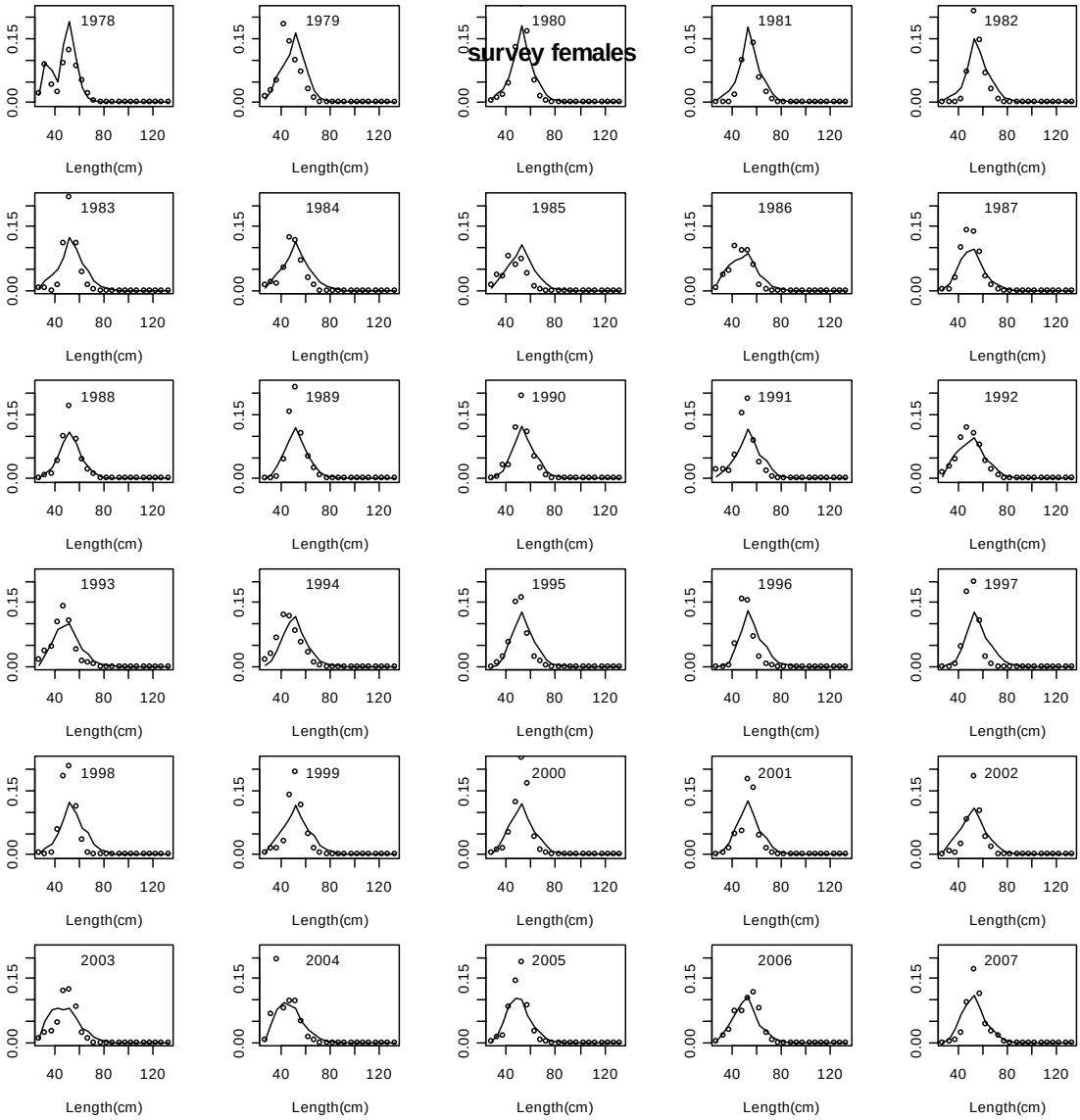


Figure 38. Model fit to the survey female size frequency data. Circles are observed survey data. Solid line is the model fit.

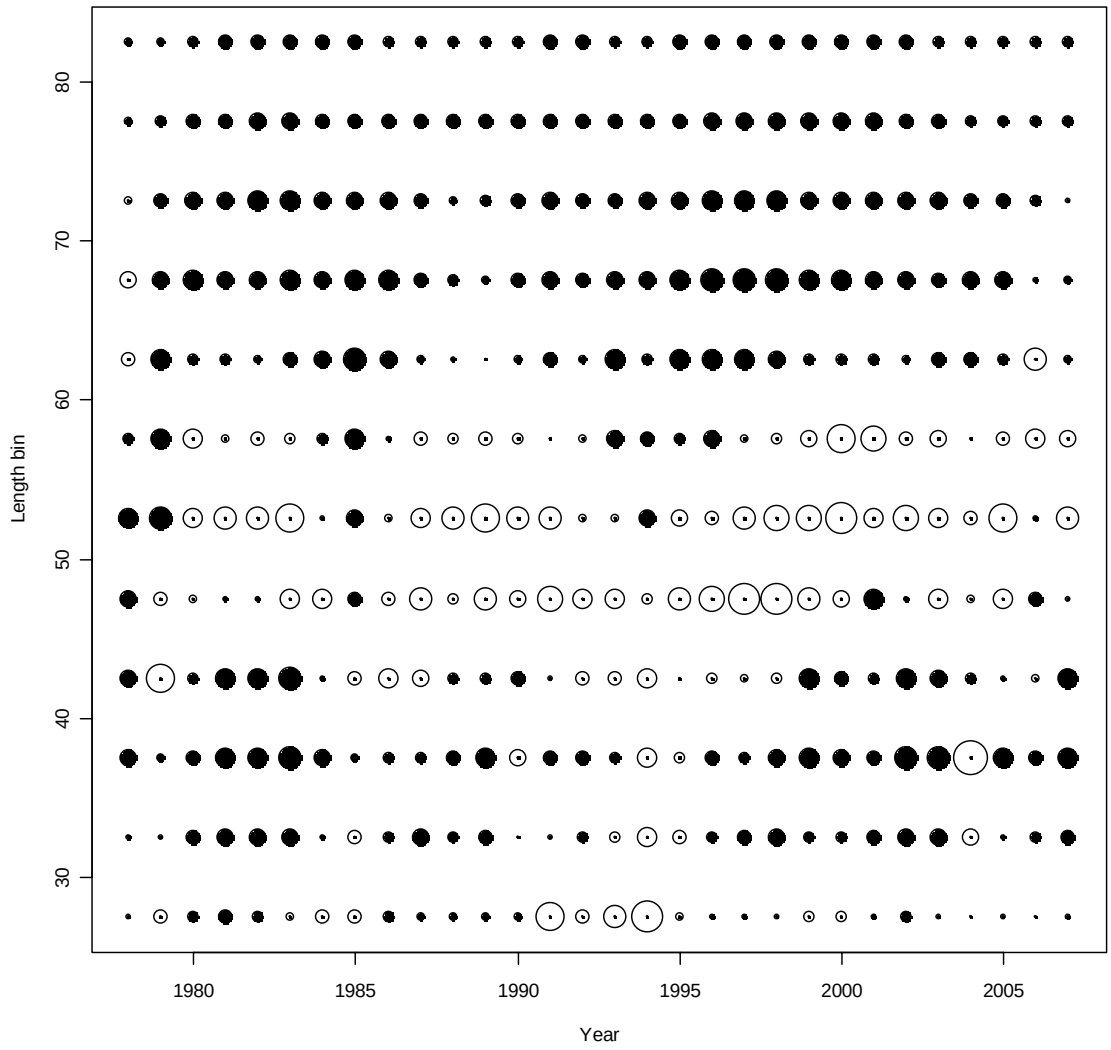


Figure 39. Residuals of fit to survey female size frequency. Filled circles are negative residuals.

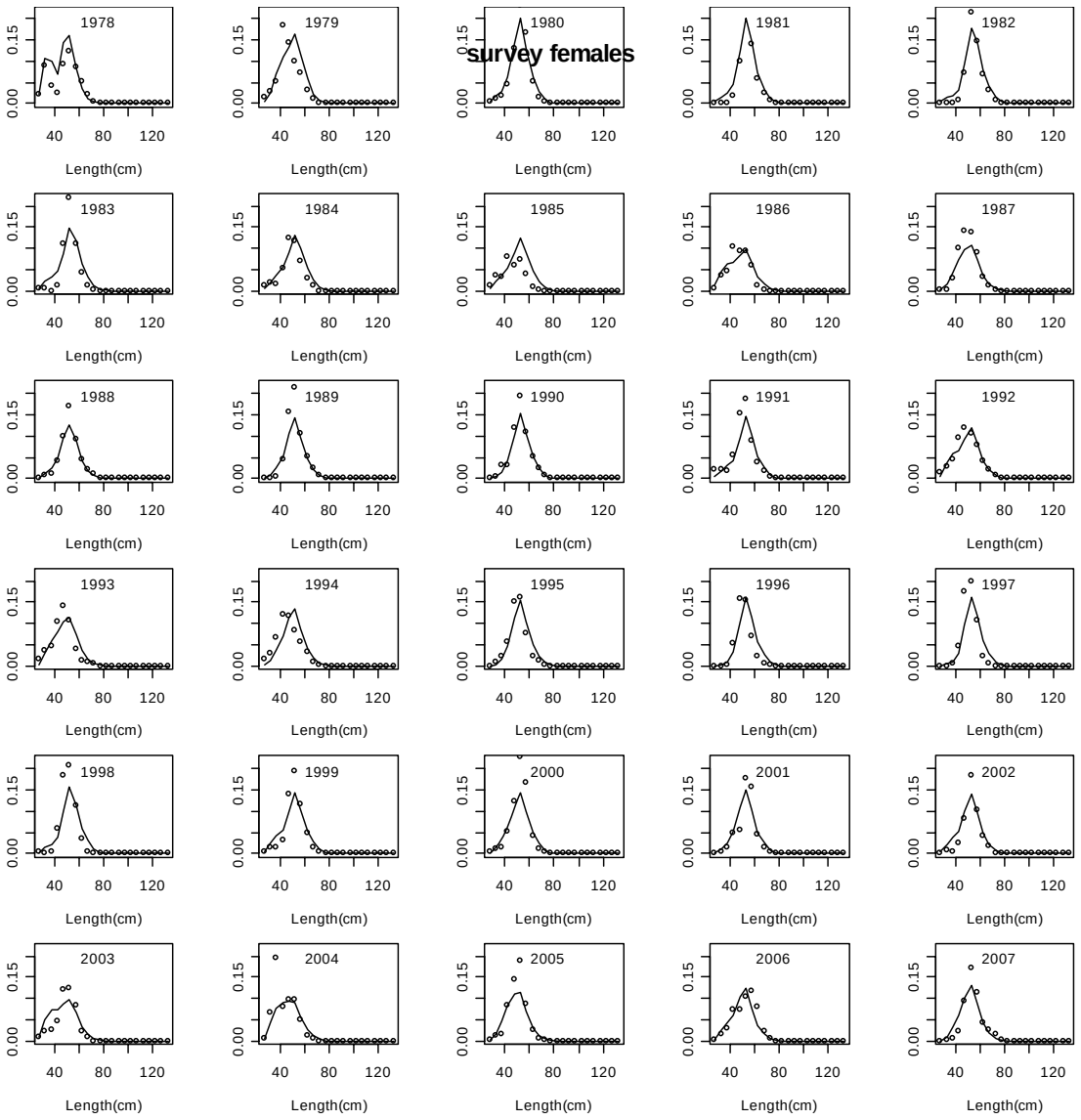


Figure 40. Model with maturity estimated. Fit to the survey female size frequency data. Circles are observed survey data. Solid line is the model fit.

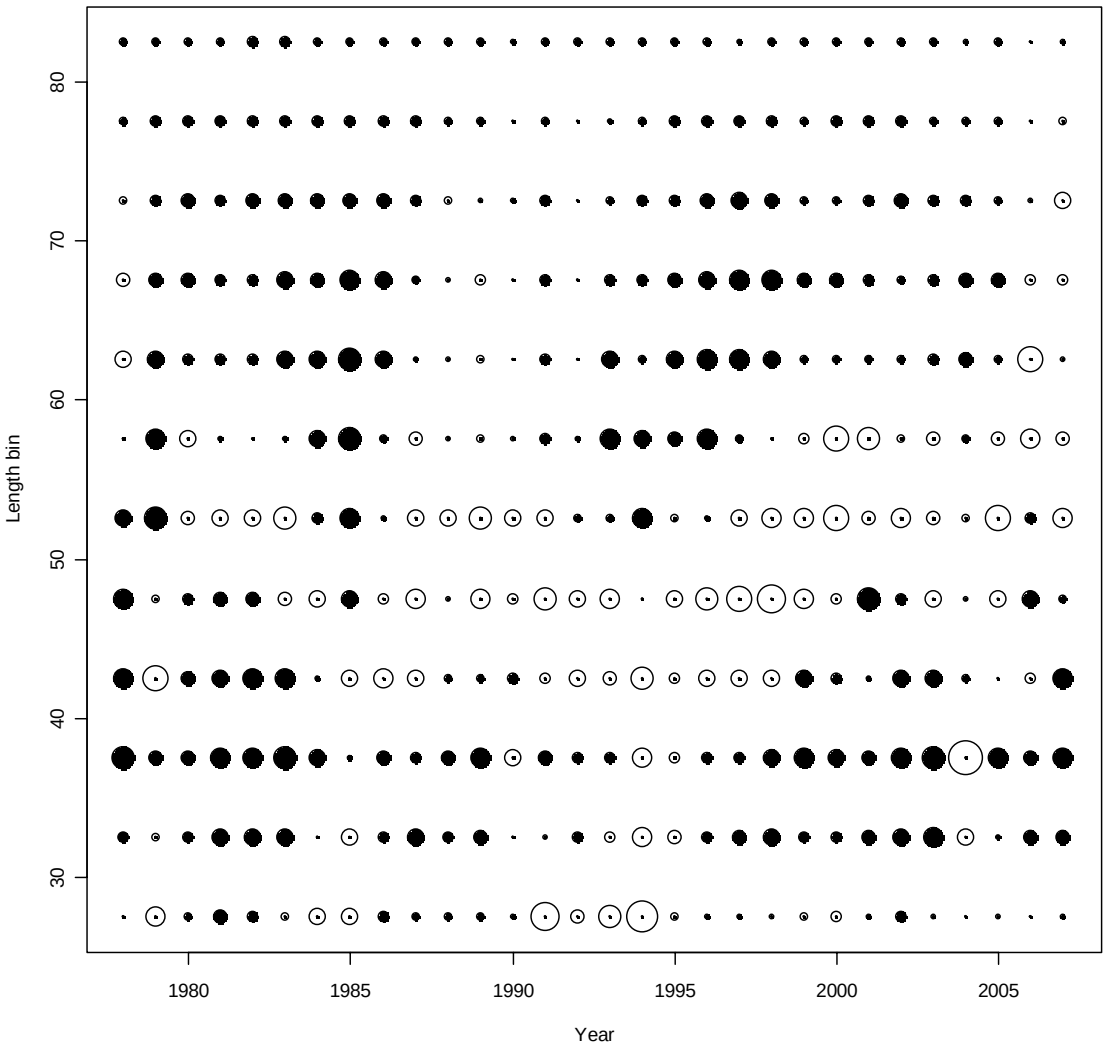


Figure 41 . Model with maturity estimated. Residual fit to female survey length frequency.

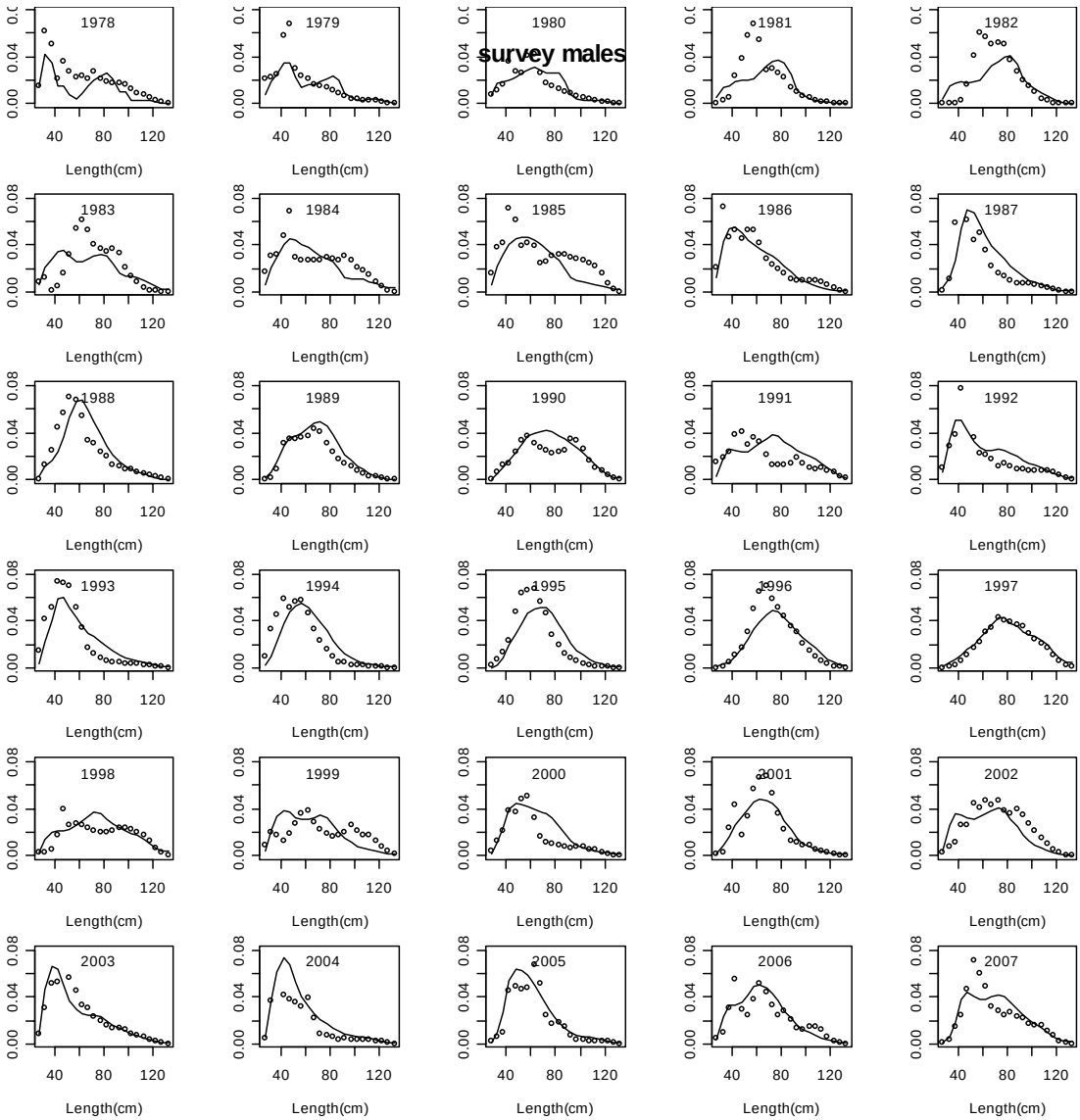


Figure 42. Model fit to the survey male size frequency data. Circles are observed survey data. Solid line is the model fit.

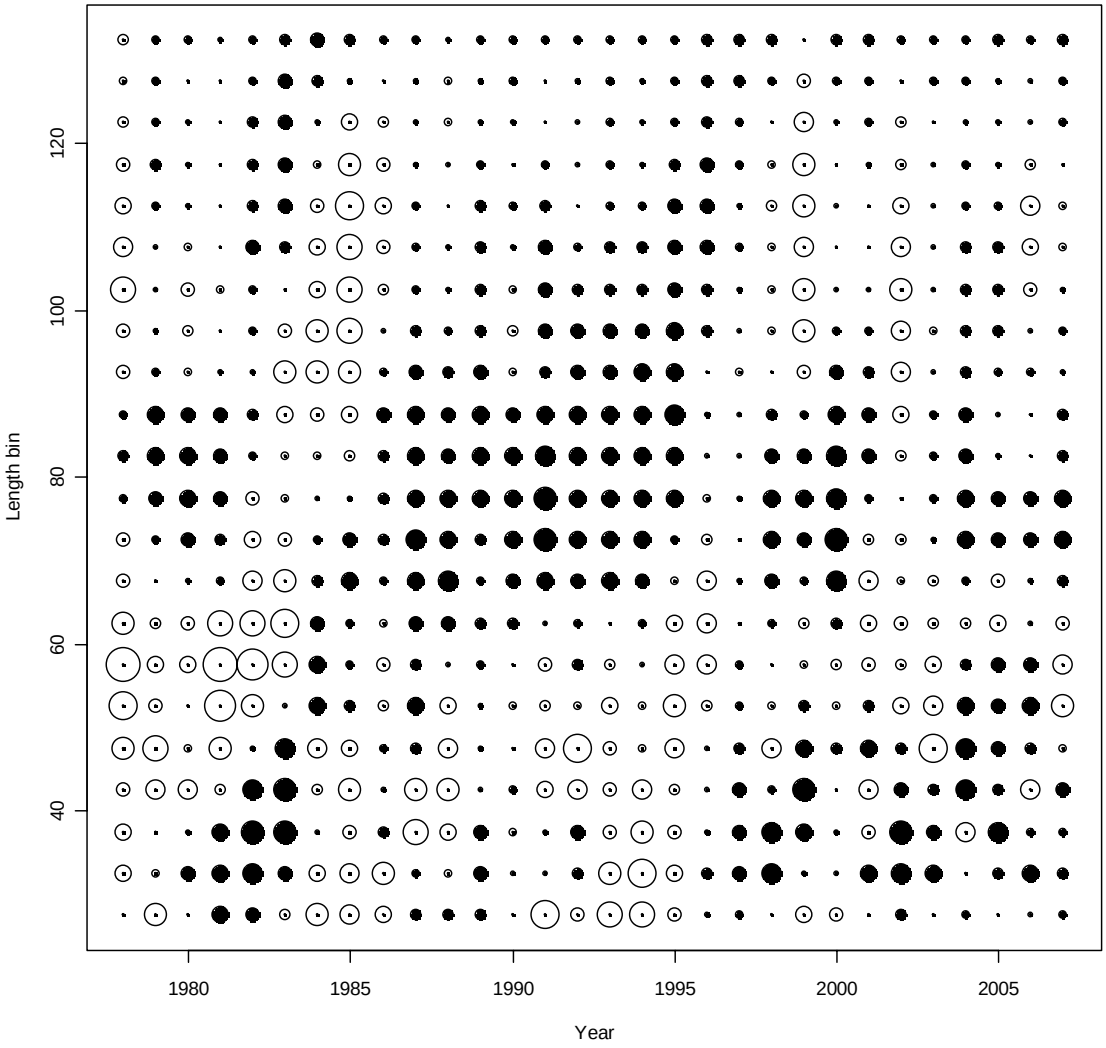


Figure 43. Residuals for fit to survey male size frequency. . Filled circles are negative residuals (predicted higher than observed).

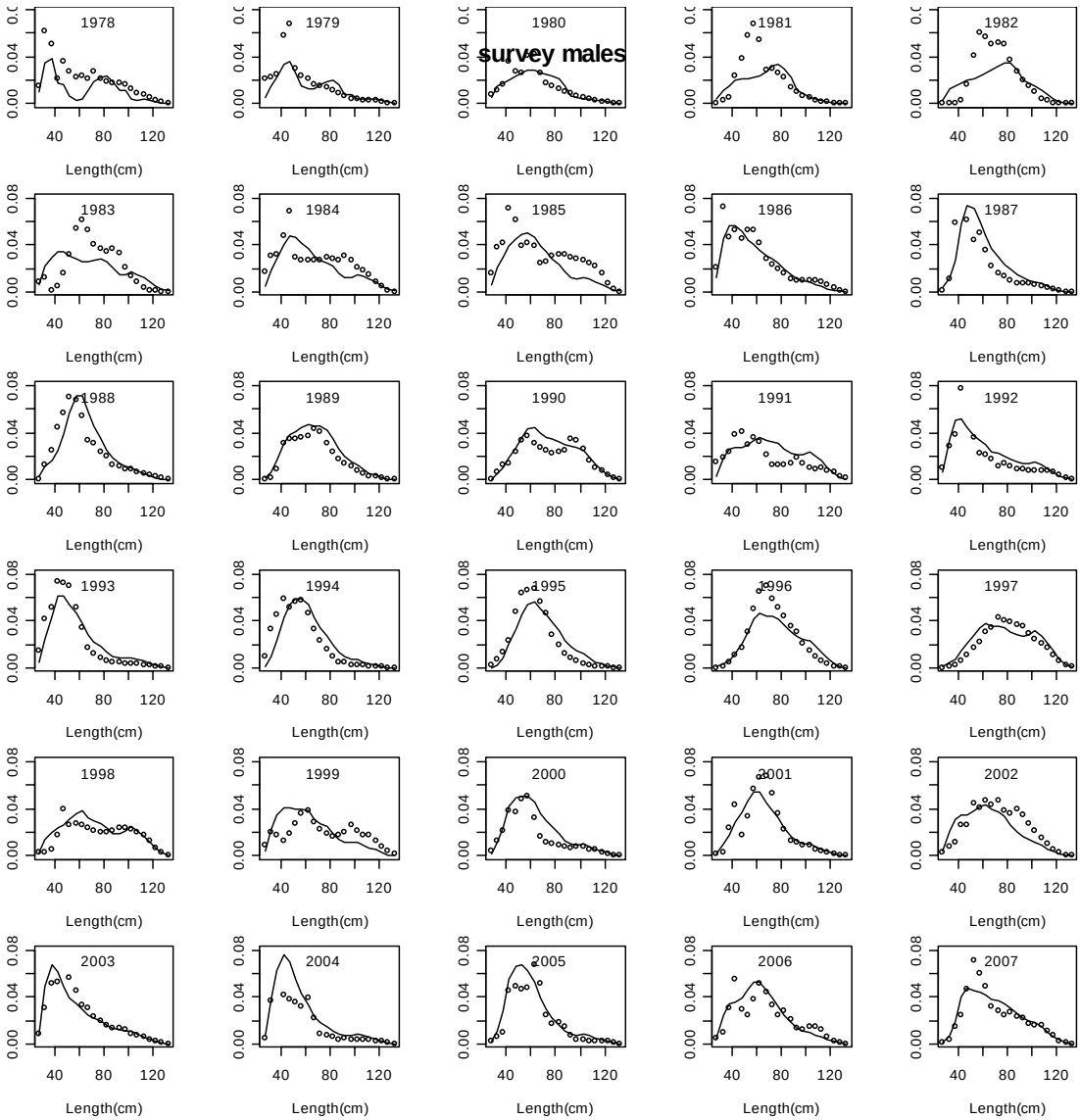


Figure 44. Model (maturity estimated) fit to the survey male size frequency data. Circles are observed survey data. Solid line is the model fit.

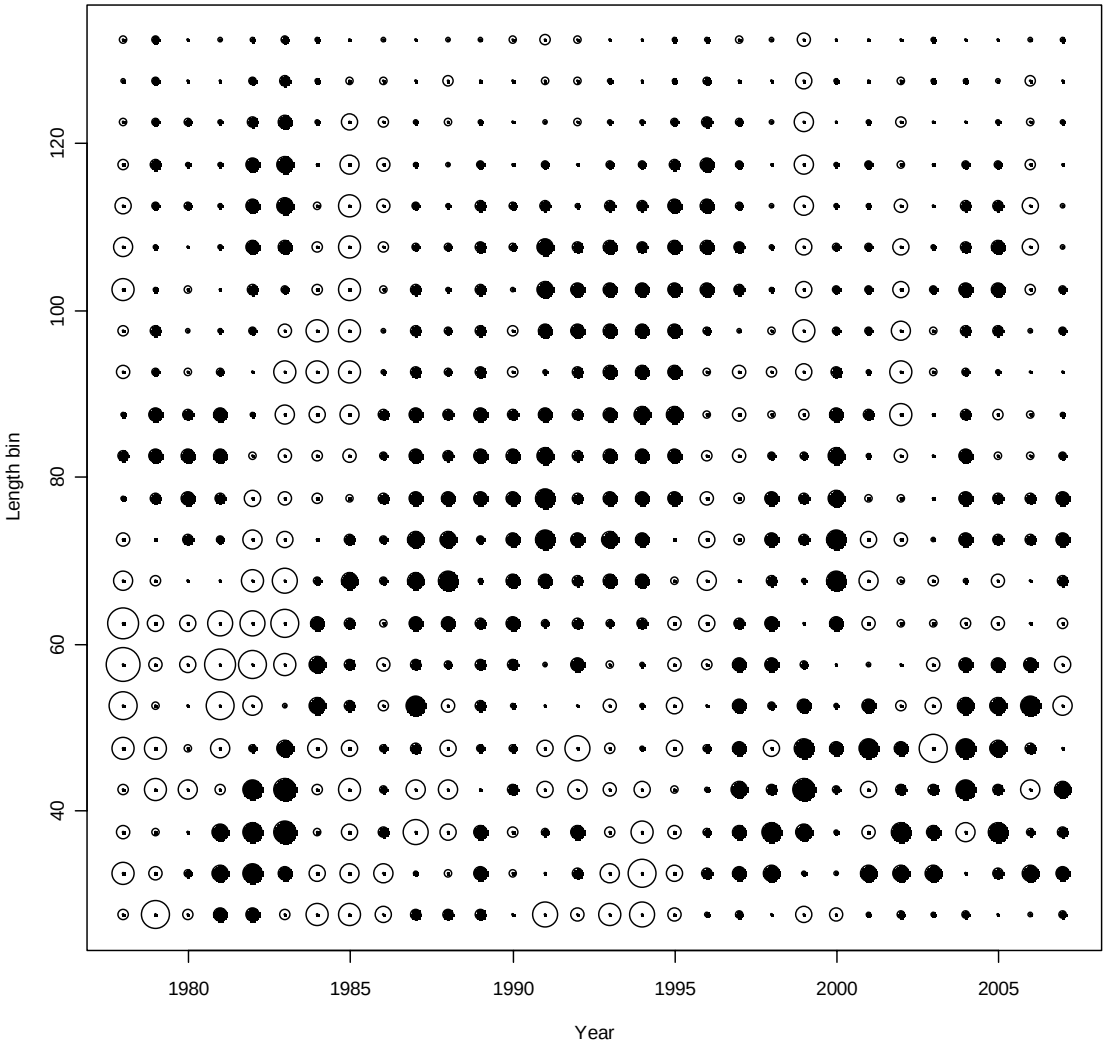


Figure 45. Model with maturity estimated. Residuals for fit to survey male size frequency. . Filled circles are negative residuals (predicted higher than observed).

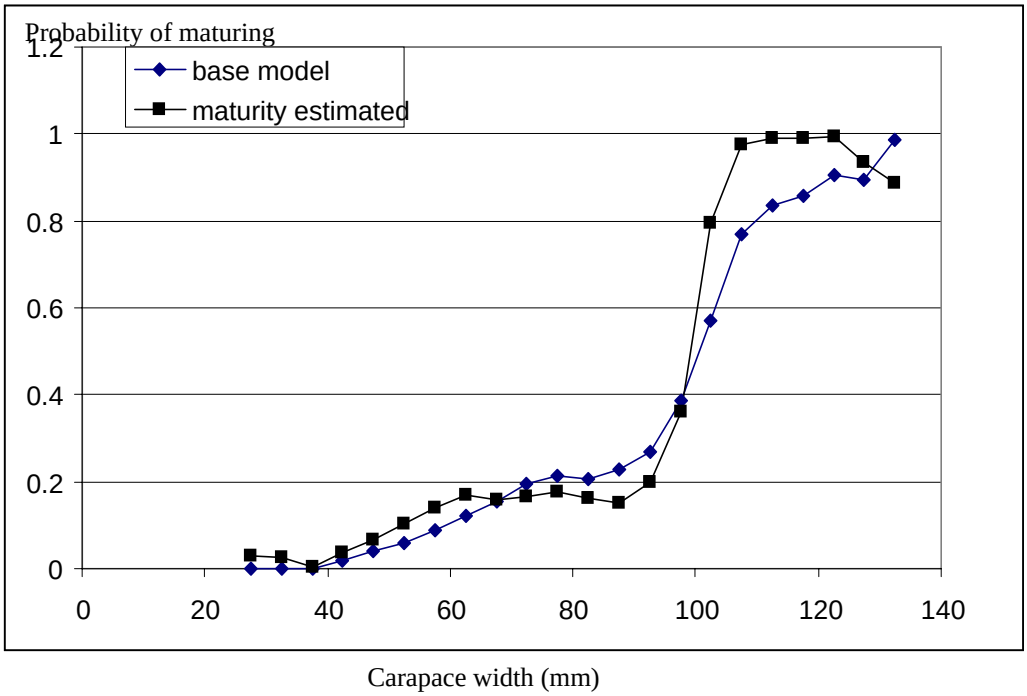


Figure 46. Male probability of maturing for the base model (estimated outside model) and for the alternative model (estimated as a smooth function with 22 parameters).

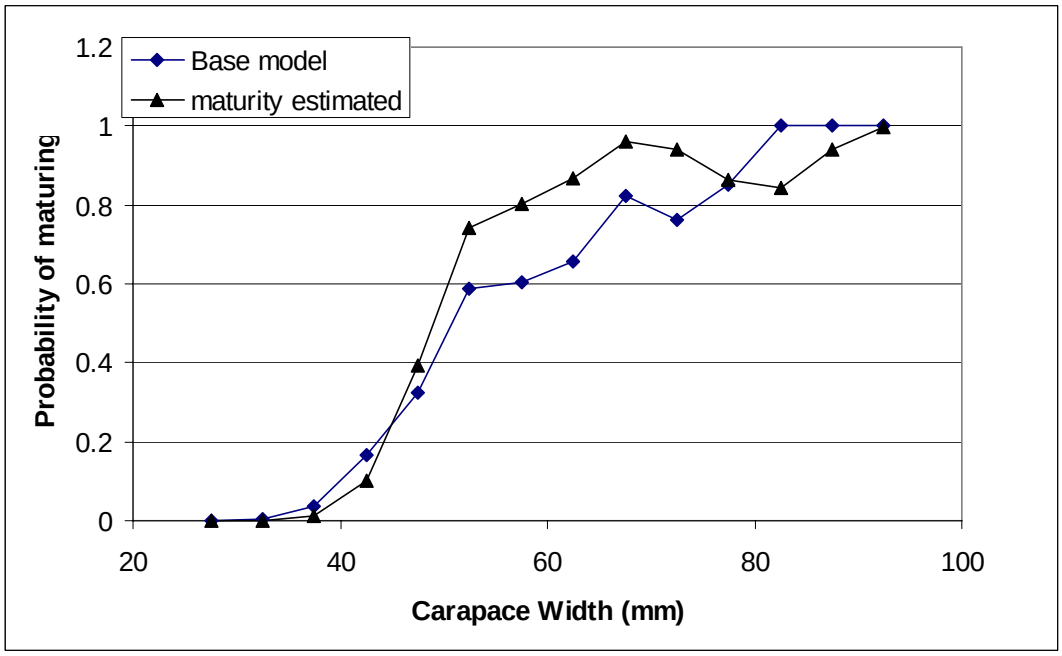


Figure 47. Female probability of maturing for the base model (estimated outside model) and for the alternative model (estimated as a smooth function with 22 parameters).

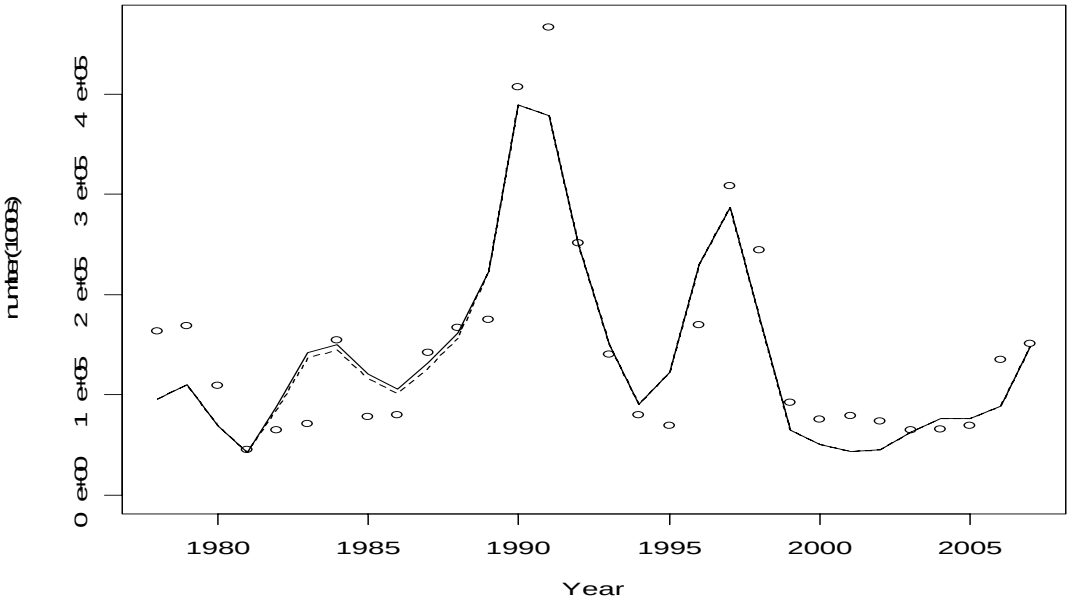


Figure 48. Observed survey numbers of males >101mm (circles), model estimates of the population number of males >101mm(solid line) and model estimates of survey numbers of males >101 mm (dotted line).

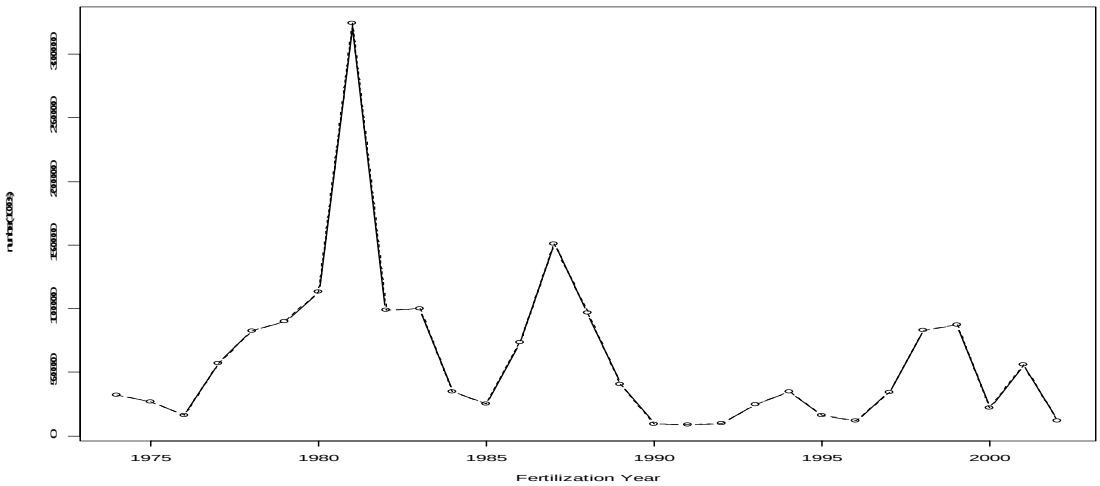

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Figure 49. Recruitment to the model for crab 25 mm to 50 mm. Total recruitment is 2 times recruitment. Male and female recruitment fixed to be equal.

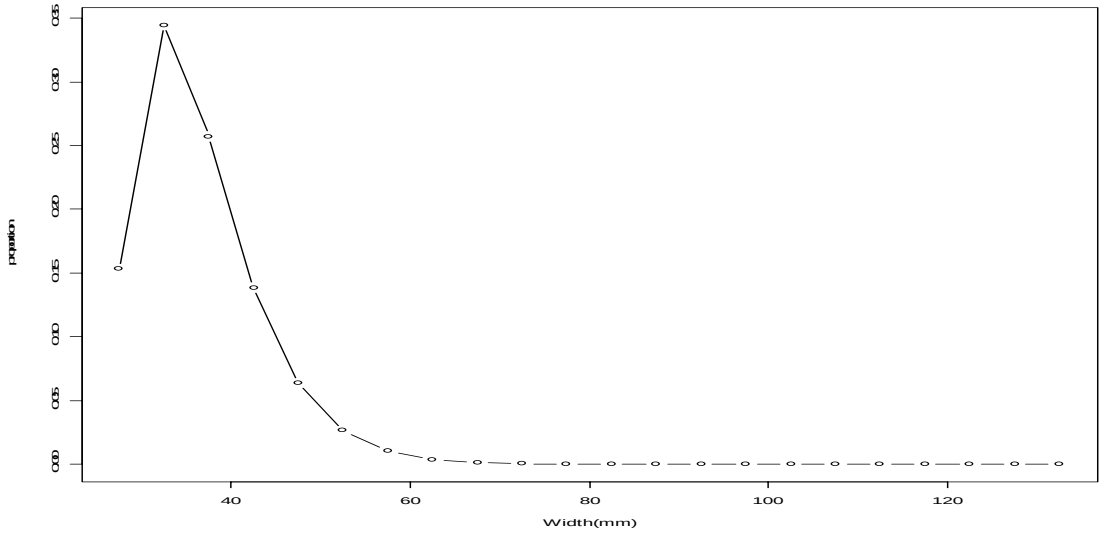


Figure 50. Distribution of recruits to length bins estimated by the model.

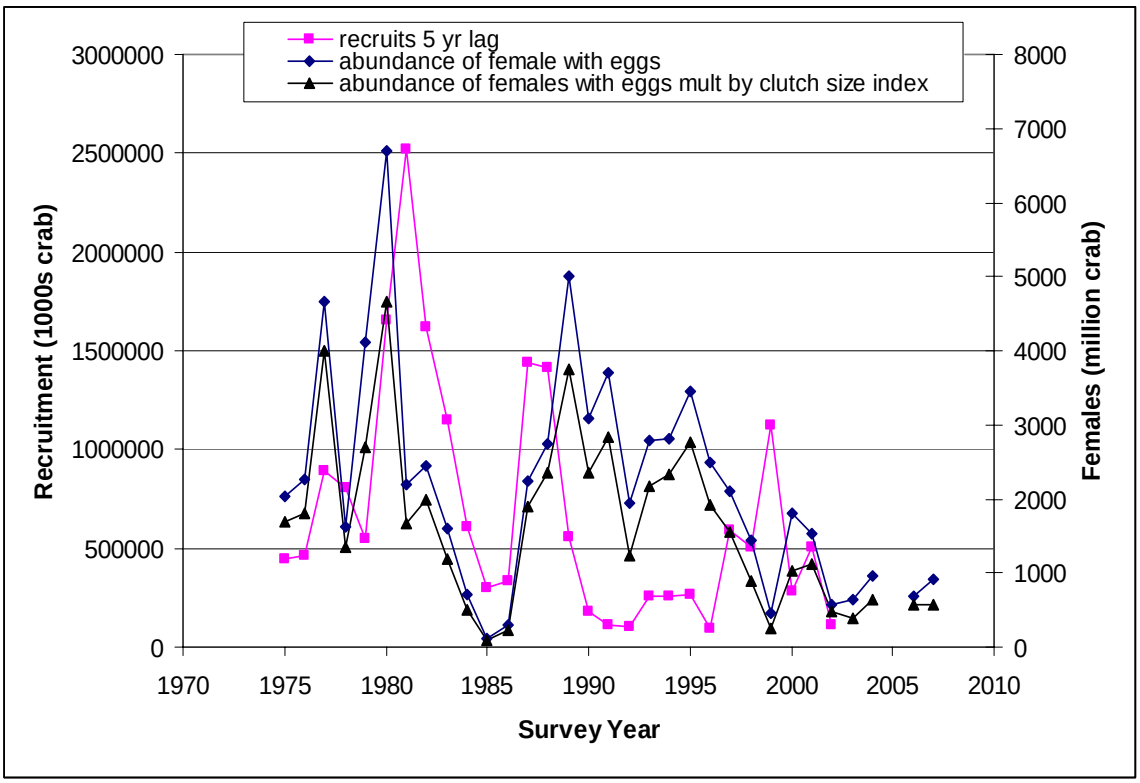

Figure 51. Model estimates of recruitment (fertilization year), survey abundance of females with eggs, and abundance of females with eggs multiplied by the fraction of full clutch from 1975 to 2004.

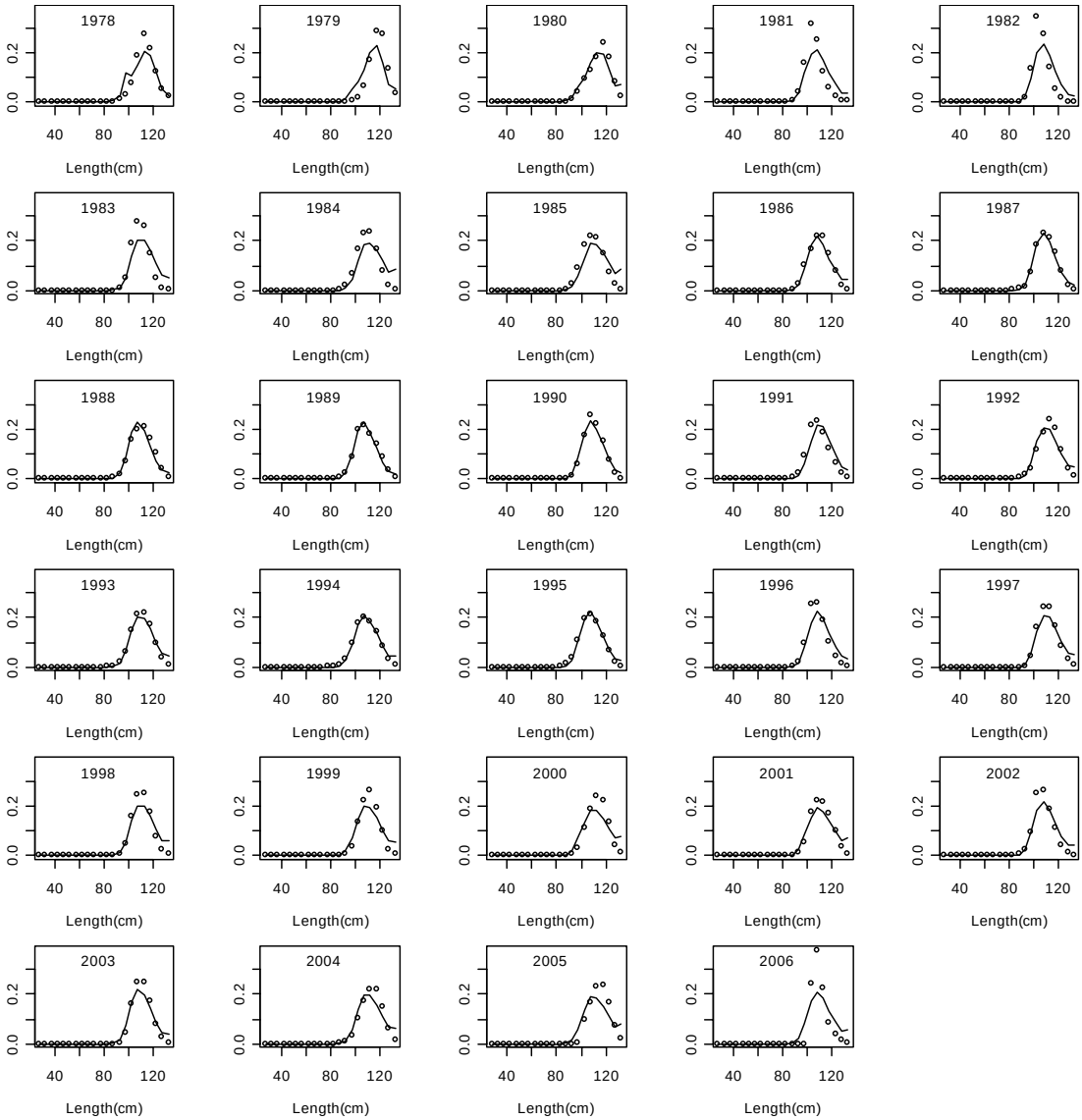

Figure 52. Model fit to the retained male size frequency data, shell condition combined. Solid line is the model fit. Circles are observed data. Year is the survey year.

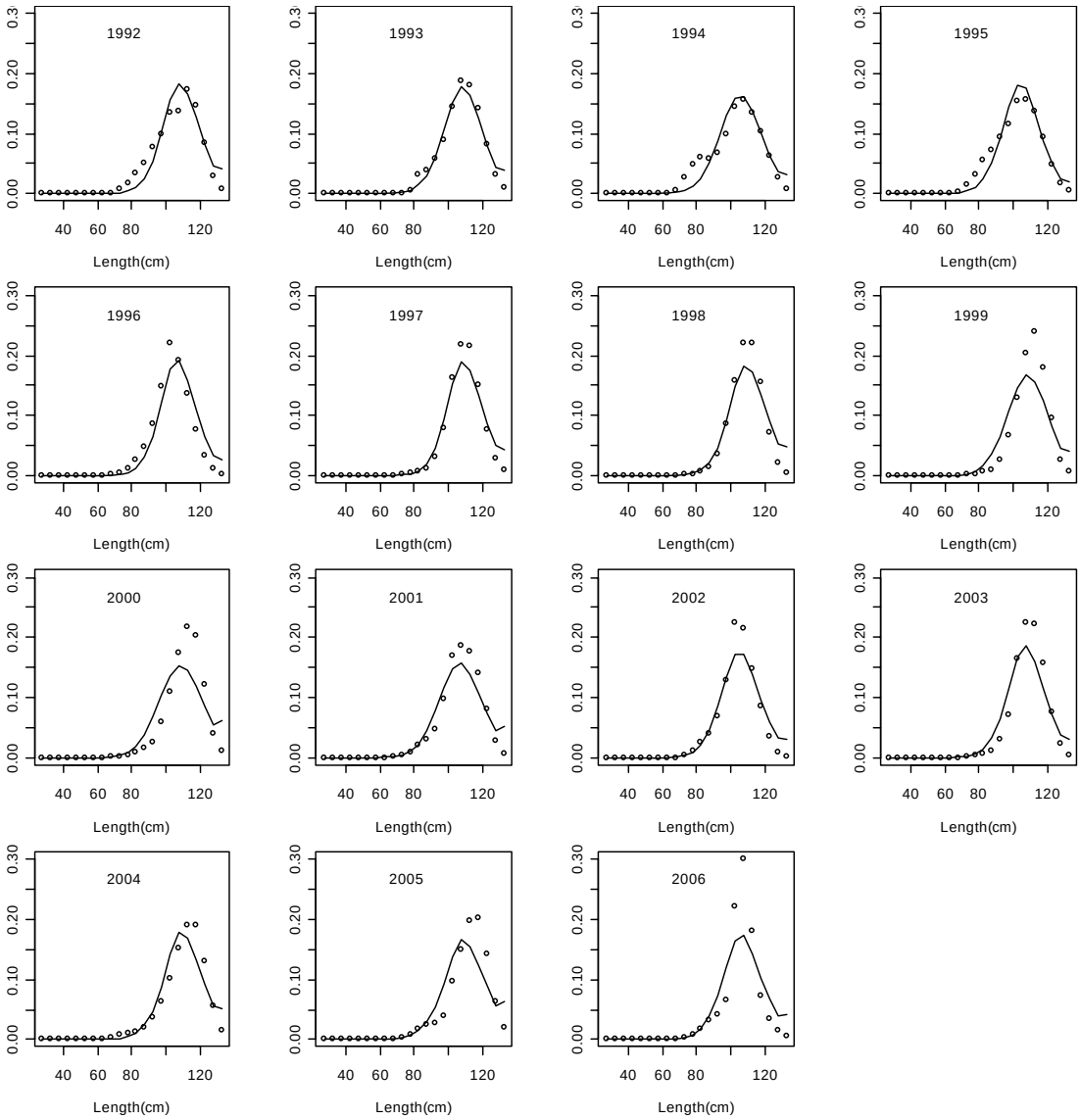

Figure 53. Model fit to the total (discard plus retained) male size frequency data, shell condition combined. Solid line is the model fit. Circles are observed data. Year is the survey year.

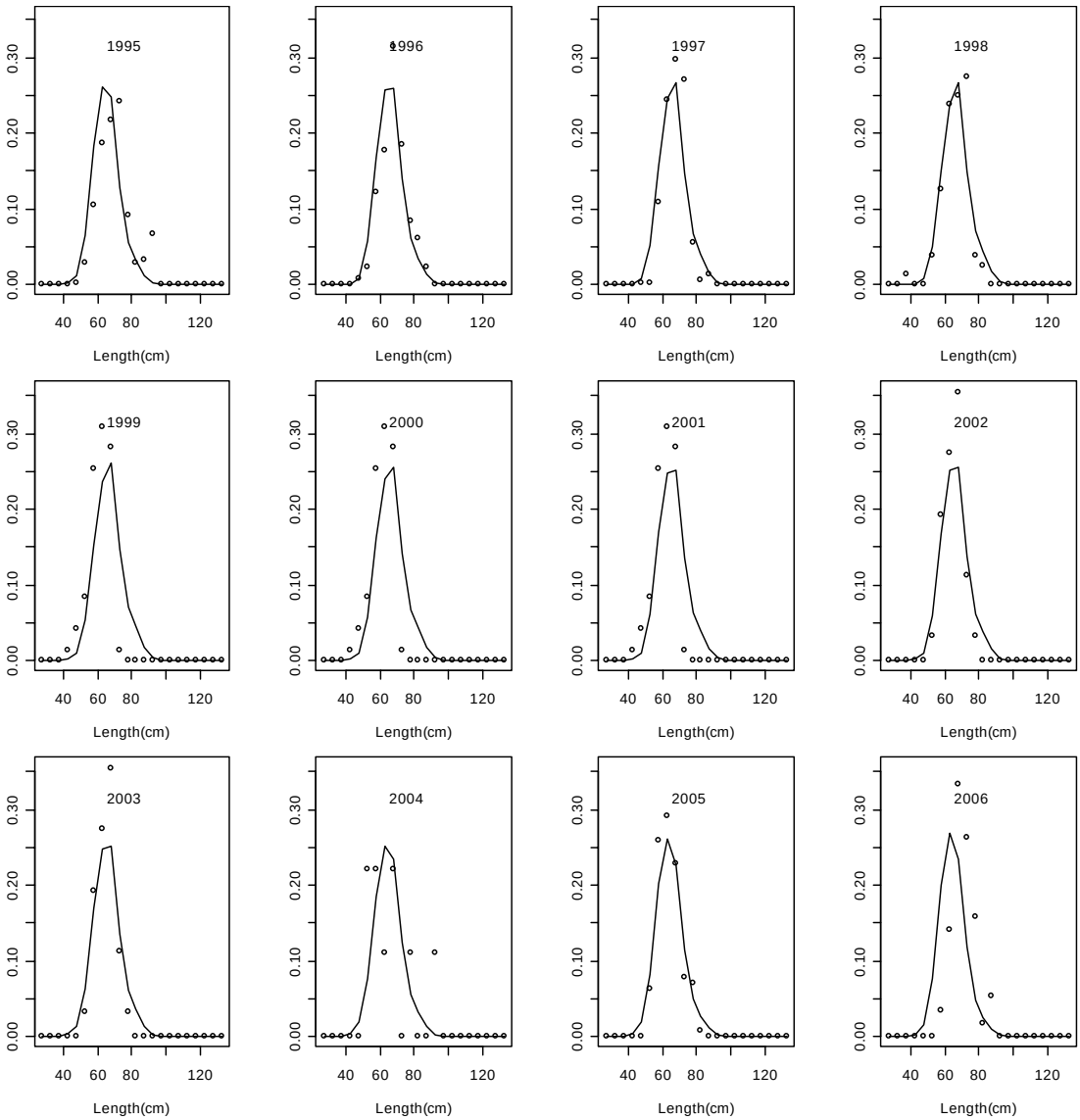

Figure 54. Model fit to the discard female size frequency data. Solid line is the model fit. Circles are observed data. Year is the survey year.

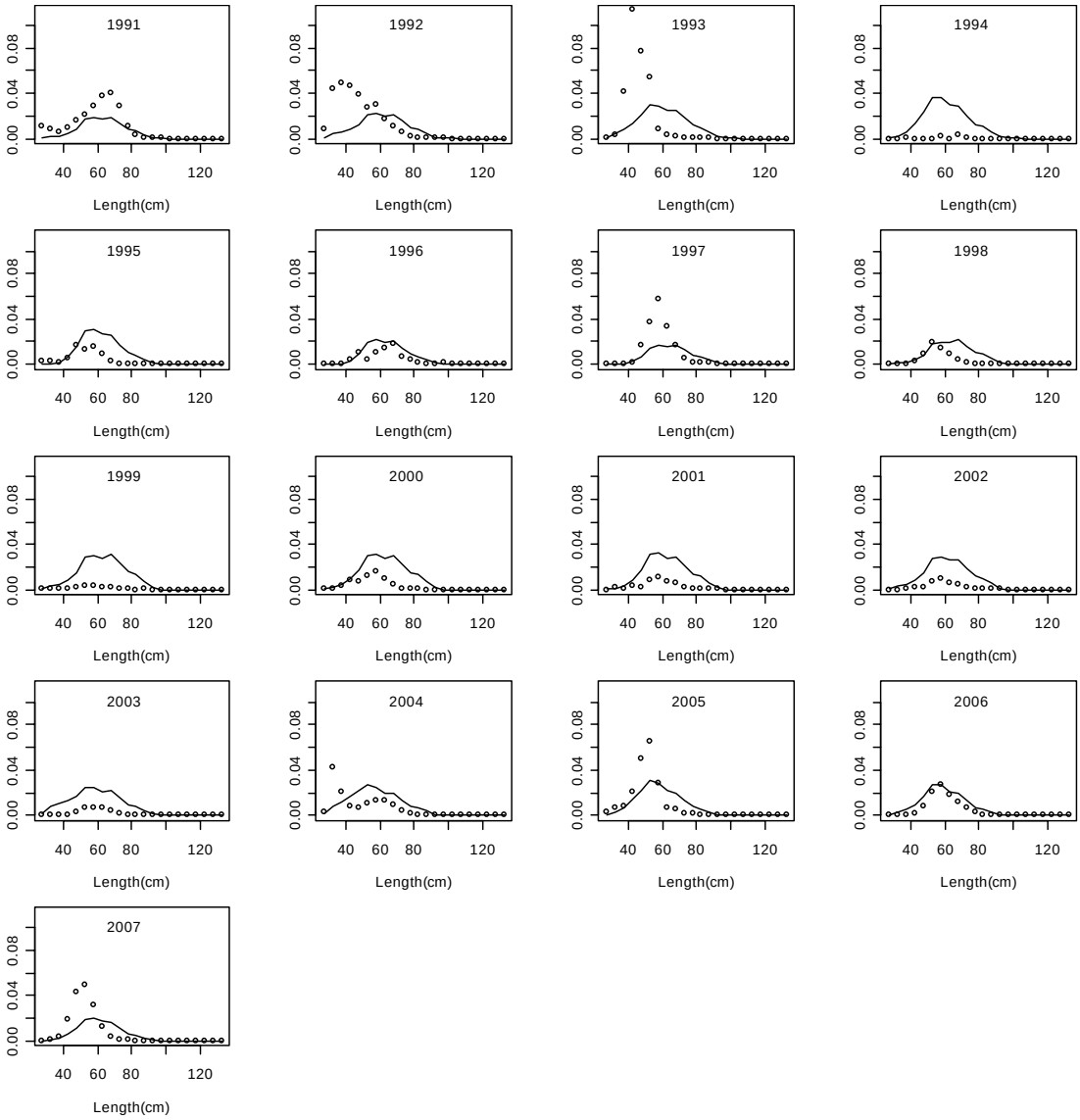


Figure 55. Model fit to the groundfish trawl discard female size frequency data. Solid line is the model fit. Circles are observed data. Year is the survey year.

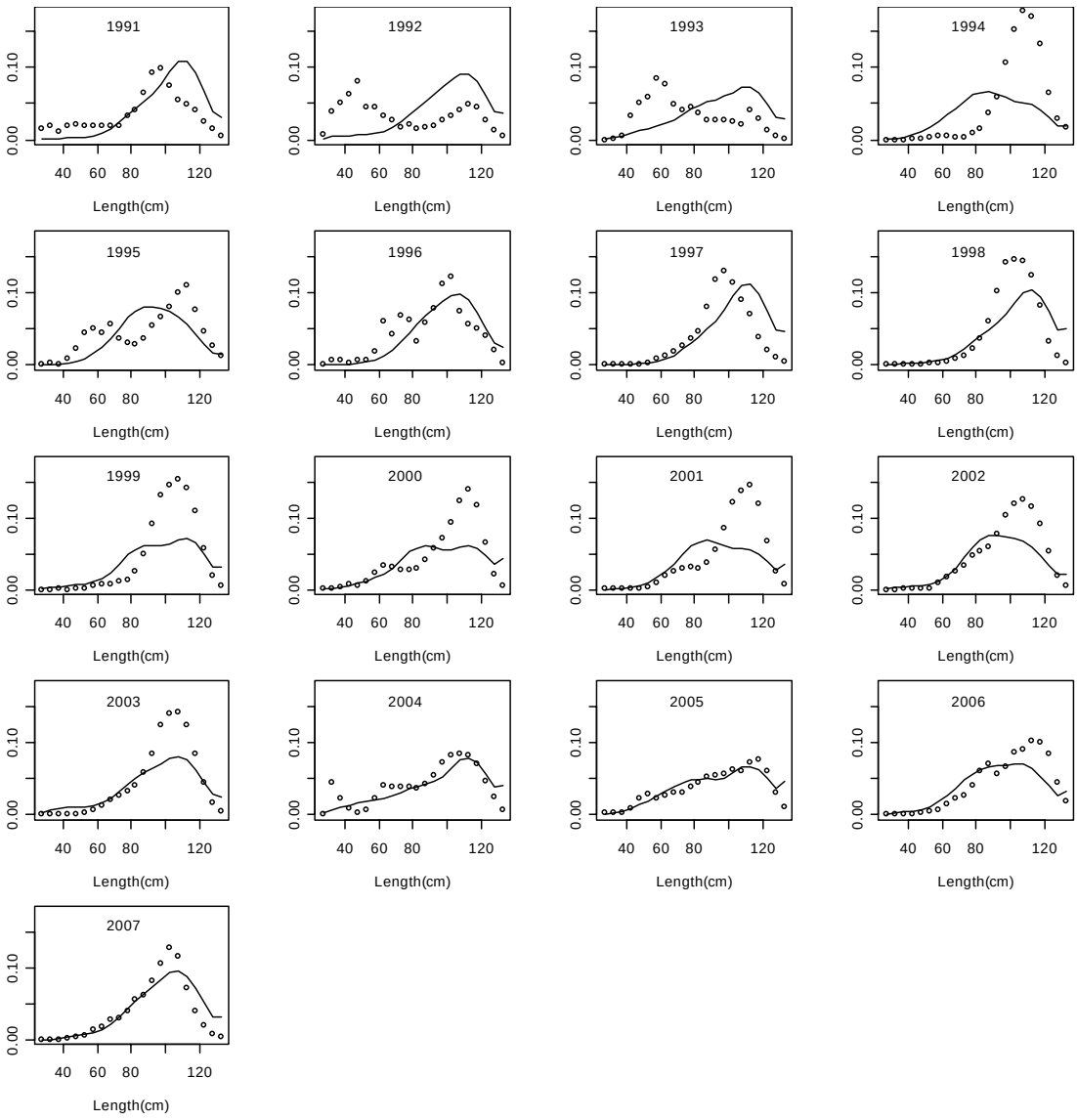


Figure 56. Model fit to the groundfish trawl discard male size frequency data. Solid line is the model fit. Circles are observed data.

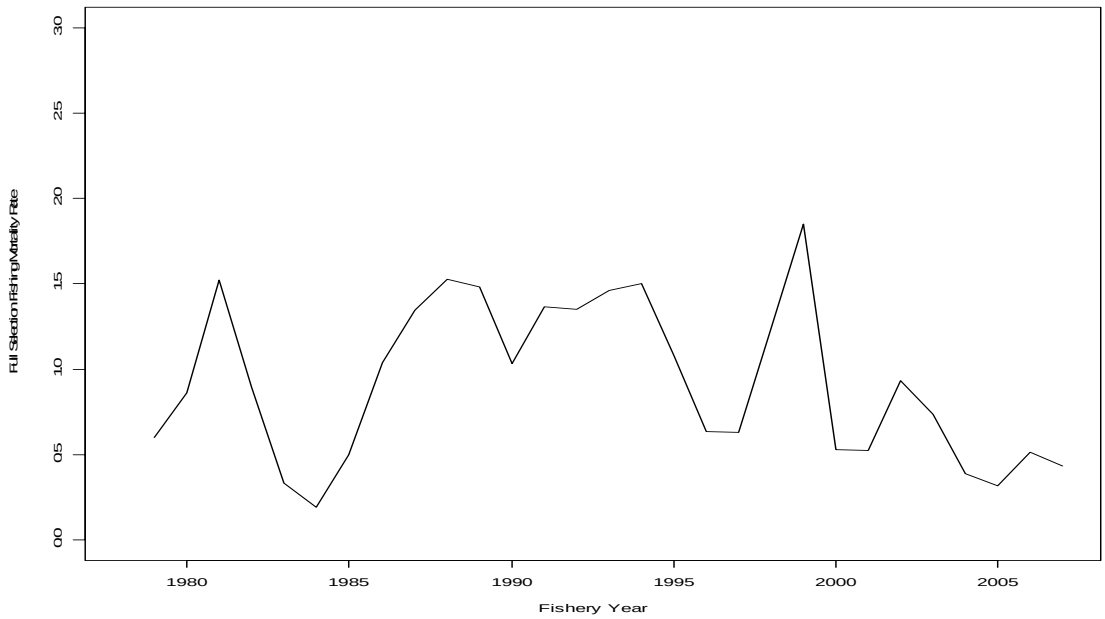


Figure 57. Full selection fishing mortality estimated in the model from 1979 to 2007 fishery seasons (1978 to 2006 survey years).

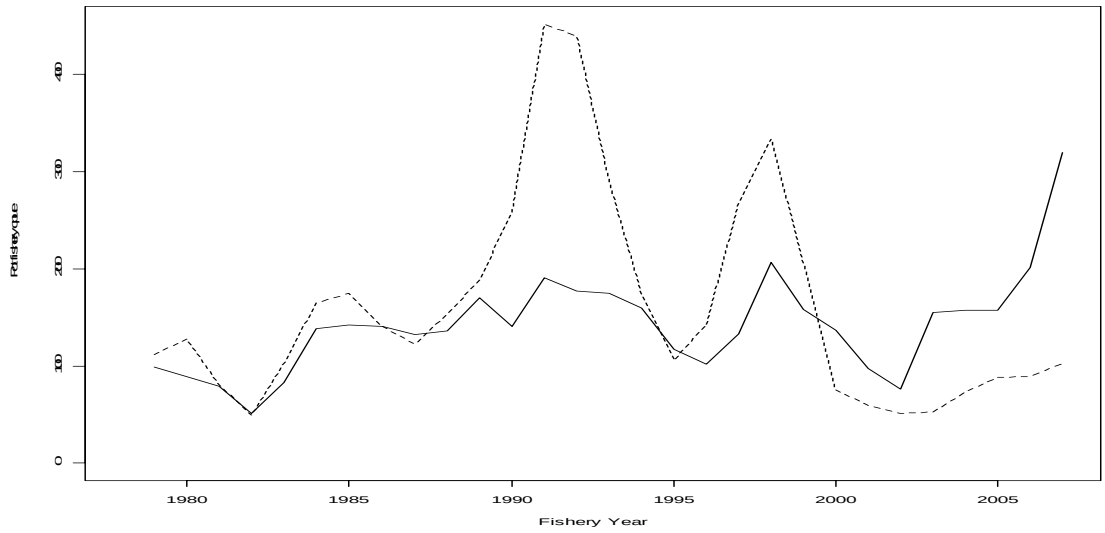


Figure 58. Fit to pot fishery cpue for retained males. Solid line is observed fishery cpue, dotted line model fit.

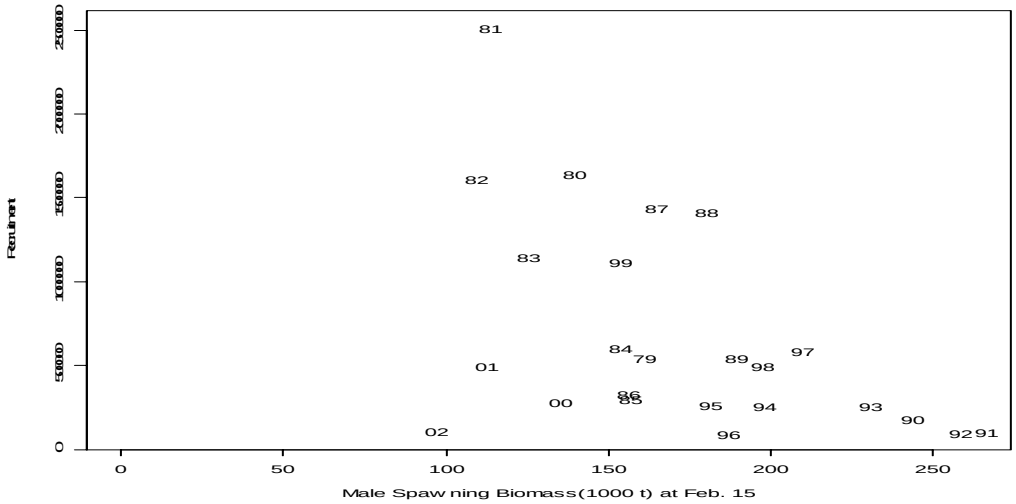


Figure 59. Spawner recruit estimates using male mature biomass at time of mating. Numbers are fertilization year assuming a lag of 5 years. Recruitment is half total recruits in thousands of crab.

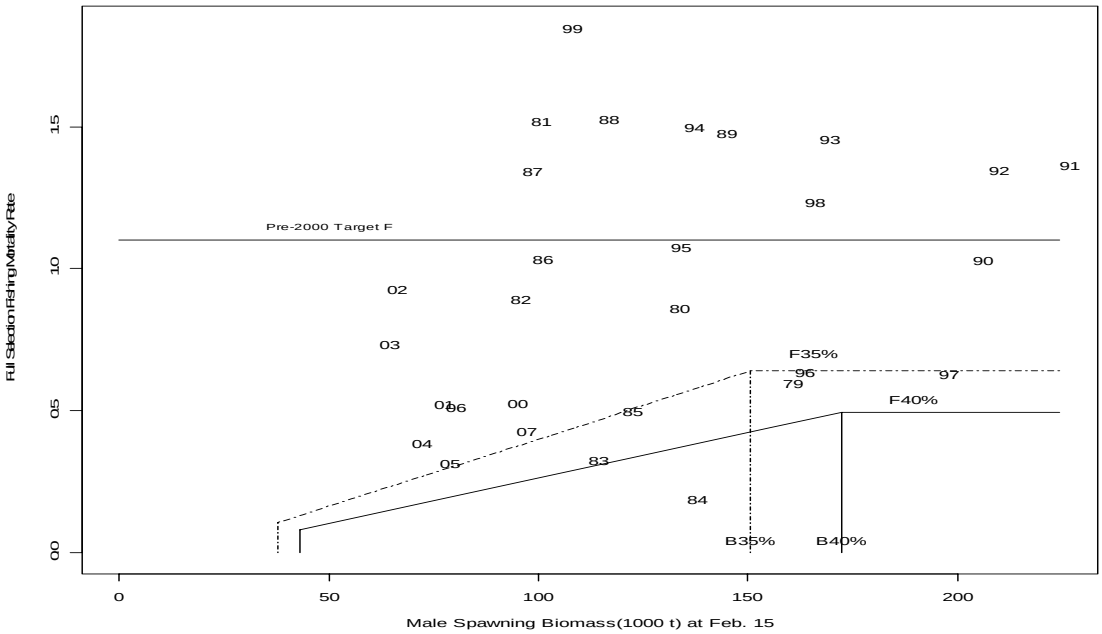


Figure 60. Harvest control rules. Two control rules are shown, one for F40% and one for F35% with alpha = 0.1. The pre-2000 target F of about 1.1 was the target F that resulted from the harvest strategy used before the 2000 fishery season. Vertical lines labeled B40% and B35% are estimated from the product of spawning biomass per recruit fishing at F40% or F35% respectively and mean recruitment from the stock assessment model.

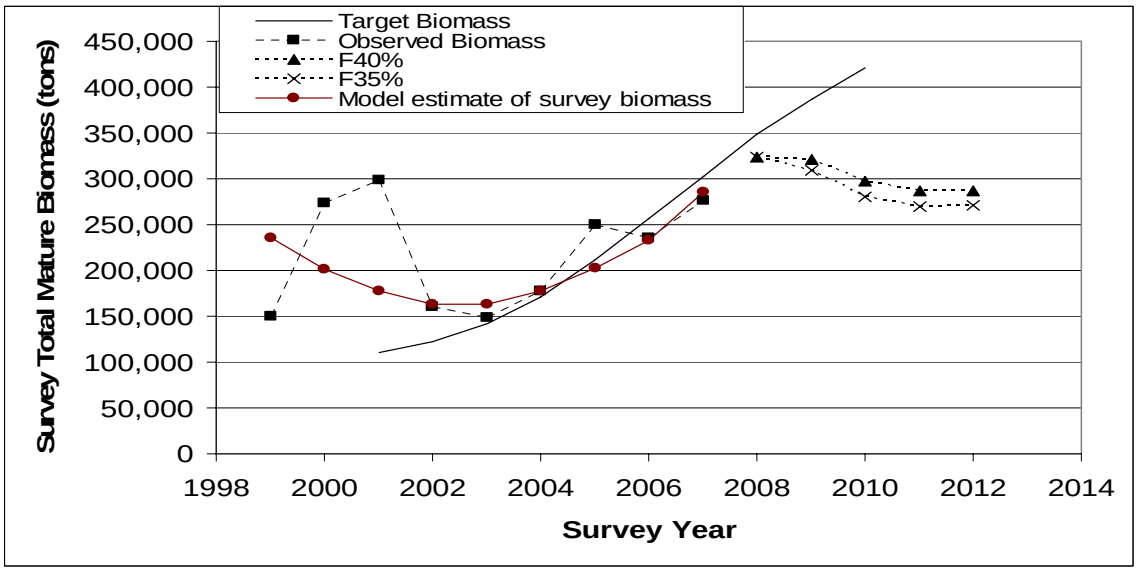


Figure 61. Target survey total mature biomass by year from rebuilding plan simulations, observed survey total mature biomass and model estimates of survey total mature biomass for the F40% and F35% harvest strategies. **2010 is 10 years from the start of the rebuilding plan**

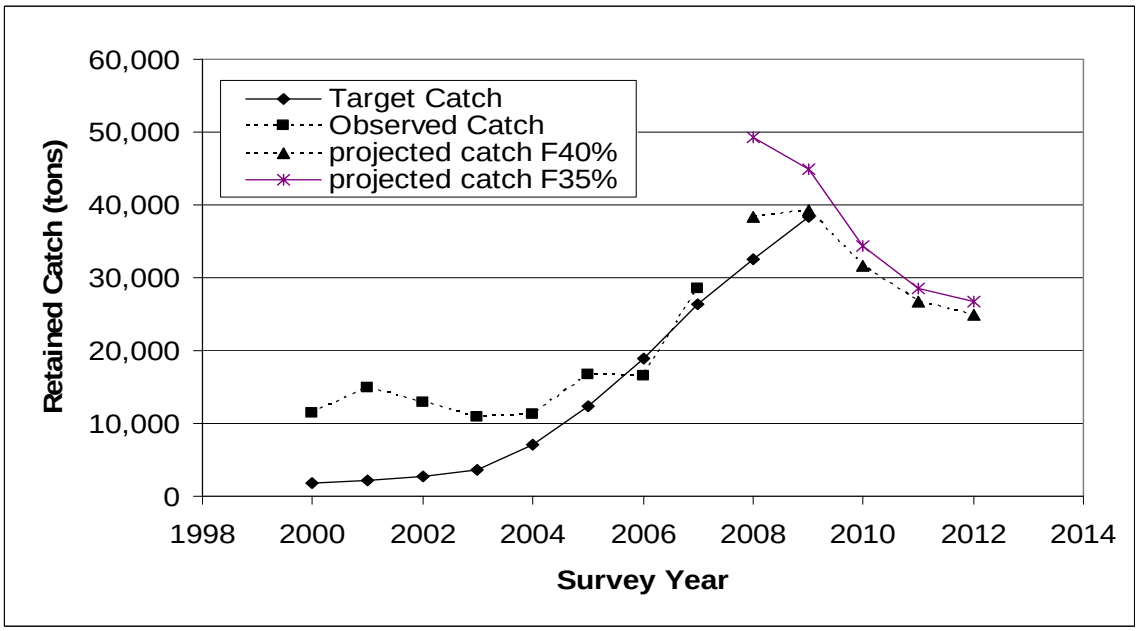


Figure 62. Target average retained catch by year from rebuilding plan simulations, observed retained catch for 2001 to 2007, and projected retained catch for 2008 to 2010 using the F40% and F35% harvest strategies.

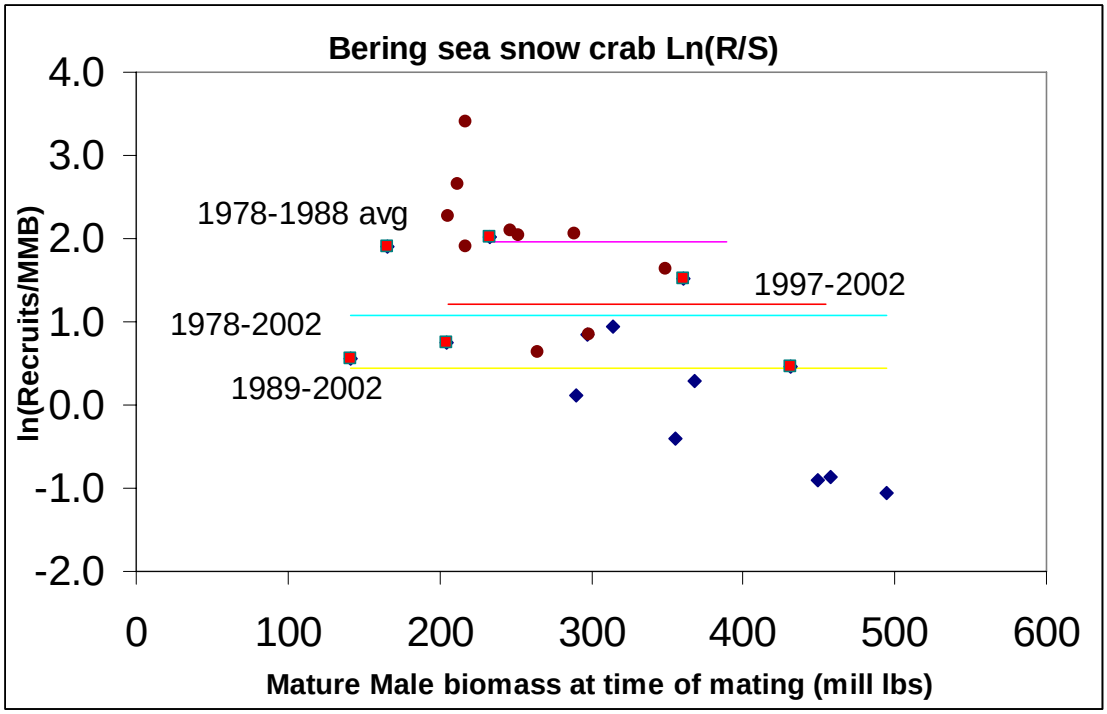


Figure 63. Productivity of snow crab (Ln(recruitment/mature male biomass at mating)) for different levels of mature male biomass at mating. Average values for various time periods are shown on the plot. Different symbols for MMB indicate which average they were included in.

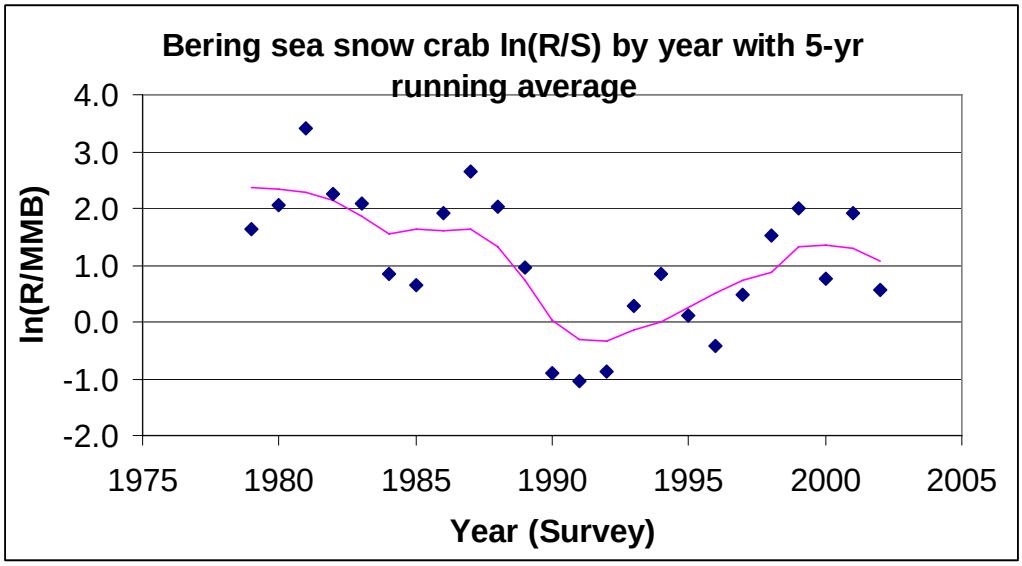


Figure 64. Productivity (ln(recruitment/Mature male biomass at mating)) from 1978 to 2002, with a 5-year running average.

# Appendix A.

Table A.1. Model equations describing the population dynamics.

| | | |
|---|---|---|
| $N_{s,t,1} = pr_l R_{0,s} e^{\tau_{s,t}}$ | $\tau_{s,t} \sim N(0,\sigma_R^2$ | Recruitment |
| DIRECTED POT CATCH<br>$C_{t,s,l} = \sum_{s,l} (1-e^{-F_{t,s,l}Sel_{t,s,l}})e^{-M_s Cmid_l} N_{t,s,l}$<br><br>TRAWL BYCATCH<br>$C_{t,s,l} = \sum_{s,l} (1-e^{-F^{trawl}_{t,s,l}Sel^{trawl}_{t,s,l}})e^{-M_s Cmid_l} N_{t,s,l}$ | $1 \le t \le$<br>$1 \le l \le$ | Catch taken as a pulse fishery at midpoint of catch(survey is considered start of the year). |
| $Nimmature_{new,t+1,s,l+1} =$<br>$(Nimmature_{new,t,s,l} e^{-Zimmat_{new,t,s,l}}) Gr_{s,l}(1-\phi_{s,l})$<br>$Nmature_{new,t+1,s,l+1} =$<br>$(Nimmature_{new,t,s,l} e^{-Zimmat_{new,t,s,l}}) Gr_{s,l}(\phi_{s,l})$<br>$Nmature_{old,t+1,s,l+1} =$<br>$(Nmature_{new,t,s,l} e^{-Zmat_{new,t,s,l}}) + (Nmature_{old,t,s,l} e^{-Zmat_{old,t,s,l}})$ | $1 \le t <$<br>$1 \le l \le$ | Numbers at size. New is less than one year from terminal molt, old is > one year from terminal molt. |
| $SB_{t,s} = \sum_{l=1}^{L} w_{s,l} (Nmature_{new,t,s,l} + Nmature_{old,t,s,l})$ | | spawning biomass by sex |

Table A.1. continued.

| | | | |
|---|---|---|---|
| $Z_{t,s,l} = \sum_{fishery} F_{t,fishery,s,l} + M$ | | | Total Mortality |
| $C_{t,fishery} = \sum_{s} \sum_{l} C_{t,fishery,s,l}$ | | | Total Catch in numbers |
| $p_{t,l} = C_{t,l} / C_t$ | | | proportion at size in the catch |
| $Y_t = \sum_{l=1}^{L} w_{t,l} C_{t,l}$ | | | Catch biomass |
| $F_{t,fishery,s,l} = s_{t,s,l} F_{t,fishery}$ | | | Fishing mortality by length using selecitivities and full selection F |

| | | | |
|---|---|---|---|
| $F_{t,s,l} = \sum_{fishery} F_{t,\,fishery,s,l}$ | | | Total F over all fisheries (total pot and trawl fisheries) |
| $S_{s,l} = \frac{1}{1+e^{-a_s(l-b_s)}}$ | | | Fishery selectivity for total catch by sex s, and size bin l. |
| $S_{male,l} = \frac{1}{1+e^{-a_{male}(l-b_{male})}} \frac{1}{1+e^{-c_{ret}(l-d_{ret})}}$ | | | Fishery selectivity for male retained catch by size bin l is the selectivity for total catch (male) multiplied by the retention curve (ret) |
| Table A.1. continued.<br>$S_{surv,l} = q\frac{1}{1+e^{-a_{surv}(l-b_{surv})}}$ | | | Survey selectivity by size – same for males and females |
| $S_{trawl,s,l} = \frac{1}{1+e^{-a_{s,trawl}(l-b_{s,trawl})}}$ | | | Trawl bycatch selectivity by size and sex |
| $SB_{s,t} = \sum_{s} \sum_{l=1}^{L} w_{s,l} s_{surv,l} N_{s,t,l}$ | | | Total Survey biomass |
| $Gr_{s,l\to l'} = \int_{l'-2.5}^{l'+2.5} Gamma(\alpha_{s,l}, \beta_s)$ | | | Growth transition matrix using a Gamma distribution |
| $width_{t+1} = a_s + b_s width_t$ | | | Mean post-molt width given pre-molt width |

Table A.2. Negative log likelihood components.

| | |
|---|---|
| $\lambda \sum_{t=1}^{T} \left[ \log(C_{t,\,fishery,obs}) - \log(C_{t,\,fishery.pred}) \right]^2$ | Catch using a lognormal distribution. |
| $-\sum_{t=1}^{T} \sum_{l=1}^{L} nsamp_t * p_{obs,t,l} \log(p_{pred,t,l})$ - offset | size compositions using a multinomial distribution. Nsamp is the observed sample size. Offset is a constant term based on the multinomial distribution. |
| offset = $\sum_{t=1}^{T} \sum_{a=1}^{A} nsamp_t * p_{obs,t,a} \log(p_{obs,t,a})$ | the offset constant is calculated from the observed proportions and the sample sizes. |
| $\sum_{t=1}^{ts} \left[ \frac{\log\left[\frac{SB_{obs,t}}{SB_{pred,t}}\right]}{sqrt(2) * s.d.(\log(SB_{obs,t}))} \right]^2$ | Survey biomass using a lognormal distribution, ts is the number of years of surveys. |
| $s.d.(\log(SB_{obs,t})) = sqrt(\log((cv(SB_{obs,t}))^2 + 1))$ | |
| $\lambda \sum_{s=1}^{2} \sum_{t=1}^{T} (e^{\tau_{s,t}})^2$ | Recruitment, where $\tau_{s,t} \sim N(0, \sigma_R^2)$ |
| | |
| | |
| | |

Table A.3. List of variables and their definitions used in the model.

| Variable | Definition |
|---|---|
| T | number of years in the model(t=1 is 1978 and t=T is end year |
| L | number of size classes (L =22) |
| $W_l$ | mean body weight(kg) of crabs in size group l. |
| $\phi_l$ | Proportion of immature crab that become mature at size l. |
| $R_t$ | Recruitment in year t |
| $R_0$ | Geometric mean value of recruitment |
| $\tau_t$ | Recruitment deviation in year t |
| $N_{l,a}$ | number of fish in size group l in year t |
| $pr_l$ | Fraction of annual recruitment (Rt) distributed to length bin l |
| $C_{t,l}$ | catch number of size group l in year t |
| $p_{t,l}$ | proportion of the total catch in year t that is in size group l |
| $C_t$ | Total catch in year t |
| $Y_t$ | total yield in year t |
| $F_{t,s,l}$ | Instantaneous fishing mortality rate for size group l, sex s, in year t |
| M | Instantananeous natural mortality rate |
| $E_t$ | average fishing mortality in year t |
| $\varepsilon_t$ | Deviations in fishing mortality rate in year t |
| $Z_{t,l}$ | Instantantaneous total mortality for size group l in year t |
| GR | Growth transition matrix |
| $S_{s,l}$ | selectivity for size group l, sex or shell condition s. |

Table A.4. Estimated parameters for the model.

| Parameter | Description |
|---|---|
| $\log(R_0)$ | log of the geometric mean value of recruitment, one parameter |
| $\tau_t$ $1978 \le t \le 2007$ , 30 parameters | Recruitment deviation in year t |
| Initial numbers by length for each sex and shell condition, 88 parameters. | Initial numbers by length |
| $\log(f_0)$ | log of the geometric mean value of fishing mortality |
| $\varepsilon_t$ $1978 \le t \le 2007$ , 30 parameters, one set for retained catch, one set for female discard, and one set for trawl bycatch equals 97 total. | deviations in fishing mortality rate in year t |
| Slope and 50% selected parameters of the logistic curve | selectivity parameters for the total catch (retained plus discard) of new and old shell males. |
| Slope and 50% selected parameters of the logistic curve(shell condition combined) | Retention curve parameters for the retained males. |
| Slope and 50% selected parameters of the logistic curve (6 parameters) | Selectivity parameters for survey male and female crabs for three survey periods (1978-81, 82-88,89 to present). |
| Slope and 50% selected parameters of the logistic curve | Selectivity parameters for trawl bycatch male and female |
| Slope and 50% selected parameters of the logistic curve(2 parameters) | Selectivity parameters for crab fishery female bycatch |
| M | Natural mortality |
| Q for survey selectivity, 3 parameters | Survey catchability |
| Parameters for the linear growth function, intercept a and slope b (2 parameters male, 2 parameters female). | Growth parameters estimated from Bering sea snow crab data (14 observations). |
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